H. Douglas Goff
Richard W. Hartel

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Seventh Edition

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H. Douglas Goff
Department of Food Science
University of Guelph
Guelph, ON, Canada

Richard W. Hartel
Department of Food Science
University of Wisconsin
Madison, WI, USA

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Preface

We are pleased to present the seventh edition of the long-standing title, *Ice Cream*. The first edition was written by Prof. Wendell S. Arbuckle of the University of Maryland and published in 1966. Prof. Arbuckle had joined Prof. J. H. Frandsen in coauthoring *Ice Cream and Related Products* in 1961. Frandsen was the senior author of two other ice cream books in 1915 and 1950. So, the lineage of this book can be traced back to the infancy of the industrial ice cream industry. Prof. Arbuckle published subsequent editions in 1972 (second), 1977 (third), and 1986 (fourth), before his death in 1987. In 1996, Prof. Robert T. Marshall of the University of Missouri completely revised the Arbuckle manuscript and published the fifth edition under the names of Marshall and Arbuckle. We (H. D. Goff and R. W. Hartel) joined Prof. Marshall to prepare the sixth edition, published in 2003, under the names of Marshall, Goff, and Hartel. Prof. Marshall has since retired, leaving us to prepare the seventh edition.

We have completely revamped this edition. Every chapter has been rewritten, updating with state-of-the-art knowledge and new references as appropriate. Material has been realigned to make what we feel is a more coherent presentation. New chapters on ice cream structure (Chap. 11) and ice cream shelf life (Chap. 12) have been added. We have made the book suitable for an international audience by converting completely to SI units, although we indicate the equivalent US unit as appropriate, and we have incorporated international production and consumption data, legislation information, and global industry practices.

Both of us have been involved in ice cream research for 25 years. Prof. Goff has also been teaching ice cream courses at the University of Guelph and in various places around the world for 25 years. This book reflects our combined knowledge. We have maintained the focus on science and technology of ice cream. We do not present any information about marketing, retailing or restaurant operations. The book is intended for people with a science and technology background, or at least those who want to learn more of the technical aspects of ice cream production. It is intended for anyone involved in the industry, from Research and Development, Quality Control, or Manufacturing in large-scale operations right through to small-scale entrepreneurs who want to understand the principles behind the product they

are making. Suppliers to the industry should gain a tremendous insight into the complexities of the product, the functional roles of the ingredients, and the manufacturing and cleaning processes employed by the industry. And, of course, it is for students, both Undergraduate students who are learning about ice cream, perhaps with the intention of entering the industry some day, and Graduate students who are furthering our knowledge with their research. The students of today are the industry leaders of tomorrow.

We dedicate this edition to our own students who have contributed thousands of hours to ice cream science. This edition has been a year in the making and much family time has been consumed, so sincere appreciation is extended to our families without whose support and encouragement we would not have accomplished our goals. We also gratefully acknowledge all of the contributors to various chapters.

Guelph, ON, Canada — H. Douglas Goff
Madison, WI, USA — Richard W. Hartel

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Introduction

Frozen dairy desserts are characterized by containing milk solids (which may or may not include milk fat) and being consumed in the frozen state, and they are frequently also aerated. Within the frozen dairy desserts category, ice cream is the most widely consumed product. Our meaning of ice cream varies globally, due to differing regulations and traditions of composition, and hence can be found with many formulation variations:

- Regular ice cream (usually defined by minimum levels of fat, which may be dairy or nondairy, and also minimum levels of either food solids or milk protein or milk solids, alone or in combination).
- Higher-fat premium-type products, although these usually also meet the normal definitions of ice cream.
- Low-fat or nonfat versions or no-sugar-added or sugar-free versions, which may or may not meet the usual definitions of ice cream.

All of these categories are available in multiple flavors and shapes (including handheld or impulse products). The category can be further divided according to hard-frozen products, those that contain a second freezing step after the dynamic freezing step, and soft-frozen products, those that are consumed directly and immediately after dynamic freezing with no hardening step. Also, frozen dairy desserts include frozen custard, frozen yogurt and sherbet, all of which could be hard or soft frozen, and frozen milkshakes and smoothies. Frozen desserts in general (again, characterized by being consumed in the frozen state and may also be aerated) would also include products that contain no milk-derived ingredients, for example, sorbets, water ices, or plant-protein-based products such as soy/tofu frozen desserts.

Ice cream, and most all of the other frozen desserts described above, generally contain seven categories of ingredients: fat, milk solids-not-fat (the principal source of protein), sweeteners, stabilizers, emulsifiers, water, and flavors. For the wide range of frozen desserts, production is similar. Mix, the unfrozen blend of ingredients,

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is manufactured by blending, pasteurizing, homogenizing, cooling, and aging at 4 °C. Subsequently the mix is frozen to approximately −5 °C through a scraped-surface freezer while under shear ("dynamic" freezing, which incorporates air and produces small, discrete air bubbles and ice crystals). Flavoring materials that will remain discrete in the product (fruits, nuts, candy, or bakery pieces) can be added after dynamic freezing, followed by packaging or shaping (as in the case of "novelty" or "impulse" products). Finally these products are blast frozen to a temperature of −25 to −30 °C. Although our book is entitled "Ice Cream," and has been since its inception more than 50 years ago, it should be recognized that our content coverage is sufficiently broad to encompass all frozen dairy desserts, indeed all "ice cream-like" frozen desserts, due to similarities in both composition and manufacturing.

The Changing Characteristics of the Industry

The ice cream industry globally consists of a few multinational (e.g., Unilever, Nestle, Häagen-Dazs, Baskin-Robbins) and national firms that supply products sold either through food or mass merchandising stores or retail/food service, and a very large number of small-medium local or regional firms that supply products sold through local retailers or scooping shops. Globally, these artisanal ice cream manufacturers make up about 10% of production volume but as much as 20% of the value of the industry, although precise numbers are difficult to determine. The ice cream industry is estimated to be valued at US$ 73.8 billion in sales worldwide (data from Euromonitor International, 2011), growing at >5% per year (2006–2010) with the biggest growth in Latin America, Eastern Europe, Africa, and the Middle East (all growing at >10% per year, 2006–2010), although Western Europe and North America, the two largest markets, show much lower growth. Western Europe represents the largest market, with sales of US$ 24.1 billion in 2010, followed by North America at US$ 17.1 billion, Asia Pacific at US$ 15.9 billion, Latin America at US$ 6.5 billion, and Eastern Europe at US$ 4.9 billion. By country, the US market was the largest, at US$15.6 billion, followed by Italy at US$ 6.8 billion, China at US$ 4.4 billion, and Australia, Brazil, Russia, and the United Kingdom, all at US$ 2.2–2.4 billion.

Ice cream is considered by most people to be a dairy product, and if manufactured with fresh cream and fresh milk as ingredients, more than 80% of its content is dairy-derived. However, if manufactured with a nondairy fat and reconstituted milk powder, in many cases less than 10% of its content is dairy-derived, and thus it can just as easily be considered a food product with a dairy ingredient. Hence, some manufacturers, particularly in the United States, are multiproduct dairy companies while globally, ice cream is also manufactured by several multinational food companies, including Nestle, Unilever, and General Mills, who do not necessarily produce other dairy products.

In North America, the organization that represents most of the large firms of the industry is the International Dairy Foods Association (IDFA), headquartered in Washington, DC. Many of the small firms belong to the National Ice Cream Retailers

Association (NICRA), headquartered in Columbus, OH. Across the world, there are many other ice cream-specific trade associations, such as the Ice Cream Alliance in the UK, or national dairy trade associations that also represent ice cream interests. In Europe, ice cream associations of the various EU member countries are represented by Euroglaces, the European Ice Cream Association, with headquarters in Brussels. Globally, the International Ice Cream Consortium is an association of noncompeting ice cream companies that cooperate on technical and business matters. The International Dairy Federation, headquartered in Brussels, also has an interest in the ice cream sector, having sponsored at least three major international conferences on the subject in the last 15 years.

The history of frozen desserts shows that great efforts have been made to produce and consume these highly enjoyable foods. Those who first consumed them were the elite of society. Today's offerings cater not only to more wealthy consumers but also to the masses, with prices of products in the market varying by as much as a factor of 10 for equivalent volumes. It is estimated that 90% of Americans eat ice cream. The average retail price of supermarket ice cream is about $2.00–3.00 per liter, about eight servings, making the cost of a serving average less than $0.25–0.40, a remarkable buy for the nutrition and appetite satiation that it brings.

Production and Consumption Trends

Global production of ice cream was 16.3 billion liters in 2010, up from 15.3 billion liters in 2006 (Table 1.1). Of the global production in 2010, 31% was in Asia Pacific, 29% in North America, 20% in Western Europe, 7% in Eastern Europe, and 6% in Latin America. By country, US was the largest producer at 4.4 billion liters, followed by China at 2.9 billion liters, Japan at 0.9 billion liters, Germany at 0.65 billion liters, and Italy at 0.6 billion liters (Table 1.1). Global per capita consumption of ice cream and related products (it is difficult to know exactly what is included in these data from different countries, due to differing regulations on the definition of "ice cream") is presented in Table 1.2. In 2010, Australia ranks first at 17.9 L, followed by New Zealand at 15.8 L, the United States at 14.2 L, Finland at 12.5 L, Canada at 10.5 L, and Italy at 10.0 L. Many Western European countries fall into the range of 7–10 L per capita. Even though China and Japan are world leaders in production, their per capita consumption is much lower than North America and Western Europe, with Japan at 6.9 L and China at 2.1 L, below the world figure at 2.4 L (Euromonitor data 2011). It is also interesting to compare the US$ annual expenditure on ice cream per capita by country, which provides not only a measure of the size of the market but also an indication of the sophistication of products in that market, although average cost of living in these countries also needs to be taken into account. By this measure, in 2010 Italy is the top at US$ 113 per capita, followed by Australia at US$ 103, Finland at US$ 88, Norway at US$ 84, Sweden at US$ 71, and Denmark at US$ 65. The USA sits at US$50 per capita while China is at US$ 3 per capita on ice cream expenditures.

Table 1.1 Global ice cream production by year, region, and country, '000 kL (data from Euromonitor International, 2011)

	2006	2007	2008	2009	2010
World	15,370.0	15,678.8	15,742.7	16,001.1	16,347.5
Asia Pacific	4,317.9	4,536.9	4,724.5	4,722.5	4,901.1
North America	4,898.2	4,793.8	4,592.7	4,726.9	4,742.9
USA	4,531.0	4,430.1	4,230.5	4,367.4	4,386.4
Western Europe	3,226.2	3,284.5	3,300.4	3,384.1	3,436.7
China	2,484.7	2,639.0	2,776.1	2,740.2	2,868.6
Eastern Europe	1,131.1	1,158.0	1,147.6	1,111.8	1,128.9
Latin America	874.7	949.9	991.5	1,031.7	1,075.3
Japan	873.9	880.9	887.5	886.1	884.0
Germany	674.3	677.1	659.9	656.1	651.7
Italy	546.1	572.6	561.8	594.2	607.0
Middle East and Africa	491.5	517.7	542.5	570.1	597.6
United Kingdom	495.4	488.1	496.2	515.1	531.7
Russia	555.4	540.8	517.7	505.6	499.1
Australasia	430.4	438.0	443.4	454.0	464.9
Australia	362.2	368.9	374.6	385.8	396.1
France	370.5	368.7	369.4	386.9	395.3
Brazil	267.3	310.2	325.4	345.3	369.2
Canada	367.2	363.6	362.2	359.5	356.5
Spain	337.7	342.8	349.3	349.8	350.9
South Korea	266.6	270.1	262.4	263.8	266.2
Turkey	125.8	156.2	179.7	190.9	203.5
India	95.1	115.3	137.6	158.7	183.3
Argentina	135.0	146.5	159.3	169.7	175.6
Ukraine	171.5	185.8	177.9	149.7	164.2
Poland	113.7	123.9	134.8	143.0	152.5
Indonesia	113.6	123.3	135.1	142.7	149.2
Chile	124.5	129.0	132.7	134.0	136.9
Iran	99.3	104.8	110.4	116.9	124.0
Mexico	111.3	115.5	112.6	112.7	113.4
Netherlands	83.3	85.3	89.3	95.4	100.2

Global and regional market shares by volume and by monetary value according to point of manufacture/consumption—take-home products, impulse products, and artisanal/parlor sales—are shown in Tables 1.3 and 1.4. The take-home category is defined as grocery store purchases and home consumption, the impulse category is categorized by handheld, single serving eat-on-the-spot products (sometimes referred to as novelty products), while the artisanal and parlor category is defined as being manufactured at the site of purchase and consumption or sold directly by the manufacturer to the consumer (e.g., ice cream parlors and street vendors). Impulse products make up the largest share by volume globally, followed closely by take-home products, although the value of take-home products is much lower than the value of impulse products. The impulse product category has been increasing in market share over the period 2006–2010, especially by monetary value. The artisanal

Table 1.2 Per capita consumption of ice cream and related products in selected countries, 2006–2010 (data from Euromonitor International, 2011)

	2006	2007	2008	2009	2010
Australia	17.5	17.5	17.5	17.7	17.9
New Zealand	16.3	16.3	16.1	15.8	15.8
USA	15.2	14.7	13.9	14.2	14.2
Finland	12.8	12.8	12.7	12.6	12.5
Canada	11.2	11.0	10.9	10.7	10.5
Italy	9.3	9.7	9.4	9.9	10.0
Norway	8.9	9.2	9.4	9.6	9.8
United Kingdom	8.2	8.0	8.1	8.4	8.6
Denmark	8.9	8.7	8.7	8.5	8.4
Chile	7.6	7.8	7.9	7.9	8.0
Germany	8.2	8.2	8.0	8.0	8.0
Sweden	8.0	7.5	7.6	7.7	7.7
Spain	7.7	7.7	7.8	7.7	7.6
Portugal	7.5	7.7	7.8	7.6	7.5
Ireland	7.9	7.6	7.3	7.3	7.2
Japan	6.8	6.9	7.0	6.9	6.9
Slovenia	5.7	6.0	6.2	6.4	6.5
Belgium	6.2	5.9	5.8	6.1	6.3
France	6.1	6.0	5.9	6.2	6.3
Netherlands	5.1	5.2	5.5	5.8	6.1
South Korea	5.5	5.6	5.4	5.4	5.4
Argentina	3.5	3.7	4.0	4.2	4.3
Ukraine	3.7	4.0	3.9	3.3	3.6
Russia	3.9	3.8	3.6	3.6	3.5
World	2.3	2.4	2.3	2.4	2.4
China	1.9	2.0	2.1	2.1	2.1
Brazil	1.4	1.6	1.7	1.8	1.9
Mexico	1.1	1.1	1.1	1.0	1.0

Table 1.3 Global market share (% by category) of ice cream characterized by point of manufacture/consumption, 2006–2010 (data from Euromonitor International, 2011)

	Take-home products		Impulse products		Artisanal/parlor	
	Volume	Value	Volume	Value	Volume	Value
2006	44.0	26.5	48.3	50.8	7.7	22.7
2007	43.1	26.0	49.0	51.0	7.9	23.0
2008	42.0	25.1	50.0	51.7	8.0	23.2
2009	42.4	24.9	49.4	52.0	8.2	23.1
2010	41.9	24.6	49.8	52.6	8.3	22.8

and parlor market is small but has been increasing in volume over the period 2006–2010, but this is not reflected by similar increases in value. There are very large regional differences in market share distribution, impacted in large part by the presence of home freezers. In North America, the take-home product market is

Table 1.4 Regional market share (% by category) characterized by point of manufacture/consumption, 2010 (data from Euromonitor International, 2011)

	Take-home products		Impulse products		Artisanal/parlor	
	Volume	Value	Volume	Value	Volume	Value
North America	70.7	38.5	23.9	36.4	5.4	25.1
Latin America	44.4	24.0	41.3	57.5	14.3	18.5
Western Europe	42.6	23.1	38.4	43.6	19.0	33.3
Eastern Europe	39.4	29.6	56.3	61.6	4.3	8.8
Asia Pacific	12.3	9.4	84.9	78.6	2.8	12.0
Australasia	65.5	28.5	30.5	52.4	4.0	19.1

Table 1.5 Production statistics for frozen desserts in the United States, 1990–2010

	Year					
	1990		2000		2010	
Product	Million Gallons	% of total	Million Gallons	% of total	Million Gallons	% of total
Regular ice cream	823.6	57.7	979.6	60.9	920.2	60.5
Low- and nonfat ice cream	352.3	24.7	404.1	25.1	398.2	26.2
Frozen yogurt	117.6	8.2	94.5	5.9	74.4	4.9
Sherbet	50.3	3.5	51.9	3.2	53.1	3.5
Water ices	50.7	3.6	65.8	4.1	59.7	3.9
Others	32.4	2.3	11.6	0.7	14.7	1.0
Total	1,426.8	100.0	1,607.6	100.0	1520.3	100.0

Source: USDA, National Agricultural Statistics Service, as reported by IDFA (2010)
Note: 1 US gallon = 3.78 L

considerably larger by volume than the impulse product market, but by value they are close. This is in stark contrast to the market shares in Asia Pacific, for example, where impulse products make up a very large share of the ice cream volume and value. Western Europe tends to be more evenly split between the two categories. In Western Europe, the artisanal and parlor markets are also quite substantial, fully 1/3 of the value of the industry. In North America, this market represents 1/4 of the value of the industry.

Although not quite the largest consumer of ice cream and related products, the United States is the largest producer, at 1,520 million US gallons (5.75 billion liters) in 2010. This compares to productions of 1,427 million US gallons in 1990 and 1,607 million US gallons in 2000, indicating a slight decline in the last decade (Table 1.5). Per capita production also shows a decline from 22.76 quarts (21.5 L) in 2000 to 19.10 quarts (18.1 L) in 2010 (Table 1.6). The 20-year trend in production shows steady growth in low-fat and nonfat products and decline in frozen yogurts (Table 1.5), while from per capita data we see a decline in all categories from 2000 (Table 1.6), especially in regular ice cream which dropped from 13.88 (13.1 L) quarts to 11.99 quarts (11.3 L), down from a high of 15.55 quarts (14.7 L) in 1960. In 2010, US frozen dairy dessert production could be subdivided as follows: 60.5% regular ice cream, 26.2% low-fat and nonfat ice cream, 4.9% frozen

Table 1.6 Per capita production of frozen dairy desserts in the United States (quarts), 1920–2010

Year	Ice cream	Low-fat and nonfat	Frozen yogurt[a]	Sherbet	Water ices	Others	Total
1920	6.43						6.43
1940	9.64	0.32		0.24		0.09	10.29
1960	15.55	3.23		0.91	0.74	1.11	21.54
1970	14.95	5.63		0.96	0.73	1.15	23.42
1980	14.61	5.17		0.80	0.59	0.41	21.58
1990	13.21	5.65	1.89	0.81	0.81	0.52	22.89
2000	13.88	5.66	1.24	0.75	0.93	0.16	22.76
2010	11.99	5.19	1.16	0.70			19.10

Source: Data published by the US Department of Agriculture and reported by IDFA, 2011
Note: 1 US quart = 0.945 L
[a]Data were not collected by USDA on frozen yogurt production before 1989

yogurt, 3.9% water ice, and 3.5% sherbet (Table 1.5). 93.5% of regular ice cream was hard frozen, while 6.5% was soft frozen. Of the low-fat category, 39% was hard frozen while 61% was soft frozen and of frozen yogurts, 29% was hard frozen while 71% was soft frozen, demonstrating the dominance of lower-fat ice cream products and frozen yogurts for soft-frozen mixes.

Of the 1,520 million US gallons (5.75 billion liters) of frozen desserts produced in the United States in 2010, California leads all states in the production of frozen desserts with 169 million US gallons per year, followed by Indiana at 110 million US gallons, Texas at 72 million US gallons, and Pennsylvania at 51 million US gallons. These four states produced 25% of the US production. The number of plants producing ice cream dropped from 1,628 in 1970 to 949 in 1980 to 713 in 1990 and to about 400 in 2000, and that has remained constant through 2010. During the same time, production per plant increased dramatically. For example, the average production per plant in 2010 was nearly four million US gallons (15.1 million liters) compared with 1.1 million US gallons in 1985. In 2010, the ice cream industry employed 18,500 people with a total annual payroll of US$ 750 million. The value of shipments from production was close to US$ 8.9 billion. Supermarket sales of packaged ice cream and sherbet represented US$ 4.2 billion and frozen novelties US$ 2.6 billion.

There are many thousands of retail stores and foodservice establishments that freeze ice cream, yogurt, sherbets, sorbets, and ices. However, most of the mix frozen by these firms is made in large factories that deliver directly to the ice cream retailer's door. The amount of frozen dessert mixes produced by the industry for freezing outside the mix-producing plant exceeds 800 million gallons in the USA. Managers of most small establishments have found it to be far more economical to purchase pasteurized mix than to make it in-house. The products are personalized by the ways they are flavored, frozen, packaged, handled, marketed, and served.

Monthly production figures for the United States indicate that ice cream consumption is seasonal (Fig. 1.1); however, it is much less so than former years.

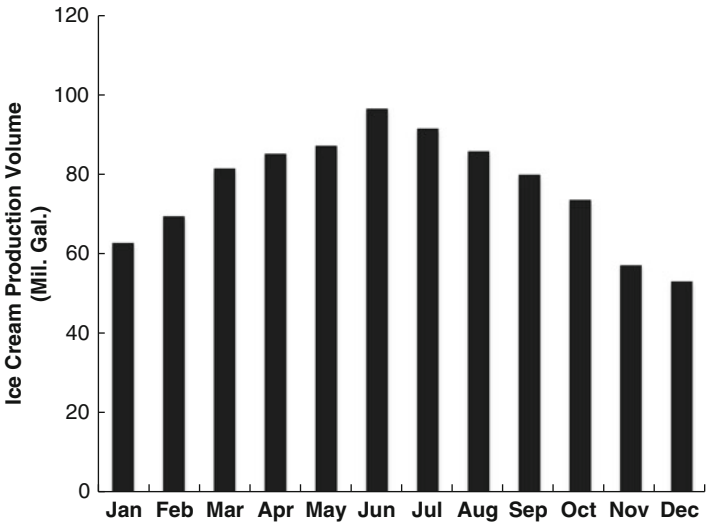

Fig. 1.1 Ice cream production volume by month in the United States in 2010. Source: Data published by the US Department of Agriculture and reported by IDFA, 2011

Whereas, in 1921 production in July was twice the monthly average for the year, this statistic dropped to 1.6 times the monthly average by 1941. Further leveling of production followed, and for the last 45 years production in July has ranged from 1.2 to 1.3 times the monthly average for the respective years. Lowest production occurs in November through January with average production at 70–80% of the monthly average for the year.

The ice cream industry is very progressive with many new product introductions annually. Some of the current formulation trends in the industry include a growing interest in "reduced" or "no" claims for fat, calories, or sugar; the use of nutritionally functional additives (e.g., vitamins or minerals) or flavors showing added nutritional functionality (e.g., high in antioxidants); a renewed focus on frozen yogurt, particularly with probiotic cultures, although this represents a very small segment of the overall total market of frozen desserts; and formulations approved as kosher or halal compliant. Products are also marketed with a growing social awareness, including fair trade to primary producers, organic products, environmental sustainability, and social responsibility by aligning products with particular social justice causes.

In Canada, total frozen dairy dessert mix production declined from 171,271 kL in 2006 to 111,938 kL in 2010, which appears to be a substantial loss of market. However, in 2006, nondairy fats became permitted in "ice cream"-like products due to a change in regulations, provided they are clearly labeled as "frozen dessert" and not "ice cream," and the production of these products is not captured in the frozen dairy dessert mix category. This probably accounts for such a dramatic decline in the production statistics, although probably not representing a decline in total

production per se. In many other countries of the world, "ice cream" can be made from nondairy fats while "dairy ice cream" must contain milk fat. This makes comparison of statistics difficult. Canadian hard ice cream production declined from 299,256 kL in 2006 to 189,310 kL in 2010, although during this same time period, low-fat/nonfat frozen dairy desserts grew from 29,168 to 40,227 kL, soft ice cream grew from 19,955 kL to 21,971 kL, and sherbets grew from 5,426 kL to 5,966 kL.

A Brief History of Ice Cream

A very thorough global history of ice cream was commissioned by Unilever and published to celebrate the millennium (Reinders 1999). Weir and Weir (2010) and Quinzio (2009) have both written recent histories of ice cream, and a history of American ice cream was written by Funderburg (1995); the reader is referred to these monographs for complete details of the evolution, sociological impact, and industrial development of ice cream.

Although the traditions of ice cream consumption, and hence manufacture, run very deep in the United States, the product was introduced to the United States from Europe, and many European countries not only have a long history with ice cream but also have a long-standing sociological love affair with the product that mirrors the American experience. Ice cream was not invented per se but rather evolved from centuries-old practices involving the cooling of foods and beverages with snow, which was described in Roman historical writings back to the first century AD. Legend has it that when the thirteenth-century Venetian merchant Marco Polo returned to Italy from his famous journey to the Orient, he brought recipes for water ices said to have been used in Asia for thousands of years. This legend, however, is unsubstantiated based on any historical writings. So, too, is the legend surrounding the Italian-born Catherine de' Medici, who is said to have brought Italian-trained chefs to the Royal Court of France after her marriage in 1533 and with them the secret of ice cream.

Probably the first major step in the evolution of modern ice cream came with the development of processes for freezing of water using salt (or saltpeter) and ice, which was described as early as 1530 in Italy but was not utilized for the freezing of sweet food mixtures until the middle of the seventeenth century. By then, water ices were beginning to be served at the banquet tables of the European royal courts and nobility. Perhaps the first published recipe for water ices came from the French *confiturier* Nicolas Audiger in 1692, in which he claimed he had been serving such desserts at the Court of Louis XIV of France since 1662. François Massialot also described the freezing of water ices in his cookery book also of 1692. In a 1712 edition, Massialot added a recipe that included milk, which he referred to as "Fromage à l'Angloise." Recipe books from the early eighteenth century suggest that the English preferred recipes based on cream and sugar while the French preferred recipes for water ices or milk and egg whites. This dairy-based "warm-eating" ice cream evolution was perhaps more associated with colder climates, compared to the "cold-eating" sorbets and water

ices of the Mediterranean, warm-climate, countries. The first English recipe for dairy-based ice cream appeared from Mary Eales, confectioner to Queen Anne, in 1733 and was repeated again by Hannah Glasse in her cookery book of 1742. Three cookery books devoted entirely to ice cream appeared in the middle of the eighteenth century from France, the first in 1750 by Menon, the second in 1751 by Joseph Gilliers, and the third in 1768 by M. Emy, a 240-page treatise, *L'Art de Bien Faire les Glaces d'Office*. It gave formulas for "food fit for the gods" and offered, besides the scientific and practical, theological and philosophical explanations for phenomena such as the freezing of water. Very elaborate porcelain serving pails and dishes for ice cream and water ices that consisted of inner and outer bowls for maintaining the dessert in an ice/salt slurry, to keep it cold, also began to appear in the eighteenth century (e.g., Sèvres from France, which was founded in 1738).

In 1686, the Cafe Le Procope was founded in Paris by an Italian named Francesco Procopio Dei Coltelli, and water ices were manufactured and sold. This restaurant is still operating today. Coltelli perhaps began the migration of Italian-trained artisanal ice cream makers to other European countries, notably England, where they carried on their trade. If the Italians didn't invent ice cream, they certainly contributed to bring it to the people on the street. The Italian "Hokey Pokey" man, a corruption of their cries in Italian *O, c'è un poco* ("try a little"), became well established as the street vendor of ice cream, not only in England but throughout continental Europe.

Honey was probably the first major sweetener used for frozen desserts, although the manufacture of sugar preceded the development of the ice cream industry. Sugarcane was grown in India where a process for making sugar from it was known as early as the first century. However, the use of bone in the refining process was frowned upon. The first authentic evidence of crystalline sugar dates from Persia in AD 627. By the eighth century, a process of refining was used in Egypt, Mesopotamia, and Spain. The sugar industry was established in Europe during the reign of Napoleon in the early 1800s. Growth of sugarcane in tropical regions of the Americas began in the sixteenth century. In the mid-eighteenth century, white cane sugar in loaf form costs as much as $2.75 per pound. The development of beet sugar in the early nineteenth century caused prices to drop so that the masses could afford the sweetener.

Ice cream probably came to the United States with the early English colonists. The first written evidence of ice cream in America was in a letter of May 17, 1744 by a guest of proprietary Governor William Bladen of Maryland. The letter stated that "a dessert no less curious, among the rarities of which it was composed, was some fine ice cream which with the strawberries and milk, eat most deliciously." Thomas Jefferson gets credit for introducing vanilla to America following his tour as Minister to France in 1784–1789. He requested vanilla pods from Paris in 1791 when he could not purchase them in Philadelphia. The New York Gazette dated May 19, 1777 contained an advertisement that read in part "May be had almost every day—ice cream." George Washington spent about $200 for ice cream in New York during the summer of 1790. But the masses had to wait for developments of ice harvesting, insulated ice houses, and the hand-cranked ice cream freezer

invented by Nancy Johnson (patent number 3254, Sep. 9, 1843). W. G. Young patented the "Johnson Ice Cream Freezer" in 1848, and 99 others were patented during the next 25 years. The first wholesale ice cream industry in the United States was established in 1851 in Baltimore, Maryland by Jacob Fussell. Plants were established soon thereafter in Boston, St. Louis, New York, Washington, Chicago, and Cincinnati. Two of the most important contributions to the development of the industry were the perfection of mechanical refrigeration (1878) and the invention of the direct expansion ice cream freezer (1913). Ice had been scarce in summer months when people had the greatest desire to eat a cooling food. Collection of ice during winter and storing in ice houses were both labor intensive and expensive.

The development of condensed and dry milk, the introduction of the pasteurizer, homogenizer (the latter by August Gaulin of Paris, France, in 1899), separator, and improved freezers, and other processing equipment accompanied a slow growth in the industry until after 1900. The ice cream soda was introduced in 1879. Italo Marchiony, an Italian emigrant, began making edible ice cream containers for his own business circa 1896 in New York City. He was granted a patent for his special mold in 1903; however, the drawing for the patent "shows a mold for shaping cups with tiny handles—not a cone" (Funderberg 1995). A Syrian waffle concessionaire, E. A. Hamwi, started rolling waffles into the shape of a cone, and an ice cream vendor in the adjoining booth used them as ice cream containers at the 1904 St. Louis World's Fair. Several other claims for invention of the ice cream cone are provided by Funderburg (1995).

Annual production of ice cream in the United States in 1905 was only four million gallons. At that time there was no national trade organization, and only one college, the Pennsylvania State College of Agriculture, offered instruction in ice cream manufacture, the first short course having been in 1892. Most products were being made without much guidance in quality or content. In 1905, Thomas D. Cutler founded The Ice Cream Trade Journal, the predecessor to Ice Cream Field and that to Dairy Field.

In the 1900–1919 era, the United States experienced rapid industrialization and urbanization. Ice cream standards were adopted by some states, and many dairy organizations were formed. New York City was the first municipality to inspect dairy farms for sanitary milk production practices, and the first dairy show was held in Chicago in 1906. Chicago led the way toward safe ice cream and dairy foods by adopting the first compulsory pasteurization regulation in 1909; however, it left the loophole that the requirement applied to milk from herds that had not been tested for tuberculosis. In 1917, the newly organized Association of Ice Cream Supply Men, the forerunner of today's International Association of Food Industry Suppliers (IAFIS), held its first trade exposition in Boston.

In 1905, Emery Thompson, manager of the ice cream and soda fountain in a New York City department store, developed the gravity-fed batch ice cream freezer. The invention enabled nearly continuous production. The company remains under family ownership and continues to supply freezers to industry. The first ice cream filling and packaging machines were introduced by Mojonnier Brothers and Sealright firms around 1920, and in 1923 the Nizer Cabinet Company introduced

the first automatic electric freezer. The first commercially adopted continuous ice cream freezer was perfected by Clarence Vogt of Lexington, KY around 1926. The Eskimo Pie, Good Humor ice cream bar, and Popsicle were all invented around 1920. Christen Nelson invented the I-Scream bar in 1919. After Nelson took Russell Stover as his partner, Stover named the bar the Eskimo Pie. The Popsicle was first called the Epsicle in honor of its inventor, Epperson, a concessionaire of an amusement park. The idea came to him, legend has it, when he left a glass of lemonade containing a spoon in an open window on a cold night. By morning the lemonade was frozen. He immersed the glass in water and removed the frozen mass. He patented the invention in 1924. The ingenuity of Harry Burt and the prompting by his daughter led to the Good Humor Ice Cream Sucker, a chocolate-coated ice cream bar on a stick.

William Breyer opened his first ice cream store in Philadelphia in 1882. Five more stores were opened soon thereafter. By 1896, demand for ice cream caused Breyer's sons, Fred and Henry, to open their first ice cream plant and to adopt for their label the briar leaf that is still the logo of Breyer's ice cream. A second plant was added in 1904. In 1905, the Breyers Ice Cream Company became the first firm to use brine-cooled freezers. By 1914, the firm's sales of ice cream surpassed one million gallons. In 1925 and 1927, new plants opened in Long Island City, NY, and Newark, NJ, respectively, and the firm became a division of National Dairy Products Corporation. Sales were expanded to the Northeast and Mid-Atlantic states. In 1969, the firm became part of Kraftco Corporation (later Kraft, Inc.), and distribution was extended to the Southeastern United States. Sales began west of the Mississippi River in 1984. Unilever, an Anglo-Dutch company, purchased the Breyers ice cream business in 1993, combining it with the Gold Bond-Good Humor Ice Cream Company and changing the name to Good Humor-Breyers Ice Cream Company. Good Humor had been acquired by Thomas J. Lipton Ltd., a subsidiary of Unilever, in 1961. By the year 2000, the firm ranked first and second, respectively, in income from frozen novelties and ice cream in the United States. Globally, Unilever's ice cream brands include Wall's, Streets, HB, Algida, Miko, Frisko, Langnese, and several others, and their most popular product names include Carte d'Or, Cornetto, Magnum, Solero, and Vienetta.

In 1928, William Dreyer, who had celebrated his arrival on a German ship in 1906 by making ice cream, joined with Joseph Edy, a confectioner, to found the Grand Ice Cream Company in Oakland, CA. Dreyer, in 1929, added walnuts and bite-sized marshmallows, cut from large ones with his wife's sewing shears, to make the first batch of rocky road ice cream. William Dreyer, Jr. assumed leadership of the firm in 1953 and then sold it to key officers in 1963. Under the leadership of T. Gary Rogers and William F. Cronk, who bought the company in 1977, Dreyer's expanded from the Western states to states east of the Rocky Mountains where the brand was named Edy's Grand Ice Cream in honor of the cofounder. In 1981, the firm went public and began a direct-to-store delivery network. Expansion through licensing agreements added the names Starbucks Coffee Company, M&M Mars®, and Godiva Chocolatier, Inc. to selected product labels. The firm began global sales in 1992 and became the leading marketer of packaged ice cream in the United States

in 1994. In 2002, Nestlé purchased a controlling interest in Dreyer's Grand Ice Cream Inc. and took full control in 2006, which also gave them the rights to the manufacture of Häagen-Dazs products in North America. Nestlé had previously purchased Carnation in the USA in 1985. Globally, Nestlé mostly sells ice cream under its own name, but its other ice cream brands include Delta (Greece), Peters (Australia), Hjem-Is (Scandinavia), Mövenpick, and many others.

In 1945, Irving Robbins opened the Snowbird Ice Cream Store in Glendale, CA, offering 21 flavors. His brother-in-law, Burt Baskin, soon opened an ice cream store called Burtons. The next year the two competitors became partners and opened a chain of six stores under the name Baskin-Robbins. Nine years later they adopted the "31" Baskin-Robbins logo and embarked on a nationwide franchise program. London-based J. Lyons & Co., Ltd. (later Allied Domecq) purchased Baskin-Robbins in 1973 and began expansion internationally in 1974. As part of Dunkin Brands, they were acquired by a group of private equity firms in 2006. Today, they have more than 5,800 retail locations, 2,800 of which are located in the United States. Baskin-Robbins sells ice cream in over 30 countries. Manufacture is either done by corporate locations or through co-packing arrangements.

The founders of Dairy Queen, "Grandpa" and Alex McCullough, father and son, respectively, were operators of an ice cream mix plant in Kankakee, IL. In 1938, they persuaded a retailer to run a 10-cent "all-you-can-eat" trial of a new soft-frozen dessert at his walk-in ice cream store. Within 2 h he had dished out more than 1,600 servings of the new dessert. In 1939, Alex McCullough persuaded Stoelting Brothers to perfect and manufacture a soft serve freezer originally designed by Harry M. Oltz of Hammond, Indiana. The first Dairy Queen store was started in Joliet, IL in 1940. Numbers of Dairy Queen stores exploded from about 100 in 1947 to 1,446 in 1950. The first Dairy Queen store opened in Canada in 1953. The "Dilly" Bar had its debut from Dairy Queen in 1955. Dairy Queen opened its first store in Japan in 1972 and in the Middle East in 1979. As of 2010, Dairy Queen had more than 5,700 stores in 19 countries, including 652 locations outside the United States and Canada, being one of the largest soft serve franchises in the world.

Häagen-Dazs was founded by Reuben Mattus in the Bronx, New York, in 1961, after having worked in his mother's ice cream business for several years before. He devised the name to reflect old-world traditions. His products expanded from New York City to the US East Coast and across the USA by 1973. In 1976, his daughter Doris opened the first Häagen-Dazs retail store. Pillsbury purchased the Häagen-Dazs company from Mattus in 1983 and General Mills bought Pillsbury in 2001. Thus General Mills now manufactures and markets Häagen-Dazs worldwide, although as a result of a previous arrangement with Dreyer's, when Nestlé purchased Dreyer's in 2002, they obtained the rights to the manufacture and marketing of Häagen-Dazs products in North America under license from General Mills.

Ben Cohen and Jerry Greenfield met in 1963 while in the seventh grade. Fifteen years later they opened their first Ben and Jerry's homemade ice cream shop in a renovated gasoline station in Burlington, Vermont. From these humble beginnings, the company grew to multinational prominence and was purchased in 2000 by Unilever, who continues to operate it separately from their other ice cream companies.

The many areas of progress reviewed in the preceding discussion, as well as many others too numerous to cite, have been made possible largely because of advances in transportation, general availability of electricity and, consequently, of refrigeration, improved packaging, and improved qualities of ingredients, not the least of which are those made from milk. Modern automated, high-volume operations provide a plentiful supply of ice cream in a wide variety of fat contents, flavors, packages, and prices. Novelty manufacturers produce thousands of items of many different types per minute. Specialty producers, often at the retail store level, produce ice cream cakes, pies, and molded items. Since its earliest beginnings, the ice cream trade has become big business.

Overview of Ice Cream Composition and Manufacture

Frozen dairy dessert mixes generally contain seven categories of ingredients: fat (dairy or nondairy), milk solids-not-fat (the principal source of protein), sweeteners, stabilizers, emulsifiers, water, and flavors. Once whipped and frozen, air becomes another important component. The frozen dairy desserts industry is largely represented by ice cream but nevertheless is highly segmented according to composition. Table 1.7 shows the compositional range of typical mix components for a number of frozen dessert products.

Dairy and other ingredients used to supply mix components are chosen on the basis of availability, cost, and expected quality. Fat derived from milk ingredients (cream or butter) or from nondairy fats that are typically solid at refrigerated temperature (coconut, palm, or palm kernel oil) provides texture and structure.

The milk solids-not-fat (MSNF) ingredients contain the lactose, casein and whey proteins, minerals (ash), vitamins, and other minor components from milk, although the ratio of these may be altered by the type of dairy-derived ingredient that is selected (e.g., whole milk protein vs. whey protein). Proteins contribute much to the development of structure in ice cream, including emulsification, whipping, and water holding capacity. Emulsification properties of proteins in the mix arise from their adsorption to fat globules at the time of homogenization. Whipping properties of proteins in ice cream contribute to the formation of the initial air bubbles in the mix. The water holding capacity of proteins leads to enhanced viscosity in the mix, which imparts a beneficial body to the ice cream, increases the meltdown time of ice cream, and contributes to reduced iciness.

In addition to providing sweetness, sweeteners improve the texture and palatability of the ice cream and enhance flavors. Their ability to lower the freezing point of a solution imparts a measure of control over the temperature-hardness relationship. The sweeteners (including lactose from the MSNF component) must be balanced to achieve the proper solids content, the appropriate sweetness level, and a satisfactory degree of hardness.

Ice cream stabilizers are a group of ingredients (usually polysaccharides such as guar, locust bean gum, carboxymethyl cellulose, and xanthan) that produce

Table 1.7 Approximate composition (% by wt.) of commercial frozen desserts by formulation category

Group	Milk fat	Milk solids-not-fat	Sweeteners[a]	Stabilizers[b] and emulsifiers	Total solids
Nonfat ice cream	<0.5	12–14	18–22	1.0	28–32
Low-fat ice cream	2–5	12–14	18–21	0.8	28–32
Light ice cream	5–7	11–12	18–20	0.5	30–35
Reduced-fat ice cream	7–9	10–12	18–19	0.4	32–36
Economy ice cream	10	10–11	15–17	0.4	35–36
Standard ice cream	10–12	9–10	14–17	0.2–0.4	36–38
Premium ice cream	12–14	8–10	13–16	0.2–0.4	38–40
Superpremium ice cream	14–18	5–8	14–17	0–0.2	40–42
Frozen yogurt: regular	3–6	9–13	15–17	0.5	30–36
Frozen yogurt: nonfat	<0.5	9–14	15–17	0.6	28–32
Sherbet	1–2	1–3	22–28	0.4–0.5	28–34

[a]Includes sucrose, glucose, corn syrup solids, maltodextrins, polydextrose, and other bulking agents, some of which contribute little sweetness

[b]Includes ingredients such as locust bean gum, guar gum, carrageenan, cellulose gum, and cellulose gel, as stabilizers, and also mono- and diglycerides and polysorbate 80, as emulsifiers

smoothness in body and texture, retard or reduce ice and lactose crystal growth during storage (or mask the effects of crystal growth), especially during periods of temperature fluctuation, known as heat shock, and provide uniformity to the product and resistance to melting. Their function is mainly through their interactions with water. Emulsifiers (mono- and diglycerides and sorbitan esters, such as polysorbate 80) are sometimes integrated with the stabilizers in proprietary blends, but their function and action is very different from the stabilizers. They are used to improve whipping quality of the mix, produce a drier ice cream to facilitate molding, fancy extrusion, and novelty product manufacture, provide smoother body and texture in the finished product, and produce a product with good stand-up properties and melt resistance. Their function is related to their activity at the air/serum and fat/serum interfaces. In some formulations, eggs also provide similar emulsifying properties.

Frozen dairy dessert products are all consumed in the frozen state and rely on a concomitant freezing and whipping process to establish the desired structure and texture. The manufacturing process for most of these products is similar and involves the preparation of a liquid mix; whipping and freezing this mix dynamically under high shear to a soft, semi-frozen slurry; incorporation of flavoring ingredients to this partially frozen mix; packaging or shaping (as in the case of "novelty" or "impulse" products) the product; and further freezing (hardening) of the product under static, quiescent conditions (Fig. 1.2). The liquid mix is prepared by blending the desired ingredients, followed by pasteurization (batch or continuous), homogenization, and cold aging. Batch pasteurization is very common due to the ease of ingredient blending. Scraped-surface freezers are used for the first freezing step (which incorporates air and produces small, discrete ice crystals, typically at −5 °C). Continuous freezers dominate the medium- to large-scale processing industry, while batch freezers are limited to small-scale processors, retailers, including restaurants, and product

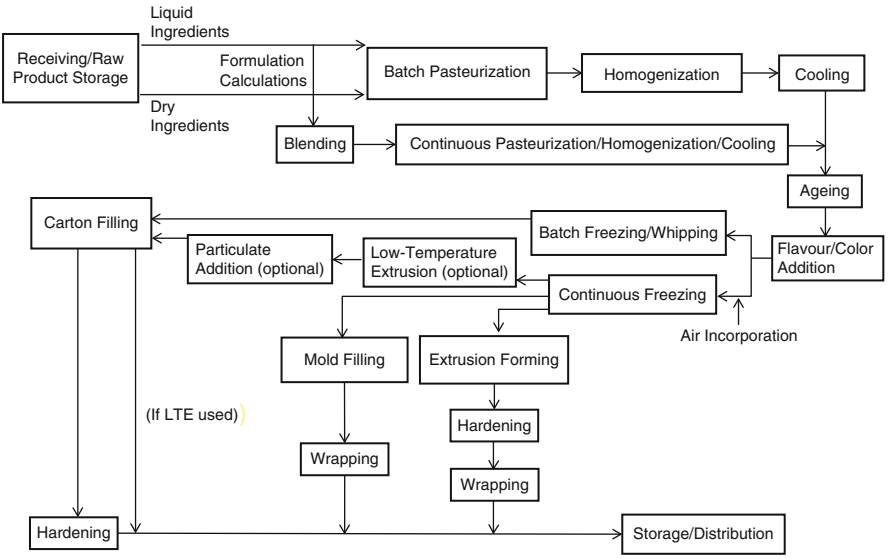

Fig. 1.2 Schematic flow chart of ice cream processing, showing specific lines for batch or continuous pasteurization, batch or continuous freezing, and carton filling, molded novelties or extruded novelties

development applications. Forced-air convection freezers, such as air blast tunnels, or plate-type conduction freezers are used for the second freezing step, to reduce the internal temperature to −25 to −30 °C. Flavoring materials that are homogenous throughout the product are added before the first freezing step while flavoring materials that will remain discrete in the product (fruits, nuts, candy or bakery pieces, ripple sauces) are added after the first freezing step. Novelty or impulse products are manufactured by either molding of soft-frozen ice cream or extrusion and cutting of stiff-frozen ice cream from continuous freezers.

Ice cream is a frozen foam, the air being incorporated during the dynamic freezing process. Air quantity is calculated as overrun, the increase in volume that occurs as a result of the whipping when compared to the volume of the original mix. Overrun is calculated as:

$$\%\ \text{overrun} = [(\text{volume of product-volume of mix}) / \text{volume of mix}] \times 100$$

For example, if 10,000 L mix is frozen into 20,000 L ice cream, the overrun is 100%.

Overrun can also be calculated for individual containers by determining the portion of mix displaced by air in the specific package as follows:

$$\%\ \text{overrun} = [(\text{mix weight} - \text{product weight}) / \text{product weight}] \times 100$$

For example, if a 2 L package of ice cream weighs 1,100 g net and 2 L of mix weights 2,200 g net, the overrun is 100%. See Chapter 6 for further details of overrun calculations.

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Chapter 2
Composition and Formulations

Introduction

Ice cream is comprised of a mixture of air, water, milk fat or nondairy fats, milk solids-not-fat (MSNF), sweeteners, stabilizers, emulsifiers, and flavors. The functions and limitations of each of these components are described in Table 2.1. An ice cream mix is the unfrozen blend of the ingredients used to supply these constituents, except the air and flavoring materials. Mix formulations are defined as percentages of the constituents, e.g., percentage of fat, MSNF, sugars, stabilizers, and emulsifiers (the sum of which equals the total solids). These components can be combined in varying proportions within acceptable ranges. Furthermore, a wide variety of ingredients can be chosen to supply these constituents, and both the percentage and the source of a constituent can affect quality of a mix. For example, milk fat and MSNF can be derived from multiple combinations of cream, butter, and fresh, concentrated or dry whole milk or skim milk. Ingredients to supply the mix components will be discussed in Chap. 3.

The composition of ice cream varies in different countries and in different localities and markets within each country (Table 2.2). The best ice cream composition for a manufacturer to produce is often difficult to establish. Consideration must be given to legal requirements, quality of product desired, raw materials available, plant equipment and processes, trade demands, competition, and cost. These considerations will affect the choice of a minimum, average, or high component concentration and the selection of ingredients (Table 2.3). Some firms may choose to manufacture products from only one mix formulation while others may cater to economy, regular, and premium markets with several formulations.

The milk fat content of ice cream may vary from less than 1 to 20%, depending upon such factors as regulations, expected characteristics, price, and competition. Within the ice cream category, usually at >8–10% fat, as the fat content of ice cream is increased, the MSNF must be decreased so as to avoid high viscosity and the potential for "sandiness" (i.e., the crystallization of milk sugar or lactose in the finished ice cream). Local preferences, qualities of ingredients, and the technique of

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Table 2.1 Functions and limitations of selected ice cream constituents

Constituent	Functions	Limitations
Milk fat	Increases richness of flavor Lubricates and insulates the mouth	Relatively high cost and smoothness of texture Hinders whipping May limit consumption due to high calories and satiating effect
Nondairy fats	Provides good structure and texture at lower cost than milk fat, if appropriate solid fat content	Contributes little to flavor and may impart of off-flavor May contribute to greasy texture
Milk solids-not-fat; milk/whey protein concentrates	Improves body and texture (protein) through emulsification and water holding capacity Promotes development of overrun	High amount may cause cooked or salty flavor Potential for sandiness (lactose crystallization) at high concentration
Whey solids	Less expensive than conventional sources of MSNF	High amount of lactose causes freezing point depression Potential for sandiness greater than for conventional sources of MSNF
Sugar	Lowers freezing point Imparts sweetness to the ice cream Improves flavor/texture	Excess sweetness possible Lower hardening temperature needed Ice cream is softer, affecting scooping and the potential for greater recrystallization
Corn syrup solids	Lower cost than sugar Improve body and texture Increase stability of the ice cream	Impart off flavor and chewy texture when overused
Stabilizers	Enhance smooth texture Provide body Enhance shelf life	Excess chewiness may occur Increase melt resistance
Egg yolk solids	Improve whipping ability Impart custard flavor	Foamy melted product Egg flavor may be undesirable
Emulsifiers	Promote fat destabilization, leading to dryness, smoothness, and good melting properties	Increase potential for churning of fat
Total solids (TS)	Smoother texture Firmer body Higher nutrient content Lessen excess coldness	Heavy, soggy, or sticky body Reduce coldness
Flavoring	Increases acceptability	Intensities and harshness may be unacceptable
Coloring	Improves attractiveness Aids flavor identification	Artificial shades Allergic reactions of some people to yellow no. 5 or no. 6 Some consumers dislike added colors

Table 2.2 Minimum standards for ice cream among several of the major ice cream producing and consuming countries

Country	Milkfat (%)	Milk protein (%)	Total milk solids (%)	Total solids (%)	Food solids per liter (g)	Weight per liter (g)
Australia	10	–[a]	–	–	168	–
Brazil	3[b]	2.5	–	–	152	475
Canada	10	–	–	36	180	–
Denmark[c]	5	–	–	–	–	–
Finland[c]	8	2.5	–	–	–	–
Germany[c]	10	–	–	–	–	–
Italy[c]	8	2.5	–	32	–	–
New Zealand	10	–	–	–	168	–
Norway[c]	9	–	–	35	–	500
United States	10	–	20	–	192	540
United Kingdom[c]	5	2.5	–	–	–	–

[a]Not specified

[b]Minimum total fat is 8%, balance can be comprised of nondairy fat

[c]Standards specific to "Dairy Ice Cream," whereas "Ice Cream" allows nondairy fat and has unspecified compositional standards, except the UK, which specifies 5% nondairy fat and 2.5% milk protein in "Ice Cream"

Table 2.3 Average values for fat and total solids contents, overrun and cost amongst the categories of ice cream

Component	Economy	Standard	Premium	Superpremium
Fat	Legal minimum, usually 8–10%	10–12%	12–15%	15–18%
Total solids	Legal minimum, usually 35–36%	36–38%	38–40%	>40%
Overrun	Legal maximum	100–120%	60–90%	25–50%
Cost	Low	Average	Higher than average	High

manufacture are fully as important as the composition in determining the best ice cream for a locality.

The future will continue to bring many changes in the composition and form of frozen dairy desserts as manufacturers try to gain market share and increase profitability. As an example, frozen desserts can be used to carry health-promoting constituents—vitamins and minerals or fiber or nutraceuticals (minor constituents of foods that have been shown to have health-promoting effects). The favorable effects of conjugated linoleic acid (CLA), omega-3 fatty acids, dietary fiber, and antioxidants on human health may prompt the increase of their concentrations in frozen desserts. Also, genetically engineered plants that produce flavorings are already being grown; more will be developed. They will enable more profitable production of better flavorings.

Descriptions of Commercial Frozen Desserts

Ice Cream and Related Products

Within the category of ice cream there are numerous variations of formula, dairy ingredients, sweeteners, stabilizers and emulsifiers, flavors, fruits, nuts, colors, methods of freezing, sizes, shapes, techniques for dispensing into packages, and other variables that make possible the creation of a wide variety of products (Table 1.5). Many of these are described in the following section.

Ice cream. Ice cream composition is highly regulated in many legal jurisdictions but increasingly the formerly strict compositional standards are being liberalized to allow more flexibility, as in Europe for example (Table 2.2). Readers are strongly encouraged to confirm all regulatory standards before using these for product development or export purposes, as they continue to evolve over time. The US compositional standards can be found in the Code of Federal Regulations, Title 21 Food and Drugs, Part 135 Frozen Desserts and subsections for definitions of ice cream and frozen custard, goat's milk ice cream, mellorine (ice cream with nondairy fat substituted for milk fat), sherbet and water ices. According to US standards, ice cream is a food produced by freezing, while stirring, a pasteurized mix containing at least 10% milkfat, 20% total milk solids (TMS), safe and suitable sweeteners, and defined optional stabilizing, flavoring, and dairy-derived ingredients. The finished ice cream weighs at least 4.5 lb/gal and contains at least 1.6 lb of food solids per gallon. These limits establish the maximal overrun, the increase in volume from whipping, at approximately 100% since the average mix weighs about 9 lb/gal (1,080 g/L). Furthermore the limits establish a minimum total food solids content in the mix of approximately 35.6%. Milkfat may be substituted for MSNF in 1% increments up to 14%. Other food fats are excluded except as components of flavoring ingredients or in incidental amounts added for functional purposes. Whey solids, including modified whey products, may be added to ice cream to replace up to 25% of the MSNF. For example, a product containing 12% milkfat need contain only 8% MSNF, 2% of which may be derived from sweet whey. Approved additives to mixes containing at least 20% TMS are five forms of casein and hydrolyzed milk proteins. The latter may not exceed 3% by weight of the ice cream mix (21 CFR 135—Frozen Desserts).

The regulations for ice cream products within each legal jurisdiction globally vary considerably from those of the United States (Table 2.2). In Europe, Euroglaces (the European Ice Cream Association) has prepared a Code for Edible Ices that includes standard definitions of products with appropriate translations. This was first published in 1996 and revised in 2006 to allow much more liberal compositional standards that will enable a wider range of product options to be offered to consumers. In this code, "Edible Ices" are made from a mix with approved food ingredients, have a solid or pasty texture which is obtained from freezing, and are stored, transported, sold, and consumed in a frozen state. "Ice Cream" is an edible ice and is an emulsion

typically composed of water and/or milk, edible fats, proteins, and sugars. Dairy and/or nondairy proteins are optional but dairy and/or nondairy edible fats are mandatory. "Milk Ice" is an edible ice that contains at least 2.5% of exclusively dairy fat and at least 6% MSNF and contains no nondairy proteins or fats. "Dairy Ice Cream" is an edible ice that contains at least 5% dairy fat, at least some dairy protein and contains no nondairy proteins or fats.

Many of the European countries adhere to these standards or continue to push for changing regulations to do so, although differences exist. In "Dairy Ice Cream," nondairy proteins and nondairy fats are not permitted by any country, but minimum fat and protein levels vary. For fat, Germany specifies a minimum content of 10%, Norway 9%, Italy, Belgium, Spain, Finland, and Switzerland are all at 8%, France, UK, Hungary, and Portugal at 5%, and Greece at 4%. Italy, Belgium, Spain, Finland, and UK specify a minimum dairy protein content of 2.5%, while the others simply state that dairy protein is required. Norway specifies a minimum total solids content of 35%, Italy 32%, and Switzerland 30%, while none of the others specify this value. Norway specifies a minimum weight of 500 g/L and Switzerland 450 g/L, although none of the others have such requirements. For "Ice Cream" in which the term "Dairy" is not specified, there are fewer regulations, with most countries simply stating that either dairy and/or nondairy fats are mandatory while either dairy and/or nondairy proteins are optional. Hungary and Portugal require food protein in "Ice Cream," Spain requires dairy protein and the UK requires a minimum of 2.5% dairy protein.

In Australia and New Zealand, a minimum milk fat content of 10% and 168 g food solids per L is required in "Ice Cream," although light, low-fat, and nondairy versions are all available. In Canada regular ice cream must contain at least 10% milk fat and 36% total solids but there is no minimum for TMS. Nondairy fats can replace milk fat in "Frozen Desserts," but not in "Ice Cream." Canada requires a minimum of 180 g food solids/L but no minimum weight per volume. Nevertheless, this acts to control the maximum amount of overrun that can be incorporated to practical levels. Brazil requires 3% milk fat and permits addition of other edible fats to provide the minimum of 8% total fat in ice cream. A reduction in total fat of up to 7% is permitted in fruit ice creams. Ice milk must contain at least 2.5% each of milk fat and milk protein while containing a minimum of 28% total solids. In India ice cream can be made from of milk of the cow or buffalo. The minimums for content of fat, protein, and total solids are 10%, 3.5%, and 36%, respectively. Fat content may be reduced in proportion to amounts of bulky flavorings added but not below 8%. The limit on added stabilizers and emulsifiers is 0.5% and on added starch is 5%. Overrun is specified as a maximum of 100%. Outside of these compositional standards, products are known as "Frozen Desserts."

Standards for ice cream provide opportunities for manufacturers to go beyond the minimum requirements to make a range of product qualities, defined loosely as "economy," "regular," "premium," or "superpremium" ice creams (Table 2.3). Economy ice creams typically are at the minimum requirements for composition and maximum limits for overrun, are made with the most economical ingredients, and sell for the lowest price. Increasing amounts of higher quality ingredients as

Table 2.4 Suggested mixes for hard-frozen ice cream products

Composition (%)							
Milk fat	10. 0	11.0	12.0	13.0	14.0	15.0	16.0
Milk solids-not-fat	11.0	11.0	10.5	10.5	10.0	10.0	9.5
Sucrose	10.0	10.0	12.0	14.0	14.0	15.0	16.0
Corn syrup solids	5.0	5.0	4.0	3.0	2.0	–	–
Stabilizer[a]	0.35	0.35	0.30	0.30	0.25	0.20	0.15
Emulsifier[a]	0.15	0.15	0.15	0.12	0.10	0.10	–
Total solids	36.5	37.5	38.95	40.92	40.35	40.3	41.65

[a]Highly variable depending on type; manufacturers recommendations are usually followed

well as less overrun characterize standard, premium, and superpremium products, all of which fall within the legal definitions of "Ice Cream." Whereas economy ice cream may be made using the more concentrated and shelf-stable forms of milk, such as butter, skim milk powder, and dry whey, superpremium products are more likely to be prepared from fresh concentrated milk and cream. Furthermore, economy ice creams tend to contain high amounts of corn sweeteners and stabilizers, and to be flavored artificially, whereas premium and superpremium ice creams may contain mostly sucrose as sweetener, little or no stabilizer, and natural flavors. Suggested formulations for a range of ice cream products based on component composition are shown in Table 2.4. Higher fat and total solids will lead to progressively higher quality products. As fat and total solids contents are increased, concentrations of MSNF levels, corn syrup solids, stabilizers, and emulsifiers are all generally reduced, to keep viscosity down and optimize textural quality.

Frozen custard, *French ice cream*, *French custard ice cream*. Formulations for frozen custard, also known as "French ice cream," are generally the same as for other ice creams of the same flavor, except that egg yolk solids or other optional egg ingredients are added. In the United States the minimum amount of egg yolk solids for custard is 1.4% or 1.12% for bulk-flavored products. Canada has no standard for frozen custard. The French product "glace aux oeufs" must contain at least 7% egg yolk solids. The German product called "Kremeis" contains at least 240 g of whole or whipped egg per liter of milk used in the formula.

Reduced fat. Fat-reduced ("light"), low-fat, and nonfat products have increasingly gained in popularity with the global obesity epidemic and the desire for consumers to reduce caloric intake while satisfying their demand for sweet and creamy desserts, and also with increasing nutritional knowledge regarding the increased risk of cardiovascular disease with higher intake of saturated fats. Much improvement in the quality of these products has been made in the last two decades. Formulations and ingredients for light and low-fat ice cream products are discussed in Chap. 15.

In the United States, ice cream made with 25% less fat than the reference ice cream is termed "reduced fat." Australia and New Zealand have similar definitions.

Light or Lite. In the United States, ice cream made with 50% less fat or 1/3 fewer calories than the reference ice cream, provided that in case of the caloric reduction

less than 50% of the calories are derived from fat. Canadian standards permit 5–7.5% fat by weight.

Low-fat (also "Low in fat"). In the United States, ice cream containing not more than 3 g of milkfat per serving of 4 fl oz, which can weigh as little as 60 g. Australia and New Zealand require not more than 3 g fat per 100 g of ice cream. In Canada this product with 3–5% fat by weight is labeled *ice milk*.

Nonfat (also "no fat"). In the United States, ice cream containing less than 0.5 g of milkfat per serving. This product can contain no fat ingredient or ingredient that contains fat except if the name of the ingredient in the ingredient statement bears an asterisk that refers to the statement: "adds a trivial amount of fat." Australia and New Zealand permit 0.15 g of fat per 100 g of ice cream.

Bulky flavored ice cream. A product containing a significant volume of coloring and flavoring ingredients including cocoa, fruit, nuts, confections, or cookies. In the United States, reduction in the minimal fat content is permitted as follows: 2.5 times the weight of cocoa solids or 1.4 times the weight of fruit, fruit juices, or nuts. Weights of dehydrated fruits or fruit concentrates may be calculated at their natural levels before being multiplied by 1.4. In Canadian regulations, dilution of minimum fat content from 10 to 8% by wt. and from 50 to 40 g/L for ice cream is permitted when adding bulky flavors.

Gelato. Italian-style ice cream that is typically lower in fat (4–8%) and overrun (25–60%) but higher in sugar (up to 25%, including corn syrups such as high maltose syrup) than regular formulations, which tends to keep it more soft and pliable. In addition, it is characterized by the traditional serving style of being fresh, soft-frozen, and scooped from well-decorated shallow stainless steel serving trays and having highly intense, fresh flavors. Gelato formulations are discussed in Chap. 15.

Turkish ice cream (*Maras ice cream*). Turkish ice cream is distinguished by a much more elastic texture than regular ice cream, from the presence of salep, a flour made from an orchid root, and mastic, a resin that imparts chewiness. *Maras*-style ice cream can be so sticky that it needs to be eaten with a knife and fork.

Soft serve. Ice cream and related products that are sold as drawn directly from the scraped-surface freezer without hardening. Ice cream, frozen custard, low-fat ice cream, or frozen yogurt can all be served soft-frozen although there are typically slight variations in soft-serve formulations compared to their hard-frozen counterparts. Soft-frozen products are typically prepared at the site of consumption from mixes that have been processed in dairy processing facilities and are packaged and distributed in bulk. In the United States in 2010, 6.5% of regular ice cream, 61% of low-fat ice cream, and 71% of frozen yogurt was soft-frozen. Low-fat mixes for soft serve typically contain 3–5% fat, 11–14% milk solids-not-fat, 13–15% sweetener, and 0.3–0.5% stabilizer/emulsifier. Mixes used for soft-frozen ice cream are relatively low in total solids, 30–35%, compared with those used for hard-frozen ice creams, 36–40%. However, the amount of overrun in the soft-frozen desserts is commonly 50% vs. 90–100% for hard-frozen ice creams. Soft-serve freezers are of the batch type.

The refrigeration system maintains a set temperature so that frozen product can be dispensed over an extended time. This means that mixes must be formulated to limit churning of fat caused by agitation within the freezer cylinder during times of slow product turnover. Soft-frozen products are discussed in Chap. 8.

Mellorine. In the United States, a food similar to ice cream but having the milk fat replaced in whole or part with vegetable or animal fat. It contains, by FDA Standard of Identity (21 CFR 135.130), not less than 6% fat and 2.7% protein, the milk-derived protein having a protein efficiency not less than that of milk protein. For mellorine containing bulky flavoring agents the minimal content of fat and protein is calculated in the same way as for ice cream. Vitamin A must be present at the rate of 40 IU per gram of fat. This standard of identity has not been utilized in the US market for a number of years, although products of this composition are very common in other countries and are variably referred to as "Ice Cream" (e.g., Euroglaces standard), in which the distinction is made between this and "Dairy Ice Cream" containing milk fat, or "Frozen Dessert" (e.g., Canada).

Specialty Items

Aufait: Two or more layers of ice cream with pectinized fruits or preserves spread thinly between the layers; or the fruits may be stirred gently into the ice cream as it comes from the freezer to give a marbled appearance.

Bisque. Ice cream containing appropriate flavorings and particles of grapenuts, macaroons, ginger snaps, sponge cake, or other bakery products.

Cake roll. Layered ice cream on moist cake, rolled like a jelly roll.

Confection. Ice cream with appropriate flavorings plus particles of candy such as peppermint, butter crunch, or chocolate chip.

Fanciful name. Ice cream that, because it contains a combination of flavoring ingredients, is best described with a name that "stirs the fancy" of the potential consumer, e.g., "Rocky Road."

Fancy molded. Ice cream or frozen yogurt molded into shapes of fruit or other attractive or festive forms. The group includes brick ice cream in one, two or more layers, or with fancy centers.

Fruit. Ice cream containing fruit, with or without additional fruit flavoring or color. The fruit, such as strawberry, may be fresh, frozen, canned, or preserved.

Gelatin cube. Ice cream in which fruit-flavored gelatin cubes are substituted for fruit.

Mousse. Whipped cream plus sugar, color, and flavoring and frozen without further agitation. Condensed milk may be added to improve consistency.

Neopolitan. Two or more distinct flavors in the same package.

Nut. Ice cream containing nutmeats such as walnuts, almonds, pecans, and pistachio, with or without added color or flavoring.

Puddings. High-fat ice cream containing generous amounts of mixed fruits, nutmeats, and raisins, with or without liquor, spices, or eggs. Examples are nesselrode (a mixture of chopped and boiled chestnuts, maraschino cherries, candied fruits, and liqueur or rum) and plum puddings.

Spumoni. A combination of vanilla ice cream, chocolate mousse or chocolate ice cream, cherries, and tutti frutti ice cream, or whipped cream combined with fruits arranged in a spumoni cup and hardened.

Variegated (also called ripple or swirl). Ice cream into which syrup such as chocolate, butterscotch, or strawberry has been distributed so as to produce a marbled effect in the hardened product.

Fermented Products

Frozen yogurt. Yogurt must contain live bacteria of the species *Lactobacillus delbrueckii*, subsp. *bulgaricus*, and *Streptococcus thermophilus* and is fermented to produce developed acidity, which destabilizes the casein protein to induce high viscosity and gelation. Although frozen yogurt is unstandardized in most legal jurisdictions, including the United States and Canada, it should meet similar criteria. Typically, the yogurt bacteria are added to a portion of milk that has been previously heated to 85°C for 15 min. The mixture is then incubated at about 42°C to permit acid and flavor to be produced. This cultured material is then added to the other ingredients of the mix that have been pasteurized. A typical composition in the final product might be 2% milk fat, 14% MSNF, 15% sugar, 0.35% stabilizer, and 68.65% water. This would result from combining 20% of plain, nonfat, unsweetened yogurt at 12.5% MSNF with 80% of a sweet mix containing 2.5% fat, 14.4% MSNF, 18.75% sugar, and 0.44% stabilizer. Final titratable acidity, expressed as lactic acid, would be about 0.30%, which some regulatory bodies have set as a minimum standard for acidity. Other countries prefer to set a standard for numbers of viable bacteria in the product at some time after manufacture, e.g., 10^7/g. Some processors have added the probiotic (health-promoting) bacteria, *L. acidophilus* and/or *Bifidobacterium* spp. and/or *L. casei*, (the so-called ABC cultures) to frozen yogurt. These have the potential to become resident in the colon when ingested in high numbers where they provide numerous health benefits. Additionally, prebiotics, such as inulin, may be added to the product as nutrients for the probiotic bacteria. Frozen yogurts are discussed more fully in Chap. 15.

Lacto. A product similar to sherbet but made with fermented rather than fresh milk. The source of fermented milk can be yogurt or cultured buttermilk.

Sherbets and Related Products

Sherbet. Sherbets are frozen dairy desserts characterized by being low in milk ingredients, high in sugar, and slightly acidified. Milk solids, including milk fat, is usually limited to 5% while total sweetener content, sucrose and corn syrup solids, can approach 30% or greater in a product that contains 32–35% total solids. A general formulation might contain 1–2% milk fat and 3–4% milk solids-not-fat. Sherbets typically have an acidity not less than 0.35%, which is normally adjusted with citric acid but is calculated as lactic acid. Most sherbets are flavored with fruit, fruit juice or juice concentrates, and artificial flavorings. Citrus flavors (lime, lemon, orange) are quite common. Examples of non-fruit sherbets are those flavored with spices, chocolate, or coffee. Particulates, such as pieces of fruit, may also be added to sherbets. Overrun is typically low, for example 50%. Sherbet formulations are discussed in Chap. 15.

Soufflé. Sherbet containing egg yolk or whole eggs.

Ices and Related Products

Water ice. Also known as ice, the product is made of fruit juice, nutritive sweetener and stabilizer, with or without additional fruit acid, flavoring, color or water, and frozen with or without agitation. No dairy products or egg ingredients other than egg white are contained. A typical composition might be 14% sugar, 3.5% corn syrup solids, 0.4% stabilizer, 0.25% citric acid, and 1–2% flavor. The mix need not be pasteurized if potable water is used, although it provides a guarantee against possible yeast and mold growth from environmental contaminants. Water ices are normally quiescently frozen to make novelty items, see Chap. 9 for further details.

Sorbet or sorbetto. Sorbets are similar in composition to sherbets but excluding all dairy ingredients. They contain frozen fruit and/or fruit juice, are high in sugar, and may be stabilized with egg white, pectin, or other gum stabilizers. The volume of air whipped in is up to 20%, although with little or no protein it is hard to stabilize much volume of air. Euroglaces defines a fruit ice as an edible ice that contains at least 15% fruit (or 10% for acid, strong-flavored or exotic fruits) and a sorbet as a fruit ice that contains no added fat and at least 25% fruit.

Granita. Water ice containing sugar, water, and flavors, similar to sorbet although frozen with very little agitation so it is coarser in texture with larger ice crystals.

Novelties

The category of handheld, single-serving products is often referred to as “impulse” products, due to their typical purchase from freezers in small retail shops or vending machines, or “novelties,” implying the category is dominated by new, novel, and

exciting shapes and flavors. Such novel forms of frozen desserts include bars of various shapes (with and without sticks), sandwiches, cones, molded items, rolls, and cakes. These are discussed in detail in Chap. 9.

Drinks

Milk shakes. Milk shakes, like soft-frozen products, are usually prepared for consumption at the retail outlet directly from milk shake mixes that have been processed at a dairy processing facility and packaged and shipped in bulk containers. These products are common in fast-food outlets. A typical mix contains 3% milk fat, 13% milk solids-not-fat, 8% sugar, 3% corn syrup solids, and 0.4% stabilizer, giving a total solids content of 28.4%. Milkshakes can also be prepared in an ice cream retail shop with scooped ice cream and milk and whipped/stirred in a high-speed blender, in a more traditional manner than with a freezing machine.

Smoothie. A blend of fresh or frozen fruit, fruit juice and frozen milk shake mix, yogurt or sherbet. Smoothies are a category similar to milkshakes but containing a wider range of other flavoring ingredients. Many formulations exist for smoothies, but most typical is a blend of whole fruit and/or fruit juice or vegetable juice, cream or yogurt and crushed ice. The mixture is blended in a high-speed blender and served promptly.

Frappé (*or frappe*). An ice made with a mixture of fruit juices frozen to a slushy consistency, or juices mixed with crushed ice, and served as a drink. In many European countries and New England states, the term can also be used to refer to a milkshake.

Complexities of Composition

Some of the characteristics of ice cream mix that merit consideration are the desired flavor, body and texture; anticipated product cost and input costs; handling properties (including mix viscosity, freezing point, and whipping potential/overrun); food energy and nutrient value; color; and general palatability and quality of the finished product. In developing a formula to fulfill the needs of any particular situation, numerous factors must be considered. These include composition standards; the nature of the competition; type of manufacturing operation; source, availability, quality, and cost of ingredients; and production capacity. Although the methods of processing and freezing influence the characteristics of the mix and of the finished product, the effects of constituents supplied by the ingredients are also important. Therefore, each constituent contributes to the characteristics of the ice cream.

Although the traditional ingredients of ice cream were cream, concentrated or condensed milk, sugar, stabilizer, and high quality flavoring, ice cream manufacturers have found it highly desirable to use a variety of alternative ingredients, including

concentrated sources of milkfat or nondairy fats, various milk protein powders, and various corn starch hydrolysate sweeteners.

It is important to remember that MSNF in ice cream are typically nearly twice as concentrated as in milk. Therefore a concentrated source of MSNF, such as condensed skim milk or milk powder, is required. The MSNF portion of cream and milk is insufficient to supply the desired levels of MSNF in the mix. Also, water is a major component in a mix formulation (100-total solids = water, so therefore typically 60–65% water in a 35–40% total solids mix). Water can be supplied by milk or skim milk, also a small amount by that coming from cream or liquid sweeteners, or it can be from a potable water supply (municipal or well water).

Ingredient labels for representative vanilla ice creams in the United States follow with the ingredients listed in the order of highest to lowest use concentration, as they are required on the package. A total of 24 different ingredients appeared on the ingredient labels of the 38 samples examined in the market survey. The lists were composed by taking the most frequently used ingredients for each class of product. Therefore, the lists are unlikely to match exactly that on a single manufacturer's container.

Superpremium: cream, skim milk, sugar, egg yolk, vanilla extract.

Premium: milk, cream, sugar, high fructose corn syrup, egg yolk, mono-/diglycerides, carob bean gum, guar gum, lecithin, carrageenan, vanilla extract, caramel color.

Regular, *no artificial flavor*: milkfat, nonfat milk, sugar, corn syrup, high fructose corn syrup, whey, cellulose gum, carrageenan, vanilla extract, annatto color.

Regular, *natural and artificial flavor*: milk, cream, buttermilk, corn syrup, whey, high fructose corn syrup, sugar, mono-/diglycerides, cellulose gum, guar gum, calcium sulfate, polysorbate 80, carrageenan, natural and artificial flavors, annatto.

Reduced fat, *sugar free*: milk, cream, polydextrose, maltodextrin, egg yolk, guar gum, locust bean gum, carrageenan, vanilla extract, vitamin A.

Light, *no sugar added*: skim milk, cream, sorbitol, maltodextrin, polydextrose, whey protein, mono-/diglycerides, cellulose gum, natural and artificial vanilla, cellulose gel, carrageenan, acesulfame K, aspartame, vitamin A, annatto color.

Low-fat: nonfat milk, cream, sugar, corn syrup, whey, polydextrose, maltodextrin, guar gum, cellulose gum, locust bean gum, carrageenan, mono-/diglycerides, annatto color, vanilla extract, vitamin A.

Nonfat: nonfat milk, sugar, corn syrup, maltodextrin, polydextrose, mono-/diglycerides, microcrystalline cellulose, guar gum, cellulose gum, carrageenan, vanilla extract, vitamin A.

Fat free premium: skim milk, corn syrup, sugar, pectin, vanilla, vitamin A.

Fat free, *sugar free*: skim milk, maltodextrin, polydextrose, sorbitol, whey protein, mono-/diglycerides, natural and artificial flavors, cellulose gum, carrageenan, acesulfame potassium, vitamin A, aspartame.

In a companion survey of ingredient labels of chocolate ice creams in the United States the only two ingredients in addition to those found in the vanilla ice creams were cocoa and chocolate liquor. The latter was found only in premium ice cream. Chocolate liquor would not, of course, be found in fat free products, because the cocoa butter content would furnish too much fat to permit a label claim of less than 0.5 g of fat per serving. There also was a higher incidence of the use of whey in chocolate than in vanilla ice cream, probably because the potential for the whey flavor to be detected by consumers is much less with a highly flavored than with a delicately flavored product.

The survey disclosed that manufacturers used a wide variety of label statements to show sources of milk solids in products with lowered fat content. Whereas, skim milk and nonfat milk are interchangeable words, some manufacturers appeared to consider skim milk to represent the liquid form and nonfat milk to represent the dried form of the product, so they listed both on the label.

Among the ice creams with full fat content, the choices of label terms to indicate sources of milk solids were skim milk, milk and cream, 37%; nonfat milk (or skim milk) and milkfat, 30%; milk and cream, 20%; milk and nonfat milk, 10%; and skim milk and cream, 3%. Since it would not be possible to supply enough milkfat with milk and nonfat milk to make a full fat ice cream, the products so labeled should be considered mislabeled.

Canada permits the use of category terms to indicate the presence in frozen desserts of one or more products within the category. “Milk Ingredients” are those products that have the same chemical composition as milk with either concentration of SNF components or fat, e.g., milk or skim milk in the fresh, concentrated or dried form, cream, and butter. “Modified Milk Ingredients” are those milk products that differ in chemical composition from milk, i.e., the fat or protein has been fractionated or the ratio of lactose:protein:minerals have been modified, although this is generally by physical processing rather than chemical modification per se, e.g., whey and whey products, caseinates, buttermilk, and fractionated milk fat.

Energy Value and Nutrients

The energy value of a food represents the contribution that food makes to the total energy requirements of the body. The unit customarily used by nutritionists for measuring human energy needs and expenditures and the energy value of foods is the kilojoule (SI unit) or kilocalorie (pre-SI unit, although still commonly used to designate energy content of foods). A kilocalorie is the amount of heat required to raise the temperature of 1 kg of water by 1 °C. A calorie is the amount of heat required to warm l g of water 1 °C, although the common use of the term “Calorie” (properly denoted by capital C) refers to a kilocalorie. 1 kcal = 4.18 kJ.

Digestion is the disintegration of the food into simple nutrients in the gastrointestinal tract to prepare them for absorption. Metabolism consists of the chemical changes that nutrients undergo from the time they are absorbed into the body until

they appear as excretory products. It includes the distribution of the absorbed food, the building (anabolism) and breaking down (catabolism) of tissues, and the absorption and release of energy. All nutrients are equally important to the extent they are needed in a particular diet.

The energy value and nutrients of ice cream depend upon the food value of the ingredients from which it is made. The milk products that go into the mix contain the constituents of milk, but in different amounts. On a weight basis ice cream contains three to four times as much fat, and about 12–16% more protein than does milk. In addition, it may contain other food products, such as fruit, nuts, eggs, candies, and sugar, and these may enhance its nutritive value. Ice cream contains about four times as much carbohydrate as milk. Like milk, ice cream is not a good source of iron and some of the trace minerals.

Ice cream is an excellent source of food energy. The fact that the constituents of ice cream are almost completely assimilated makes ice cream an especially desirable food for growing children and for persons who need to maintain or put on weight, for example the elderly. For the same reason, though, portion control is essential for persons who need to reduce or who do not wish to gain weight, so that it becomes part of a balanced and healthy diet and the contribution it makes to energy is fully accounted for.

Energy (Caloric) Content

The wide variation in the composition of ice cream and related products makes it impractical to provide nutritional data that will apply to all products. It is, however, possible to calculate for practical use the food energy value of a given product if the composition is known.

The total energy value of ice cream depends on (1) the percentage of carbohydrates including lactose, added sweeteners, many bulking agents, and sugars that may be present in fruit or flavoring; (2) the percentage of protein including that from milk, whey protein-based fat replacers, nuts, eggs, or stabilizer; and (3) the percentage of fat from any source including cream, emulsifier, egg, cocoa, or nut fat.

When the energy contents of fats, proteins, and carbohydrates are measured in a calorimeter, their yields are 39.7 kJ/g (9.45 kcal/g), 23.7 kJ/g (5.6 kcal/g), and 17.2 kJ/g (4.1 kcal/g), respectively. Not all the digestible food material is assimilated by the body. On average 5% of the fat, 8% of the proteins, and 2% of the carbohydrates are not absorbed. The amount of energy normally expected to be derived from milk per gram of fat, protein, and carbohydrate is as follows: fat 40.0 kJ (8.8 kcal), protein 17.9 kJ (4.3 kcal), and carbohydrates 16.2 kJ (3.9 kcal). These values are the amounts of energy released from the food nutrients as heat units or calories. They are referred to as physiological fuel values. In every day usage these numbers are rounded to 37 kJ (9 kcal), 17 kJ (4 kcal), and 17 kJ (4 kcal), respectively. Neither minerals nor vitamins furnish appreciable amounts of energy. The type of sugar has little relation to the fuel value derived from it, and all sugars have about the same energy value.

The energy value of 100 g of vanilla ice cream containing 12.5% fat, 11% MSNF, 15% sugar, and 0.3% gelatin (a protein) may be calculated as follows, assuming for the MSNF that lactose content is about 52% and protein content is about 36%:

Fat: 12.5 g fat × 37 kJ/g (9 kcal/g) = 462.5 kJ (112.5 kcal)
Carbohydrates: [15 g sugar + (11 g MSNF × 0.52 g lactose/g MSNF)] × 17 kJ/g (4 kcal/g) = 352.2 kJ (82.9 kcal)
Protein: [(11 g MSNF × 0.36 g protein/g MSNF) + 0.3 g gelatin] × 17 kJ/g (4 kcal/g) = 72.4 kJ (17.0 kcal)
Total: 462.5 kJ (112.5 kcal) + 352.2 kJ (82.9 kcal) + 72.4 kJ (17.0 kcal) = 887.1 kJ/100 g (212.4 kcal/100 g)

The energy value of a serving of ice cream varies with the composition of the mix and the weight of mix per volume of finished ice cream. In the United States, the serving size of ice cream for nutritional labeling purposes has been set at one-half cup or 4 fl oz (Federal Register, Vol. 58. No. 158, August 18, 1993, p. 44053). The serving size is 85 g for frozen flavored and sweetened ice, pops, and frozen fruit juices. Sundaes have a one-cup serving size. In Canada, a standard serving size is 125 mL.

Obviously, the weight of a serving of ice cream and the composition are the major variables. Ice cream is sold by volume with a minimum weight specified. Weight can be estimated by calculating the density of the mix and multiplying by the volume of mix per serving. Mix density varies from about 1.06 to 1.15 g/mL but density of the frozen product is a function of overrun and composition. The typical 4-fl-oz serving of ice cream contains between 65 and 68 g of mix when the overrun is 100%. If the overrun is 50%, the same 4 fl oz weighs 94–102 g. Overrun calculations are discussed and demonstrated in Chap. 6. As an example, let us calculate the energy content in a high solids, high-fat mix that contains 16% fat, 10% MSNF, and 17% sweeteners (47% total solids) on a weight basis and is frozen at 100% overrun.

1. Calculate mix density where densities of constituents are fat = 0.93 g/mL, MSNF = 1.58 g/mL, and water = 1 g/mL (see Chapter 6 for further details).

$$\text{Density} = \frac{100}{(16/0.93) + (31/1.58) + 53} = 1.095 \text{ g/mL}$$

2. Calculate the weight of mix in 4 fl oz (118.3 mL) when overrun is 100% (one-half of the volume is air). The mix constitutes 2 fl oz × 29.58 mL/fl oz = 59.16 mL and 59.16 mL × 1.095 g/mL = 64.78 g
3. Calculate energy content:

Carbohydrates: [17 g sweetener + (10 g MSNF × 0.52 g lactose/g MSNF)] × 17 kJ/g (4 kcal/g) = 377.4 kJ (88.8 kcal)
Protein: (10 g MSNF × 0.36 g/g MSNF) × 17 kJ/g (4 kcal/g) = 61.2 kJ (14.4 kcal)
Fat: 16 g fat × 37 kJ/g (9 kcal/g) = 592 kJ (144.0 kcal)
Total by wt.: 1030.6 kJ/100 g (247.2 kcal/100 g)

Table 2.5 Composition and energy content per serving of ice creams of widely varying fat content and overrun

Fat	MSNF	Sweeteners[a]	Density	Weight	Overrun	Energy content	
Percentages (g/mL)			(g/serving)	(g)	(%)	(kcal/4 fl oz)	(kJ/125 mL)
16	10	17	1.095	64.8	100	160	710
16	10	17	1.095	97.2	50	240	1,065
10	10	17	1.042	61.6	100	120	535
10	10	17	1.042	92.4	50	180	800
5	13	17	1.120	66.2	100	105	470
5	13	17	1.120	99.3	50	160	710
0	13	22	1.150	67.9	100	90	400
0	13	22	1.150	102.0	50	135	600

[a]Includes maltodextrins, polydextrose, and corn syrups that may constitute parts of low-fat and nonfat ice creams

Table 2.6 Summary of average quantities per serving declared on nutrient labels of various categories of vanilla ice cream and frozen yogurt in central US markets

Descriptor	Weight (g)	Calories (kcal)	Fat (g)	Protein (g)	CHO[a] (g)	Sugars[b] (g)	Calcium (% DV)[c]	*n*[d]
Fat free/sugar free	71	90	0	3.0	19.0	4.0	8.0	2
Nonfat	67	98	0	3.5	21.0	16.0	9.5	5
Low-fat	71	103	2.2	3.0	18.2	15.2	9.0	10
Light	67	110	3.0	3.0	17.0	15.0	10.0	5
Reduced fat[e]	67	100	4.5	3.0	13.0	4.0	9.0	5
Regular (category i)[f]	69	170	8.0	2.5	16.0	14.5	7.0	4
Regular (category ii)[g]	65	135	7.2	2.1	16.0	13.4	8.0	13
Regular (category iii)[h]	65	130	7.5	2.0	14.5	12.0	8.0	2
Premium	74	160	9.5	2.6	16.0	14.4	8.5	9
Superpremium	106	260	16.3	5.0	23.0	21.3	15.0	3
Frozen yogurt	–	110	2.0	3.0	18.0	14.0	9.0	6

[a]Total carbohydrate, including sugars and polysaccharides
[b]Mono- and disaccharides, including lactose
[c]Calcium expressed as % daily value in a 2,000 calorie diet
[d]Number of samples per category
[e]Reduced fat ice cream sweetened with nonnutritive sweeteners
[f]Flavored with natural vanilla
[g]Flavored with natural and artificial vanilla
[h]Flavored with artificial vanilla

Total by serving: 1030.6 kJ/100 g (247.2 kcal/100 g) × 65.85 g/serving (118.3 mL or 4 fl oz) = 678.6 kJ (162.8 kcal)

Using the same approach, the energy content per serving has been calculated for a variety of ice creams at high and low overrun values (Table 2.5).

Energy values of one serving of representative types of ice cream vary widely as shown on nutritional labels (Table 2.6). Consumers often ask what impact consumption of ice cream may have on their weight. Data in Tables 2.5 and 2.6 show that one serving of ice cream contributes from less than 5% to more than 10% of the

calories of a 2,000 calories daily intake, which is generally deemed appropriate for adults whose activity levels are limited. As in all aspects of healthy eating, variety and moderation are important practices.

Protein Content

Ice cream has a high concentration of MSNF, which is 34–36% milk protein when obtained from traditional sources thus giving ice cream a protein content of 2.5–4% by weight. The milk proteins contained in ice cream are of excellent biological value, because they contain all the essential amino acids. Milk proteins are important sources of tryptophan and are especially rich in lysine. Milk proteins are not only known to be complete in amino acid composition, but the assimilation of ingested milk proteins is 5–6% more nearly complete than for other proteins in general. Proteins and essential amino acids are generally not deficient in the average diets of people from ice cream-consuming countries, although specific target groups, such as the elderly, may obtain needed protein from ice cream.

Protein content is calculated from determinations of the nitrogen content in the food (generally by the Kjeldahl, Dumas or similar methods, see Chap. 14). Early analysis of proteins showed that they have close to 16% nitrogen. The general practice then was to multiply the nitrogen content by the 6.25 conversion factor for the protein content. The accepted value for milk protein is 6.38.

Amounts of protein claimed on Nutrition Facts labels for a single serving of vanilla ice cream generally range from 2.0 to 3.5 g (Table 2.6). The amount is generally inversely related to the fat content (due to lowering of MSNF with increased fat, as discussed above), although the superpremium products also showed high protein values, to contribute to high totals solids. Additionally, when whey solids are added to replace up to 25% of the MSNF of a mix, protein is decreased. Dry whey contains about 12% protein as compared to about 35% in MSNF. Likewise, many of the blended milk powders used for MSNF in mix contain 20–25% protein, reduced from the 36% typically of skim milk solids. Hence the artificially flavored ice creams, those with perhaps lowest cost, also showed lower fat and lower protein than the naturally flavored ice creams.

Fat Content

Milkfat consists mainly of triacylglycerides of fatty acids, 95.8% on a weight basis. Glycerides are compounds in which one, two, or three fatty acid molecules are linked by ester bonds with the trihydric alcohol, glycerol. Mono-, di-, and triacylglycerides contain one, two, and three fatty acids, respectively. Milkfat is highly complex, containing almost 400 fatty acids. It is unique among fats and oils in that it contains 11.8 and 4.6 moles of butyric (4-carbon) and caproic (6-carbon) acids,

respectively, per 100 moles of total fatty acids. All of the butyric and 93% of the caproic acids are esterified to the third carbon (sn-3 position) of the glycerol molecule. Milkfat also contains 2.25% diacylglycerols, 1.11% phospholipids (nine different ones), 0.46% cholesterol, 0.28% free fatty acids, and 0.08% monoacylglycerols. Although milkfat is relatively low in polyunsaturated fatty acids (about 4.5%), it contains about 27% monounsaturated fatty acids.

Milkfat content in ice cream is usually determined by extracting and weighing the ether-soluble fraction (see Chap. 14). Interest in milkfat is centered on its nutritional and functional attributes. It supplies energy, essential fatty acids, fat-soluble vitamins, saturated and unsaturated fatty acids, and sterols including cholesterol. Several minor constituents are also present with unique healthful properties, unlike some of the vegetable fats. It functions to provide unique flavor, to carry fat-soluble flavors, to lubricate the mouth, and to affect the structure, thus the texture, of frozen desserts.

The nondairy fats in use are typically quite highly saturated to make them solid at refrigerated temperature for structure formation in ice cream, as discussed in Chap. 3. From a nutrition and health viewpoint, it would be desirable to use less saturated fat and/or to replace some of the saturated fat with unsaturated fat, since high levels of saturates in the diet have been associated with higher levels of cardiovascular diseases. The contribution of saturated fat from ice cream to one's total diet should be small, however, if ice cream is consumed in moderation.

Carbohydrate Content

Carbohydrates include starch, dextrin, cellulose, sugars, pectins, gums, and related substances. Carbohydrates serve as a source of heat and energy in the body. They are broken down to simple sugars under the action of specific enzymes secreted into the digestive tract and the principal end product is glucose. Sugars of several kinds may be used in the manufacture of ice cream. The commonly used sugar is sucrose, a disaccharide comprised of glucose and fructose, both of which are absorbed by the body after digestion. Sucrose from either sugar cane or beets is identical in composition. Corn syrup solids, now used extensively to replace a portion of the sucrose, come from the hydrolysis of starch to maltodextrins and lower molecular weight starch fragments, maltotriose, maltose, and glucose (dextrose). All of this is digested in the body to glucose, which is absorbed. In high fructose corn syrup, some of the glucose is converted to fructose (levulose), which is also absorbed by the body. The sugars of most fruits are sucrose, fructose, and glucose. Invert sugar, a mixture of equal amounts of the monosaccharides fructose and glucose, is sometimes used.

Lactose, milk sugar, is a disaccharide of glucose and galactose that constitutes over one-third of the solid matter in milk and approximately 20% of the carbohydrate in ice cream. Lactose is unique in that it is found only in milk, whereas other types of sugars are fairly widely distributed in nature. Adults, especially those of Asian and African descent, may produce insufficient lactase enzyme (β-D-galactosidase) to fully hydrolyze the lactose in a full serving of ice cream. Lactose cannot be absorbed

through the intestinal wall unless it has been split from the disaccharide to the monosaccharide form. This condition may result in physical discomfort due to bloating and, in extreme cases, to diarrhea. These symptoms arise when the lactose moves into the large intestine where it raises the osmotic pressure causing water to migrate into the intestine (hence the diarrhea). Furthermore, the lactose is a substrate for coliform bacteria of the colon. They ferment it, producing liberal quantities of acid and gas, the latter causing the victim to have a bloated feeling. Lactose reduced ice cream formulations are discussed in Chap. 15.

Mineral Content

Certain inorganic elements are essential for growth and performance. Those needed in substantial amounts, calcium, phosphorus, magnesium, sodium, potassium, and sulfur, are termed major minerals or macronutrients. Those needed in small amounts, copper, cobalt, iodine, manganese, zinc, fluorine, molybdenum, and selenium, are termed trace minerals. The inorganic nutrients are interrelated and should be in particular proportions in the diet. Calcium and phosphorus are of vital concern since they are very important nutritionally, especially for building strong bones and teeth, and for unique functionality in dairy foods. About 85% of the phosphorus in the human body is combined with calcium in bones and teeth. Milk and its products, including ice cream, are among the richest sources of calcium.

The mineral content of ice cream derives almost entirely from the MSNF and is therefore found in proportion to the content of MSNF, which can range from about 6 to 14%, although it is normally more like 9–11%. It should be noted, though, that when protein is lowered in MSNF due to use of whey powder or blended MSNF ingredients with low protein, this will affect the mineral content. Calcium averages about 13.8 mg/g MSNF so 70 g servings of ice cream with these extremes of concentration would contribute from 90 to 105 mg of calcium to the diet. The average, 97.5 mg, is 8–12% of the Recommended Daily Allowance (RDA) for calcium in the human diet (the RDA for children is 700–1,000 mg, teenagers 1,300 mg and for most adults is 1,000–1,200 mg, Institute of Medicine 2011), as shown on most Nutrition Facts labels (Table 2.6). Similarly, 1 g of MSNF contains about 10.7 mg of phosphorus, and 70 g of the ice creams formulated at the extremes of MSNF content would contain about 70–85 mg of phosphorus. Since the RDA for phosphorus is 1,250 mg/day for persons ages 9–18 and 700 mg/day for adults (Institute of Medicine 2011), it is obvious that ice cream can be a significant source of phosphorus. One serving can furnish about 7–10% of the RDA. Unlike calcium, phosphorus and magnesium, people generally consume too much sodium in their diet, mainly from processed and prepared foods. The sodium content of MSNF is about 5 mg/g MSNF or 30–40 mg per serving of ice cream. The Tolerable Upper Intake Level for sodium is, on average, 2.3 g/day (Institute of Medicine 2011), so a serving of ice cream is well below the limit and not a significant issue for those wanting to reduce sodium intake. Not all sodium in ice cream comes from the MSNF, however, as salt may be

added to the mix as an ingredient (although there is no specific reason to do this, see Chap. 3) or salt may come from various flavoring materials that are incorporated into the ice cream mix pre- or post-freezing.

Fortunately, milk contains little copper or iron, the two minerals that catalyze oxidation. Since ice cream is often stored for weeks to months, it is imperative that contamination of any of the ingredients with these two minerals be prevented. This is a major reason why manufacturers exclude copper from dairy equipment.

Vitamin Content

Like milk, ice cream is an important source of several vitamins, the content depending primarily on how much milk solids is contained and the weight of a serving. The fat-soluble vitamins, A, D, E, and K, are contained mainly in the fat and are absent in unfortified nonfat products. Milkfat is a good source of vitamin A. In the United States, manufacturers are required to add vitamin A to low-fat and nonfat ice creams. The content of water-soluble vitamins is proportional to the concentration of MSNF in plain ice creams. The highest concentration is expected in nonfat ice cream and the lowest concentration in high-fat ice cream. Fruits and nuts also contribute some of these vitamins. Ice cream is considered a good source of riboflavin. As with calcium, 70 g of ice cream contributes about 10% of the RDA of riboflavin, i.e., about 18 μg/g of MSNF and from 75 to 175 μg/70 g of ice cream. Ice cream can also furnish significant amounts of thiamin, B6, and pantothenic acid.

Palatability and Digestability

The high palatability of ice cream is an important factor in choice of it as a food. Chewing is not required with most flavors, and the smooth velvety texture soothes the palate. Its coldness makes it especially desirable during hot weather. Digestibility is generally high. The exception can be with the lactose malabsorbing person. Thus, ice cream is an ideal food for times when other foods do not appeal. No other food contributes so much food value in as attractive and appealing form or is so universally liked and distributed as is ice cream.

The Balanced Mix

A balanced mix is one in which the proportions of the ingredients will produce a satisfactory finished product—a frozen dessert in which the defects, if any, cannot be further corrected by any change in the composition or ingredients of the mix. The structure of ice cream, and the functional contributions of its components, is very complicated. Full knowledge of these functional contributions of mix components

is required to ensure the mix formulation is properly balanced. Ice cream structure is described fully in Chap. 11.

Defects caused by adding defective ingredients, such as rancid or feed flavor, or by manufacturing errors cannot be corrected by changing the concentration of the constituents. Therefore, they do not indicate a poorly balanced mix. However, other defects, such as (1) lack of flavor—insufficient concentration of flavoring, (2) lack of richness—insufficient concentration of fat, (3) sandiness—too high concentration of lactose, (4) shrinkage—generally associated with low protein levels, or (5) weak body—low total solids or low stabilizer, may be corrected by changing the composition of the mix. These defects indicate that the mix is unbalanced.

Balancing is done to give desirable results under certain limited conditions of processing and handling the mix or of handling the finished ice cream. For example, a mix may be properly balanced for a finished ice cream that is to have a rapid turnover, but the components might cause sandiness if the ice cream were to be stored for an extended time. Another mix may be properly balanced for freezing in a batch freezer but not in a continuous freezer. A mix may be thrown out of balance by changing the source of the constituents. For example, if the fat in the mix is obtained from butter, the mix may need additional emulsifier to improve its whipping ability and to give it the proper balance, but if the mix is made with sweet cream, the additional emulsifier would not be necessary. Knowledge and understanding of the role of each constituent together with its advantages and limitations are necessary in selecting a desired composition and in properly balancing a mix. Usually an ice cream mix that is properly balanced for average commercial conditions will have between 36 and 42% total solids and between 20 and 26% TMS (obtained by adding the percentage of fat to the percentage of MSNF). This does not apply to a mix for ice cream with lowered fat content, a sherbet, or an ice. (Calculations for balancing mixes are given in Chap. 6.) For easy reference the functions and limitations of the constituents of ice cream are summarized in Table 2.1, and these will be discussed more thoroughly in Chap. 3.

Nutrition Labeling Based on Composition

In the United States, the Food and Drug Administration has responsibility for food legislation, including The Nutrition Labeling and Education Act. Firms affected by this Act are those that sell more than $500,000 of all food and nonfood products and sell more than $50,000 of food per year. Packages having less than 12 $in.^2$ (30.5 cm^2) of surface area and on which there is no nutrition claim are exempt from the rule. Those packages must bear an address or telephone number that a consumer can use to obtain the required nutrition information. Major provisions of the regulations as they affect labeling of frozen desserts are presented in the following.

All nutrient and food component quantities shall be declared in relation to a serving. A serving is an amount of food customarily consumed per eating occasion by persons 4 years of age or older. Furthermore, the serving size is to be expressed in common household measure. For frozen desserts in the United States, this reference

size was set at one-half cup (4 fl oz, 118 mL), including the volume of coatings and wafers for novelty type products. This regulation, combined with the minimum weight per gallon stipulation of the US federal standard for ice cream, 4.5 lb/gal minimum weight, sets the minimum weight of a serving at 63.8 g. This is calculated as follows:

$$4.5\ \text{lb/gal} \times 453.6\ \text{g/lb} \times 1\ \text{gal/128 fl oz} \times 4\ \text{fl oz/½ cup serving} = 63.8\ \text{g/½ cup serving (round to 64 g)}$$

By consulting the weight per serving declared on the container one can easily calculate the target overrun of the manufacturer. In a 2002 survey by Prof. R. T. Marshall of the University of Missouri, the declared weight per serving of regular vanilla ice cream in half-gallon containers averaged 66 g with a standard deviation of 2 g. Seven of the 14 brands surveyed declared the serving size as 65 g. The maximal net weight per serving was 71 g, which, if a mix weight of 9 lb/gal is assumed, is equivalent to the overrun shown in the following calculation:

$$\text{Wt. of 4 fl oz of mix} = 9\text{lb/gal} \times 453.6\text{g/lb} \times 1\text{gal/128floz} \times 4\text{oz} = 127.6\text{g}$$

$$\frac{127.6\ \text{g mix/4 fl oz} - 71\ \text{g ice cream/4 fl oz}}{71\ \text{g ice cream/4 fl oz}} \times 100 = 80\ \%$$

This formula can be used for any similar calculation by substituting the actual weight per gallon of mix and the target weight in g/serving to calculate the desired overrun, or if the desired overrun is known, to calculate the desired weight per serving. For example: If a 120 mL container of mix weighs 140 g and the same volume of the finished ice cream weighs 80 g, the overrun is $(140-80)/80 \times 100 = 75\%$ (see Chap. 6, section "Overrun Calculations").

In addition to the minimum weight per volume, the US standard requires ice cream to contain at least 1.6 lb of food solids per gallon (192 g/L). This equates to 22.7 g of food solids per 4 fl oz (118 mL) serving. Thus, the minimum TS in the mix would be 35.44% when overrun is set at 100%. The minimum fat content, unless the label contains a descriptor, is 10% in plain ice cream. This equates to 6.4 g/serving, and the label would read 6 g of fat. The total milk solids must equal at least 20%, so the minimum MSNF in this ice cream would be 10%. The estimated protein content would be 36% of the MSNF, or $64\ \text{g} \times 0.1 \times 0.36 = 2.3$ g, and the label would read 2 g. If the remainder of the solids of the mix is composed of 10% sugar, 5% corn syrup solids, and 0.44% stabilizer/emulsifier, the amount of carbohydrate is 15% of 64 g plus the amount of lactose in the MSNF. If all of the MSNF is supplied by concentrated skim milk, the lactose can be estimated as 56% of the weight of the MSNF. Total carbohydrate would be $[0.10 + 0.05 + (0.56 \times 0.10)] \times 64\ \text{g} = 13.18$ g, and this would be rounded to 13 g. The calcium content would be about 90 mg, and this is 9% of the Recommended Dietary Allowance for men and women between the ages of 25 and 50 (Institute of Medicine 2011).

The label must also show amounts per serving for calories, calories from fat, total fat, saturated fat, cholesterol, sodium, total carbohydrates, sugars (mono- and disaccharides including lactose), dietary fiber, and protein. Furthermore, the % Daily Value must be given as referenced to a 2,000-calorie-per-day diet for the above components, for vitamins A and C, and for the minerals calcium and iron. The Daily Value is based on the RDA, averaged over gender and age. A label typical for regular vanilla ice cream is shown in Fig. 2.1. The list of nutrients covers those most important to the health of today's consumers, most of whom, in developed countries, need to be concerned about getting too much of certain nutrients rather than too few vitamins or minerals as in the past. Canadian regulations issued in 2003 are similar to those of the United States. A standard serving size is 125 mL. The following is the core information to be listed in the order presented per serving: energy value (kJ and/or kcal), amounts of fat, saturated fat, trans fat, cholesterol, sodium, carbohydrates, fiber, sugars, protein, vitamin A, vitamin C, calcium, and iron. Optional health claims permitted highlight the dietary characteristics that reduce the chance of developing diseases such as osteoporosis, heart disease, some types of cancer and hypertension.

At the same time as labeling regulations were changed in the United States, the Federal Standard of Identity for ice milk was dropped. This action was made possible by the adoption of descriptors to describe foods in terms of selected important characterizing ingredients. The most important characterizing ingredient of ice cream is milk fat, and the descriptors used are as follows:

Reduced fat: 25% less fat than the reference product.

Light: 50% reduction in total fat from the reference product, or one-third reduction in calories if fewer than 50% of the calories are from fat.

Low-fat: not more than 3 g of total fat per serving.

Nonfat or fat free: less than 0.5 g of fat per serving.

Interestingly, in the calculation of the amount of fat contained, the values expressed are the free fatty acid portion, and the glycerol portion is not included. The average molecular weight of milk fat is approximately 780 g/mole, and glycerol makes up approximately 5% of the triacylglycerides. Therefore, the traditional ether extraction test of milk fat detects about 5% more lipid than must be considered in writing the nutrition facts label.

These lower fat products must not be deemed nutritionally inferior in the nutrients shown on the nutritional label; therefore, vitamin A, a fat-soluble vitamin carried by milk fat must be added. Since milk fat contains an average of nearly 40 International Units of vitamin A equivalents per gram of fat and regular ice cream is required to contain at least 6.4 g of fat per serving, the amount of vitamin A to be contained in ice creams with lowered amounts of fat would be $40 \times 6.4 = 256$ IU, and this is 5.12% of the US Recommended Daily Allowance. The rounding rule specifies that for vitamins amounts are expressed in 2 IU; therefore, the label would read 6% of the Daily Value. (Readers are referred to 21 CFR 104.20 for rules on fortification of foods.)

These lower fat products must possess physical and functional properties that resemble those of the product they replace, i.e., flavor, body, texture, and appearance must be

Fig. 2.1 Example of nutrition facts label on a half-gallon package of regular vanilla ice cream

Nutrition Facts

Serving Size 1/2 cup (66 g)
Servings Per Container 16

Amount Per Serving

Calories 130 Calories from Fat 70

	% Daily Value*
Total Fat 7g	**11%**
Saturated Fat 4.5g	**22%**
Cholesterol 30mg	**10%**
Sodium 55mg	**2%**
Total Carbohydrate 16g	**5%**
Dietary Fiber 0g	**0%**
Sugars 15g	
Protein 2g	

Vitamin A 6% • Vitamin C 0%

Calcium 8% • Iron 0%

* Percent Daily Values are based on a 2,000 calorie diet. Your daily values may be higher or lower based on your calorie needs:

	Calories:	2,000	2,500
Total Fat	Less than	65 g	80 g
Sat Fat	Less than	20 g	25 g
Cholesterol	Less than	300 mg	300 mg
Sodium	Less than	2,400 mg	2,400 mg
Total Carbohydrate		300 g	375 g
Dietary Fiber		25 g	30 g

Calories per gram:
Fat 9 • Carbohydrate 4 • Protein 4

in semblance of ice cream. The same safe and suitable ingredients are to be used as for ice cream, and it is permissible to add fat analogs and water to replace fat and calories. Furthermore, it is permissible to lower the content of lactose by ultrafiltration, to add hydrolyzed dairy proteins, and to utilize safe and suitable sweeteners such as aspartame and acesulfame potassium (acesulfame K). In each case the label of the product must identify each ingredient. Finally, these products may weigh as little as 4.0 lb/gal (480 g/L), one-half pound less than the whole fat variety of ice cream.

It is permissible to label some ice creams as "healthy." Such a product must contain, on a per serving basis, not more than 3 g total fat, 1 g saturated fat, 15% of calories from saturated fat, 60 mg of cholesterol, or 360 mg of sodium. Additionally, it must contain at least 10% of the Daily Value of at least one of the following nutrients: vitamin A, vitamin C, calcium, iron, protein, or fiber.

The market survey of US ice creams referred to above reveals the mean values shown in Table 2.6 for selected nutrients in variously labeled retail ice creams.

An informal survey of 11 ice cream products in Canada in 2011 showed that nine products ranged from 540 to 600 g/L (90–110% overrun), while two were from 700 to 900 g/L (40–70% overrun). The declared energy content ranged from 120 to 160 kcal/125 mL serving, with the two dense products reporting 195 and 290 kcal/125 mL serving. It was also interesting to note that all those who were using cream as a milk fat source declared that on the label, rather than the category term "Milk Ingredients," presumably to enhance consumer perception of their products.

The website at http://laws.justice.gc.ca./eng/regulations/C.R.C.,_c._417/index.html contains Canadian general regulations for packaging. The Canadian laws specific to Nutrition Facts labeling can be found at http://www.hc-sc.gc.ca/fn-an/label-etiquet/nutrition/index-eng.php.

For those countries establishing or amending nutrition labeling regulations the Codex Alimentarius Commission produced "Codex Guidelines on Nutrition Labeling" (CAC/GL 2-1985, revised 1993, 2003, 2006, 2009, 2010). The following principle stated in the document applies to regions in which nutrition labeling is voluntary: "Nutrition labeling should not deliberately imply that a food which carries such labeling has necessarily any nutritional advantage over a food which is not so labeled." The document states that where nutrient labeling is applied, the following should be declared: energy value; amounts of protein, available carbohydrate and fat; the amount of any nutrient for which a nutrition claim is made; and the amount of any other nutrient considered relevant for maintaining a good nutritional status. Major components of the document are (1) definitions; (2) conversion factors for calculating energy values and protein content; (3) methods for presenting nutrient content; (4) nutrient reference values; and (5) tolerances. The document can be downloaded free from the CODEX web pages.

The ingredient label should list the constituents of the frozen dessert by source in order of dominance. For example, for ice cream made with water, 10% fat from butter, 11% MSNF from nonfat dry milk, 10.5% sugar, 6% corn syrup solids, 1.4% egg yolk solids, 0.2% stabilizer, 0.05% butter flavoring, 3% pecans, and 0.01% yellow No. 5 food coloring, the ingredient label would read as follows: water, nonfat dry milk, sugar, butter, corn syrup solids, pecans, egg yolk, stabilizer (mono- and diglycerides, carob bean gum, guar gum, vegetable lecithin, carrageenan), butter flavoring, Yellow No. 5 (a food color). The word stabilizer may be left out and the parentheses deleted surrounding the names of those ingredients. On the Canadian label "Milk Ingredients" have the same chemical composition as the milk fat or SNF fraction of milk, e.g., milk or skim milk, cream, and butter, whereas "Modified Milk Ingredients" are those milk products that differ in chemical composition from milk (fractionated fat or altered ratio of MSNF components), e.g., whey and whey products, caseinates, buttermilk and fractionated milk fat. Since water is used for rehydration

of milk solids, it does not need to be listed as an ingredient when using the category term "Milk Ingredients" or "Modified Milk Ingredients."

Some consumers are sensitive to peanuts, other nuts, egg protein, casein protein, Yellow No. 5 and other allergens. Failure to list on labels substances that cause allergic reactions has resulted in many recalls of products from the market at very high costs to the manufacturer. Producers must be vigilant to avoid cross-contamination between batches of product containing food allergens. Such an occurrence can result in the presence of allergens in product for which there is no mention on the ingredients label. In ice cream processing, a likely cause of this is failure to remove an allergenic ingredient from equipment before processing a succeeding mix. The freezer, ingredient feeder, and their supply lines pose high-risks for cross-contamination. However, the most risk is associated with rework in which sources of the product include multiple flavors or mixes. The US FDA makes available the document "Guidance on Inspections of Firms Producing Food Products Susceptible to Contamination with Allergenic Ingredients." It can be accessed at http://www.fda.gov/ora under "Inspectional References." In Canada, an overwhelming number of ice cream manufacturers use the phrase "May contain traces of peanuts/nuts" or "Produced in a plant that also processes pants/nuts" on all products, to indicate to the consumer the risk of potential cross-contaminations.

To minimize risk of unlabeled allergens in a product the FDA makes the following recommendations:

1. Check labels to ensure potential allergens are listed thereon.
2. Conduct audits of labels to confirm they match the finished product.
3. Do not store allergenic materials next to non-allergens.
4. Control dusts of allergens.
5. Design systems to minimize the amount of equipment exposed to an allergen.
6. Schedule long run times to minimize product changeovers.
7. Run non-allergen containing products before those containing allergens.
8. Remove all allergenic ingredients, products, and their packaging materials from the production system before introducing another set of materials. Have a person responsible to check and sign off on this.
9. Add rework that contains allergens to that product only.

Recommendations 1 and 2 presume that persons sensitive to dairy ingredients are well aware of their presence. The greater the number of potential allergens used in a frozen dessert the greater the number of potential customers that will avoid consumption of that product.

Reference

Institute of Medicine (2011) Dietary Reference Intakes (DRIs): estimated average requirements. Food and Nutrition Board, Institute of Medicine, National Academies, Washington, DC

Chapter 3
Mix Ingredients

Introduction

To manufacture ice cream of the highest quality, it is essential to have ingredients of excellent quality, a mix that is formulated and balanced to provide proper function of each component, and excellent processing, freezing and hardening processes. However, the selection of high-quality ingredients is, without doubt, the most important factor in successful manufacture of frozen desserts. The clean, fresh, creamy flavor desired in ice cream can be achieved only by the use of ingredients that have been carefully produced and handled and are themselves of excellent flavor quality. Frozen desserts can be made with a wide variety of ingredients, which can be grouped by type as shown in Table 3.1. The functions and limitations of the components of mix were described in Chap. 2, Table 2.1. This chapter will focus on the sources and selection of the mix ingredients. The approximate composition and density of selected ingredients used in frozen dairy dessert mix are shown in Table 3.2. Regulations for permissible ingredients may differ by country, as discussed in Chap. 2. The contributions of all of these components to the structure and texture of ice cream are discussed in Chap. 11.

Composition of Milk

Because milk is the source of dairy ingredients in ice cream, it is important to understand its composition and properties. Readers are referred to Walstra et al. (2006) or Fox and McSweeney (2003, 2006, 2009) for further details of milk composition and properties. Milk is comprised of water, milk fat, and milk solids-not-fat (MSNF). The latter two components comprise the total milk solids. MSNF are the solids of skim milk and include lactose, proteins, minerals, water-soluble vitamins, and enzymes plus some minor constituents (Table 3.3). These solids are also referred to

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Table 3.1 Essential and optional ingredients for frozen dairy dessert mixes

Dairy fat	*Water*
Cream	Potable water
Plastic cream	Milk: whole, partly skimmed, or skim
Butter	Cream
Anhydrous milk fat/butter oil	Condensed milks
Nondairy fat	Liquid sweeteners
Palm oil	*Stabilizers, thickeners*
Palm kernel oil	Sodium carboxymethyl cellulose (cellulose gum), guar gum, locust bean gum, sodium alginate, propylene glycol alginate, xanthan, carrageenan, modified starches, microcrystalline cellulose (cellulose gel), gelatin, calcium sulfate, propylene glycol monostearate or other monoesters, others
Coconut oil	
Other safe and suitable vegetable oils	
Milk solids-not-fat	*Emulsifiers*
Concentrated (condensed/evaporated) milk	Mono- and diglycerides, distilled monoglycerides (saturated or unsaturated), polyoxyethylene sorbitan monostearate (60) or monooleate (80), others
Sweetened condensed milk	
Milk powder, skim or whole	
Sweet cream buttermilk, concentrated or dried	
Whey, concentrated or dried	
Milk protein concentrates	
Whey protein concentrates or isolates	
Hydrolyzed or modified milk proteins	
Sodium caseinate	
Sweetening ingredients	*Egg products*
Sucrose (“sugar”), cane or beet	Whole egg: liquid, dried, frozen
Invert sugar	Yolk: Liquid, dried, frozen
Corn (or other starch hydrolysate) syrup, varying DE, liquid or dried	*Salts*
	Sodium chloride
High maltose syrup, liquid or dried	Sodium salts of citric acid
Fructose or high fructose syrup, liquid or dried	Phosphates—disodium, tetrasodium, or hexameta forms (~0.1% of product)
Maltodextrin	Ca or Mg oxides or $Ca(OH)_2$
Dextrose	*Flavoring*
Maple syrup, maple sugar	Natural or artificial flavors
Honey	*Coloring*
Brown sugar	Natural or artificial colors
Sugar alcohols, e.g., maltitol, sorbitol	
High-intensity sweeteners, e.g., sucralose, aspartame, acesulfame K, stevia	

as skim milk solids or serum solids. Milk is produced in the mammary gland from constituents supplied via the blood. Some constituents filter or dialyze into the milk, but most are synthesized in the mammary tissues and are secreted by the gland. Milk is a structurally complex physiochemical system. Its components are dispersed in true solution (lactose, whey proteins, some minerals, and minor components), as colloids (casein and complexed minerals) and as an emulsion (milk fat).

Milk fat is suspended in milk as tiny globules that are held in an emulsified state. Charges on the globule membranes cause them to be repulsed from each other. They

Table 3.2 The approximate composition and density of ice cream ingredients

Ingredient	Fat (%)	MSNF (%)	Sugar (%)	Protein (%)	TS[a] (%)	Density (lb/US gallons)	Density (kg/L)
Water	0.00	0.00	0.00	0.0	0.00	8.33	1.000
Skim milk	0.00	8.60	0.00	3.2	8.60	8.63	1.036
Milk	3.00	8.33	0.00	3.1	11.33	8.60	1.032
	4.00	8.79	0.00	3.2	12.79	8.60	1.032
	5.00	9.10	0.00	3.3	14.10	8.60	1.032
Cream ("plastic" cream)	18.00	7.31	0.00	2.6	25.31	8.45	1.014
	30.00	6.24	0.00	2.2	36.24	8.35	1.002
	35.00	5.69	0.00	2.1	40.69	8.31	0.997
	40.00	5.35	0.00	1.9	45.35	8.28	0.994
	50.00	4.45	0.00	1.6	54.95	8.20	0.984
	80.00	1.80	0.00	0.6	81.80	7.95	0.954
Cream/sugar blend	43.00	7.50	30.00	2.8	80.50	9.60	–
Butter, unsalted	82.50	0.50	0.00	0.8	83.00	7.92	0.951
Butter oil	99.00	0.00	0.00	0.0	99.00	7.50	0.900
Milk fat, anhydrous	99.90	0.00	0.00	0.00	99.90	–	–
Evaporated milk, bulk	10.00	23.00	0.00	8.5	33.00	9.20	1.104
Condensed milk	8.00	22.00	0.00	8.2	30.00	8.99	1.079
	10.00	26.00	0.00	9.7	36.00	9.00	1.080
Condensed skim milk	0.00	20.00	0.00	7.4	20.00	8.98	1.078
	0.00	30.00	0.00	11.1	30.00	9.35	1.122
Condensed milk, sweetened	8.00	23.00	42.00	8.5	73.00	10.87	1.305
Condensed skim milk, sweetened	0.50	30.00	42.00	11.1	72.50	11.00	1.321
Skim milk powder[b]	0.70	96.3	0.00	36.0	97.00	–	–
Whole milk powder	26.00	72.00	0.00	27	98.00	–	–

(continued)

Table 3.2 (continued)

Ingredient	Fat (%)	MSNF (%)	Sugar (%)	Protein (%)	TS[a] (%)	Density (lb/US gallons)	Density (kg/L)
Buttermilk, dry	5.00	91.00	0.00	33.7	96.00	–	–
Whey, dry	0.00	93.00	0.00	12.9	93.00	–	–
Whole eggs	11.15	0.00	0.00	12.1	25.4	–	–
Egg yolk	33.00	0.00	0.00	15.8	51.20	–	–
Egg yolk, dry	61.30	0.00	0.00	30.5	95.30	–	–
Sugar, granulated	0.00	0.00	100.00	0.0	100.00	7.50	0.900
Dextrose	0.00	0.00	92.00	0.0	92.00	7.50	0.900
Corn syrup							
30 DE	0.00	0.00	36.00[c]	0.0	79.50	11.81	1.417
42 DE	0.00	0.00	48.00[c]	0.0	80.30	11.98	1.417
62 DE	0.00	0.00	68.00[c]	0.0	81.00	11.81	1.417
Honey	0.00	0.00	75.00[c]	0.0	82.30	11.98	1.438
Cocoa powder	10–22	0.00	0.00	18–21	97.00	–	–
Chocolate liquor	49.00	0.00	0.00	14	94.00	–	–

[a]TS = total solids, 100 − TS = moisture (%)
[b]Also known as nonfat dry milk
[c]Reported as sweetness relative to sucrose

Table 3.3 Approximate composition of bulk cow's milk, as wt. % or mg/100 mL for minerals

Constituents	Mean	Normal variation
Water	87.4	85–89
Fat	3.8	3.5–4.1
Protein	3.2	3.0–3.4
Lactose (milk sugar)	4.9	4.7–5.1
Ash (minerals), mg/100 mL	700	670–730
Calcium	120	
Magnesium	12	
Phosphorus	95	
Sodium	50	
Potassium	150	
Chloride	100	
Sulfate	10	
Citrate (as citric acid)	170	
Nonfat solids	8.8	8.4–9.3
Total solids	12.6	11.9–13.3

are lighter in weight than the serum (skim milk) that surrounds them so they rise slowly in milk to form a layer of concentrated fat called cream. Some cows produce proteins called agglutinins that are adsorbed on surfaces of the fat globules. Agglutinins cause fat globules to stick together, and this increases the rate of creaming (cream formation). Normal milk contains about 2.4 billion fat globules per mL, and the globules vary in size from 0.5 to 10 μm in diameter or larger, depending on the breed of cow and stage of lactation. The layer of phospholipid, proteins, and other molecules that surrounds fat globules protects the glycerides from being hydrolyzed (split apart with the addition of water) by natural or microbial lipases in the serum phase of the milk. Milk fat is comprised mainly of triglycerides, which are in turn comprised of three fatty acids and glycerol, $C_3H_8O_3$, connected through ester linkages.

Milk fat contains about 250 different fatty acids with numbers of carbon atoms in them ranging from 4 to 24, but only 11 of these fatty acids are present at 1% or greater. About one-third of these fatty acids contain one or more double bonds between carbons in the carbon chain. These are called unsaturated fatty acids, and they have lower melting points than do fatty acids of the same carbon chain length that are fully saturated with hydrogens. Milk fat is unique in its content of fatty acids that have short chains of carbon atoms. These fatty acids are butyric (C4), caproic (C6), and caprylic (C8). By combining long-chain saturated fatty acids with short-chain and unsaturated fatty acids in the triglycerides, the mammary tissues of the cow produce milk fat that is melted at body temperature (37°C) but is a semisolid at room temperature (as in butter at 22°C). At freezing/whipping temperatures after aging, 4°C, about two-thirds of the fat will be solid (the other third still liquid), and this plays an extremely important role in fat structuring

(discussed in Chap. 11). Blends of nondairy fats, discussed below, often mimic this "two-thirds solid at 4°C" rule of thumb.

Substances associated with milk fat besides the triglycerides include the phospholipids, lecithin, cephalin, and sphingomyelin; the sterols, cholesterol, and ergosterol; the carotenoids, carotene, and xanthophyll; and the vitamins, A, D, E, and K. Lecithin is formed by replacing one fatty acid of a triglyceride with phosphoric acid and choline, the latter being a nitrogenous base that is a part of the B vitamin complex. Milk contains about 0.075% lecithin and cephalin, and milk fat contains about 0.6% lecithin. Cholesterol is the principle sterol in milk, comprising about 0.015%, and 75–85% of it is associated with the lipid fraction. Ergosterol is the precursor of vitamin D, and carotene is the precursor of vitamin A. Beta-carotene imparts the yellow color to milk fat.

The proteins of milk are subdivided into caseins and whey proteins. Caseins comprise 75–80% of the total protein of milk and occur only in milk. The major casein proteins are α_{s1}-, α_{s2}-, β-, and κ-casein. They occur together as colloidal micelles in milk and can be removed by ultracentrifugation. Casein micelles can be observed by electron microscopy as porous spheres. Their diameters range from 50 to 500 nm. Micellar casein carries large amounts of calcium and phosphate principally, but also other minerals including magnesium and citrate. It is precipitable with proteolytic enzymes (e.g., chymosin or rennin), alcohols that dehydrate the micelles, salts that combine with it, and acids that neutralize its charge at approximately pH 4.6. Casein micelles are otherwise very stable, especially to heat. Whey proteins are comprised of α-lactalbumin, β-lactoglobulin, serum albumin, immune globulins, and some minor proteins. Whey proteins are not precipitated with acid at pH 4.6 nor by chymosin, but they begin to be precipitated by heat at about 77°C (170 °F). Whey proteins contain no phosphate whereas some fractions contain sulfur.

Lactose or milk sugar is dissolved in milk and as such is responsible for the major part of the reduction in freezing point of milk below that of water. Lactose, which is found only in milk, is a disaccharide made up of glucose and galactose. It is only about 1/5 to 1/6 as sweet as sucrose. This carbohydrate is fermentable by many lactic acid-producing bacteria that are commonly added to fermented products. The lactose content of milk normally ranges from 4.8 to 5.1%. It is a reducing sugar that is optically active, having a specific rotation of 52.5°. In solution, lactose exists in two forms with the β-form comprising about 60% and the remainder in the α-form, depending on the temperature. Crystalline lactose exists in three forms, α-lactose hydrate, $C_{12}H_{22}O_{11} \cdot H_2O$; α-lactose anhydride, $C_{12}H_{22}O_{11}$; and β-lactose anhydride, $C_{12}H_{22}O_{11}$. The crystals of lactose occur in many forms and are of high importance to ice cream manufacturers because of the possibility of their formation in the frozen product giving it a "sandy" texture (see further details below).

The nonvolatile salts of milk are the minerals that are found in the ash that remains after heating milk at a high temperature in a muffle furnace to completely oxidize the organic constituents. The mineral content of milk ranges from 0.65 to

0.75%, while the average content of minerals in the salt form is 0.9% (Table 3.3). These mineral salts, in the forms of citrates, phosphates, or oxides, affect the functional and nutritional properties of milk. Calcium and phosphorus are the most important minerals of milk both nutritionally and functionally. Calcium and phosphate are both carried within the casein micelle and play important roles in micelle stability. Milk contains many trace elements, and their concentrations are dependent on the type and composition of rations fed to cows.

Numerous other inorganic and organic substances occur in milk, some of which produce effects far out of proportion to their concentrations. These minor constituents include gases, enzymes, nonprotein nitrogenous substances, flavorful substances, non-lactose carbohydrates, vitamins, and pigments. The gases, carbon dioxide, nitrogen, and oxygen, are dissolved in milk in the approximate volume percentages of 4.5%, 1.3%, and 0.5%, respectively. The gas content decreases on heating milk or exposing it to vacuum.

The enzymes of milk may be produced in the mammary gland during the secretory process or by bacteria growing in the milk. The enzymes that occur naturally in milk include acid and alkaline phosphatases, lipase, esterases A, B, and C, xanthine oxidase, protease, amylase, catalase, and carbonic anhydrase. Enzymes, being proteins, may be inactivated by heat, and they tend to be most active at the body temperature of the cow.

Of the 19 vitamins normally present in fresh raw milk, vitamins A, B_{12}, riboflavin, thiamin, and niacin are present in significant concentrations. Riboflavin is responsible for the green color of whey.

The nonprotein nitrogenous substances of milk include ammonia, urea, creatine, and free amino acids. The flavorful substances, other than the main constituents, include carbonyl compounds, lactones, and methyl sulfides.

Fat Ingredients

The fat component of frozen dairy dessert mixes increases the richness of flavor (especially milk fat), is a good carrier and synergist for added flavor compounds, produces a characteristic smooth texture by lubricating the palate, helps to give body, and aids in producing desirable melting properties. The fat in a mix also aids in lubricating the freezer barrel while the ice cream is being frozen. Limitations on excessive use of fat in a mix include cost, a hindered whipping ability, decreased consumption due to excessive richness, and high caloric value. During freezing of ice cream, the fat emulsion that exists in the mix will partially coalesce (destabilize) as a result of emulsifier action, air incorporation, ice crystallization, and high shear forces of the dasher and scraper blades in the dynamic freezer barrel. This partial coalescence is necessary to set up the structure and texture in ice cream, which is similar to the structure in whipped cream. Structural formation is discussed in detail in Chap. 11.

Milk Fat

Milk fat contributes significantly to the rich, full, and creamy flavor and to the smooth texture of ice cream. Part of the flavor contribution comes from the short-chain, volatile fatty acids that are part of the triglycerides of milk fat, particularly butyric acid. (When cleaved from the triglyceride, however, butyric acid contributes to the flavor defect of rancidity; see Chaps. 5 and 14 for further details.) The best source of milk fat for ice cream mix is fresh cream from fresh milk. If the quality is good, free from rancidity and lipid oxidation, cream provides the best flavor of all the milk fat-based ingredients. It is liquid, which facilitates ease of handling. However, it is also likely the most expensive of the various fat sources. Cream, like milk, supports the growth of bacteria well, so it should be stored at 4°C (39 °F) or less. The titratable acidity of cream containing 40% fat should not exceed 0.10%. In traditional and premium formulations, cream is often combined with concentrated or dried milk (whole or nonfat), the major source of concentrated MSNF, and with milk (whole or nonfat), which provides the water to balance the mix. The disadvantage to the use of cream is that, because of its perishability, a constant supply is necessary. Some ice cream manufacturers separate their own cream from milk while others purchase the cream from other dairies. Sweet cream may be relatively expensive and difficult to obtain in good quality at certain seasons and in some markets. These factors often make it necessary for manufacturers to consider other sources of milk fat.

Frozen cream is sometimes stored during the months of surplus and low price. Only the best fresh cream should be stored frozen. It should be pasteurized at 75°C for 15 min to minimize development of off flavors. Milk and cream should be protected from contact with copper or iron. These metals dissolve in milk and cream catalyzing oxidation that imparts oxidized (cardboard-like and metallic) flavor during storage of frozen cream. This is the reason why dairy equipment is constructed of stainless steel, plastic, rubber, or glass. Frozen cream should be stored at −25°C for not more than 6 months. Although storing cream frozen may be economical, flavor is never quite as good as when the cream was fresh. Rancid, fishy, oily, and tallowy flavors are likely to result from oxidation of frozen cream. However, legal regulations may prohibit addition of antioxidants to cream. Added sugar (10%) helps frozen cream retain freshness and to melt faster with limited separation of fat, since the sugar dissolves in the aqueous phase and lowers its freezing point, hence creating an unfrozen solution that surrounds and protects the fat globules. However, the added sugar represents additional volume that must be stored in the frozen state. A good rule of thumb in making mixes is to use a maximum of 60% frozen cream with 40% fresh sweet cream.

Cream that has been separated twice (so-called “plastic” cream, due to its rheological properties) can be a source of concentrated fat for frozen desserts. It contains about 80% milk fat and has a consistency similar to that of butter. It is prepared by separating and then reseparating cream of 30–40% fat through a special separator. Although plastic cream is stored and handled the same as butter, it has the advantage

over butter of essentially retaining the fat-in-serum emulsion of cream. Because some of the emulsion may be broken during separation and cooling of the product in a swept-surface heat exchanger, it is necessary to ensure complete homogenization and emulsification of mixes made with plastic cream, as with mixes made with butter, butter oil, or frozen cream.

Unsalted butter (sweet butter) of good quality can be an important source of milk fat for frozen desserts. It may be comparatively less expensive than cream, can be transported at low cost, can be stored at 4°C (39 °F) or lower, preferably freezer temperatures, for several weeks to months with little loss in quality, and is nearly always available. Salted butter would produce undesirable salty flavors in the mix and affect the freezing point, increasing the unfrozen water content, but the use of unsalted butter means that the preservative properties of the salt are not present, so storage temperatures must be sufficiently low for adequate preservation and shelf life. The off flavors common to defective butter (whey, storage, oxidized/metallic, old cream, or rancid) will impart very undesirable flavors to ice cream. The use of butter in ice cream mixes often results in undesirable freezing properties, if it has not been properly homogenized and emulsified. This is because both composition and physical structure of butter differ from those of cream. Churning of cream into butter releases much of the natural emulsifiers, components of the milk fat globule membrane, from the ruptured fat globules into the buttermilk. Furthermore, the emulsion is broken and inverted during churning, and it must be restored to a fat-in-serum form in the ice cream mix. This can be done by proper re-emulsification, that is, sufficient homogenization and protein and emulsifier content for fat globule membrane formation. Another major disadvantage of butter is the difficulty with handling a solid and blending it into the mix. It often requires more physical handling than would a liquid source such as cream. It also must be melted and dispersed into the liquid mix during preparation, and this can be difficult. Therefore, the use of butter is mostly limited to batch pasteurization operations. If it is pre-blended for HTST systems, it must be first melted and then dispersed hot into the milk. This causes a loss of regeneration capacity in the pasteurizer (see Chap. 5).

Anhydrous milk fat (butter oil) can be a source of milk fat for ice cream mix manufacture. It is especially desirable for reconstituted products manufactured in countries where there is no domestic supply of dairy ingredients. Anhydrous milk fat stores better than butter without as much concern for oxidation, due to the fact that it has virtually no moisture in it. This fact also makes it more economical to transport. For mix manufacture, it is handled in much the same way as butter.

Milk fat–sugar blends are made by mixing butter or anhydrous milk fat with sucrose alone or with a blend of sucrose and MSNF. The product is a physical blend only as the sugar does not dissolve into the fat. Upon reconstitution of the blend in water with heating, the sucrose will readily dissolve into the water phase. Therefore, these blends are handled in much the same way as butter during mix making. The advantages of using such blends reside in the convenience during storage and mix handling for some processors depending on plant configuration. These blends can also be transported across some international borders as a nondairy blend, since the majority component is sugar, and this often reduces tarification. Microbial growth is

inhibited by the low water activity of milk fat–sugar blends; therefore, they keep well at −18°C for up to 1 year.

Milk fat can be fractionated into a hard fraction (high-temperature melting fraction, enriched in saturated triglycerides) and a soft fraction (low-melting temperature fraction, enriched in unsaturated triglycerides) by using a thermal crystallization process, and this is done industrially in Europe to produce fractions that are either liquid or solid at 20°C (sometimes referred to as olein or stearin, respectively). Whereas the hard fraction is a value-added product with enhanced functionality for the baking industry, the soft fraction can be utilized by the ice cream industry to advantage. It is enriched in C18:1, C18:2, and C18:3 fatty acids, thereby reducing the saturated fat content, which may be of interest for perceived nutritional benefit. This product is more prone to oxidation than either milk fat or the hard fraction, so has to be of high quality for ice cream application. As long as the usage level does not exceed approximately half of the milk fat content in the mix, there should be sufficient solid fat at freezer temperature to obtain adequate fat structuring properties in the ice cream, and this can be controlled by modifying the emulsifier level as needed (Abd El-Rahman et al. 1997). Modifications to the diet of the cow can also modify fatty acid profiles, causing enrichment in unsaturated fatty acids. Gonzalez et al. (2003) showed successful incorporation into ice cream of high-oleic and high-linoleic fractions of milk fat, with incorporation limits also dictated by oxidation potential and the necessity of sufficient solid fat for adequate levels of fat structuring. Bazmi et al. (2007) observed that milk fat which had been enriched in its soft fraction (olein) showed a higher ability for aeration with a more uniform air bubble size distribution and bubbles coated with a thicker layer of fat droplets for enhanced stability. They concluded that enrichment of milk fat with its soft fraction would enhance foaming properties and foam stability in ice cream.

Nondairy Fats

Fats and oils from plant (vegetable) sources are used extensively as fat sources in ice cream in the United Kingdom, parts of Europe, Asia and Latin America, and to an increasing extent in North America, as discussed in Chap. 2 (legal nomenclature of these products varies by country, as also discussed in Chap. 2). They are generally much less expensive than milk fat. Five factors of great interest in selection of fat source are the rate at which the fat crystallizes (which determines, in part, the aging time); the crystal structure of the fat; the temperature-dependent melting profile of the fat, especially at refrigerator and freezer temperatures (both factors determine how well the fat aggregates on freezing); the content of high-melting triglycerides, which can produce a waxy, greasy mouthfeel; and the flavor and purity of the oil. High molecular weight triglycerides are generally flavorless themselves, but often carry other flavor components. Likewise, they can play a role in the release of flavoring agents during consumption. For example, Hyvonen et al. (2003) reported a slightly faster flavor release from ice cream with vegetable fat compared with dairy fat.

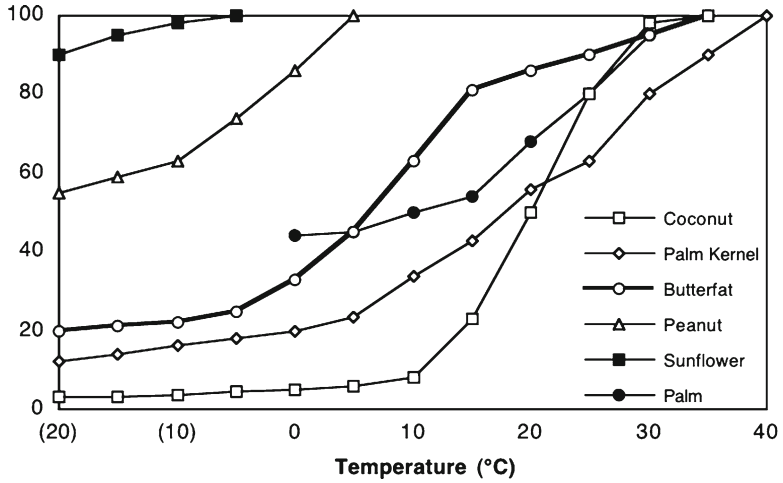

Fig. 3.1 Variation of liquid fat content with temperature for fats suitable for use in ice cream

For optimal partial coalescence during freezing, it is important that the fat droplet contain an intermediate ratio of liquid:solid fat at the time of freezing. If too much oil is present during dynamic freezing, it spreads at the air surface, leading to collapse of the air bubbles and undesirable texture. It is difficult to quantify this ratio as it is dependent on a number of compositional and manufacturing factors; however, one-third to two-thirds crystalline fat at 4–5°C is a good working rule (see discussion of fat partial coalescence in Chap. 11 for further details). The polymorphic form of the fat may also affect the distortion of the fat globule caused by crystallization, which can have a large impact on the rate of partial coalescence of the fat during freezing. Thus, information about solid fat content alone is insufficient to predict the capacity of the fat to form appropriate structures within the ice cream.

Crystallization of fats occurs in three steps: subcooling of the oil (below the equilibrium crystallization temperature) to induce nucleation, heterogeneous or homogeneous nucleation (or both), and crystal propagation. In bulk fat, nucleation is predominantly heterogeneous, with crystals themselves acting as nucleating agents for further crystallization, and subcooling is usually minimal. However, in an emulsion, each droplet must crystallize independently of the next. For heterogeneous nucleation to predominate, there must be a nucleating agent available in every droplet, which is often not the case. Thus in emulsions, homogeneous nucleation and extensive subcooling are expected.

The melting profiles for a range of bulk fats that are used in ice cream formulations are illustrated in Fig. 3.1. Emulsified fats may show considerably higher liquid oil contents, depending on the holding time after cooling and on the crystallization kinetics. Milk fat contains about 30% liquid oil at the temperature of whipping/freezing in the scraped-surface freezer (the temperature at which fat structuring occurs); however palm kernel oil (PKO) and coconut oil will be much harder whereas palm oil will be somewhat softer and the other various sources of vegetable

oils (corn, sunflower, safflower, canola, peanut, etc.) will remain uncrystallized. The type of crystallization within a fat can also be quite complex. PKO, for example, which is comprised mostly of saturated fats, shows only one broad melting range. These triglycerides form mostly compatible mixed crystals. Likewise coconut oil is comprised largely of medium chain triglycerides that produce a very solid and very stable fat. Choo et al. (2010) reported that virgin coconut oil could be used in ice cream formulations but that it lowered the melting resistance of the ice cream compared to milk fat, due to its high solid fat content at the whipping/freezing (fat structuring) temperature. Palm oil, on the other hand, shows two melting temperature ranges, the higher melting temperature range related to trisaturated triglycerides and the lower melting range related to mixed saturated and unsaturated triglycerides, which are not compatible in mixed crystals. Two distinct populations of crystals can give rise to differing properties of the fats.

Blends of oils often used in ice cream manufacture are selected to take into account such physical characteristics as flavor, solid fat content and fat crystallization characteristics, availability, stability during storage, and cost. Hydrogenation was used extensively in the past to achieve the appropriate melting characteristics, but recent concerns about elevated levels of *trans* unsaturated fatty acids in hydrogenated fats have resulted in a move back toward more natural, unhydrogenated fats and appropriate blending to achieve desired functional properties. Thermal crystallization can be used to fractionate palm oil (or any fat or oil with a wide temperature range of melting) into palm stearin (hard fraction) and palm olein (soft fraction). Also new to the fats and oils markets are several cultivars (e.g., sunflower) that have been produced with enriched monounsaturated oil content and reduced polyunsaturated fat content, for greater stability against oxidation and enhanced shelf life. For ice cream use, PKO and coconut oil are often blended with an unsaturated oil to reduce the solid fat content, whereas palm oil may have sufficient liquid fat content.

Im et al. (1994) determined that the content of unsaturated fatty acids in frozen desserts could be increased considerably with minimal risk of oxidation of the stored ice cream. They found no effects on the sensory quality or functional properties when they used a mixture of canola oil and soybean oil with milk fat in making a frozen dessert containing 10% fat. The mixture of 7.8 parts milk fat:3 parts canola oil:1.2 parts soybean oil provided a ratio of 3:2:1 of saturated to monounsaturated to polyunsaturated fatty acids. Frozen dessert with the fatty acids in a ratio of 1:1:1 of saturated to monounsaturated to polyunsaturated was more prone to oxidation. Persson (2009) also reported on the development of a nutritionally optimized fat blend for ice cream manufacture with enhanced unsaturated fat content but good fat structuring properties due to the crystallization properties of the fats utilized in the blend.

Sung and Goff (2010) focused on the development of a structural fat network in ice cream as influenced by the solid:liquid fat ratio at the time of freezing/whipping. The solid fat content was varied with blends of a hard fraction of PKO and high-oleic sunflower oil (HOSO) ranging from 40 to 100% PKO. It was found that blends comprising 60–80% solid fat produced the highest rates of fat destabilization that could be described as partial coalescence (as opposed to coalescence), lowest rates

of meltdown, and smallest air bubble sizes. Lower levels of solid fat produced fat destabilization that was better characterized as coalescence, leading to loss of structural integrity, whereas higher levels of solid fat led to lower levels of fat network formation and thus also to reduced structural integrity. Mendez-Velasco and Goff (2011, 2012) showed that higher levels of unsaturated oils can be incorporated into fat blends for ice cream by using either unsaturated emulsifiers to enhance fat structuring with minimal amounts of solid fat or by homogenizing liquid oil droplets separately from solid fat droplets and by maintaining the liquid oil in a more stable emulsified state (higher levels of adsorbed protein) to allow the solid fat droplets to participate more completely in fat structuring. The contribution of solid fats and liquid oils to ice cream structure is discussed further in Chap. 11.

Fat Replacers

The development of high-quality, lower fat alternatives to traditional ice cream products has been an area of active interest and work for many years, due to consumer interest in low-fat products and nutritional recommendations to lower fat intakes. As a result, a large amount of product development time has been used in searching for a combination of ingredients that will replace the textural and flavor characteristics of fat in ice cream (Ohmes et al. 1998; Aime et al. 2001). These often involve the use of fat replacers. High-quality frozen desserts containing 5–6% fat can be produced without fat replacers, but mixes containing less than 4% fat usually require additional ingredients specifically chosen for their fat-replacing properties. Fat replacers can be carbohydrate, protein, or lipid based. Their main requirement is to provide fewer calories to the product than do traditional fat sources, either through reduction of required weight in the mix or through caloric reductions per unit weight of ingredient. Ice cream products are very complex systems, both in structure and flavor, and fat contributes greatly to both. In creating products that are meant to deliver to the consumer the same attributes as ice cream but with less fat or calories, it is imperative that the structural contribution of fat be considered to the same extent as is flavor. The goal is to deliver high-quality products and develop lasting market share for these products. A great deal of technical literature exists on the various properties of the fat replacement ingredients being marketed by a number of commercial firms. Readers are referred to Wylie-Rosett (2002), Jonnalagadda and Jones (2005), and Ognean et al. (2006) for further details on the composition, properties, efficacy, and safety of fat replacers/substitutes.

Several terms have been used to describe the extent and efficacy of fat replacement. “Fat replacer” is the generic term used to encompass all the related terms. The term “extender” is used to define partial removal of fat from a particular food and substitution with a replacement ingredient. “Substitutes” or “analogs” have the characteristics of fats but contain fewer calories or no calories. “Mimetics” replace part of the fat of a product; they imitate a particular function(s) but not all functions of fat in a food.

The fat-based replacers currently available are monoglycerides, structured lipids, and sugar-fatty acid polyesters. Protein-based fat replacers contain microparticulated protein particles or modified whey protein concentrates (WPCs) that simulate colloidal fat. There is a wide range of carbohydrate-based fat replacers including those derived from modified starches or maltodextrins of various sources, microcrystalline cellulose (MCC), methyl cellulose, hydroxypropyl methyl cellulose, polydextrose, pectin, inulin, and various other dietary fibers. Each of these will be described briefly below.

Emulsifiers are commonly used in ice cream to promote fat destabilization. They can also be used to advantage in low-fat products primarily because they promote the finer distribution of air bubbles and ice crystals enhancing smoothness. In aqueous solutions, they also can form micelles and crystallize into unique structures that have colloidal properties. Recommended concentrations of mono- and diglyceride with 60% alpha mono content are 0.5% in a 3% fat low-fat frozen dessert and 0.6% in a 0% fat mix (Barford 2001).

Structured lipids refer to combined short- and long-chain fatty acid triacylglycerols combined to provide unique fat-like properties with only half the calories (~5 kcal/g). One product on the market, known generically as salatrim from "short and long acyl triglyceride molecules," combines acetate, propionate, and butyrate short-chain fatty acids with long-chain stearate. It has been suggested for use in low-fat frozen desserts.

Carbohydrate fatty acid polyesters are synthetic products that have fat-like properties but are nondigestible and pass through the body unaltered. Olestra, a sucrose-based fatty acid polyester with 8–10 fatty acids esterified to sucrose hydroxyl groups, is one such product that has received considerable attention. It has also been suggested for use in low-fat frozen desserts, although due to concerns about the effect of olestra on absorption of other nutrients and its effect on stool, its use has also raised some concerns (Wylie-Rosett 2002). Currently there is little or no use of olestra in frozen dessert products.

Protein-based fat replacers are typically derived from WPC. These proteins are usually processed by thermally aggregating under shear to produce minute particles (0.5–2-um diameter) that can promote a creamy textural sensation. This process is called microparticulation. Size of the particulates is an important determinant of mouthfeel. The particles, being hydrophobic on their surfaces due to their content of nonpolar amino acids, resist interactions with each other. They can be spray dried and reconstituted without affecting particle integrity. They hold water and disperse well in aqueous systems. Simplesse is one such commercially available microparticulated whey protein. The application of simplesse into frozen dessert products has recently been studied by Aykan et al. (2008). They showed an improvement in texture from the use of Simplesse in light and low-fat formulations, although it also led to higher mix viscosity. Other modified WPCs have also been developed (e.g., DairyLo) to provide fat replacement properties.

Maltodextrins have been widely used as bulking agents in reduced-fat ice creams. These products are starch hydrolysates (see "Corn Sweeteners" in the next section) with DE <20, but those with fat-replacing properties are typically DE <10. As our

understanding of starch digestibility has improved, the development of digestion-resistant starches has also provided new opportunities for fat replacement and caloric reduction. Maltodextrins have lost the starch granular structure and are completely soluble, but they can form thermoreversible gels or macromolecular networks that give rise to their fat mimetic properties. Hence, they can impart a creamy mouthfeel to low-fat frozen desserts with some success.

MCC is comprised of cross-linked, microscopic, insoluble aggregates of aligned cellulose polymers. MCC is usually combined with carboxymethyl cellulose (CMC) to make a colloidal blend (e.g., Avicel). It is primarily used to provide a colloidal particle to low-fat products to improve their creamy mouthfeel perception. Colloidal MCC requires high shear and homogenization for proper dispersion and functionality. It can be used advantageously in low-fat mixes at a rate of 0.2–0.8%.

Methylcellulose and hydroxypropyl methylcellulose are surface-active polymers that form films in solution then gel upon heating, which gives rise to lubricating properties and creaminess in the mouth simulating mouth coating by fat. These molecules have both polar and nonpolar substituents that permit them to reduce interfacial tension between films that are formed between water and fats. Hydroxypropyl methylcellulose has been suggested for use in low-fat frozen desserts. Typical use levels are 0.2–0.8%.

Polydextrose (e.g., Litesse) is a randomly bonded melt condensation polymer of dextrose and lesser amounts of sorbitol and citric acid. It resists breakdown by the enzymes of the human digestive tract so that it yields just 1 kcal/g. The small degree of digestion that produces this caloric output resides in the bacteria of the intestines. The primary function of polydextrose is as a bulking agent. It replaces the bulk of sugar when sugar is replaced by a high-potency sweetener. Polydextrose itself is not sweet, but it has some fat-sparing properties when used in frozen desserts. Solutions of polydextrose have higher viscosities than sucrose or sorbitol at equivalent concentrations. This higher viscosity contributes to desirable mouthfeel. At equivalent solids substitution levels, polydextrose combined 60:40 with sorbitol provides the same freezing point depression as does sucrose.

There have also been several recent developments in the use of other dietary fibers in fat-reduced frozen dessert products. Once such example is the current interest in oat fiber ingredients (e.g., Oatrim, enriched in beta-glucan), for use in low-fat frozen desserts, due also in part to their perceived benefits to health as a dietary fiber. Another dietary fiber of recent interest is inulin, a fructose oligosaccharide of DP 4–20. It has recently been studied in frozen dessert applications by Akalm et al. (2008) and by Aykan et al. (2008), both showing an improvement in sensory qualities although higher mix viscosities. Pectin-based fat replacers are also available. They are comprised of either high methoxyl or low methoxyl pectins, which are well known for their water binding and gelling properties. When processed under high shear, particles are formed that help to create fat mimetic properties.

Other gums and cellulosic substances can mimic some of the functions of fat. They contribute to viscosity, to foam stability, and to control of ice crystal growth.

Some blends of gums interact synergistically to form microscopic spherical particles that mimic the rheology and mouthfeel characteristics of emulsified fat. These blends may contain guar, locust bean, and xanthan gums; carrageenan; sodium CMC; and MCC.

Schmidt et al. (1993) studied the rheological, freezing, and melting properties of ice milks manufactured with protein-based or maltodextrin-based fat alternatives. They concluded that the protein-based alternatives produced products more similar to ice cream than did the carbohydrate-based products. This was due in part to the functional contributions of proteins, especially in the area of emulsification and air incorporation, and also to the colloidal nature of the microparticulated proteins. The same was concluded by Liou and Grün (2007).

No fat replacer is satisfactory for all applications. Used in combinations, they can compensate for the loss of several functions of fat. Chief among their deficiencies are lack of creaminess, milk fat flavor, and ability to carry fat-soluble flavors (Hyvonen et al. 2003; Frost et al. 2005; Liou and Grün 2007). It has proven much easier to develop high-quality "light," reduced-fat products with good consumer acceptability compared to low-fat or nonfat products, which require use of some combination of the fat replacers discussed above.

Milk Solids-Not-Fat/Protein Ingredients

MSNF contributes significantly to the flavor and texture of ice cream. If cream is used as the fat source in ice cream or if milk or skim milk is used as the principal water sources (discussed below), then these ingredients supply some MSNF to the mix, but it is insufficient to deliver the functionality required from the proteins and to develop enough total food solids. Therefore, all ice cream formulations must include a unique source of MSNF, usually either concentrated or dried milk sources, to reach sufficient levels in the mix. MSNF have an indirect effect on flavor. The proteins help give body and a smooth texture to the ice cream, through emulsification of the fat, foam formation and stability of the air bubbles, and viscosity enhancement in the unfrozen phase. Protein content is usually 3–4% in the mix (from a conventional 9–12% MSNF source at 36% protein), although the minimum quantity depends in part of the ratio of casein proteins:whey proteins. Since the processing steps occur sequentially, it may be difficult to deliver optimal protein functionality, for example, a protein present for its good foaming properties may adsorb onto fat interfaces before the foaming step, making it unavailable for foam stability. The optimal protein blend for ice cream, however, has to find the right combination to deliver the best functionality at the least cost.

Lactose adds total solids to the formulation, adds to the sweetness produced largely by the added sugars, and contributes also to the freezing point depression of the other sugars. Lactose can be problematic, however, both due to the number of consumers who are lactose malabsorbers (lactose intolerance, see Chap. 15) and also its low solubility and tendency to crystallize, creating the defect of sandiness

(see Chap. 12). For these reasons, excessive lactose concentrations should be avoided. Lactose content is usually less than 6–7% in the mix, although the limit before sandiness is a problem that depends considerably on the stabilizer that has been used.

The mineral salts from MSNF sources carry a slightly salty flavor that rounds out the finished flavor of ice cream. They also contribute to freezing point depression (see Chap. 6), which needs to be carefully considered when using whey ingredients that are high in mineral salt content.

Concentrated Milks

Plain concentrated (condensed, evaporated) skim milk has been the traditional source of MSNF for mixes, used more frequently than any other source of concentrated milk products due to several advantages it can bring to mix quality and manufacturing convenience. It contains 25–35% MSNF and is prepared by evaporating water from skim milk using vacuum and heat. Modern evaporators with high vacuum and multiple effects do not expose the milk to high temperature during processing, so they produce excellent flavor. The liquid nature of the product helps manufacturers with mix ingredient handling. Concentrated milks are normally pasteurized but not sterilized, so the product is perishable and must be refrigerated. A regular supply of fresh product is necessary, since the shelf life is limited.

Sweetened condensed milk is sometimes used as a source of concentrated MSNF. It has a unique, slightly caramelized flavor that can be used to distinguish the flavor of a particular mix. The added sugar (40–44%) improves the keeping quality over that of plain concentrated products, because sugar raises the osmotic pressure and lowers the water activity (a_w). Sweetened condensed milk is highly viscous; hence it is not so easily handled as is plain concentrated milk. A common defect in this milk is the formation of large lactose crystals. As the product is made, minute crystals of lactose are induced in it by seeding the concentrate with lactose powder while cooling. If these crystals grow excessively large, the texture will be sandy.

Superheating concentrated milk to a high temperature increases the viscosity at ordinary temperatures. The use of superheated condensed milks in ice cream increases firmness and resistance to melting of the ice cream, especially in formulations where no stabilizers or emulsifiers are used, but also increases cooked flavor. Because superheated concentrated products cost more than plain concentrated products and carry a higher risk of being defective, they are mostly used when manufacturers wish to omit stabilizers. Another method of achieving the same result is to pasteurize the mix for an extended time.

The titratable acidity test can be applied to concentrated milk products. When the products are diluted to the same MSNF concentration as skim milk, the acidity should be approximately the same as fresh skim milk, about 0.15%.

Dried Skim and Whole Milk

Skim milk power (nonfat dry milk) is an excellent traditional source of MSNF when concentrated milks are unavailable, expensive, or inconvenient. It should be purchased in only such quantities as will be used in several weeks and, preferably, should be kept in cold storage. Otherwise, staleness is likely to develop. Low, medium, or high heat powders can be used successfully in ice creams. The denaturation of whey proteins caused by high preheating temperatures tends to produce desirable body and texture characteristics in ice cream, especially when time and/or temperature of mix pasteurization is/are not held above the regulatory minimums. However, the lower the preheating treatment, the better the "fresh" flavor that should be expected. The storability, availability, and low moisture content of skim milk powder are important advantages, but being hygroscopic and prone to oxidize, it must be protected well from moisture, heat, and oxygen during storage. It is also available in the instantized form, which aids in solubility in situations when blending is difficult, such as in small operations. However regular spray-dried skim milk powder is used almost exclusively in frozen dessert mixes due to its lower cost. High-quality skim milk powder is bland, slightly cooked and mildly sweet in flavor, lightly cream colored, free of caking, easily soluble, and hydrates well to its pre-dried structure.

Although significant advances have been made in the technology of production, packaging, and storage of dry whole milk, it is used infrequently in frozen desserts. The major reason is the high risk that whole milk powders will become oxidized and contribute a stale flavor.

Whey Products

Dry whey solids are used widely in frozen desserts, because they are relatively inexpensive sources of milk solids. Federal standards in the US permit substitution of up to 25% of the MSNF as whey solids. In Canada and the EU, there is no legal restriction. Whey contains water, lactose, whey proteins, and a small amount of fat but very little casein. While skim milk powder contains 54.5% lactose and 36% protein, whey powder contains 72–73% lactose and only about 10–12% protein. Thus, it can aggravate some of the problems associated with high lactose, viz., lowered freezing point and potential for sandiness. The only advantage of whey powder is its low cost.

However, an increasing number of whey products are available that have high protein and reduced lactose contents. Most are processed by membrane technology. There has been a great deal of attention to the use of these whey products in ice cream. While the lactose is the problematic component of whey, the whey protein provides very good functional properties. Thus, many of these products can provide much higher quality than can traditional whey ingredients. The level of lactose in whey can be reduced by enzymatic hydrolysis to glucose and galactose; however,

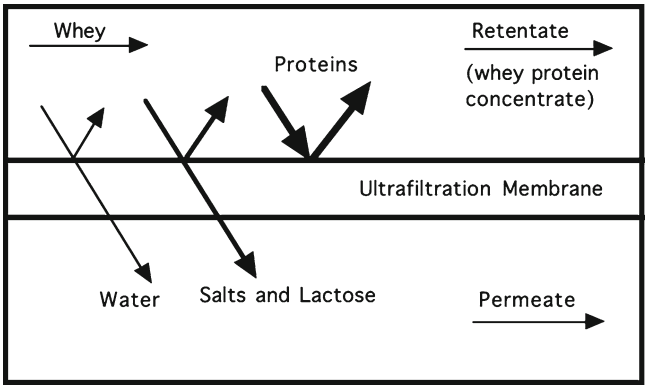

Fig. 3.2 Schematic illustration of the process of ultrafiltration as applied to whey to produce whey protein concentrates. The same process can be applied to milk or nonfat milk to concentrate proteins and fat while reducing lactose and salts levels

the freezing point depression effect of the higher monosaccharide content can cause problems. Ash content in whey can be reduced by demineralization. WPCs with similar protein and lactose contents to skim milk solids can be produced by ultrafiltration (Fig. 3.2). This process utilizes a membrane that allows only low molecular weight components to pass through it, so when whey is ultrafiltered, the retentate becomes enriched in protein as permeate (the solution of water, lactose, and minerals) is continually removed. Protein content can vary from low values of 20–25% to 75% or more, depending on the amount of permeate removed.

Whey protein functionality differs from that of micellar casein, due to the very different structures involved. Sourdet et al. (2002, 2003) studied the effects of varying whey protein to casein ratios in ice cream formulations and heat treatments on structure and stability in ice cream. They showed that enhanced whey protein ratios, to an optimum, could improve ice cream characteristics, but heat treatment played an important role in whey protein functionality. Whey proteins can be modified to improve functionality for ice cream mix through either high-pressure processing (Lim et al. 2008a, b; Huppertz et al. 2011) or through heat aggregation (Relkin et al. 2006). Whey protein isolates (WPI) from ion exchange processing, which contain no lactose, are also available for blending with other ingredients to provide the MSNF content desired for ice cream formulations when no lactose is desired. WPI has been shown to increase mix viscosity and increase ice cream hardness and melting resistance (Akalm et al. 2008).

Milk Powder Blends

It has become common practice to utilize milk protein-based powder blends in ice cream formulations as a replacement source for some of the traditional sources of MSNF.

These are proprietary blends of WPCs, milk protein concentrates (MPCs) or skim milk powder, caseinates, and whey powders formulated with less protein than skim milk powder, and thus less cost. The ratio of casein proteins:whey proteins is also decreased relative to the traditional sources of MSNF. They are available from a number of milk ingredient suppliers. However, they must be blended with an appropriate balance of whey proteins and caseins to fulfill the functional roles of proteins in ice cream. Often, the protein has been modified physically, chemically, or enzymatically to improve its functionality. Caution must be exercised in excessive use of these powders, as they do contain higher amounts of lactose than skim milk powder and protein may be limiting in some applications. Experimentation with individual mix formulations is thus required.

Other Milk Solids-Not-Fat Ingredients

Special commercial milk protein products are often used as constituents of ice cream mix. These products include sodium caseinate, MPCs and other delactosed milk products, modified MSNF, certain mineral salts, and combinations of some of these products with whey products. The products function to improve whippability, resistance to heat shock, and body and texture.

It is possible to produce concentrated protein products from the casein portion of milk proteins, the most common for use as a food ingredient being sodium caseinate. A small percentage of sodium caseinate in ice cream (0.5–1%) may be useful in contributing to functional properties, particularly aeration and emulsification. However, the functionality of sodium caseinate is different than that of micellar casein, the form in which it is found in milk ingredients. Thus, its functional properties need to be considered when proposing its use. It can contribute positively to aeration. It thus serves as an aid to whipping and tends to improve texture. It also provides very good emulsification of the fat, but may lead to an emulsion that is too stable to undergo the required degree of partial coalescence. This can be offset by using emulsifiers to replace caseinate at the fat–serum interface, although caseinate is more difficult to displace than micellar casein. It is most desirable to have the caseinate in the serum phase rather than at this interface. The risk of introducing a stale flavor via sodium caseinate can be significant.

The main purposes of using low lactose products in ice cream are to reduce the risk that sandiness will develop during storage of the product and to provide alternative products to consumers who are lactose malabsorbers. Additionally, because lactose, being dissolved, lowers the freezing point of the mix, removal of a portion of it permits drawing of ice cream from the freezer at a higher temperature than if all of the lactose is left in the product. The use of low lactose milk solids may increase apparent mix acidity, because the increased protein concentration increases the concentration of buffering substances in the product. However, increasing the protein concentration of a mix can improve texture and resistance to heat shock.

Low lactose milk solids are derived from skim milk that has been ultrafiltered (UF) or diafiltered. For example, concentrating skim milk by UF to one-half its initial volume reduces the total lactose by one-half while concentrating the proteins to double their initial concentration (Fig. 3.1). If the retentate from the process (permeate is the water and dissolved materials that pass through the ultrafiltration membrane) is brought back to volume with water, and the process of filtration under pressure is repeated to reduce the volume to one-half the initial volume (referred to as diafiltration), only one-fourth of the initial lactose will remain in the retentate. Use of such MPCs in place of traditional sources of MSNF has resulted in smoother texture, higher freezing point, and harder body of ice cream (Alvarez et al. 2005). Higher protein in frozen desserts made with retentate increases the amount of water of hydration and thus can reduce the amount of stabilizer needed. By adding an alternative carbohydrate, such as dextrose, to the mix, the freezing point can be lowered and the body softened (Geilman and Schmidt 1992). Patel et al. (2006) increased protein content in ice cream mix by 30%, 60%, or 90% using MPC or WPC and showed that increased protein content led to smaller ice crystal size and firmer texture. Use of UF retentate and, particularly, diafiltered retentate to replace MSNF, and especially to replace whey solids, in frozen desserts greatly increases the amount of the dessert that can be eaten without the chance of discomfort by lactose malabsorbers.

Nondairy Protein Ingredients

There are a number of nondairy frozen desserts in the market, based on soy ingredients, nut ingredients, and other combinations. These are discussed in more detail in Chap. 15. Nondairy proteins have also been added to dairy mixes, where allowed depending on the legal jurisdiction (e.g., such is not permitted in the United States or Canada). Pereira et al. (2011) showed that up to 20% of milk protein could be substituted for soy protein in ice cream formulations. The soy-supplemented formulations exhibited good physical properties. Beyond 20% substitution, however, flavor problems developed.

Sources of Water

Potable Water

All mixes require a source of water to standardize the content of fat and MSNF. Good quality mixes can be prepared from the fat and MSNF sources described above and water. However it may also be common practice to use fluid milk as the main source of water. If water is used, it must be high quality and potable, free of

contamination. Water varies in pH, alkalinity, and hardness, but unless any of these parameters are extreme, water does not need to be chemically treated (e.g., softened or mineral-adjusted) before use. When water is used to balance the mix, a larger portion of dry or concentrated skim milk is used to supply MSNF compared to milk.

Milk, Skim Milk, and Buttermilk

Fresh milk or skim milk can be used in the mix to provide the source of water necessary for balancing the formulation whenever available at reasonable prices, as it is also usually an economical and high-quality source of MSNF. Fat present in whole milk must be accounted for when determining the required amount of the concentrated fat source. Fresh whole or skim milk must have a low titratable acidity, a low bacteria count, and a clean flavor. It should be noted, though, that the contribution of MSNF from milk and cream (if used as the fat source) is insufficient to reach the level of MSNF required in most ice cream formulations, thus requiring the use of a concentrated source of MSNF, as discussed above.

Sweet cream buttermilk is obtained by churning cream that has not developed detectable acidity, that is, cream that is of a quality suitable for use in any retail product. Sweet cream buttermilk can also be used as a source of water and MSNF in the mix and has beneficial effects on the whippability of mixes and contributes richness of flavor. Buttermilk is especially desirable in ice cream made without added emulsifiers, low in fat content, or with any form of de-emulsified milk fat (e.g., butter), because it may be enriched in milk fat globule membrane material that is segregated from butter during the churning process. Concentrated or dry buttermilk may also be available, to be used as a concentrated source of MSNF. Buttermilk or concentrated buttermilk should be treated as any other fresh pasteurized milk product. Dry buttermilk can be kept for several weeks to a few months depending on storage conditions (store in a dry cool place), type of package (protect from air and moisture), moisture content, and the initial quality. Because dry buttermilk normally contains a higher fat content than dry skim milk (churning is less efficient at fat removal than centrifugal separation), it may be prone to oxidation during prolonged storage, especially at elevated temperatures. The significant fat content of the buttermilk needs to be considered in calculating fat content within the mix.

Sweeteners

Many kinds of nutritive sweeteners are used in ice cream (Tables 3.1, 3.2, and 3.4). They include cane and beet sugars, many types of corn sweeteners, maple sugar, honey, invert sugar, fructose, molasses, malt syrup, brown sugar, and lactose.

Table 3.4 Characteristics of sweeteners and bulking agents for frozen desserts

Ingredient	Average molecular weight	Relative sweetness[a]	Total solids (%)	Relative freezing point depression[b]	Maximum total sugar supplied[c] (%)
Dextrose	180	74	92	1.90	40
Fructose	180	173	100	1.90	40
Sucrose	342	100	100	1.00	100
Lactose	342	16	100	1.00	d
Maltose	342	32	100	1.00	40
Honey	~270	75	74	1.46	45
Invert sugar	~270	95	77	1.12	30
High fructose corn syrup					
90%	180	125	77	1.88	50
55%	185	98	77	1.85	50
42%	190	86	71	1.80	50
High maltose corn syrup					
55 DE	411	55	81	0.83	40
Corn syrups					
64 DE	298	68	82	1.15	25–50
42 DE	428	48	80	0.80	25–50
36 DE	472	42	80	0.72	25–50
32 DE	565	40	80	0.61	25–50
20 DE	900	23	80	0.38	e
Maltodextrins					
15 DE	1,200	17	95	0.29	e
10 DE	1,800	11	95	0.19	e
5 DE	3,600	6	95	0.10	e

[a] Sweetness relative to sucrose on an as is or product basis
[b] Factor to estimate freezing point depression relative to solids equal in weight to sucrose
[c] Percent of sugar on a sweetness basis generally acceptable from a quality viewpoint
[d] Lactose provides low sweetness, but amount is limited by tendency to crystallize
[e] Lower DE corn starch products build body and provide bulk rather than sweetness

The traditional and still the most common choice of sweetener system in mixes is a combination of sucrose (10–12%) and corn sweeteners derived from hydrolysis of corn starch (corn syrup solids, CSS, usually 3–5%). The main function of sweeteners is to increase the acceptance of the product by making it sweet and by enhancing the pleasing creamy flavor and the delicate fruit flavors. Lack of sweetness produces a flat taste; too much tends to overshadow desirable flavors. The desired sweetness of ice cream is that approximately equivalent to 13–16% sucrose in a 36–38% total solids mix. Sweetness depends on the concentration of sweetener in the water of the mix; thus, decreasing the water of the mix is equivalent to increasing the sweetness. Sweeteners, being dissolved, lower the freezing point of the mix, and this leads to an increased rate of melting. High levels can also reduce whippability, especially important for batch freezer operation. The major considerations in blending sweeteners are relative sweetness, contribution to total solids, and freezing point depression of the mix.

Table 3.5 Relation between total solids (°Brix), °Baumé and density for sucrose syrups

		Density	
Total solids (°Brix)	°Baumé	(kg/L)	(lb/US gallon)
61.0	33.0	1.29	10.78
62.0	33.5	1.30	10.83
63.0	34.0	1.31	10.88
64.0	34.5	1.31	10.92
65.0	35.0	1.32	10.97
66.0	35.5	1.32	11.02
67.0	36.0	1.33	11.07
68.0	36.5	1.34	11.13
69.0	37.0	1.34	11.18
70.0	37.5	1.35	11.23
71.0	38.0	1.35	11.28
72.0	38.5	1.36	11.33
73.0	39.0	1.36	11.39
74.0	39.5	1.37	11.44
75.0	40.0	1.38	11.49

Density (kg/L) = 145/(145 − °Baumé), at 20°C
One US gallon of water (3.78 L) at 68 °F (20°C) weighs 8.322 lb (3.78 kg)

Sucrose: Crystalline and Liquid

Sucrose, commonly known as granulated or table sugar, is made from sugar cane or sugar beets. Being crystalline, it is approximately 99.9% solids (i.e., carries very little water or other impurities) and has a density of 1.588 g/mL. It is highly soluble so is available also as a syrup containing approximately 67% solids. Sucrose remains soluble in ice cream to very low temperatures (~ -20°C, depending on the formulation). To freeze-concentrate sucrose to >65% saturation requires ~90% of the water in a normal formulation to be frozen and the kinetics of crystallization at such low temperature and high viscosity are formidably slow. Hence it generally remains supersaturated at <-20°C. In very rare instances, sucrose has crystallized from ice cream at these low temperatures, although the factors contributing to this are unknown. Sucrose concentrations in mix formulations are limited by high levels of sweetness. Sucrose depresses the freezing point; each 1% increase in sucrose in an ice cream mix lowers the freezing point about 0.1°C (0.2 °F) (see Calculations in Chap. 6). Sucrose may be used as the sole sweetener in ice cream with excellent results, especially in high solids (e.g., premium or superpremium) formulations where the additional body from CSS is not wanted. However, use of sucrose as the sole sweetener in ices or sherbets may result in formation of crystals on the surfaces. This defect in ices and sherbets can be avoided by using one part of dextrose to 3.5 parts of sucrose.

Syrups or liquid sweeteners provide the convenience of handling in large systems, since the metering of them can be controlled with computers and in-line

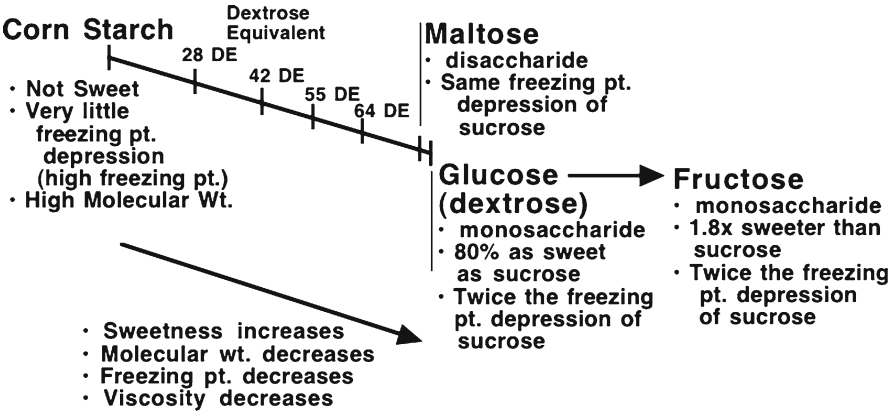

Fig. 3.3 An illustration of the products that result from the hydrolysis of corn starch and their properties relevant to ice cream manufacture

metering devices. The total solids content of sucrose syrups can be measured with hydrometry or refractometry and reported as °Brix, a scale which is calibrated by density of % sucrose solutions (Table 3.4). Another scale used with hydrometers is °Baumé, which is calibrated against density of % salt solutions, although this is presently in far less use than °Brix. The Baumé and Brix scales can be related for sucrose syrups as shown in Table 3.5.

Corn Sweeteners

It has been common practice in the industry for many years to substitute sweeteners derived from corn starch or other starch sources such as potato, tapioca, rice, oat, or wheat for a portion or all of the sucrose. A typical conventional sweetener blend for an ice cream mix usually includes 10–12% sucrose and 3–5% CSS (corn starch hydrolysate syrup, commonly referred to as "glucose solids," but not to be confused with glucose, the monosaccharide). The use of CSS in ice cream is generally perceived to provide enhanced smoothness by contributing to a firmer and more chewy texture, to provide better meltdown characteristics, to bring out and accentuate fruit flavors, to reduce heat shock potential, which improves the shelf life of the finished product, and to provide an economical source of solids.

Starch is a high molecular weight polymer of the monosaccharide glucose (also known commonly as dextrose) and is comprised of two fractions, amylose, a linear fraction, and amylopectin, a branched fraction (waxy starch). During the hydrolysis process, amylose and amylopectin are continually and systematically cleaved at the 1,4 glucosidic linkages by enzymes (randomly by α-amylase to reduce total molecular weight, and sequentially by either glucoamylase to produce dextrose or β-amylase

Table 3.6 Density of corn syrup solutions as a function of total solids concentration and degree of starch conversion, for low conversion (32 DE), regular conversion (42 DE), and high conversion (64 DE) corn syrup solids

	Density (kg/L)			Density (lb/US gallon)		
Total solids (%)	32 DE	42 DE	64 DE	32 DE	42 DE	64 DE
78	1.406	1.405	1.390	11.72	11.71	11.58
80	1.420	1.418	1.406	11.83	11.82	11.72
82	1.435	1.432	1.420	11.96	11.93	11.83
84	1.449	1.446	1.432	12.08	12.05	11.93
86	1.463	1.460	1.446	12.19	12.17	12.05

to produce maltose) resulting in controllable mixtures of medium (oligosaccharides) and low (dextrose, maltose, maltotriose) molecular weight units (Fig. 3.3). Each bond hydrolyzed produces a free aldehyde group that has the same reducing ability as does dextrose. This makes it possible to monitor the process of hydrolysis, the extent of which is termed the dextrose equivalent or DE.

Maltodextrins are only slightly hydrolyzed; consequently they range in DE from 4 to 20 and are only slightly sweet. Maltodextrin can be used in the production of low-fat frozen desserts where it is desirable to find ingredients that contribute greatly to body in low solids formulations. There are several maltodextrin ingredients available that are specifically designed for low-fat systems. The medium molecular weight saccharides (dextrins) are effective stabilizers and slow the formation of large ice crystals, thus improving heat-shock resistance. They also improve cohesive and adhesive textural properties, resulting in positive contributions to the body and meltdown of ice cream. The smaller molecular weight sugars provide smoothness, sweetness, and flavor enhancement. Dextrose, being a monosaccharide, causes greater freezing point depression than sucrose, maltose, or lactose. With the appropriate use of enzyme technology, corn syrup manufacturers have the ability to control the ratios of high to low molecular weight components, and the ratios of maltose, the disaccharide, to dextrose, the monosaccharide. High maltose syrups reduce the effect of dextrose on freezing point.

Starch hydrolysate products having 20 to about 70% of the glucosidic linkages broken are known as corn syrups. They are classified based on degree of conversion as low conversion, 28–38 DE; regular conversion, 39–48 DE; intermediate conversion, 49–58 DE; and high conversion, 59–68 DE. The ratio of higher to lower molecular weight fractions can be estimated from the dextrose equivalent (DE) of the syrup. Figure 3.3 shows that as the DE increases, the sweetness increases but the freezing point decreases, and the contribution to viscosity and chewiness in the mouth decreases. Thus, optimization of DE and concentration of corn sweeteners are required for the most beneficial effects. These sweeteners are available in liquid (~80% solids) or dried form. Densities of liquid products based on composition are shown in Table 3.6. Dry products are also available that have been agglomerated to produce powders with high wettability and little dust. Ice cream manufacturers usually use liquid or dry corn syrup products with a 28–42 DE.

With further enzyme processing (using glucose isomerase), dextrose can be converted to fructose (Fig. 3.3), as in the production of high fructose corn sweeteners

(HFCS). The resultant syrups are much sweeter than sucrose, although they have more monosaccharides and thus contribute more to freezing point depression than does sucrose. The most commonly used type is HFCS 42. It contains 42% fructose, 52% dextrose, and 6% higher saccharides. HFCS 90 is a super sweet mixture of 90% fructose, 7% dextrose, and 3% higher saccharides. Compared with sucrose, high fructose corn syrups (42, 55 and 90%) are from 1.8 to 1.9 times as sweet and lower the freezing point nearly twice as much (Table 3.4). Another product of the corn syrup industry is high maltose syrup. Whereas high fructose syrup is high in monosaccharide composition, high maltose syrup would be high in disaccharide composition, which would have been closer to the same impact on freezing point depression as sucrose, compared to fructose. Satisfactory use of HFCS requires optimization of the concentrations of all sweeteners, to achieve the right balance of sweetness, freezing point depression, and total solids. Blends of high fructose syrup (mostly for sweetness), high maltose syrup (to balance the freezing point depression), and low-DE syrup (to enhance mix viscosity and ice cream body) can be utilized to provide appropriate sweetness, freezing point depression, and total solids, in the absence of sucrose (Goff et al. 1990a, b).

Pure crystalline glucose (dextrose) and fructose are also available from the corn sweetener industry. These are both monosaccharides and thus should not be used alone. They can be used in combination with other sweeteners to achieve the desired freezing point depression and ice cream firmness. Dextrose is a white granular material that contains approximately 99.8% sugar solids. Because it is only about 80% as sweet as sucrose, 1.25 parts of dextrose are required to replace 1 part of sucrose. Dextrose lowers the freezing point nearly twice as much as does sucrose on a weight for weight basis, because it has about one-half the molecular weight of sucrose.

Maple and Brown Sugars

Maple sugar and brown sugar contain characteristic flavoring components that limit their use in ice cream. For example, only 6% of maple sugar in the mix will produce a distinct maple flavor. An additional impediment to their use is their comparative high cost.

Both maple and brown sugar are very high in sucrose. Maple sugar contains about 86% sucrose, 10% moisture, and 4% invert sugar, whereas maple syrup contains about 52% sucrose, 45% moisture, and 3% invert sugar.

Honey

Honey is comprised of about 74.5% invert sugar, 17.5% moisture, 2% sucrose, 2% dextrin, and 4% miscellaneous matter. It is used in ice cream principally to provide honey flavor in a honey–vanilla ice cream. The milder flavored and lighter colored honeys are generally preferred. Sweet clover or alfalfa honeys are most commonly

used. Usually both the desired sweetness and honey flavor will be provided by a combination of 9% honey and 8% sucrose. If more honey is used, freezing and hardening difficulties may be experienced. There is also the possibility of using honey in combination with low- or medium-DE CSS, because they do not depress the freezing point as much as do other sweeteners. A combination of 12% honey and 8% low-DE CSS would allow the use of a greater percentage of honey without freezing difficulties. Honey flavor may blend poorly with other flavors, aside from honey–vanilla, so the addition of other flavors to honey-flavored ice cream is seldom advisable.

Sugar Alcohols

The group of mono- and disaccharide sugar alcohols, the polyols, includes sorbitol, mannitol, xylitol, erythritol, lactitol, maltitol, isomalt, and some related hydrogenated starch hydrolysates. They are extensively described in Wilson (2007) and Nabors (2001). Their main use in frozen dairy desserts is in low-sugar or sugar-free formulations. Generally, they contribute to a much lower glycemic index than conventional sweeteners so they are very beneficial in the diets of insulin-dependent diabetics (Whelan et al. 2008). Since the numbers of people with diabetes is increasing at an alarming rate, the interest in formulations containing the sugar alcohols is also increasing for both consumers and manufacturers (see Chap. 15 for a discussion of formulations). They are often combined with the intense sweeteners to arrive at satisfactory combinations, for example, maltitol and sucralose to match both the freezing curve and sweetness of sucrose-containing formulations. They also function as bodying/bulking agents, sweeteners, and crystallization inhibitors. These substances vary in their relative sweetness, freezing point depression, solubility, heat of solution (cooling effect), stability, laxation potential, caloric content, and cost. Although polyols are considered fully caloric in Canada (4 kcal/g), the European Union recognizes a caloric value of 2.4 kcal/g as an acceptable average for all polyols for labeling purposes. In the United States, self-determination of the caloric content is permitted, and some of the acknowledged values from the FDA are 2.6 kcal/g for sorbitol, 1.6 kcal/g for mannitol, 2.4 kcal/g for xylitol, 2.1 kcal/g for maltitol, 2 kcal/g for lactitol, and 2 kcal/g for isomalt.

Sorbitol and mannitol are monosaccharide alcohols found naturally in fruit juices of apples, pears, cherries, and plums. Mannitol is the major constituent of manna, an exudate of the ash tree, or as a component of mushrooms and marine algae. Sorbitol and mannitol can also be produced by hydrogenation of glucose and fructose, respectively. Both weigh the same, but sorbitol is 0.6× as sweet while mannitol is 0.5× as sweet as sucrose. Sorbitol is hygroscopic while mannitol is not. They both provide a cooling effect in the mouth due to their negative heat of solution. As monosaccharides, they have twice the freezing point depression effect as sucrose on a per weight basis. Both are generally recognized as safe (GRAS) in the USA and are approved for use in Canada, the EU, and many other countries. The laxation thresholds, in g/day, are considered to be 50 for sorbitol and 20 for mannitol.

During digestion, small amounts of sorbitol and mannitol are slowly absorbed through the wall of the small intestine and metabolized by the liver. However, most of the utilization occurs in the colon where the polyols are converted to volatile fatty acids by bacteria. Because they enter the glycogenolytic pathways without dependence on insulin, polyols do not cause appreciable increases in blood glucose levels when eaten.

Xylitol is a five-carbon polyol with similar sweetness as sucrose. It is the sweetest of the polyols and has the most cooling effect. As a lower molecular weight sweetener than the monosaccharides, it could not be used in ice cream at a one-to-one replacement for sucrose due to its freezing point depression effect.

Maltitol differs from sorbitol and mannitol in its physical properties because it is hydrogenated maltose, a disaccharide. It provides similar freezing point depression and sweetness as sucrose and does not provide the cooling effect of sorbitol and mannitol. Its laxation threshold is set at 100 g/day before a warning label must be used. It is widely approved for food use in many countries. Because it mimics the properties of sucrose well, it is probably the most extensively used of the polyols for ice cream manufacture.

Lactitol is the product of hydrogenation of lactose, thus also a disaccharide polyol. It has similar freezing point characteristics to sucrose, but it has only 0.3–0.4× the sweetness of sucrose. Its use is permitted in most countries.

Isomalt forms when sucrose is enzymatically rearranged to isomaltulose and the latter is hydrogenated. Sorbitol and mannitol are equimolar building blocks of isomalt. It is approximately one-half as sweet as sucrose and is non-cariogenic but tends to crystallize because of low solubility in water (25% at 20°C compared to 67% for sucrose).

Combinations of the sugar alcohols, starch hydrolysates, and oligosaccharides have been studied for their contributions to mix rheology, ice cream thermal characteristics and physical properties, and sensory quality (Soukoulis et al. 2010). The thermal melting profile of the mix, ice cream hardness, and meltdown rate (structural collapse) were all affected by variations in the sugar alcohols, as expected, but these physical properties were found to correlate well with sensory properties, suggesting the importance of these variables in product development of novel sweetener-modified formulations. Whelan et al. (2008) likewise reported that once freezing profiles of sugar alcohol-containing products were matched to controls, all other variables were also found to match well. Sweetness of such formulations can be modified by the high-potency sweeteners (described next) with no further effect on physical properties.

Nonnutritive Sweeteners

Many high-potency sweeteners are either commercially available or are in various stages of testing and regulatory approval. With increasing levels of diabetes in the USA and globally, consumer interest in no sugar added or sugar-free formulations

is rising, hence so too is the use of these sweeteners not only in caloric management but also in diabetes management (Gougeon et al. 2004). They are used successfully in some products, soft drinks for example, where sweetness is desired but total solids and other physical characteristics of sucrose, for example, freezing point depression, are not important. In ice cream and related products, however, total solids and freezing point depression are very important to consider when replacing sugar for caloric reduction or blood glucose control. It is perhaps easy to find a high-potency sweetener to replace the sweetness of sucrose and CSS, but what is then used to produce freezing point depression and to build total solids without contributing to blood glucose or caloric intake? Polydextrose is one such low-calorie bulking agent that can be used at a significant concentration without greatly affecting viscosity, but it contributes little to freezing point depression. Another factor to consider in looking at sugar replacement for caloric reduction is that the sugars contribute only a small fraction of the calories in frozen desserts compared to the contribution of fat. Therefore, fat replacement should be targeted first and sugar replacement only if further reductions are required. The more common high-potency sweeteners are described below, but these limitations to their use should be recognized. Intense, nonnutritive sweeteners are extensively described in Wilson (2007), Gougeon (2004), and Nabors (2001). Some of them are in fact digested and thus caloric, but they are often considered nonnutritive due to the very low concentrations required in foods to provide adequate sweetness.

The use of these sweeteners in diabetes management is receiving ever-increasing attention. Current evidence confirms that low-calorie sweeteners do not stimulate appetite or affect mechanisms that regulate hunger and satiety. Intakes of up to the acceptable daily intake value for each of aspartame, sucralose, saccharine, and cyclamate do not affect glycemic control or blood lipids in persons with diabetes (Gougeon 2004).

Saccharin, discovered in 1879 at Johns Hopkins University, is an organic compound that produces no glycemic response. It is approximately 300–500 times as sweet as sucrose but produces a slight aftertaste on its own. It can withstand long periods of storage as well as heat. It has been thoroughly studied throughout its history and, despite earlier concerns about its safety, has been declared safe by numerous scientific bodies. It is widely permitted in more than 100 countries including the USA, but its use in manufactured products, including ice cream, may be restricted.

Aspartame (common trade name NutraSweet) was discovered in 1965 by a chemist who was attempting to develop an antiulcer medicine. It is the methyl ester of two amino acids, L-aspartic acid (aspartate) and L-phenylalanine, both of which occur naturally in foods. Furthermore, it is digested in the same manner as other amino acids. However, it contributes few calories to a serving of ice cream because of the low concentration of it needed to sweeten as compared with sucrose (~200 times as sweet as sucrose). The taste of aspartame is quite similar to that of sucrose. It shows sweetness synergy with several other sweeteners, for example, saccharin and acesulfame K, and enhances some flavors. At high temperature in dry environments, aspartame undergoes hydrolysis and loss of sweetness, but this is not an issue in the normal pasteurization of ice cream mixes. More than 100 scientific studies were conducted to support the food additive petition made to the US Food and

Drug Administration, making it one of the most thoroughly studied food additives in history. Its safety continues to be critically and comprehensively monitored and thus far confirmed. Persons with the rare hereditary disease phenylketonuria (PKU) must control their intake of phenylalanine from all sources, including aspartame. These persons, about 1 in 15,000, are diagnosed at birth by a blood test performed on all newborn. Because aspartame use in foods may introduce a new source of phenylalanine in the diet, products containing this sweetener must carry a warning statement on the label. Aspartame has been declared safe by numerous scientific bodies, the Joint FAO/WHO Expert Committee on Food Additives of Codex Alimentarius and the regulatory agencies of more than 100 countries around the world, including the USA and the EU.

Acesulfame potassium (acesulfame K, common trade name Sunett) is an organic salt, containing sulfur and nitrogen. It is 150–200 times as sweet as sucrose. It is excreted through the human digestive system unchanged and, therefore, is nonnutritive and noncaloric. It is now widely approved by many countries (Gougeon 2004). Acesulfame K is very stable and soluble, does not decompose on heating, and has a synergistic sweetening effect with aspartame, cyclamate, and several nutritive sweeteners. Since both acesulfame K and aspartame are charged and carry a metal ion as a salt, it is possible to produce sweetener–sweetener salts with favorable properties. Chemically combined mixtures of acesulfame and aspartame have been shown to provide a sweetness profile very similar to sucrose.

Sucralose (common trade name Splenda) is the generic name of a high-intensity, noncaloric sweetener derived from sucrose through chlorination. It looks and tastes like sugar but is, on the average, 600 times sweeter. It is useful and becoming widely used in a wide range of foods and beverages including frozen desserts. In general, the sweetness of sucralose decreases with increased sweetener concentration or pH and with decreased temperature. It remains stable during pasteurization treatment and at pH ranges common to frozen desserts, that is, from 3 to 7. It is also now widely approved.

There are several naturally occurring intensely sweet substances, including thaumatin and stevia. Thaumatin is reportedly 2,000–3,000× sweeter than sucrose but leaves a licorice aftertaste in high doses. It has limited regulatory approvals. Stevioside, the sweet compound, is extracted from the leaves of the stevia herb and is reportedly 100–150× sweeter than sucrose. It, too, has limited regulatory approval but is growing in popularity due to its natural extraction process.

Stabilizers

Ice cream stabilizers are a group of ingredients (usually polysaccharides) commonly used in ice cream formulations. The primary purposes for using stabilizers in ice cream are:

- To increase mix viscosity.
- To stabilize the mix to prevent wheying off (e.g., carrageenan).
- To aid in suspension of flavoring particles.

- To produce a stable foam with easy cutoff and stiffness at the barrel freezer for packaging.
- To retard or reduce ice and lactose crystal growth during storage, especially during periods of temperature fluctuation, known as heat shock.
- To slow down moisture migration from the product to the package or the air.
- To help to prevent shrinkage of the product volume during storage.
- To provide uniformity to the product and resistance to melting.
- To produce smoothness in texture during consumption.

Many of these functions are attributed to enhanced viscosity of the unfrozen phase in ice cream. Stabilizers must also have a clean, neutral flavor, not bind to ice cream flavors, contribute to acceptable meltdown of the ice cream, and provide desirable texture upon consumption. Limitations on their use include excessive mix viscosity; contribution to a heavy, soggy body; and production of undesirable melting characteristics. Although stabilizers increase mix viscosity, they have little or no impact on freezing point depression.

Most ice cream manufacturers use commercial stabilizer/emulsifier blends formulated by specialized firms with ingredients that they purchased from primary suppliers. These blends usually are combinations of stabilizers and emulsifiers but are sometimes referred to in short as stabilizers. The most frequently used ingredients in mixtures for regular ice cream are guar and locust bean gums (LBGs), cellulose gum (the primary hydrocolloids), carrageenan (the secondary hydrocolloid), mono/diglycerides, and polysorbate 80 (the emulsifiers). Historically, gelatin was used in most formulations or home recipes as an ice cream stabilizer. However, the ice cream industry has made many improvements in the stabilization and emulsification of ice cream and other frozen desserts, and a range of polysaccharide gums has been available since the 1950s or 1960s, which, for both functional and economical reasons, has largely displaced the use of gelatin. Blends are formulated to deliver the desired functionality for mixes with specific formulation characteristics and production demands, to disperse readily, to dissolve at selected temperatures, to minimize dust formation, and to be priced satisfactorily for the intended product. Food scientists working with the primary and secondary sources of these important ingredients will continue to contribute to their successful use and to high quality of the frozen desserts that consumers demand.

The amount and kind of stabilizer/emulsifier blend needed in ice cream varies with mix composition; ingredients used; processing times, temperatures, and pressures; storage temperature and time; and many other factors. Generally, the best advice is to follow the recommendations of the supplier. Usually 0.2–0.5% of a stabilizer/emulsifier blend is used in the ice cream mix. Excessive use of stabilizer leads to an ice cream defect known as gumminess, in which the product does not melt sufficiently quickly in the mouth and retains excessive chewiness. Some stabilizers lead to gumminess at lower concentration than others, so product development requires caution when optimizing stabilizer concentrations for physical functionality.

The stabilizers function very differently than the emulsifiers (see Chap. 11 for more detailed discussion of their role in ice cream structure and Chap. 12 regarding their role in ice cream shelf life). Stabilizers are all very large, bulky

macromolecules. They have a great ability to interact with water through hydration (water holding) and swelling, thus occupying a large solution volume and, at sufficient concentration, entangling and interacting with each other. Therefore they are also frequently referred to as hydrocolloids. This behavior greatly modifies the rheological characteristics of solutions, and it is the modification of rheological properties and interaction with water that gives rise to their functional properties. It must be remembered that freeze concentration of the unfrozen phase results in a polysaccharide concentration several times higher than what was present in the original mix. As ice freezes out of solution in frozen desserts, stabilizer concentration, which may be only 0.25–1.0% in the unfrozen mix, increases manyfold in the unfrozen milieu. Thus, investigation of the effectiveness and action of stabilizers must occur at these elevated concentrations, where molecular interactions, both among themselves and with proteins, are greatly enhanced. Stabilizers and their properties have recently been reviewed by Bahramparvar and Tehrani (2011).

The hydrocolloids used as stabilizers in frozen desserts fall into the following categories (frequently used ones in italics). Except for gelatin (a protein), these hydrocolloids are polysaccharides, polymers of sugar residues.

Proteins	Gelatin
Plant exudates	Arabic, ghatti, karaya, and tragacanth gums
Seed gums	*Locust* (*carob*) *bean*, *guar*, psyllium, starch, and modified starches
Microbial gums	Xanthan
Seaweed extracts	Agar, alginates, *carrageenan*
Pectins	Low and high methoxyl
Cellulosics	*Sodium carboxymethylcellulose* (*cellulose gum*), microcrystalline cellulose (cellulose gel), methyl and methylethyl celluloses, hydroxypropyl and hydroxypropylmethyl celluloses

Functionality of these hydrocolloids varies and can be modified by changing the chemical structure of the natural forms. Individual hydrocolloids, regardless of type, seldom perform all of the desired functions. Each has a particular effect on body, texture, meltdown, and stability in storage. Therefore, to gain synergism in function, individual substances are usually combined as mixtures of stabilizers and emulsifiers. Components selected vary with the composition of the mixes and the outcomes expected from their use, including cost. Most of the hydrocolloids used are incompatible in solution with milk proteins, especially casein micelles (Bourriot et al. 1999a, b; Schorsch et al. 1999, 2000), and thus will cause a phase separation known as wheying off (see Chap. 11). Carrageenan can retard this separation phenomenon at very low concentration and thus is used extensively in most stabilizer blends. Much experimentation is involved in determining the right combination and concentrations of the several available hydrocolloids to perform the functions desired for a given formula and market niche.

Characteristics of Individual Stabilizer Ingredients

Alginate: Alginate is an extract of the brown algae, kelp, a seaweed. It is a polysaccharide comprised of the sugar acid monomers mannuronic acid and guluronic acid, as either polymers of each or as mixed polymers. It is a charged polymer that is neutralized with an ion. The soluble form, sodium, ionizes in water and the polymer reacts with calcium ions to produce an insoluble gel of calcium alginate; this reaction is used to form a host of fabricated foods gelled with sodium alginate and calcium chloride. The most common form for ice cream is sodium alginate, but propylene glycol alginate is also sometimes used. To prevent the gelation reaction with calcium ions in milk, sodium alginate is blended with a calcium chelator, such as disodium phosphate, which then reacts to form tricalcium phosphate. Sodium alginate dissolves readily in cold or hot water, but can be degraded if held hot for too long. It is not widely used in ice creams.

Carboxymethyl Cellulose (*CMC*): CMC, known also as cellulose gum, is derived from the cellulose of plant material. Cellulose is comprised of glucose monomers but is not digestible by humans, nor is it soluble as it is extensively cross-linked through hydrogen bonds. To make it soluble and useful as a food ingredient, cellulose is derivatized by adding side group constituents such as carboxymethyl groups, which open up the backbone structure of the polymer. Because CMC is charged, it is neutralized with an ion, usually sodium. The parameters of importance in selecting CMC's for food use include the degree of substitution of carboxymethyl groups (the more highly substituted, the more soluble it becomes), the uniformity of substitution (the more random the substitution, the more thixotropic the behavior in water due to the presence of unsubstituted regions that can interact with each other; thixotropic means thinning with shearing time), and the degree of polymerization (the longer the molecule, the more viscous the solution). CMC is easily dissolved in the mix, and has a high water-holding capacity so is considered a very good ice cream stabilizer.

Carrageenan: Carrageenan is derived from an extract of red algal seaweed, including the original source *Chondrus crispus* (Irish Moss), *Gigartina skottsbergii*, *Gigartina radula* and other *Gigartina* sp., *Furcellaria* sp., *Eucheuma cottonii* and other *Eucheuma* sp., and *Sarcothalia chrispita*. It is produced in coastal regions of such countries as Chile, the Philippines, Canada, the United States, France, Spain, Denmark, and Ireland. Chile and the Philippine islands lead in world production. It is a polymer of galactose with a sulfate ester content of 20% or more. There are at least three natural forms classified by the amount of sulfate in the molecules. Lambda-carrageenan has ~35% ester sulfate groups and is cold soluble; iota carrageenan has ~32% ester sulfate groups and is less soluble; and kappa (κ)-carrageenan has ~25% ester sulfate groups and can form rigid, thermoreversible, high-strength gels. κ-2 carrageenan is a block copolymer of kappa and iota. Carrageenans are negatively charged, and, therefore, can be neutralized with potassium, sodium, and calcium ions. These extracts of red seaweed are not found in pure form. Instead they

are marketed as mixtures in which the dominant fraction determines the classification (Bixler et al. 2001).

In ice cream applications, κ-carrageenan fractions are frequently used not as a primary stabilizer but as a secondary hydrocolloid to prevent wheying off of mix, a condition promoted by the other stabilizers due to their incompatibility in solution with milk proteins. Hence it is included in most blended stabilizer formulations at usage rates of 0.01–0.015%. At higher concentrations, the carrageenan would begin to gel and fail to function well. At typical usage levels, carrageenan contributes very little to viscosity in hot mixes. However, as mixes cool, the κ-carrageenan undergoes a conformational change from a coil to a helix at around 40°C. The helical form produces structures that increase viscosity and create a weak gel, enhanced by addition of potassium ions, that is easily broken by shear. In the quiescent state, this gel is capable of holding dispersed particles in suspension (e.g., cocoa fibers in chocolate milk). After homogenization and cooling of mix, as casein micelles begin to separate from polysaccharides in solution, this weak gel of kappa carrageenan helices stabilizes casein micelles to prevent further phase separation at a visual level (Bourriot et al. 1999b; Schorsch et al. 2000; Vega and Goff 2005; Vega et al. 2004, 2005). Kappa and iota carrageenans also react electrostatically with positive regions of κ-casein, which contributes to prevent phase separation by interacting with the carrageenan network (Spagnuolo et al. 2005). These phenomena improve resistance to separation of protein- and polysaccharide-rich phases in ice cream mixes. This can be a special problem with soft-serve or shake mixes for fast-food restaurant applications, when the mix must have a shelf life of several days, and in ice cream during melting. Protein-polysaccharide phase separation and the functionality of κ-carrageenan are described more fully in Chap. 11.

Gelatin: Gelatin is a protein derived from collagen of animal origin. It was used almost exclusively in the ice cream industry as a stabilizer but has gradually been replaced with polysaccharides of plant origin due to their increased availability and reduced cost. However, gelatin is a good ice cream stabilizer and is still used to some extent. It forms a weak gel that melts readily in the mouth giving no impression of gumminess. Gelatin hydrolysates have received some recent research attention also as ice recrystallization inhibition agents (see below).

Guar gum: Guar gum is derived from the bush *Cyamoposis tetragonolba*, a member of the legume family grown in India and Pakistan for centuries and now grown to a limited extent also in the USA. The gum is contained in the endosperm of the bean, about 80% of the endosperm by weight. It is comprised of a galactomannan polysaccharide made up of a backbone of mannose with single-branched galactose units similar in structure to LBG. However, it is more heavily substituted than LBG at a rate of about one galactose to every two mannose units. The substitution is not uniform, so some unsubstituted regions exist within the molecule. Nevertheless, the high degree of substitution means that it is easily hydrated and thus dissolves readily in cold water (10–30°C). This property makes it highly desirable as a polysaccharide for use in HTST applications, where blending of the stabilizer into the mix

is done preferably cold and little time is provided for polysaccharide hydration. It produces highly viscous and thixotropic (thinning with shearing time) mixes at low concentrations within about 2 h.

Locust Bean Gum (*LBG*): LBG, also known also as carob bean gum, is derived from the beans of the ancient tree *Ceratonia siliqua* grown mostly around the Mediterranean. The gum is contained in the endosperm of the bean, about 90% of the endosperm by weight. Like guar, it is comprised of a galactomannan polysaccharide but is less heavily substituted than guar at a rate of about one galactose to every four mannose units. The substitution is very uneven, giving rise to regions that are heavily substituted ("hairy" regions) and regions that are not ("smooth" regions). As a result, LBG solutions are highly viscous at low concentration. Also, it can form gels under some circumstances, such as freezing and thawing, due to cross-linking among the smooth regions, while guar cannot (Goff et al. 1999; Patmore et al. 2003; Regand and Goff 2002, 2003). The lower level of substitution also means that LBG is less soluble than guar, and thus needs pasteurization temperature to get it fully dispersed and hydrated. This makes it more difficult to use in some mix processing applications, but it is highly regarded as a good ice cream stabilizer.

Microcrystalline Cellulose (*MCC*): Known also as cellulose gel. As with CMC, cellulose is used to make MCC, but it is chemically depolymerized with acid to rid the cellulose microfibril of amorphous (non-cross-linked) regions. These regions are usually associated with the ends of the polymers since a cellulose microfibril is much longer than an individual molecule. MCC is primarily used as a texture modifier in low-fat desserts rather than as a stabilizer (see discussion in "Fat Replacer" section above).

Xanthan: Xanthan is a bacterial exopolysaccharide produced by the growth of Xanthomonas campestris in culture. The gum is recovered from the culture broth by precipitation with isopropyl alcohol. Xanthan structure is comprised of a main chain of glucose, similar to cellulose, and every other glucose unit has attached to it a trisaccharide side chain consisting of two mannose units and one glucuronic acid unit. The side chains are closely aligned with the backbone giving xanthan a fairly inflexible rod conformation. This conformation gives rise to the properties of xanthan solutions: uniform viscosity over a wide temperature and pH range, high viscosity at low concentration, high degree of pseudoplasticity (shear dependence of viscosity), and good solubility at 10–30°C. While it is common in products like salad dressings where its pseudoplasticity characteristics are highly desirable, it is not used frequently in ice cream.

Ice Structuring Proteins

The biological world is filled with examples of organisms, for example, fish, insects, bacteria, and plants, that have the ability to tolerate or avoid freezing in

their natural environments. Many of these do so by secreting groups of proteins that have the ability to depress the freezing point (antifreeze proteins), promote ice nucleation, and/or reduce the rate of ice recrystallization. The recrystallization inhibition proteins function by adsorbing to the surface of an ice crystal, thus blocking further growth of ice at that crystal surface. These proteins have been referred to as "ice structuring proteins," ISP's (Clarke et al. 2002). There has been some interest in the last few years in using isolated ISP's to help control ice recrystallization in ice cream, especially for situations where ice cream stabilizers are not sufficiently effective or are undesirable in the formulation, and they have proven to be effective at lowering rates of ice recrystallization in ice cream (Goff et al. 2002; Regand and Goff 2005, 2006; Crilly 2007). Unilever has developed a specific strain of yeast to express a proprietary ISP for ice cream applications. They reported that, in addition to ice recrystallization inhibition, the combined changes of ice crystal shape and interaction conspire, through ice network formation, to alter the properties of ISP-containing products. Typical gross effects of this ice network formation in ice cream and water ice products are to increase firmness and structure, improve physical stability, improve retention of shape and definition (especially novelty products), retard dripping, and enhance flavor and color retention (Crilly 2007). To date, ISPs are not sufficiently available commercially for other ice cream manufacturers to take advantage of them, but research in this area is continuing.

Novel research into the effect of gelatin hydrolysates as ice structuring peptides has recently been reported by Damodaran (2007) and Wang and Damodaran (2009). They reported that hydrolysates from controlled enzymatic hydrolysis of gelatin resulted in a group of peptides that exhibited inhibitory activity on ice crystal growth comparable to the natural antifreeze proteins.

Propylene Glycol Monoesters

Propylene glycol monoesters, such as propylene glycol monostearate (PGMS), have recently been introduced into stabilizer blends specifically for control of ice recrystallization (e.g., Danisco IcePro). The effectiveness of PGMS has been demonstrated by Aleong et al. (2008). They showed that PGMS (0.3%) dramatically reduced ice crystal sizes in ice cream and in sucrose solutions frozen in a scraped-surface freezer before and after heat shock, but had no effect in quiescently frozen solutions. PGMS also resulted in smaller fat globule size distributions and enhanced partial coalescence in the mix and ice cream, respectively, compared to control samples but at a much lower level compared to glycerol monostearate, despite its molecular similarity. Low temperature scanning electron microscopy revealed highly irregular crystal morphology in both ice cream and sucrose solutions frozen in a scraped-surface freezer. There was strong evidence to suggest that PGMS directly interacts with ice crystals and interferes with normal surface propagation of ice crystals. Shear during freezing may be required for its distribution around the ice

and sufficient surface coverage. PGMS did not, however, affect mix viscosity, so that this ingredient would be complementary to other hydrocolloid gums to provide full stabilizer functionality.

Emulsifiers

Emulsifiers have been used in ice cream mix manufacture for many years. They are usually integrated with the stabilizers in proprietary blends, but their function and action differ remarkably from those of stabilizers. They are used to:

- Promote nucleation of fat during aging, thus reducing aging time.
- Improve the whipping quality of the mix, due to their function at the air interface, resulting in reduced air cell sizes and homogeneous distribution of air in the ice cream.
- Produce a dry and stiff ice cream as they enhance fat destabilization, facilitating molding, fancy extrusion, and sandwich manufacture.
- Increase resistance to shrinkage and rapid meltdown, due to a combination of the above two factors.
- Increase resistance to the development of coarse/icy textures, due the effect of fat agglomerates, more numerous air bubbles, and thinner lamellae between adjacent air bubbles on the size and growth of ice crystals.
- Provide smooth texture in the finished product, due to fat structuring and the interaction of fat agglomerates with the mouth during consumption.

An emulsifier is a substance that produces a stable suspension of two liquids that do not mix naturally, typically oil and water. In ice cream mixes, there is sufficient protein present to adequately emulsify the mix, so emulsifiers are not needed for fat emulsification in the classic sense. Their mechanism of action in promoting fat destabilization can be summarized as follows: they lower the fat/water interfacial tension in the mix, resulting in protein displacement from the fat globule surface, which, in turn, reduces the stability of the fat globule allowing partial coalescence during the whipping and freezing process. This leads to the formation of a structure of the fat in the frozen product that contributes greatly to texture and meltdown properties (Goff and Jordan 1989). The extent of protein displacement from the membrane, and hence the extent of dryness achieved, is a function of the emulsifier type and concentration.

The traditional ice cream emulsifier in old formulations and recipes was egg yolk. Like gelation as a stabilizer, however, the use of eggs or egg yolk has given way in modern formulations to specific ingredients that deliver much greater functionality at much less cost. Emulsifiers used in ice cream manufacture today are of two main types: the mono- and diglycerides and the sorbitan esters. Blends of each are common as the mono- and diglyceride component may be more functional at the air interface, giving rise to a smaller distribution of air cells and providing a measure of control over the action of the polysorbate 80, which is more functional at the fat interface promoting partial coalescence of the fat. Typical concentrations in use are 0.1–0.2% mono- and diglycerides and 0.02–0.04% polysorbate 80.

Characteristics of Individual Emulsifier Ingredients

Egg Ingredients: Egg yolk contains numerous amphiphilic materials, including phospholipids and lecithin-protein complexes, with good emulsifying properties. These provide surface-active properties at the fat–water interface, although they are not as efficient at promoting partial coalescence of the fat as are the glycerol or sorbitan esters. Egg whites provide proteins with good water-holding properties, but they are not surface active, so the yolk is the functional part of the egg for emulsifying. The yolk portion of the egg is ~35–45% by weight and contains ~50% total solids. Recommendations for egg ingredient use for acceptable functionality are 2–3% whole eggs, 0.5–1.0% egg yolk, or 0.3–0.5% dried egg yolk. Liquid egg ingredients must be pasteurized and are available in either fresh or frozen form.

In addition to their role as emulsifiers, whole eggs or egg yolks can also be used to enhance flavors. "French"-style ice creams, as in French vanilla, for example, are characterized by an egg yolk flavor and a more yellowish color. Likewise, custard-style ice cream (discussed in Chap. 8) contains at least 1.4% egg yolk solids, derived from either egg yolks or whole eggs. The unique smoothness of custard type ice creams can be attributed at least partially to the large amount of emulsifying properties in the egg yolks. Herald et al. (2008) studied the use of egg alternatives and showed that modified corn starch, WPC, or soy protein isolate can each contribute some of the textural properties of eggs or egg yolks in custard-style ice creams but none of them matched the control for flavor characteristics.

Mono- and Diglycerides: Mono- and diglycerides are derived from the partial hydrolysis of fats of animal or vegetable origin and reesterification with an excess of glycerol. For ice cream applications, mono- and diglycerides are usually greater than 40% alpha monoglyceride in content, as it is this form which is most amphiphilic and hence functional. The diglyceride portion is very fat-soluble so contributes much less functionality. The fatty acid can be saturated or unsaturated, with the latter being more effective at promoting dryness (Goff and Jordan 1989; Barford 2001).

Distilled Monoglycerides: Specific glycerol esters, such as glycerol monostearate (or a blend of saturated monoglycerides) or glycerol monooleate (or a blend of unsaturated monoglycerides), can also be used rather than the more random form of mono- and diglycerides, but they are more expensive to process. Unsaturated monoglyceride is rather unique in its interaction with some of the nondairy fats, providing a fat structure that can give rise to a very dry, stiff extrusion with excellent meltdown resistance (Granger et al. 2003, 2005; Zhang and Goff 2004, 2005; Bazmi et al. 2007; Sung and Goff 2010; Mendez-Velasco and Goff 2012).

Polysorbate 80: The sorbitan esters are similar to the monoglycerides in that the sorbitan esters have a fatty acid molecule such as stearate or oleate attached to a sorbitol (glucose alcohol) molecule, whereas the monoglycerides have a fatty acid molecule attached to a glycerol molecule. To make the sorbitan esters water-soluble, polyoxyethylene groups are attached to the sorbitol molecule. Polysorbate 80, polyoxyethylene sorbitan monooleate, is the most common of these sorbitan esters.

Polysorbate 80 is a very active drying agent in ice cream and is used in many commercial stabilizer/emulsifier blends. Although it is normally a component of the stabilizer/emulsifier blend, it can be added in pure form directly to the mix flavor tank post-homogenization and will become effective at enhancing dryness within a few minutes.

In formulations where it is desirable not to include synthetic emulsifiers, a few other more natural options are available. In addition to the egg ingredients discussed above, buttermilk, condensed or dry, when used as the source of MSNF in mixes, also provides enhanced emulsifying properties to the mix, due to the protein–phospholipid complexes found associated with the natural milk fat globule membrane in milk and enhanced in buttermilk during churning. Segall and Goff (2002a, b) introduced processing modifications to enhance fat colloidal interactions in the absence of emulsifier, by limiting protein adsorption at the fat interface during homogenization and introducing further protein to the mix post-homogenization.

Mineral Salts

Various mineral salts (Table 3.1) have been used to help control churning and separation of the fat in mixes during freezing and to increase the stiffness and smoothness of the finished ice cream. For example, calcium sulfate, added at a concentration of 0.1% before pasteurization, produces a dry, stiff ice cream from the freezer and reduces the rate of melting. Titratable acidity of mixes is raised when mineral salts are added. Sodium and magnesium phosphates, calcium and magnesium oxides, and sodium bicarbonate can all be used to improve body and texture of the finished product made from some mixes.

Calcium and magnesium oxides or carbonates are recommended in preference to the sodium products because the strong wetting effects of sodium counteract and nullify most of the beneficial effect the additive might have on the protein. Sodium citrate and disodium phosphate are effective protein stabilizers.

Disodium phosphate, sodium tetrapyrophosphate, sodium hexametaphosphate, and sodium citrate have been studied for their possible effect on controlling the churning defect of soft-serve ice cream. The mineral salts, used at concentrations of 0.1 and 0.2%, were blended with the stabilizer before mix preparation. The products were compared with a control that did not contain the added salt. Without exception the ice cream samples containing one of the salts showed less fat destabilization than the control sample drawn after the same length of time in the freezer. These buffering salts most likely influenced fat emulsion stability through some mechanism involving the milk proteins. The effects of these salts on acidity were very small.

Costa et al. (2008) added calcium chloride to ice cream for nutritional fortification purposes at an amount required to double the calcium contributed by the MSNF and found that it caused a substantial increase in fat destabilization and in ice crystal size and recrystallization. This was exacerbated, rather than alleviated, by the addi-

tion of κ-carrageenan. This outcome could be attributed to the effect of the calcium ions on casein micelles. Thus it was concluded that calcium fortification in ice cream requires close attention to the complex milk salt:protein equilibria and the ramifications of changes to calcium distribution on resulting structure formation in ice cream.

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Chapter 4
Flavoring and Coloring Materials

Introduction

Frozen desserts are valued by consumers for their wide range of excellent quality flavors that can appeal to all tastes. Addition of flavors also provides manufacturers with an opportunity to differentiate their products and compete for market share. The important flavoring substances for frozen desserts are vanilla, chocolate and cocoa, confectionery and bakery inclusions, fruits and fruit extracts, nuts, spices, and liqueurs, although other flavors can be incorporated into frozen desserts quite easily, if there is a market for them. Regular flavor evaluation clinics help to ensure high-quality products, and consumer taste panels and focus groups are good ways to ensure that a market exists for a flavor before launching it. Flavor launches can be expensive for packaged products but perhaps less risky for smaller scooping operations.

Globally, the distribution of flavors that appeal to the consumer is surprisingly similar (Table 4.1). In all the major ice cream consumption countries, vanilla, chocolate, and strawberry are among the top five, while caramels, nut flavors, and other fruit flavors make up much of the remainder. It is easy to find a vast array of exotic flavors, including various vegetable, spice, savory, and piquant flavors, but it is also apparent that these make up only a small market share within each country.

North American ice creams are known for their wide range of flavors and flavor combinations, including complex flavors with multiple combinations of flavoring ingredients, often including large inclusion pieces. Some ingredient manufacturers have flavor lists consisting of 500 or more flavor formulas. Flavor preferences change with time. Confectionery, bakery, and candy flavors have, to some extent, displaced fruit-based flavors over the last two decades. Recent preferences are shown in Table 4.2. International flavor inspirations are also fairly new introductions: for example, Thai red curry and coconut milk; Asian flavors including green tea, green bean, and yellow corn, or durian; Mexican flavors including dulce de leche or chipotle; and Caribbean flavors such as coconut, mango, or guava. Children's flavors, such as bubble gum, tiger tail (orange ice cream with black licorice, or banana ice cream with

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Table 4.1 Top ice cream flavors in order of purchase (2010) by country (data from Euromonitor International, 2011)

	Australia	United States	Canada	Italy	United Kingdom	Denmark	Sweden	China
Vanilla	1	1	1	4	1	1	1	2
Chocolate	2	2	2	1	2	2	2	1
Strawberry	3	8	3	5	3	3	3	3
Neopolitan		3						
Lemon				3				
Chocolate chip	4	5			4			
Nut		4		2		6		
Pear							4	
Rum and raisin	5					9	6	
Licorice						5	7	
Banana	6					7		
Cookies and cream		6						
Stracciatella				6				
Toffee/caramel/ butterscotch			4		6	4		
Exotic fruits				7	5		5	4
Cherry								
Mango	7							
Mint chocolate chip		7	6					
Coffee			5	8		8		5
Maple walnut			7					

Table 4.2 US supermarket sales of ice cream by flavor category (2010)

Flavor category	% by vol.
Vanilla	28.8
Chocolate	14.3
Bakery/cake/cookie	13.6
Chocolate chip/other choc	8.6
All nut flavors	4.7
Strawberry	3.3
Neopolitan	2.5
Coffee	1.6
All other flavors	22.6
	100.0

Source: International Dairy Foods Association, 2011

chocolate ripple), or cotton candy, can also be found in many flavor presentations. Seasonal introductions of ice cream flavors can take advantage of holiday flavors: fruit and nut, sticky toffee or date pudding, candy cane, or eggnog for Christmas are good examples. Easter or Halloween introductions might also be popular.

Two important characteristics of flavor are type and intensity. Generally the delicate flavors are easily blended and tend not to be objectionable at high concentrations. Harsh flavors tend to be objectionable, even at low concentrations. In any

case flavors should be only intense enough to be recognized easily and to present a delicate, pleasing taste. Choosing a mix composition and mix ingredients is often less of a problem for the manufacturer than is standardization of flavoring material for several reasons:

- The many flavoring materials available make it difficult to make a proper choice.
- The supply of flavors may vary from time to time in quality and availability.
- Serving conditions affect how pronounced a flavor will be perceived.
- No two consumers have exactly the same sense of taste, so choice of flavor varies widely. While a particular flavor combination may be unique, it may not gain much market share.

Because flavor is so important in influencing consumer acceptance, it is easy to lose sales when a product is poorly flavored. Defects are noted when there is too much or too little flavoring, unnatural or atypical flavoring, and lack or excess of sweetness. Flavorings also can affect appearance: lack or excess of particles, particles too large or too small, uneven distribution of particles or variegate, ribbon that is too thick or thin, and wrong ingredient or color.

Flavorings are available as liquids, syrups, semisolids, and solids. Liquid flavorings, such as vanilla or other flavors that are continuous throughout the product, and colors are added to the mix just prior to freezing. With continuous freezers, particulate ingredients (those that remain distinct in the ice cream such as fruits, nuts, and candy or bakery pieces) are added to the soft ice cream as it exits from the barrel freezer either by an ingredient feeder (see Chap. 7) or a positive displacement ripple (variegating) pump (swirls or ribbons of syrups such as chocolate, butterscotch, marshmallow, or fruit syrups). With batch freezers, incorporation of flavoring particulates is more manual, either incorporating them into the barrel through the top (mix) opening just before draw from the freezer if the particulate is not easily broken up or the mixing of it is acceptable, or drawing ice cream into a bowl or hopper where particulates can be stirred in manually before packaging, to try to maintain the discrete nature of the particulate.

Flavors can be extracted from a vast array of natural substances with a wide diversity of aromas. Natural flavoring substances are sometimes limited in supply, however, and can be quite expensive. Flavor chemists can duplicate natural flavors by identifying the compounds that make up a natural flavor and their concentrations, with the use of techniques such as gas chromatography and mass spectrometry. By appropriate blending of synthetic sources of these compounds, artificial flavors can be formed. These chemically produced types have been made available in almost unlimited quantities and at relatively low cost.

The US Code of Federal Regulations, paragraph 101.22 of Title 21, defines "natural flavor" or "natural flavoring" as the essential oil, oleoresin, essence or extractive, protein hydrolysate, distillate, or any product of roasting, heating or enzymolysis that contains the flavoring constituents derived from a spice, fruit or fruit juice, vegetable or vegetable juice, edible yeast, herb, bark, bud, root, leaf or similar material, meat, seafood, eggs, dairy products, or fermentation products thereof, whose significant function in food is flavoring rather than nutritional. Artificial flavors are not derived from these materials, rather are comprised of aromatic chemicals. Liqueur flavorings

include alcohol, whiskey and distilled beverages, fruit brandy distillate, brandy flavor essence, and fruit liqueurs.

Specific labeling instructions for flavorings and colorings are also listed in 21 CFR 101.22. In the labeling of frozen desserts to indicate flavors, it is necessary to designate whether the flavoring(s) is/are natural, artificial, or a mixture of both. The name of the flavoring must appear on the principal display panel in letters at least one-half as high as the name of the food. Foods that contain artificial flavors, artificial colors, or preservatives must be labeled as necessary to render the statement likely to be read by the ordinary person under conditions of purchase and use of the food. Flavor suppliers are required to certify that flavors supplied are in fact natural, artificial, or mixtures of the two.

The International Dairy Foods Association developed the following guidelines to fulfill the labeling standards of the FDA for all flavors of ice cream:

Category I—Those products that contain no artificial flavor. The label reads the name of the flavor followed by ice cream, e.g., *vanilla ice cream*.

Category II—Those products that contain both natural and artificial flavor, but the natural flavor predominates in quantity. The label reads the name of the flavor followed by the word flavored and ice cream, e.g., *vanilla flavored ice cream*.

Category III—Those products that are flavored exclusively with artificial flavor or with a combination of a natural and artificial flavor in which the artificial predominates. The label reads artificially flavored, the name of the flavor, and ice cream, e.g., *artificially flavored vanilla ice cream*.

Economy brands of ice cream commonly contain predominantly artificial flavoring as well as lower solids content than the average trade brand. The latter commonly contains pure and artificial flavor with pure flavoring predominating. Premium and superpremium products contain only pure extracts and flavors to complement the relatively high content of dairy solids and the very high qualities of all of the ingredients. Usage concentration of flavorings is usually high in premium and superpremium products.

Volatile flavors in frozen desserts are affected by the ingredients of the mix, especially by the fat. Frost et al. (2005) showed faster increases and subsequent declines in dynamic flavor perception (berry, coconut, banana, vanilla) in ice creams with lower fat levels (comparing 3, 6, and 12% milk fat). Headspace gas chromatography has also disclosed that the amount of release of flavor volatiles from frozen desserts is associated with their solubility in water or fat. For example, ethyl acetate, a hydrophilic volatile, was comparatively abundant in volatiles from strawberry ice cream containing 9 or 18% milk fat or vegetable fat. In contrast, the concentration of ethyl hexanoate, a hydrophobic molecule, was much higher in the headspace of the nonfat ice cream than in those containing either concentrations of fat (Miettinen et al. 2002). Therefore, the hydrophilic–lipophilic balance (HLB) of the flavor volatile is an important determinant of its release in the mouth of the consumer. Liou and Grün (2007) examined the effect of fat mimetics on flavor release in ice cream and reported that the protein-based fat mimetic released flavor in a more similar pattern to high milk fat whereas the carbohydrate-based fat mimetic released flavor in a more similar pattern to the low milk fat ice cream.

Vanilla

Natural Vanilla Flavor

Vanilla flavor is extracted from the cured pods of the plant genus *Vanilla*, a tropical climbing orchid. Food-grade vanilla flavor of high quality comes from only one species, *V. planifolia* (Madagascar vanilla or Bourbon vanilla, Bourbon the former name of the island of Réunion). Vanilla is cultivated in a warm moist tropical climate where the annual rainfall averages between 190 and 230 cm. An average minimum temperature of 24 °C and maximum temperature of 30 °C are required throughout the growing season of 9–10 months. Global vanilla bean production in 2009 was 9,800 tonnes, with Indonesia producing 58% (4,362 tonnes), Madagascar 23% (2,830 tonnes), China 9% (1,382 tonnes), and Mexico 2% (524 tonnes). This represents a substantial global change in producing countries since 2005, in which Madagascar produced 60% of the global supply (6,200 tonnes of 10,540 tonnes globally), Indonesia produced 25% (2,400 tonnes), China 10% (1,000 tonnes), and Mexico 2% (189 tonnes) (UN FAO data). Vines are typically allowed to climb up the trunks of trees within a forest canopy out of direct sunlight. They are generally kept to a height of 2 m, for easy access to the flowers and pods. Because of the closed structure of the flowers, self-pollination is almost impossible. The vanilla flower stays in bloom for less than 24 h, and pollination within that time is necessary for fruit development. Artificial pollination is carried out by hand to ensure a good yield of beans. This is a very labor-intensive process. After fertilization has taken place, about 10–12 months are required for the beans to fully mature. Each productive plant yields 25–30 odorless pods that contain about 90% moisture. Pods are greenish yellow in color, 10–25 cm long and 1–1.5 cm wide. The fresh beans have an unpleasant bitter odor and develop the characteristic pleasant aroma and brown color only upon curing, which consists of killing, sweating, drying, and conditioning (Ramachandra Rao and Ravishankar 2000; Sinha et al. 2008). Killing stops respiration and physiological functioning of the bean as a living tissue and allows for enzymatic action to begin. It is carried out by hot water scalding, 80 °C for 7–15 min. During the sweating step, 7–10 days, the beans are partially dried to reduce risk of microbial spoilage and to initiate indigenous enzymatic activity. This is done by spreading the beans out on large blankets in the sun to allow them to heat up and then wrapping them up when hot to allow the beans to wilt, a process that can be repeated several times. During this process, the aroma compounds begin to be released from their glucosidic precursors. Oxidation of polyphenolic compounds to produce browning also occurs during this stage. At the end of the sweating stage, beans are dried by exposure to warm air, usually indoors to avoid further sunlight exposure. About 5 kg of green uncured beans is required to make 1 kg of properly cured beans. Then they are conditioned by storage in closed boxes for one to several months. Various chemical and biochemical reactions occur during this process to bring out the optimal flavor and aroma compounds.

There are more than 200 volatile flavor and aroma constituents present in naturally cured vanilla beans. Of these, only 26 occur in concentrations greater than 1 mg/kg. Vanillin (4-hydroxy-3-methoxybenzaldehyde) occurs in the greatest concentration, at 1–2% w/w in cured pods. Other important flavor constituents are *p*-hydroxybenzaldehyde (0.2%), *p*-hydroxybenzyl methyl ether (0.02%), and acetic acid (0.02%) (Dignum et al. 2001; Sinha et al. 2008).

Vanilla flavor extraction can be performed by one of two methods: percolation or the oleoresin method. Percolation consists of circulating a 35–50% ethanol in water solution over and through the chopped beans under vacuum for 48–72 h. The concentration of an extraction is measured by its "fold," single fold being the equivalent of 13.35 oz of beans per gallon of solvent (100 g/L). The percolation method can attain concentrations of approximately fourfold strength. The oleoresin method consists of pulverizing whole beans and circulating ethanol over the beans under vacuum at 45 °C. The process takes about 8–9 days. Excess alcohol is removed by evaporation, producing approximately tenfold strength extract. Extracts are usually aged for more than 1 year, followed by clarification (centrifugation or filtration) and dilution to desired strength. The United States Code of Federal regulations (21 CFR 169) defines vanilla extract as being 35% ethanol or greater. The extract can contain glycerol, propylene glycol, sugar, or corn syrup. Vanilla extract can be maximum twofold strength whereas concentrated vanilla extracts can vary from three- to fivefold strength. Natural vanilla powder is a mixture of finely ground vanilla beans or vanilla oleoresin or both with sugar or other dry carrier. The amount to be used corresponds by weight to the number of ounces of a standard strength extract. For example, 1 gal of single-strength vanilla equals 8 lb of single-strength vanilla powder. Vanilla paste is made by mixing the concentrated extractives with a dry carrier to form a paste. The amount used is the same as for powders.

Consistency in Vanilla Quality

Vanilla beans vary in their composition, and the methods of fermentation, curing, extraction, and blending introduce more variation. Therefore, it is quite important that the beans meet specifications for color, flavor, and moisture and that extraction is done at the lowest practical temperature in a closed system for the minimal exposure time. Chill proofing and clarification by centrifugation or filtration are important for removing sediment and microbial spores. Aging for several weeks permits formation of esters from the acids and alcohols in the extract.

Manufacturers of vanilla products must be able to characterize their products in objective ways, and buyers need to be able to identify adulterated vanilla products. To do so requires multiple assays with sophisticated equipment.

The flavor industry and regulatory chemists use normal parameters of vanilla extract in their evaluations. These parameters include total organic acids and their profile, concentration of potassium, and amounts of polar aromatic compounds such as vanillin, ethyl vanillin, *p*-hydroxybenzoic acid, and *p*-hydroxybenzaldehyde.

Ethyl alcohol content is measured by gas chromatography. Natural and synthetic vanillins are differentiated using site-specific natural isotope ratios of deuterium to hydrogen measured by nuclear magnetic resonance spectroscopy (NMR). Phenolic compounds, including vanillin, are quantified by high-pressure liquid chromatography (HPLC). Total organic acid value is determined by precipitating the acids with lead (hence, the name Lead Number) and titrating the excess lead with Na_2EDTA. Potassium is measured by flame emission spectroscopy. Potassium values can be used in conjunction with vanillin values in natural vanilla extracts and flavors to establish the origin and maturity of the vanilla beans.

Artificial Vanilla Flavor

Vanillin can be manufactured chemically, starting with various substrates including coniferin from fir or pine trees, guaiacol, eugenol, or lignin. Most synthetic vanillin today is produced from lignin present in sulphite liquor from the cellulose industry. At present, about 97% of vanillin sold in the market comes from synthetic sources and only 3% from natural vanilla bean extraction. The cost of synthetic vanilla is less than 0.3% of the cost of natural vanillin (US$12 compared to US$4000 in 2008, Sinha et al. 2008). Natural vanillin prices remain high due to labor-intensive production and very limited countries of supply with fluctuating, climate-associated harvest yields. Artificial vanillin does not have the same flavor profile, however, and the use of hazardous chemicals in the process results in decreased consumer appeal and continued markets for natural vanilla. Hence, there is increasing interest in the production of vanillin by biotechnological conversions rather than chemical synthesis. Such methods include plant tissue/cell culture-mediated production and microbial transformations of suitable biomass substrate (Ramachandra Rao and Ravishankar 2000; Priefert et al. 2001; Dignum et al. 2001). These methods are still under investigation, however, and not yet widely adopted commercially (Sinha et al. 2008).

Vanillin may be added to vanilla extract at a concentration of up to one ounce per fold. For example, fourfold vanilla–vanillin would contain the extract of 26.7 oz of vanilla bean and 2 oz of vanillin in each gallon of 35% ethanol. Addition of vanillin at a concentration of one ounce per fold of vanilla reduces the usage of pure vanilla extract by up to 50%. A 0.75% solution of vanillin is approximately equal in strength to single-fold vanilla.

Vanilla Ice Cream

The plain ice cream mix is processed, cooled, aged at least 4 h, and then flavored by thoroughly blending the flavoring just prior to freezing. The amount of flavoring used depends on the composition of both the flavoring and the mix. For example, 3–4 mL of single-strength vanilla is used per kg of mix (5 fl oz per 10 gal of mix or

about 165 mL/100 lb). For multifold vanillas, the level of usage is slightly above that of single-fold vanilla divided by the number of folds. The quantity of vanilla must be increased as the concentration of milk fat is increased and as the content of nonfat milk solids is increased. When the concentration of sweetener is low, vanilla must be increased in quantity, but at high intensities of sweetness, variations in quantity of vanilla make comparatively small differences in consumer preference. The preferred blend of vanilla varies with fat content. Addition of Indonesian vanilla, which is somewhat harsh and woody, to Madagascar Bourbon tends to overcome the masking of "front end" flavor notes when fat content exceeds about 13%. Madagascar vanilla is usually preferred for lower fat ice creams. The preferred blend for French vanilla is Bourbon–Tahitian.

Li et al. (1997) examined the effects of milk fat concentration (0.5–10% fat) on flavor perception of vanilla ice cream. The amount of free vanillin decreased when fat content increased. However, a trained sensory panel found a significant difference only in the time required to reach maximum vanilla intensity. No significant difference was found in sweetness perception. A consumer preference panel showed that, as fat content was increased, sensory quality improved, and overall preference increased.

Chocolate and Cocoa

Chocolate and cocoa are obtained from the cacao bean. *Theobroma cacao* (cocoa, food of the gods) is the tree from which cocoa beans are harvested, which grows in tropical regions about 10° north and south of the equator. There are four principal types: Forastero, the more common variety from West Africa and Brazil; Criollo, about 5% of world production; Nacional from Ecuador; and Trinitario, a disease-resistant hybrid of Criollo and Forastero from Central and South America. Forastero cocoas are dark brown, strongly flavored, slightly bitter, and comparatively high in fat content. Criollos are lightly colored and mildly nutty in flavor. Optimal conditions for growth of *Theobroma cacao* are 20–30 °C, 1,500–2,500 mm annual rainfall well distributed throughout the year, 70–80% daytime relative humidity to 90–100% nighttime RH, and 2,000 h of sunshine per year. West African countries are ideal for growing cocoa as a cash crop. The major producing countries are Côte d'Ivoire (Ivory Coast, 30% of 4.1 million tonnes global production in 2009, UN FAO data), Indonesia (20%), Ghana (16%), Nigeria (9%), Brazil (5%), Cameroon (5%), and Ecuador (3%). The reader is referred to Afoakwa (2010) for details of cocoa bean production and processing.

Chocolate may have both physiological and psychological health benefits, a subject of much recent research. Flavonoid-rich cocoa may reduce risk of atherosclerotic development with cardioprotective implications. Polyphenolic compounds present in cocoa may exert antioxidant properties and lead to enhancement of immune function. Chocolate has been reported to release phenylethylamine and serotonin into the human system, producing aphrodisiac and mood-lifting effects.

Cocoa trees in shady plantations are kept to a height of 3 m tall, for easy harvest. Pods, which form after buds emerging from the bark of the tree are fertilized, reach maximum size after about 75 days. They are allowed to mature for another 65 days before ripening. A further 10 days are allowed before harvesting. Pod size can be up to 1 kg at the time of harvest. After harvesting, the golden red-colored ripened pods are split open, and the 30–40 almond-sized beans inside are removed with the sweet, mucilaginous white pulp material for fermentation. The wet beans and pulp are typically heaped and covered with leaves. Microbial activity of the cocoa pulp during fermentation generates heat and produces ethanol and acetic and lactic acids, which kill the physiological and respiratory functioning of the bean and are susceptible to several types of enzymatic degradation. The yeast-based fermentation begins anaerobically, but as fermentation proceeds, the liquification of the pulp and drainage and sweating lead to aerobic conditions, during which lactic acid bacteria dominate the fermentation and temperatures of 45–50 °C are achieved. Flavor development occurs continually during the fermentation process, resulting from a series of very complex chemical transformations of green bean constituents, especially polyphenols. After fermentation of 5–7 days, beans are removed from heaps and spread on platforms or mats for a further 7–8 days of sun drying. Flavor development continues during the drying process as does brown color development. More than 600 flavor compounds have been isolated from cocoa, although perhaps as low as 20 key volatile compounds may contribute to the majority of cocoa flavor after fermentation and drying. Moisture content should be less than 6–8% following drying. The beans are then washed clean of the dried pulp, dried slowly and sufficiently to prevent mold growth, and then sorted and graded prior to shipment to manufacturers of chocolate and cocoa. Bean quality is affected by genetics; environment; exposure to microorganisms, insects, insecticides, and rodents; and by size, integrity, and moisture content.

Processing Cocoa Beans

Bean processing begins with cleaning of extraneous materials, blending of batches of beans to provide the characteristics and uniformity desired, breaking of shells, and removing of cotyledons (called “nibs”) from within the shells (Fig. 4.1). This stream of beans and shells is sieved into fractions, and the beans are separated from the broken shell by streams of air in a winnowing machine. Sterilization with steam and roasting with dry heat (90–170 °C) are also employed, to eliminate microbial contamination and initiate further flavor and color development. Whole beans can be roasted before shell removal or nibs can be roasted after. Nibs break away from shells much easier after in-shell roasting, although there can be some loss of fat into the shell. Another optional process employed at the same time is alkalization (*Dutching*, after van Houten, the Dutch scientist who developed the process). Beans or nibs can be alkalized, usually with potassium or sodium carbonate. The pH of natural nibs is about 5.2–5.6. Alkalization can bring the pH up to above 7.0, as high

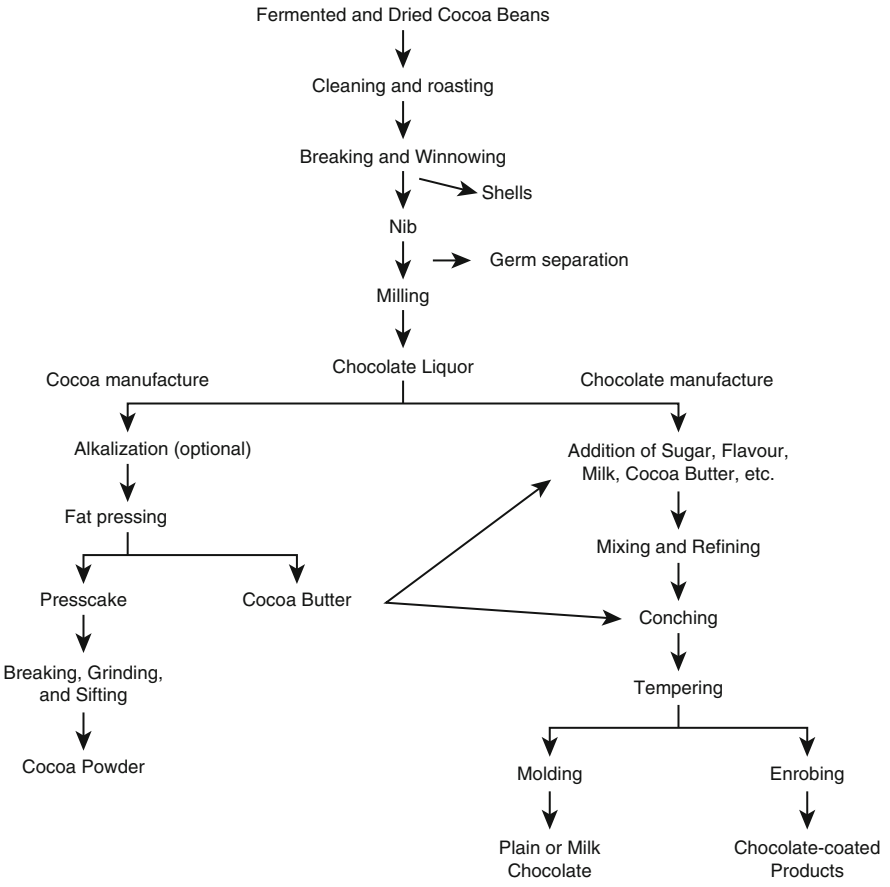

Fig. 4.1 Flow chart illustrating the processing of cocoa beans and the production of cocoa powder and chocolate products

as 8.0. This modifies both color (turning from reddish brown to darker brown or black as the pH is increased) and flavor (acidity and astringency are reduced, but then bitterness evolves as pH increases). After pretreatments, the nibs are ground to form cocoa liquor, the melted and solidified mass of nibs. The nib contains about 55% cocoa butter, contained within a cellular structure. Grinding releases and melts the cocoa butter, which can then be solidified into the solid chocolate mass, also known as chocolate liquor. This can be poured and cooled in molds that form it into large slabs or into smaller sizes that are sold in retail stores as bitter cooking chocolate.

Melted cocoa fat can be pressed from the hot chocolate liquor by means of hydraulic presses, to fractionate the liquor into the cocoa powder and free cocoa butter. Depending on pressure used, residual fat in the cocoa powder is usually 10–12% for low-fat cocoa powder or 22–24% fat for high-fat cocoa powder (referred to as "breakfast cocoa"). The solid cocoa cakes after pressing are ground to produce

powder. Cocoa contains nearly all the flavoring material from the cocoa bean, the cocoa butter being practically flavorless.

Alkalized (Dutch) cocoa is made in the same manner as natural process cocoa except that the nibs are treated with alkali (e.g., potassium carbonate) at the time of roasting. This treatment makes the cocoa more soluble and darker in color. It also brings out a full fine chocolate flavor, reduces the potential for bitterness, and counteracts the acid flavor found in natural process cocoa. The pH of Dutch process cocoa may range from 7 to 8.6, depending on the amount of alkali used. The greater the degree of alkalization, the darker the color and higher the intensity of flavor. Highly alkaline cocoas tend to lower the viscosity of chocolate mixes, but this can be offset by lowering the pH with small amounts of citric, phosphoric, or tartaric acid.

The color of cocoa is the result of several factors: (1) the source and blend of beans; (2) the degree of roasting; (3) the fat content; (4) the process, natural or alkalized; and (5) fineness of the grind (coarser is darker). Flavonoids, especially anthocyanins and procyanidins, are the main precursors of chocolate color. During fermentation, hydrolysis and oxidation convert flavonoids to quinones. Quinones react with amino acids to form Maillard reaction products that are strongly colored. They also react with other flavonoids to form brown tannins.

Flavor of cocoa is also affected by the same factors noted above for color. However, fermentation and roasting are key elements that govern chocolate flavor. The sugars and amino acids produced during fermentation are converted to characteristic chocolate flavors through the Maillard reaction during roasting. To enhance flavor of some cocoa products, some manufacturers add aromatic substances such as cinnamon, oil of cloves, oil of bitter almond, or vanillin. Small quantities of these substances can impart desirable flavor notes to cocoa and chocolate. Among the desirable flavor notes of cocoa products are cocoa (the basic flavor note), bitter, rich, bouquet, sour, astringent, and acrid. Undesirable flavor notes include burnt, earthy/moldy, hammy, smokey, metallic, rancid, cardboard, and raw.

A defect that sometimes appears in chocolate ice cream made with alkalized cocoa is a greenish black discoloration that forms where the ice cream comes in contact with exposed iron (modern packaging practices generally exclude containers that contain iron). In the alkalization process, tannins of the cocoa are solubilized by the added alkalis, and they react with the iron to form ferric tannate, a colored compound.

Chocolate Ice Cream

Chocolate products used in flavoring ice cream are natural or alkalized cocoa, chocolate liquor, blends of cocoa and chocolate liquor, or chocolate syrups. To flavor chocolate ice cream adequately requires about 4.5–5.5% chocolate liquor, 2.7–3.2% cocoa powder, or 1–2% cocoa powder with 2–3% chocolate liquor. The amount of chocolate flavoring to use in ice cream depends upon desired strength of flavor and intensity of color. Consumer preference tests should be used to determine these

Table 4.3 Suggested mix formulations for chocolate ice cream

Formulas (%)					
Fat	8.0	10.0	12.00	14.00	16.0
MSNF	12.5	12.0	11.00	10.00	8.0
Sugar	16.0	16.0	16.00	17.00	19.0
Cocoa[a]	2.7	3.0	3.00	3.00	3.5
Stabilizer–emulsifier	0.3	0.3	0.25	0.25	0.2
Total solids	39.5	41.3	42.25	44.25	46.7

[a]Or chocolate liquor can be used singly or in combination with cocoa powder (see text for details)

parameters. Extra sugar should be added to compensate for the bitter flavor of cocoa, the usual recommendation being the same weight of additional sucrose, or equivalent thereof, as of cocoa. Typically, the use of corn syrup solids would be less than that of a white mix, to help alleviate the build-up of excess viscosity. Vanilla can be used to enhance chocolate flavor. Suggested recipes are shown in Table 4.3.

Cocoa is a more concentrated source of chocolate flavor than is chocolate liquor, because it contains a higher proportion of chocolate flavoring material and less of the nearly flavorless fat. For example, the nonfat cocoa solids portion of cocoa powder typically ranges from 78 to 90% whereas the nonfat cocoa solids portion of chocolate liquor is only 40–50%. This means that on a flavor basis, you need 1.6–2 times as much chocolate liquor as cocoa powder. Also, the price of cocoa butter may make it more economical to use cocoa than chocolate liquor. Furthermore, labeling regulations necessitate the declaration of the amounts of fat and saturated fat in foods. Many consumers select against products that are high in fat, especially saturated fat. This is why some manufacturers of chocolate ice cream are opting for low-fat cocoa, which contains less than 10% fat (usually 7–9%). On the other hand, manufacturers of premium, high-fat ice creams may select breakfast cocoas (22% fat) or they may use chocolate liquor at a level of about 5% to gain the lubricating effect that cocoa butter provides as it melts in the mouth at about 33 °C (91 °F). This lubricity enhances the perception of richness in chocolate ice creams.

The intensity of chocolate flavors also depends on mix composition, particularly fat content, with an inverse relationship between flavor intensity and fat content (Prindiville et al. 1999, 2000). Welty et al. (2001) analyzed selected volatile compounds in the headspace of chocolate ice creams containing 0.6, 4.0, 6.0, or 9.0% milk fat or containing 2.5% milk fat, cocoa butter, or one of three fat replacers (Simplesse, Dairy Lo, or Oatrim). The headspace concentration of most of the selected volatile compounds increased with decreasing milk fat concentration. Fat replacers generally increased the concentration of volatiles found in the headspace compared with milk fat or cocoa butter. Few differences in flavor volatiles were found between the ice cream containing milk fat and the ice cream containing cocoa butter.

Producers of nonfat ice creams can formulate with defatted cocoa that contains about 2.5% fat blended with cocoa containing 10–12% fat to produce low-fat cocoa containing about 5% fat. Use of such a blend at 2.5–3.0% of a mix facilitates production of chocolate ice cream with <0.5% fat, and this meets the requirement for labeling

the product as nonfat ice cream. Defatted cocoa is made by extracting the residual fat. Defatted cocoa has the same flavor intensity on a nonfat solids basis as regular cocoa. However, because the fat absorbs light, defatted cocoa has a lighter color than cocoa. This is called its extrinsic color. When the defatted cocoa is dissolved in an ice cream mix, the intrinsic color becomes evident, and this color does not differ from that of a mix containing the same amount of cocoa on a nonfat solids basis. Defatted cocoa appears to be more finely ground than the cocoa from which it is made. This is because it has virtually no fat to cause the particles to adhere to each other.

The Codex Alimentarius standard for chocolate ice cream and ices states that the flavor "must come from nonfat cocoa solids." The minimal quantity needed is 2–2.5% of the mix weight.

To make allowance for the additional sweetener needed in chocolate ice cream, the US Code of Federal Regulations permits reductions in the content of milk fat and total milk solids by a factor of 2.5 times the weight of the cocoa solids. For example, when 3% cocoa is added to a mix containing 10% milk fat, the final milk fat content must be at least 9.25%. The formula for calculation is as follows:

$$[100 - (\%\ \text{cocoa} \times \text{reduction factor})]\text{lb milkfat / lb unflavored mix} = \%\ \text{milkfat in flavored mix}$$

$$[100 - (3\% \times 2.5)]\,0.1 = 9.25\%$$

In both Canada and the United States the minimum fat content of regular chocolate ice cream is 8% regardless of the amount of chocolate flavoring added.

The simplest way of adding cocoa powder to a mix is to blend it together with other dry ingredients, especially granulated sugar, and incorporate them together with the liquid ingredients in the blending device or with a powder funnel (see Chap. 5).

Homogenization pressures for highly viscous chocolate mixes may have to be lower than those for plain mixes to permit passage through plate heat exchangers. Chocolate-flavored ice creams that are low in fat require higher homogenization pressures than those containing high fat.

Chocolate mix can be the base for a number of other products, including, for example, chocolate mint (4.5–6% mint flakes by weight to chocolate ice cream), chocolate almond (4.5–6% broken almonds, by weight), chocolate marshmallow (4.5–6% miniature marshmallows, by weight), or mocha, made by combining white mix and chocolate mix at a 3:1 ratio and adding 5–8 mL/kg coffee syrup or enough coffee extract to give a mild coffee flavor. Another recent combination involves chocolate and chili for a spicy and piquant variation.

Preparing Chocolate Syrup

It may be advantageous for the smaller manufacturer to flavor chocolate ice cream by adding syrup to white mix before freezing, as opposed to making a chocolate mix. A desirable syrup can be made by adding 20 lb (9 kg) each of cocoa and sugar

to enough water to make 10 gal (40 L). To make the syrup, mix the sugar and cocoa together, then add enough water to make a heavy paste. Heat slowly and add water gradually, constantly stirring. Heat to boiling, then cool to less than 4 °C before addition to the mix to minimize heating of the mix. This syrup can be added in a ratio of 1:5 to 1:7 to a plain ice cream mix before pasteurization (12–17% by weight). The ratio of 1:5 is the highest concentration of chocolate that can be used with a plain ice cream mix containing 10% milk fat and 20% total milk solids, because the minimums for these components are 8% and 16%, respectively, in bulky flavored ice cream with no modifying label (such as reduced fat, low fat, or nonfat). The syrup can be made in quantities and stored for a few days in a cold storage room at 2–4 °C (35–40 °F).

Whenever possible, a complete mix should be made by adding the cocoa or chocolate directly to the mix before pasteurization. The temperature of pasteurization is sufficient to incorporate cocoa properly. A chocolate mix made this way whips more rapidly in a batch freezer than plain mix to which syrup is added at the freezer. Furthermore, the ice cream has better flavor, is more uniform, and contains fewer dark specks.

Chocolate ice cream is one of the most difficult to freeze in a batch freezer, because the mix whips comparatively slowly. The viscosity may be reduced and whipping time decreased by adding 0.1% of citrates or phosphates to the mix. Air in the ice cream dilutes the color so that in ice cream with high overrun it may be necessary to use dark cocoa to provide the intensity of color desired. However, very dark cocoa powders often do not impart the pleasing flavor to ice cream that less highly alkalized powders provide.

Chocolate Confections

Chocolate is used in ice cream in many forms. Included among these are chocolate chips; swirl, ribbon, or variegate; chocolate-covered nuts; chocolate-coated baked goods and fruits; and miniature low-melt filled chocolates. An example of the latter is a 5/6-inch (1.6 cm) long multicolored chocolate base ice cream cone. There are about 400 pieces per pound, and they can be flavored according to the color of the chocolate. Because of their low melting point, several of these products need to be refrigerated until they are placed in the ingredient feeder. Furthermore, the quantity added to the hopper of the feeder should be managed so that the pieces do not melt and stick together.

Fats with a melting range of 18–21 °C (60–70 °F) provide softness in chocolate pieces (inclusions) added to frozen desserts.

By substituting vegetable fat for cocoa butter, manufacturers of chocolate coatings provide the functional characteristics needed for coatings for certain ice cream novelties. Federal Standards in the USA define “sweet cocoa and vegetable fat coating,”

"sweet chocolate and vegetable fat coating," and "milk chocolate and vegetable fat coating." Coatings for bar products are discussed further in Chap. 9.

Flavoring Ingredients

There are a large variety of natural and artificial flavors available to the ice cream manufacturer from flavor suppliers. Flavors that are continuous in the ice cream are added to the mix flavor tank prior to freezing. The usage level should be specified by the supplier, but will typically be in the range of 1–3 mL/kg. Flavors are often added to the base mix before freezing prior to the addition of particulates (fruit, nuts, candy pieces, ripple sauces) to the ice cream. Natural or artificial color can also be added to the base mix at the same time as flavors.

Examples of non-particulate flavored ice creams are as follows:

Coffee. 2.5% coffee extract (a strong coffee extracted from 0.5 kg of ground coffee may be used in place of the coffee extract); 3–5 mL/kg 50% burnt sugar color may be added. Variations include various mochas, espressos, lattes, café au lait, etc.

Maple. 2 mL/kg pure maple extract and 1.3 mL/kg burnt sugar coloring. If maple sugar is used, a special mix is prepared with 10–12% sucrose and 3–6% maple sugar.

Caramel. 8% caramel syrup (62% sugar and 38% of light cream (20% fat) boiled to a light brown color).

Mint. 2.6–5.2 mL/kg pure mint extract, and color to light green. Mint varieties include peppermint, spearmint (one recent introduction contained spearmint with blackberry), and wintergreen mint.

Butterscotch. 10% butterscotch syrup and color yellow.

Eggnog. 10–12% eggnog base (can be a commercial preparation). An eggnog base may be prepared by combining 22% whole fresh eggs or 11% fresh egg yolks or 5% dried eggs, 12% sugar, 66% light cream (20% fat), and the balance in water. This mixture is heated to 71 °C (160 °F) for 20–30 min and homogenized at about 2,000 psig. Eggnog ice cream may also be prepared by using 3.5% dried egg yolks, 2 mL/kg vanilla extract, 1.5 mL/kg lemon extract, 1–1.5% rum, 2 mL/kg egg color, and spices (as desired).

Sweet potato. 40% sweet potato puree (7:1 sugar pack), 2 mL/kg vanilla extract, and 4 mL/kg orange color.

Avocado. 18% fruit, to which has been added 25% sugar.

Pumpkin. 25% cooked pumpkin puree, 1.5% preserved orange peel or orange rind, 2 mL/kg vanilla, 0.5 mL/kg cinnamon, and 0.25 mL/kg nutmeg.

Fruit flavors are available as (1) extracts from the prepared fruit, (2) artificial compounds, and (3) true extracts fortified artificially. These flavors supplement fruits in cases in which it is necessary to limit the amount of fruit, but they are often inferior in flavor to fruits and do not provide the desired fruit pulp. Defects in fruit-flavored frozen desserts may result from improperly handled fruit, use of insufficient fruit, poor incorporation of fruit, excessive fortified or artificial flavor, and/or poor quality base mix.

Alcohol-based flavors present a special challenge due to the freezing point depression induced in the ice cream by the ethanol present, and also by legal requirements for the maximum quantity of ethanol that can be present in food products. Alcohol-based flavors can also induce bitterness in the finished product. Therefore, it is often necessary to use a natural or artificial flavor along with the desired alcohol to boost the intensity of flavor. For example, rum and raisin has been a popular flavor for many years. The liqueur flavors, such as Irish cream, coffee, hazelnut, almond, or orange liqueurs, can also be quite popular, although a combination of the liqueur itself along with a natural or artificial flavor is most often used.

Spices such as cracked black pepper (introduced recently with strawberries), cinnamon, cloves, nutmeg, allspice, cardamom, ginger, and sesame can all be used sparingly as flavors in frozen desserts. Ginger ice cream is a favorite in some localities. Cinnamon, nutmeg, and cloves are often used to enhance or modify the flavor of chocolate products, and they complement puddings, eggnog, and certain flavors of punch. Recent flavor introductions in the floral line include jasmine, lavender, cherry blossom, iris, rose hip, orange blossom, chamomile, hibiscus, chrysanthemum, and eucalyptus. Spices may be purchased either in the finely ground dry form or as extracts. Their flavors are strong so that only small amounts are needed to produce the desired effect.

Salt, although not a spice, is often used in small quantities to enhance certain flavors of ice cream, especially those containing eggs—custards and rich puddings—and in nut ice creams. Some believe that a small amount of salt (approximately <0.1%) improves the flavor of ice cream. Perhaps this is a carryover from earlier times when ice cream formulations contained a lower percentage of MSNF and thus less natural milk salts. In any case, a salty flavor should be avoided unless it is specifically desired. For example, sea salt has been used recently in flavor introductions. Salty snacks have found their way into some recent flavors, including potato chip and pretzel-based inclusions. The recent tendencies of Americans to reduce intake of sodium coupled with the requirement to indicate sodium on the nutrition label have caused many manufacturers to minimize the amount of salt added to frozen desserts.

Vegetable flavors or purees are another flavor alternative. Carrot, pumpkin, sweet potato, taro, corn, beet puree, rhubarb, tomato, cucumber, and red cabbage have all been used in various formats in ice cream dessert flavors.

Color in Frozen Desserts

Ice cream should have a delicate, attractive color that readily suggests to the consumer what the flavor is. Both "certified" (within the Food, Drug, and Cosmetic Act) and "exempt from certification" (natural) colors are approved by the U.S. Food and Drug Administration for use in ice cream. Labeling regulations for the certified colors have changed in conjunction with the Nutrition Labeling and Education Act. All FD&C colors must be shown separately on the ingredient legend for most foods. However, ice cream, butter, and cheese have been exempt. With the discovery that Yellow No. 5 and Yellow No. 6 can cause allergic-type reactions in a limited number of sensitive persons, the U.S. FDA has required that ice cream ingredient labels shall declare presence of these colors when they are used. Exempt colors can be shown together as "color added" or "artificial color," or they may be listed by name. Generally the use of the term "natural color" is not permitted.

Most flavors of ice cream may require addition of at least a small amount of color, although the trends are toward less use of color when the natural color is appealing in itself and more use of color for brilliant, sharp, and contrasting appeal. For example, yellow or egg shade color was usually added to vanilla ice cream to give it the golden shade of cream suggestive of milk fat in butter, although white (no color added) vanilla ice creams seem to now dominate the market. Fruit ice creams need to be colored, because the usual amounts of fruit added are insufficient to impart adequate color. Chocolate ice cream, on the contrary, seldom needs added color. Highly alkalized cocoa, in particular, imparts high color at the used concentration.

If colors are purchased in the powder form and made up by the ice cream processor, they should be dissolved in boiling water and stored refrigerated for short times. Longer times of holding are possible when 0.1% sodium benzoate is added to limit growth of microorganisms. Although solutions of colors contain little nutrient material, it is possible for some microorganisms to grow in them. Solutions of colors of the strength normally used may be prepared as 3% solutions in water. A normal use concentration may range in dilution in the mix from 1:500 to 1:1,000.

The color of frozen desserts must have both the desired hue or shade and the proper intensity. If the intensity is too high, the product may appear to be artificially flavored even when it is not. If color is lacking, many consumers will think too little flavoring has been added. An inappropriate hue or shade gives the impression of artificiality. Hue, saturation, and lightness of color are readily measured with a color meter, for example HunterLab. A spatial representation of the color can be made using the system of the Commission Internationale de l'Éclairage (CIELab). Color is measured as reflectance of three successive flashes of a standardized light. The spectrophotometer translates the signals into L (psychometric hue), a (hues of green and red), and b (hues of blue and yellow) values.

There should be clear lines of demarcation between colors in variegated ice creams, in products containing inclusions, and in any product that contains multiple flavors (e.g., Neapolitan and certain novelties).

Particulate Inclusions

Fruits

Fruit has always been an important flavoring ingredient for ice cream (Tables 4.1 and 4.2), because the sweet nature of the fruit makes ice cream a very good carrier. The sugar content within the fruit depresses its freezing point, so that it remains softer in the ice cream than the ice cream itself. Those fruits that do not have sufficient natural sugar content are normally sweetened or otherwise prepared, so that the fruit pieces do not become frozen too hard within the ice cream. In addition to the good match of characteristics, fruits are seen as healthy ingredients, containing vitamins, minerals, and other healthful plant compounds. Recommendations by nutritionists to consume multiple servings of fruits may affect the choice of flavor of frozen desserts in the future. Berries and cherries contain anthocyanins that give them deep colors. When consumed in adequate amounts, anthocyanins are considered to be healthful in that they function as antioxidants that can neutralize effects of free radicals on cellular DNA. Pomegranates have also received considerable recent attention as high-antioxidant fruits.

Fruits are available in fresh, frozen, and heat-processed forms. Fruits may be used whole, sliced, crushed, diced, pureed (coarse, medium, or fine), or juice. It is desirable to have pieces of fruit or pulp large enough for easy recognition in the finished product. However, the use of whole or large-sliced fruit may result in coarse–icy texture. Good fruit distribution, appearance, and desirable texture and flavor result from the use of diced or pureed fruit. Usage levels vary from about 10–20% by wt., with 20–25% added sugar to the fruit. The more highly flavored the fruit, the less of it should be used in the ice cream. Citric acid solution may be added to bring out fruit flavor, about 4–6 mL of 50% citric acid solution per kg of fruit. If the fruit is quite wet, resulting in a wet extrusion from the freezer, additional emulsifier can be added. Polysorbate 80 can be effective when added directly to the flavor tank, after mix aging, and will improve dryness on extrusion to help incorporate the fruit addition.

The sugar content of the fruit pack is the main determinant of how much sugar the mix should contain. Assuming a plain mix with 15% sugar is used with 20% of a 4:1 fruit pack (4 kg fruit + 1 kg sugar, resulting in 20% added sugar), the overall sweetness would be calculated as follows:

$$\begin{aligned} 80\%\ \text{mix} \times 0.15 &= 12\%\ \text{sugar from mix} \\ 20\%\ \text{fruit} \times 0.20 &= \underline{\ 4\%\ \text{sugar from fruit}} \\ &\quad\ 16\%\ \text{sugar in the final product.} \end{aligned}$$

Use of a 2:1 fruit pack would increase the sugar concentration to 18.6%. Therefore, the sugar content of the latter mix would likely need to be lowered or the amount of fruit decreased.

In formulating a mix for fruit ice creams, total solids should be made higher than for vanilla ice creams of the same relative quality. This is necessary to offset the

effect of dilution by the fruit pack. For example, a mix that works well with a 2:1 fruit pack has the following composition: 13.5% milk fat, 10.5% sucrose, 12.5% MSNF, and 0.35% stabilizer/emulsifier. Federal Standards of Identity allow a reduction of fat and total milk solids in fruit ice creams to a minimum of 8% and 16%, respectively. However, they specify use of a factor of 1.4 in computing the reduction. For example, consider a plain mix that contains 10% milk fat to which 10% fruit and flavoring are to be added. The reduction permitted is $1.4 \times 10 = 14$ lb. And $100–14 = 86$ lb of plain mix in the finished ice cream. Therefore, the minimum milk fat concentration is $86 \times 0.1 = 8.6\%$.

Because fruit ice creams have a higher sugar content than plain ice creams, they should be drawn from the freezer about 1 °C colder. A drawing temperature of −5 °C (23 °F) for the batch freezer and of −6 °C (21 °F) for the continuous freezer is generally satisfactory.

Processed Fruits. Fruits in solid packs, aseptic or open-kettle processed, are ready to use and convenient. They have usually been stabilized with pectin or starch and cooked with sugar to 50–60°Brix. Heating enhances the flavor of some fruits, whereas it degrades quality and appeal of others. Those flavors that may be enhanced by heating include cherries and pineapple. However, heating can lower the quality of strawberries, peaches, and, to a lesser extent, raspberries. Hence, good quality fruit solid packs need to be chosen to achieve best fruit flavors. The advantages of processed fruit into solid packs include their ready-to-use convenience; transfer of procurement issues to the fruit processor, who can blend and standardize fruits purchased from around the world, depending on availability and season; standardized quality; and microbial safety.

Manufacturers of fruits and flavorings have taken advantage of new technologies to provide aseptically processed fruits that keep for months at room temperature with little change in quality. These fruits are processed in swept-surface or tubular heat exchangers that take the temperature of the fruit/sugar/acid/stabilizer mixture to 88–121 °C (190–250 °F). After heating, the mixture is held in a holding tube for about 3 min, and then is cooled in a series of swept-surface or tubular heat exchangers (Fig. 4.2) to about 27 °C (80 °F). Movement from the cooling cylinders is direct to the filling machines where the product is metered into sterile containers inside a sterile filling chamber that is bathed in sterile air (Arthey and Ashurst 2001; Barrett et al. 2005; Yui and Barta 2006). If fruit is pumped through heating, holding, and cooling coils without agitation, secondary flow effects are created that evenly heat and cool the fruit. Integrity of fruit particles in tubular heat exchangers reportedly is better maintained than in swept-surface heat exchangers, because no scrapers are used to renew surface films. The containers used for aseptically processed fruit preparations are usually multilayered bags made of polyethylene and foil. They come in sizes of 4, 10, 20, or up to 200 L. Bags are placed in cardboard or rigid plastic containers. Large refillable totes are used where there is a high demand for fruit. In small operations, containers of unused opened fruit must be refrigerated and can usually be held for a few weeks with no evidence of spoilage. Because the

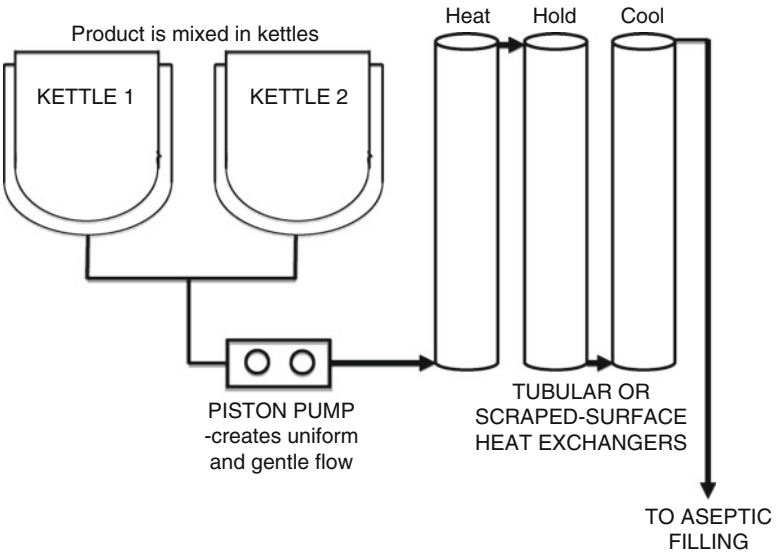

Fig. 4.2 System for aseptically processing fruits by heating and cooling with either swept-surface-type heat exchangers or in tubular-type heat exchangers (redrawn from information supplied by Lyons Magnus, Fresno, CA)

pH of fruits prepared aseptically must be 4.5 or below, the microorganisms most likely to grow are molds and yeasts.

Aseptic processing provides several advantages in the use of most fruits. Quality is usually much improved over that of kettle-type (Fig. 4.3) heat processing. Kettles, being open to the atmosphere, permit heating to only about 100 °C (212 °F). This usually takes a minimum of 20 min, and about 20 more min is required at this temperature to destroy molds, yeasts, and acid-tolerant bacteria. Heat transfer is relatively inefficient in kettles, and volatiles are able to escape to the atmosphere, causing a loss in natural flavor characteristics and the development of a "cooked note." Color usually darkens or fades. Shelf life is often short, and refrigeration or preservatives may be needed to prevent spoilage. Kettle-processed fruit is often packed in plastic pails. Scraped surface heat exchangers provide more uniform heating to fruits than do kettles. Furthermore, cooling is much faster than in kettle processing. Overall, flavor, color, consistency, convenience, and economy are maximized by aseptic processing of fruits.

Fresh and Frozen Fruits. Fresh or fresh-frozen fruit can be the best source of flavor, although there is more handling involved, which often limits their use to smaller manufacturers, and often more chance for microbial contamination as a result. Fresh fruit ice creams have a special sales appeal. The fruit should be washed and hulled or peeled and then mixed with sugar in the ratio of 2–7 kg fruit per kg sugar (Table 4.4) and held at about 4 °C for 12–24 h before using. During this time, a large part of the juice will combine with the sugar, because of osmotic action, to form syrup. This syrup will impart to the ice cream the full flavor of the fruit much better than would the fruit used immediately. Sugar can be replaced with polyols (sugar alcohols) such as sorbitol. Such fruits would be used in frozen desserts labeled sugar-free.

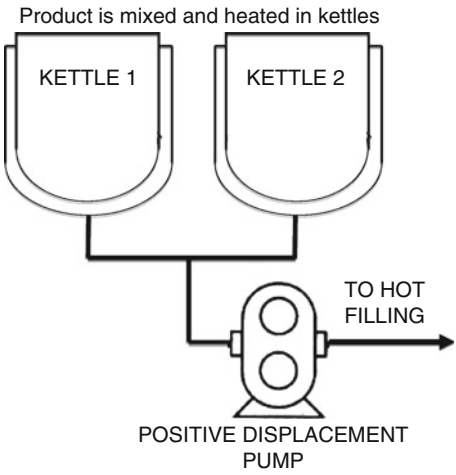

Fig. 4.3 System for conventional kettle-type processing of fruits (redrawn from information supplied by Lyons Magnus, Fresno, CA)

The amount of fruit required to impart the desired flavor depends on the characteristic of the flavor and varies from 10 to 25% of the weight of the finished product. The fruit–sugar mixture used at a concentration of 15–20% produces excellent results with many fruits. In any case, the minimum content is 3% by weight of clean, mature, sound fruits or their juice. Suggested use levels are given in Table 4.4.

Frozen fruits can also be suitable for use in frozen desserts. However, the cost of holding them frozen can be significant; furthermore, they must be thawed slowly in refrigerated space to maintain their quality. Fruits are generally always sugared prior to freezing, to reduce cellular or tissue damage to the fruit during freezing. Once thawed, frozen fruits should be used within a few hours. Frozen and thawed fruits (4+1 or 2+1 fruit/sugar packs) or fresh sugared fruits may need to be strained so that only a portion of the juice is added to the mix to avoid lowering the freezing point of the mix excessively. The strained fruit, which should be cooled to 4 °C or less, is added through the ingredient feeder. If iciness of the berries in ice cream is a problem, the percentage sugar in the pack can be increased, thus lowering the freezing point. The consequences of adding excess amounts of sugar to fruit are increases in the amount of juice exuding from the berries and the necessity to reduce the sugar content of the mix to avoid excess sweetness and low freezing point. For the fruit to have the same consistency as the ice cream at the serving temperature, the fruit should contain approximately 21% sugar, and such is provided by a 3:1 to 4:1 ratio. Another option is to also add pectin to the fresh or frozen sugared fruit preparations. Pectin-stabilized fruits have little free juice, and hence straining may no longer be required.

Specific Fruits

Strawberry. The amount of fruit used affects the body, texture, flavor, and appearance of strawberry ice cream. As the amount of fruit is increased, flavor, color, and appearance tend to improve, but texture becomes coarse. Addition of flavoring and color may be necessary to achieve the optimal product. The addition of 20% by wt.

Table 4.4 Amount and preparation of fruits and nuts for ice cream

Flavor	Fruit–sugar ratio	Quantity of fruit in mix (%)	Kind of preparation	Added color
Apple	7:1	20–25	Sliced	Light yellow green
Apricot	3:1	20–25	Sliced, diced, or puree	Light orange yellow
Banana	–	18–20	Puree	[a]
Blackberry	3:1	20	Crushed or puree	Slight red
Blueberry	4:1	20	Crushed or puree	Light blue
Cherry	5:1	15–20	Whole or crushed	Light red
Fruit salad	3:1	15	Sliced or diced	[a]
Grape	–	25	Juice	Light purple
Peach	4:1	20–25	Sliced, diced, or puree	Light
Pineapple	4:1	12–15	Diced or crushed	[a]
Plum	4:1	25	Puree	Light red
Raspberry	2:1	10–12	Crushed or puree	Light purple
Strawberry	3:1 to 4:1	15–20	Sliced, crushed, or puree	Pink
Almond	[b]	3 lb: 10 gal mix	Broken	[a]
Chocolate	[b]	2.7–3.5 lb cocoa	Powder	
		3.5–4.5 lb cocoa liquor blend	Syrup	[a]
		4.5–5.5 lb chocolate liquor		
		Per 10 gal mix		
Pecan	[b]	3 lb: 10 gal mix	Broken	
Pistachio	[b]	4 lb: 10 gal mix	Whole and broken	Light green
Walnut	[b]	4 lb: 10 gal mix	Broken	[a]
Orange	5:1	14–18 oz: 10 gal mix	Puree	Orange
Lemon	5:1	10–14 oz: 10 gal mix	Puree	Yellow green
Lime	5:1	8–12 oz: 10 gal mix	Puree	Green

[a]Natural, no color added
[b]Sugar pack may range from 2:1 to 9:1

strawberry solid pack is standard. Red color may be used to adjust color to desired intensity of pink, although pale-pink strawberry ice cream with no added color is now quite common in the marketplace. Strawberry flavor added to the mix at 3 mL/kg may also be required. Another option might be the use of 7.7% strawberry puree to the mix in the flavor tank plus 15% solid pack strawberries through the ingredient feeder.

Peach. By adding a portion of the peaches as puree to the mix (approximately 7% by wt.), or an alternative puree such as nectarine, intensities of both the flavor and color are enhanced. Light yellow color may be added to the mix in the flavor tank. Yellow-fleshed "freestone" peaches are less expensive and provide a greater concentration of flavor than do white clingstone (cling) peaches, and shreds of the peach are more evident in the ice cream when puree is made from yellow peaches. However, the flesh of the clingstone peach is more firm than that of the freestone. Some producers use a blend of the two to provide greater visibility of peach in the ice cream, used at 13 (with added puree or flavor) –20% by wt. The red flesh that occurs next to the seed of a freestone peach tends to turn purple in an acid environment. Therefore, this peach may not be suited to acidic frozen yogurt and sherbets. Peach flavor may be insufficient without the addition of flavoring or peach extract along with the fruit.

Cherry. Maraschino cherries or sour cherries with added cherry concentrate to fortify the flavor are frequently used in ice cream, added at 12–15% by wt. in the ingredient feeder. Mix can be either vanilla-flavored or cherry or black cherry-flavored. Sour cultivars of cherries are superior to sweet cherries for ice cream. Most manufacturers use natural black, Maraschino or Bordeaux cherries. Bordeaux and Maraschino cherries are made from brine cherries. Red color and flavors are added to brine cherries to make Maraschino cherries. Blue and red colors and flavors are added to brine cherries to make Bordeaux cherries. Natural black cherries are mixed with sugar, stabilizers, flavor, and color and are pasteurized. The addition of a small amount of cherry extract, oil of bitter almonds, or benzaldehyde can enhance cherry flavor. Additives should be well mixed with the fruit before adding to the ice cream.

Raspberry. If raspberries are merely pressed through a sieve, they contain the seeds; however, they may be screened also to make a seedless puree. Blends of the sieved and screened fruit are produced, giving several levels of seed content. Although 12–15% of raspberry puree containing 25% of the seeds provides an excellent raspberry flavor, the texture is made coarse due to seeds. The textural problem can be minimized by using 10–12% red or black raspberry puree with a 1:1 sugar ratio plus raspberry extract, which is usually needed to fortify the flavor. Puree can be added to the mix in the flavor tank or as a variegate.

Blueberry. Blueberries make wonderful flavors but can be difficult to work with, owing to the fact they that do not absorb much sugar so remain frozen hard in ice cream. Various forms of cooked blueberries, however, do become viable alternatives. Blueberry purees and concentrates can be used to flavor mix, while blueberry ripples can be introduced as variegates. Recent ice cream flavor introductions have included blueberry pie, blueberry ginger, blueberry muffin, blueberry cheesecake, and blueberries with mint or lavender.

Rum Raisin. Rum flavor (3–4.5 mL/kg) and yellow color are added to plain white mix in the flavor tank. Pure rum can only be used to a limited quantity, due to its effect on freezing point depression. Add 30% soft seedless raisins through the ingredient feeder.

If the raisins are not soft, they should be soaked in water and drained before being added to the ice cream.

Others. Other fruits for use in ice cream could include apricot (20% by wt. and colored light yellow), pineapple (crushed, 10% by wt., added through the ingredient feeder, often with orange concentrate added to the mix in the flavor tank), banana puree (10% added to the mix; can be made from fresh bananas if fully ripe), lemon (15% of a mixture of 56% lemon juice, 14% orange juice, 30% added sugar, added to the mix in the flavor tank, often with yellow color added), kiwi, mango, guava, or gooseberry. With many fruits, the addition of a small amount of citric acid or lemon juice may prevent discoloration of the fresh fruit and enhance flavor.

Candied or Glazed Fruits. Cherries and pineapple and such candied fruit peels as orange, lemon, and grapefruit can be used as accents to other flavor combinations. They make excellent decorative materials on fancy molded ice creams, sherbets, and ices.

Dried Fruits. Dried apricots, figs, raisins, and prunes can all be used in various ice cream flavors. They are continuously available, are shelf stable, and can be obtained in places where other types of fruit are expensive or unavailable. Dates, figs, and raisins have long been used in frozen puddings.

Fruit Concentrates. When fruits are high in price, less fruit may be used and enough fruit extract added to impart approximately the same flavor intensity as would be provided by the natural fruit. Another approach is to add fruit concentrates and essences. Popular ones are peach, blueberry, apple, grape, red raspberry, and strawberry. Supplemental use of 3.5–10% fruit equivalent of concentrates improves flavor. Adjustment of the acidity and sugar content of mixes may contribute to improved flavor when concentrates and essences are used. For example, when the base mix contained 20% fruit pack, the most favorable pH, sugar concentration, and supplementation concentration in experimental trials for selected fruits were found to be as follows, respectively:

Blueberry ice cream—pH 5.7, 15% sugar, and 5% blueberry juice concentrate.
Peach ice cream—pH 5.7, 16% sugar, and 7.5% peach juice concentrate.
Cherry ice cream—pH 5.2, 15% sugar, and 15% cherry juice concentrate.
Apple ice cream—pH 6.2, 15% sugar, and 20% apple juice concentrate.

Nuts

Nutmeats and nut extracts are used extensively in frozen desserts. Among the most popular are pecans, walnuts (English and black), almonds, pistachios, filberts, and peanuts (see Tables 4.1 and 4.2). Nutmeats should be sound, clean, free from rancid flavor, low in count of microorganisms, and free of pathogenic bacteria. Methods of eliminating microorganisms other than careful hygienic control during processing include application of dry heat, dipping in a boiling slightly salty sugar

solution for a few seconds, treating with ethylene oxide, or oil roasting. Ethylene oxide is highly effective, but the gas is toxic and must be used under carefully controlled conditions. To prevent sogginess, nuts treated in boiling water should be dried for 3–4 min at 121–149 °C (250–300 °F). Oil roasting not only provides a means of microorganism control but also helps to keep nuts crispy by slowing down moisture migration into the nut.

Nuts should be stored in a cool dry place until used. Almonds, filberts, and pistachios should be blanched to remove their skin prior to use. Specifications of permitted pieces of shell should be checked carefully by manufacturers in purchasing prepared nutmeats.

Concentrations of nuts in ice cream range from 3 to 6% by wt. depending on the nut and the accompanying flavor(s). The following are flavors and recommended amounts of nuts (calculated as percentage of the unflavored mix): banana nut, 2.2%; caramel praline, 5%; chocolate caramel nut, 1.7%; maple nut, 2.2%; mud nut, 1.7%; butter pecan, 3.3%; pecan pie, 2.2%; and black walnut, 2.8%. Butter and caramel flavors are excellent companions with nuts. Other examples of nut-based ice creams are as follows:

Burnt almond. 5–5.5% burnt or roasted almonds. Almond flavor may also be added, as well as some burnt sugar or caramel color.
Pistachio. 5% chopped pistachio nutmeats, pistachio extract to taste, and color light green. Frequently English walnuts or pecan nutmeats are used instead of pistachio nuts, in which case the pistachio flavor is secured from the extract.
Butter pecan. 3% butter crunch candy plus 2–2.5% chopped pecans or 10% buttered and candied pecans.
Maple walnut. 2.5–3.5% chopped walnuts, 2 mL/kg maple extract.
Black walnut. 5–5.5% broken black walnut meats, which may go well with chocolate, cinnamon, or fruits such as peach.
Caramel nut. 3.5% crushed nuts, 1.5 mL/kg burnt sugar coloring, and caramel flavoring.
Pineapple nut. 10% pineapple and 3.5% nuts.
Pecan crunch. 8% ground pecan crunch candy.
Banana nut. 8% crushed bananas and 2.5% chopped nuts.
Almond toffee. 4–5% broken toffee candy and 2.5% broken almonds.
Coconut pineapple. 10% crushed pineapple and 5% ground coconut.
Peanut. 5–8% crushed peanuts or peanut butter.

The incidence of allergies to nuts, especially peanuts (ground nuts), is significant and appears to be increasing, at least in Western populations. Severe nut allergies can induce prophylactic shock and death, so the presence of undeclared nuts in products must be taken very seriously by processors. Numerous recalls of frozen desserts have been necessary because of failure to label products containing nuts or because nuts were unintended contaminants of products. It is highly important that equipment used to process nut-containing products be thoroughly cleaned before nut-free products are processed. Tests for the presence of nut contaminants are available and in some cases can be utilized on rinse water following the wash of the equipment. Hence, freezing nut-containing

frozen desserts last among the flavors is recommended. Rerun from nut ice creams must not be included in mixes of other flavors including the mixing of product containing one type of nut with that containing another type of nut. In some instances, nut-containing products are frozen in separate facilities from nut-free products, and no traces of any kind of nut whatsoever are allowed into the nut-free facility. All labels must contain the name of the nut or nuts placed in the dessert. Because of the difficulty in guaranteeing that non-nut products are completely free of any nut residue from cross contamination, some manufacturers have begun to use the following label on all flavors: "May contain nuts or nut products." This, however, reduces the customer base for this product and deprives people with nut allergies of ice cream in their diet.

Bakery Pieces

Product designers have developed unique baked goods for use as inclusions in frozen desserts, and the inclusion of these bakery pieces has become quite popular in new ice cream flavors in recent years (see Tables 4.1 and 4.2). Bakery pieces are normally added at 8–10% by wt. These need to have a low melting point to allow them to be soft and chewy at −12 to −18 °C (0–10 °F), the temperature of consumption. Bakers limit moisture migration into the inclusion by coating with chocolate or a layer of oil. Some baked goods are made with low moisture to permit some rehydration in the finished product. Examples of bakery pieces as ice cream particulates include many types of cookies and cookie pieces, biscotti, brownie pieces, cheesecake, pie crust pieces, cake pieces, mini cupcakes and chocolate-covered popcorn.

Candy Pieces

Various types of candy pieces have been used in ice cream flavors, and some are quite popular (see Tables 4.1 and 4.2). Candy or confection pieces are usually added at 5–8% by wt. Some examples are as follows: crushed peppermint candy (4.5–6%); ground butter crunch candy (7%); white or dark chocolate chips (5%); crushedpeanut brittle (4.5–6%); miniature marshmallows (4.5–6%); broken toffee candy (4.5–6%); green, red or a mixture of colors of mint chips (4.5–6%); crushed English toffee (4.5–6%); preserved chopped ginger root (9%); and bubble gum (4.5–6%). An alternative to the use of hard chocolate chips is a product called liquid chocolate chip or chocolate crackle. This product is added warm through a variegating pump and hardens immediately upon entering the ice cream, thus causing a breakup of the ripple into small fragments. Although the end product is appealing, a concern is the heat shock induced in the ice cream as heat is released by the crystallizing cocoa fat. Licorice can be made by adding to plain white mix 3 mL/kg licorice paste, 1 mL/kg oil of anise, and black color.

Variegates

Variegates (stripes, ribbons, swirls) are formed in continuous processing by pumping a syrup through a special tubular apparatus with a variable speed positive displacement pump. Depending on the speed of production, such equipment may have from one to five outlet tubes that may be turned or left stationary within the stream of soft-frozen product. Distributing variegate syrups uniformly and in desired amounts into batch-frozen ice creams requires planning and practice. Common variegating flavors include chocolate ripple, strawberry ripple, raspberry ripple, butterscotch ripple, marshmallow ripple (often into a chocolate base), cake frosting variegates, and many others. Syrups (variegates) used to make swirls and ribbons in ice cream can be water-based or oil-based. Freezing can cause water-based variegates to become hard and icy. Freezing point depression of the syrup is critical—it should be formulated with sufficient sugar to remain unfrozen at temperatures well below the freezing curve of the ice cream. However, if the sugar content is too high, the sugar may crystallize. The use of corn syrups in the sugar helps maintain them in a noncrystalline state at very low temperatures. Viscosity is also critical, so that it remains distinct and does not migrate or diffuse into the ice cream. Adequate viscosity of variegating syrups can be developed with gums or starches and in some cases pectin. Starches are least expensive, but they may mask certain delicate flavor notes.

There is less concern with oil-based syrups freezing; hence they usually remain soft. The oil can crystallize, however, if it is not formulated properly. Oil-based syrups, like chocolate, will also thicken with time (before use), so they exhibit a limited shelf life. Oil-based variegates also can be prone to separation when sitting quiescently (before use).

Ice Cream with Complex Flavors

As technologies have developed, it has become possible to produce many multiple-flavored frozen desserts containing more than one type of inclusion or ripple. Such products are commonly made by adding the background flavoring to the mix, then adding the nuts, fruits, candies, confections, or ripples to the frozen product with ingredient feeders in series or parallel, followed by a variegating pump to introduce syrup. An example might be a chocolate ice cream with almond pieces and a marshmallow ripple. In some cases, multiple ice cream flavors can also be incorporated into the same product by running two or more continuous freezers and blending the output at a filling machine. Neopolitan, a blend of chocolate-, vanilla-, and strawberry-flavored ice cream, or a three-flavor chocolate, with dark chocolate, milk chocolate, and white chocolate, would be examples. These can either be swirled or deposited as three separate layers within the package, by the configuration of the filling head. Particulates or ripples could also be added into the ice cream before blending. As an example, a Neopolitan ice cream with strawberry particulates in the strawberry-flavored ice cream and chocolate chips in the chocolate ice cream portion.

Manufacturers must contend with the tendency of heavy inclusions to sink within the product before it is hardened. The tendency for inclusions to sink increases with increases in overrun or draw temperature and decreases in total solids. Additionally, there are some inclusions that stick together in the ingredient feeder. Often these may be frozen prior to addition both to prevent sticking and to limit heat transfer to the frozen product.

Weight of the added fruits, nuts, other inclusions, and variegates should be considered in establishing the final product weight per container. Overrun may need to be adjusted quite differently compared with that of a plain ice cream. These calculations are presented in detail in Chap. 6. It is important to meet the legal compositional standards for milk fat and total solids after inclusion addition and also to maintain acceptable textural quality that will not lead to the development of coarse–icy defects due to improper formulations.

The following are examples of formulas for complex flavors as simply ideas of what can be done, but it is up to the "flavorologist" to allow their creative juices to flow to make innovative and unique combinations that will attract consumers. As long as the technical challenges are overcome, the limitation is only the imagination and, of course, the demand. A great inspiration is the winner of the 2011 International Dairy Foods Association frozen dessert innovation award, "salted caramel chocolate pretzel," a combination of dark chocolate flakes and textured swirls of salty pretzel variegate added to caramel ice cream in a natural dulce de leche base and egg custard.

Peanut Butter Toffee Crisp: Add 10% caramel syrup to white mix in the flavor tank, 5% (by wt.) chilled English toffee crisp candy through the ingredient feeder and inject 7–10% peanut butter sundae pack as a variegate to the soft-frozen product.

Peanut Butter Cookie Dough: Add 3 mL/kg vanilla flavor and 5% frozen and thawed chocolate chip cookie dough to white mix in the flavor tank and inject 7–10% (by wt.) of chilled peanut butter ripple through the variegating pump.

Praline Cheesecake: Add 7.8% cheesecake base to ice cream mix in the flavor tank, 5% (by wt.) praline almonds, and 18% (by wt.) pineapple tidbits through one (preblended) or two (in series, one for each inclusion) ingredient feeders.

Carrot Cake: Add a blend of carrots, raisins, walnuts, and spices through the ingredient feeder.

Snickerdoodle Cookie: Add brown sugar and cinnamon flavors to plain mix in the flavor tank, snickerdoodle cookies through an ingredient feeder and cinnamon caramel swirl through a variegating pump.

Coconut Macaroon: Add coconut flavor to plain mix in the flavor tank, macaroon cookies through the ingredient feeder, and a coconut ripple (or raspberry ripple) through the variegating pump.

Berry Pound Cake: Add wild berry puree to the mix in the flavor tank, pound cake pieces through the ingredient feeder, and a blackberry ripple through the variegating pump.

Cherry Almond: Add black cherry flavor to plain mix in the flavor tank, or the mix could be kept as a white mix through the addition of vanilla flavor and either a combination of almonds and black cherries through multiple ingredient feeders or almonds through an ingredient feeder and a black cherry sauce through a variegating pump.

Jumble Berry: Add a mixed berry puree to mix in the flavor tank and a blend of blueberries, strawberries, raspberries, blackberries, and cranberries through an ingredient feeder.

Black Forest: Add cherry flavor to plain mix in the flavor tank, or use a chocolate mix, and add black sweet cherries through the ingredient feeder and chocolate ripple sauce (for cherry ice cream) or white frosting sauce (for chocolate ice cream) through the ingredient feeder.

Granola Berry: Add vanilla to plain mix in the flavor tank, granola clusters through the ingredient feeder, and raspberry sauce through the variegating pump.

Brownies, *Cookies, and Cream*: Add vanilla to plain mix in the flavor tank and brownie fudge, cookie pieces, and English walnuts through one (pre-blended) or two (one for the sticky brownie pieces, the other for pre-blended cookie pieces and walnuts) ingredient feeders.

English Caramels and Pecans: Add vanilla to plain mix in the flavor tank, and caramel cube pieces and chocolate pecans through the ingredient feeder.

Raspberry Mousse Cake: Plain ice cream mix flavored with raspberry and mousse-mix bases to which a mixture of brownie fudge pieces and chocolate-coated chocolate cookies is added.

Pineapple Upside Down Cake: Add pineapple flavor to plain mix in the flavor tank, pound cake pieces through the ingredient feeder, and caramel swirl through the variegating pump.

Pecan Apple Danish: Apple ice cream with a caramel cinnamon swirl and roasted, salted pecans.

Blueberry Bonanza: True-to-nature blueberry flavor that goes great with cheesecake, banana, and cream notes.

Caramel Pecan Danish: Add a cinnamon spice flavor to lain mix in the flavor tank, praline pecans through the ingredient feeder, and caramel fudge swirl through the variegating pump.

Irish Cream: Add a traditional Irish cream flavor to plain mix in the flavor tank, bittersweet chocolate flakes through the ingredient feeder, and fudge swirl through the variegating pump.

Defects in Flavoring Systems

Frozen desserts have a wide variety of flavoring ingredients added, and these, in some instances, can lead to flavor defects in ice cream. Usually the flavoring contains highly volatile components that are detected soon after a sample is tasted. The sensory analysis of ice cream is discussed in detail in Chap. 14. Defects in flavor associated with mix ingredients are discussed in Chap. 5. Some of the main flavor defects and their causes and remedies are summarized in Table 14.3. The principal defects in body and texture are described in Chaps. 11 (Structure) and 12 (Shelf Life). Some of the main body and texture defects and their causes and remedies are summarized in Table 14.4. Further details on ice cream mix and ice cream flavor and texture defects can be found in Alvarez (2009).

Lacks flavoring is perceived as bland, flat, or lacking bouquet. The cause may be addition of too little flavoring, low strength of the flavoring, or masking of the flavor by other ingredients.

Lacks fine flavor is sensed as a slightly harsh or coarse flavor, and the flavoring system usually is not in balance with the ingredients. The exact cause is often obscure.

Too high flavor is not often observed, because flavorings are usually the most costly of ingredients. There is a high economic incentive to avoid overuse of flavorings. The analyst experiences sharpness of certain flavor notes when excess flavoring is used.

Unnatural flavor is too frequently observed in frozen desserts when manufacturers attempt to lower costs by using "cheap" flavors. Various sensations characterize this category of flavor defect, but the most frequent cause is addition of artificial flavoring. Artificial flavors may be suggestive of buttery, candy, cherry, coconut, custard, lemon, maple, marshmallow, nuts, smoke, vanillin, and numerous other substances, depending upon circumstances. The practice of using fruit flavorings "with other natural flavors" (commonly referred to as WONF) can be associated with unnatural flavors. With vanilla the use of synthetic vanillin can cause a sharp, harsh flavor. Even when only pure vanilla extract is used, the source of vanilla beans, the way they are fermented, and the grinding and extraction treatments are sufficiently variable to cause evaluators to sometimes use the term "unnatural" to describe the flavoring.

It is important to recognize that not all consumers have the same taste preferences. Some persons actually prefer imitation flavors to natural ones in certain products. There is no substitute for having an analysis of the preferences of the target group of consumers to determine the best flavor profile for a specific product. The producer is most unwise to select flavorings and establish their usage concentrations based solely on taste preferences of the "boss."

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Chapter 5
Mix Processing and Properties

Introduction

Mix composition, ingredient quality, and accurate calculations are each prerequisites for the manufacture of desirable ice cream. Once the compositional requirements related to quality and quantity are met, the mix is ready for processing. Mix processing begins with combining the ingredients into an homogeneous suspension/solution that can be pasteurized, homogenized, cooled, aged, flavored, and frozen (see Fig. 1.2).

The first step in processing is composing the mix. The procedure may range in scope from a small batch operation, in which each ingredient is weighed or measured individually into a pasteurizing vat, to the large, automatic, continuous operation in which liquid ingredients are metered into a batching tank. Continuous mix-making operations vary considerably in their characteristics with some of them being adaptations of batch operations. Liquid ingredients, including stabilizers, and product blending equipment have been developed to accommodate continuous operations. Pumping of ingredients and mix through a closed system cuts costs of handling, reduces some important risks of contamination and makes possible automated cleaning in place of the equipment.

Mix Processing

Preparing the mix involves moving the ingredients from the storage areas to the mix preparation area, weighing, measuring, or metering them, and mixing or blending them. Undissolved components must be kept in suspension until they are fully hydrated or are dispersed in such small sizes that they remain suspended in the finished mix.

H.D. Goff and R.W. Hartel, *Ice Cream*, DOI 10.1007/978-1-4614-6096-1_5,

Combining the Ingredients

All liquid ingredients (milk, cream, concentrated milk, syrup, etc.) are placed in the vat, and the agitation and heating are started at once. Amounts of liquid ingredients can be measured with a calibrated measuring stick, pumped through a volumetric or mass flow meter, or directly added as predetermined volumes or weights. Systems that employ a meter on each inlet line provide the most rapid means of compounding a mix, because each liquid ingredient can be added simultaneously. If all ingredients are in the liquid form, the process is time-efficient and accurate, provided the compositions and densities of each ingredient are consistent from batch to batch and the information is used to control the metering operation. Flow meters supply the information needed to permit electronic or manual operation of pumps or valves to control ingredient flow. Automated systems of mix manufacture commonly employ microprocessors to compute the amount of each ingredient for a specific formula, start and stop the flow when the desired quantity has been transferred, and record the data useful for future reference. In plants of relatively small capacity the number of meters may be limited so that 1 m is used for more than one ingredient. If so, the densities of the ingredients must be nearly the same to provide sufficient accuracy.

To facilitate operation with a fully liquid system, it is often necessary to dissolve some dry ingredients. These are usually made in concentrated form and stored refrigerated until needed. It is of utmost importance that such ingredients be hydrated to the same concentration from batch to batch or that any change in composition be an input variable that is included in the formulation step. Liquefying dry ingredients well ahead of time for their use permits foam to dissipate and colloidal substances to hydrate fully. In cases of making small amounts in a large vessel, the depth of the liquid on the agitator will affect the extent of incorporation of ingredients and the amount of foaming.

If they are not liquefied first, dry ingredients, including skim or whole milk powder, dry whey, dried eggs, cocoa, sugar, and stabilizer, are added while the liquid materials are being agitated and before the temperature reaches 50°C (122 °F). Proper suspension to avoid lumpiness of the dry ingredients can be obtained by (1) mixing the dry ingredients with part of the crystalline sugar before adding it slowly to the liquid, or (2) sifting it slowly into the liquid. The liquid should be cool (<30°C, <86 °F) when milk solids-not-fat (MSNF), cocoa, or similar ingredients are added. Instructions of the manufacturer should be followed for addition of stabilizer/emulsifier blends to the mix. Some blends are capable of dissolving at relatively low temperatures, whereas others should not be added to a mix until the temperature reaches about 65°C (149 °F). Added frozen products, e.g., butter or frozen cream, should be cut into small pieces and allowed sufficient time to melt before pasteurization is started. With few exceptions, coloring and flavoring materials are added after pasteurization at the time the mix is frozen.

Dry ingredients can be blended into the nonfat liquid materials with an emulsifying agitator that is mounted inside the mix tank. More efficient blending is done with high shear mixers or with “powder funnels.” High shear blenders (Fig. 5.1),

Fig. 5.1 High shear blender for incorporating dry ingredients into ice cream mix (courtesy of Breddo Likwifier, www.breddo.com)

which have a relatively small capacity compared with that of a mix tank, suspend dry ingredients in a small portion of liquid components. The suspension is then transferred to the mix tank. These dry ingredient incorporators are constructed with agitators (Fig. 5.2) that form a deep vortex. Air incorporation is minimized by the flow pattern of mix away from the vortex. In no case should cream be admitted to the high shear blender, because churning is almost certain to occur.

A simple and inexpensive device for incorporating dry ingredients employs a funnel attached to a tee in a pipe immediately upstream from a centrifugal pump which, in turn, is connected to the mix vat or blending tank (Fig. 5.3). Liquid flows

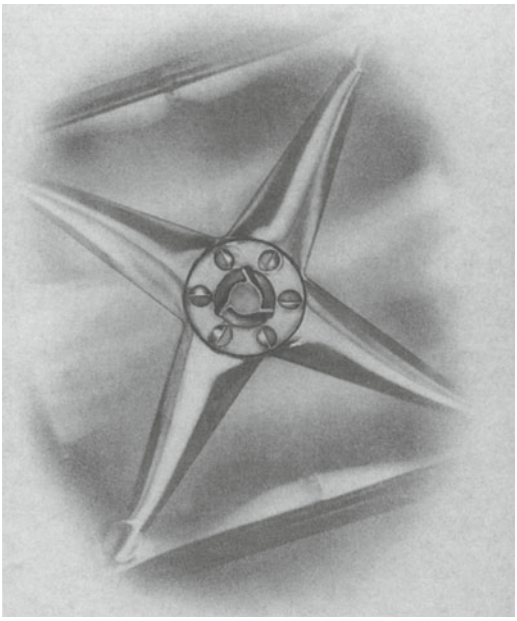

Fig. 5.2 Agitator for a high shear dry ingredient mixer (courtesy of Breddo Likwifier, www.breddo.com)

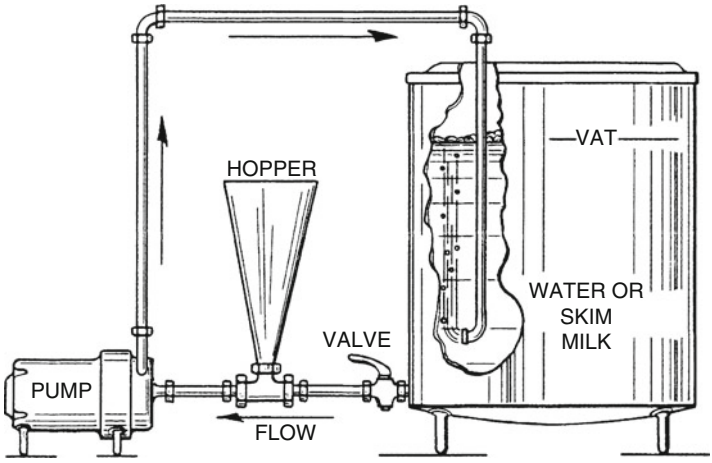

Fig. 5.3 "Powder funnel" type device for incorporating dry ingredients with liquid components of frozen dessert mixes

from the tank past the tee to the pump and is returned to the tank. The partial vacuum that is created by the operating pump draws dry ingredient into the flowing liquid and disperses it into the liquid. Avoidance of excess foaming is important when mix is pasteurized soon after blending.

Stabilizers are best dispersed into a mixture of low water activity (0.86 or lower) such as liquid sugar or corn syrup with about 70% solids. A suitable liquid sugar can

be made by blending sugar and water to make a syrup containing 66–68% solids. Sorbitol and polydextrose will work as well. Stabilizer can be added to such a solution at about 12% by wt. In this environment, stabilizer should be well dispersed by the blender in no more than 1 min. Longer times allow too much hydration and the buildup of excessive viscosity, making dispersion of the suspension into the remaining liquid quite difficult. To minimize foaming, the high shear blender should be filled to three-fourths of capacity before stabilizer is introduced, and the blender must be stopped as soon as dispersion is complete. Other dry ingredients should be incorporated before the stabilizer, and the blender should be operating as the stabilizer is introduced. Batch operation is far more satisfactory than continuous. After blending, the dispersion should be delivered beneath the surface of the mix in the batching tank or tangentially onto the sidewall of that tank to minimize foaming.

Incorporation of stabilizers into nonfat mixes is particularly difficult, especially if the mix is to be pasteurized in a plate-type heat exchanger. The reason is that nonfat mixes foam liberally and become highly viscous. As a mix containing foam goes through the homogenizer, it creates a high amount of noise, and burn-on may occur in the heating section of the pasteurizer. Stabilizers for nonfat mixes usually contain microparticulated cellulose. These minute particles migrate quickly to and stabilize the lamellae of air cells. The more air cells formed in the blender, the greater the problems encountered in the homogenizer and plate pasteurizer.

When batch or vat pasteurization is employed, heating during blending is the appropriate practice. However, economic and quality considerations should prompt the decision to blend into cold or into heated mix when continuous pasteurization is done. Regenerative pasteurization is most efficient when the mix that enters the heat exchanger is cold rather than warm. As an example, assume that mix enters the regenerator section of the heat exchanger at 5°C where it receives heat from the outflowing mix that has been heated to 80°C in the heating section of the pasteurizer. If the efficiency of heat transfer in the regenerator is 80%, the inflowing mix will be heated to 65°C, thus requiring that the temperature be raised another 15°C in the pasteurizing heat exchanger. The outflowing mix will be cooled from 80 to 20°C in the regenerator by the incoming cold mix, and it will need to lose another 16°C in the cooling section of the pasteurizer to bring the temperature to the desired 4°C. Contrast this situation to one in which the temperature of the inflowing mix is 40°C, each of the other parameters being the same as just described. The difference in temperatures between the outflowing and inflowing mixes is now only 40°C, and 80% regeneration will result in recovery of 32°C during both the heating and the cooling operations. Thus, the net reuse of energy is 60°C when the mix is cold but only 32°C when the mix is warm on entry into a regenerative-type pasteurizer. This difference of 28°C must be paid for in the forms of both heat (usually steam) and refrigeration. Of course, this simplified example does not consider that some ingredients may be inherently warm (e.g., syrups) and others cold. Furthermore, desired characteristics of the finished product, available equipment, or available ingredients may dictate the type of process that is used. Sugars, syrups, and skim milk powder dissolve slowly in cold liquids, and incorporated air does not escape cold mixes as readily as from the less viscous warm (35–40°C, 95–104 °F) ones.

Table 5.1 Minimal times and temperatures for pasteurization of ice cream mixes

Method	Time	Temperature (°C/°F)
Batch	30 min	69/155
HTST	25 s	80/175
	15 s	83/180
HHST	1–3 s	90/194
UHT	≥2 s	138/280

Source: U.S. Department of Health and Human Services. 2011. Grade A Pasteurized Milk Ordinance. Food and Drug Administration, College Park, MD

Pasteurization

Pasteurization of all mixes is required because this process destroys all pathogenic microorganisms, thereby safeguarding the health of consumers. Furthermore, most hydrolytic enzymes, even the natural ones of raw milk, that could damage flavor and texture are destroyed by pasteurization. Pasteurization adds little additional expense, because it is necessary to heat mix to dissolve or hydrate dry ingredients. Furthermore, homogenization can be best accomplished at temperatures near those of pasteurization.

The industry generally follows Federal regulations (Table 5.1) for pasteurization standards even though some states and local health authorities have similar requirements. Each manufacturer should be familiar with the regulations that apply to the market area, taking particular note of the following:

1. Whether any dairy product may be used without being re-pasteurized.
2. Maximal bacterial counts of ingredients used, even when the mix they are used in is pasteurized.
3. Time and temperature requirements of pasteurization.
4. Maximal permitted aerobic plate counts (often called Standard Plate Count) and coliform counts of the finished products.
5. Whether a product must be frozen on the premises where it is pasteurized.

Proper pasteurization consists in rapidly heating to a definite minimal temperature, holding at that temperature for a minimal time, then rapidly cooling to <5°C (<40 °F). Pasteurization (1) renders the mix substantially free of vegetative microorganisms, killing all of the pathogens likely to be in the ingredients, (2) brings solids into solution, (3) aids in blending by melting the fat and decreasing the viscosity, (4) improves flavor of most mixes, (5) extends keeping quality to a few weeks, and (6) increases the uniformity of product.

There are two basic methods of pasteurization: batch or low-temperature long-time (LTLT), and continuous or high-temperature short-time (HTST). The Pasteurized Milk Ordinance (U.S. Department of Health and Human Services 2011) provides extensive descriptions of pasteurization equipment and its proper operations. Representatives of manufacturers, users, and public health authorities have worked together to develop and adopt 3-A Accepted Practices for the Sanitary Construction, Installation, Testing and Operation of HTST and Higher-Heat Shorter-Time (HHST)

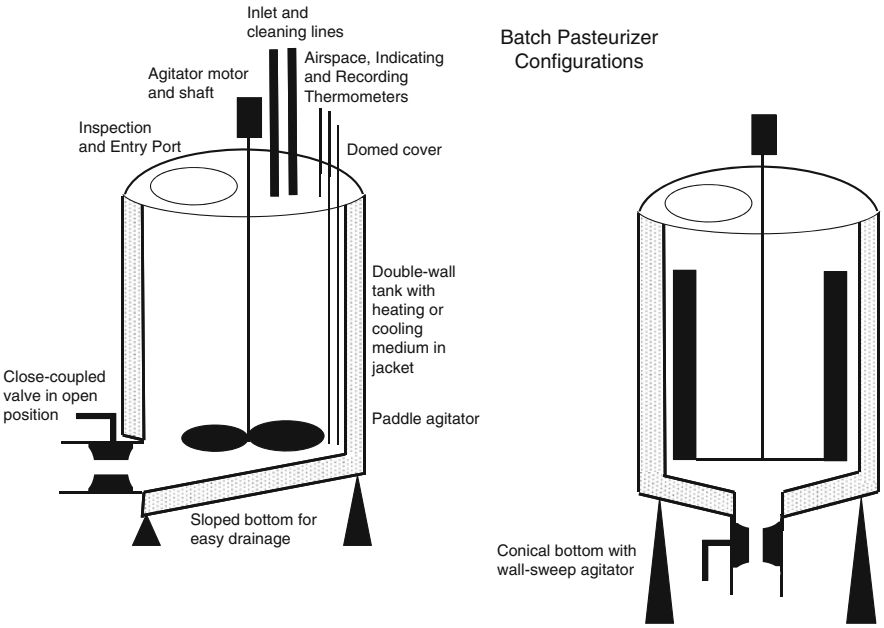

Fig. 5.4 Schematic diagram of the configuration and essential components of batch-type pasteurizers

Pasteurizer Systems (www.3-A.org), according to the provisions of the Pasteurized Milk Ordinance. Any pasteurizer, or any of the many other types of equipment that bear the 3-A symbol, is deemed to have been manufactured under the provisions of the accepted practices.

In the batch system, the mix is usually compounded in the vat, which is a double-walled (jacketed) tank, typically of 600–2,000 L size (Fig. 5.4). Smaller tanks will typically have a paddle agitator while larger ones may need a swept-wall agitator to ensure good mixing and heat transfer. Outlet valves are typically recessed into the side of the tank ("close-coupled") to ensure no dead-space exists within the valve that may not permit adequate temperature to be reached. Larger tanks may also be of a conical-bottom configuration, to ensure fast gravity drainage as the mix completes its emptying. All tanks are equipped with both indicating (stem) thermometers, which have to reach the bottom of the tank, and recording (stem) thermometers, that are tied to computer or strip-chart recorder inputs, for record keeping. In many cases, batch tanks are also equipped with air space heaters and air space thermometers, to ensure that any foam that forms on the top of the mix is also adequately pasteurized. During the pasteurization process, heat is applied, by circulating hot water between the double walls of the vat, while the ingredients are being added and blended. Once all ingredients have been added to the vat and the minimal temperature of 69°C (155 °F) has been reached, or higher if desired, timing of pasteurization is started. As soon as the minimal time of heating of 30 min has elapsed, mix is pumped through the homogenizer and then to a continuous cooling device such as a

Fig. 5.5 A plate heat exchanger used for cooling of mixes following batch pasteurization. This also provides a good illustration of plate heat exchangers used for HTST pasteurization, when properly configured

plate heat exchanger (Fig. 5.5). Only in very small operations is mix cooled in the processing vat. Heating and cooling in a vat increases the total heat treatment by a large amount resulting in a relatively high intensity of cooked flavor in the mix. However, cooked flavor is not usually objectionable in ice cream. Furthermore, the increased hydration of proteins and stabilizers induced by the LTLT method can impart improved body and texture, increase resistance to heat shock, and reduce the time needed for aging of the mix.

Continuous pasteurization can be done at several combinations of temperature and time; see Table 5.1 for specifications for HTST, HHST, and ultra high temperature (UHT) processes. As discussed above, continuous flow pasteurizers facilitate the use of regenerative heating and cooling with consequent large savings in costs for energy. Most continuous type pasteurizers consist of a series of parallel plates with grooved or waffled surfaces. Heat is exchanged from warmer liquid passing in one direction of flow on one side of the plates to cooler liquid passing in the reverse direction of flow on the opposite side of the same plates (Figs. 5.5, 5.6 and 5.7). Other continuous flow heat exchangers include double-tube, triple-tube, and steam injection designs, although these are not in common use for dairy product pasteurization. With the latter type the water added in the form of steam condenses in the

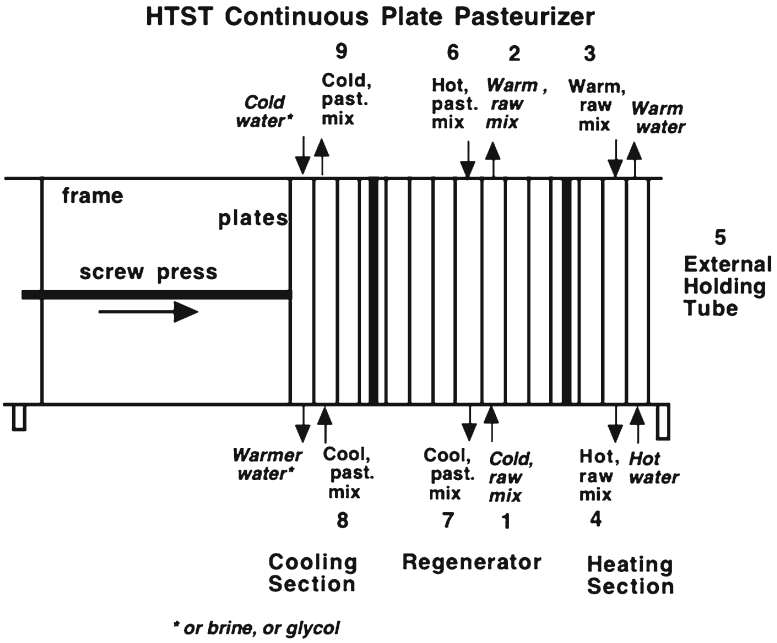

Fig. 5.6 Schematic diagram of the flow of mix through the plates of a continuous (HTST) pasteurizer. Numbering represents the various steps in the flow

mix and must be accounted for in the formulation or removed by vaporization and condensation under vacuum. Controls are necessary on such systems to ensure that the correct amount of total solids remains in the mix.

The flow of mix through the HTST system is shown in Figs. 5.6 and 5.7. Mix begins in the constant level tank, which is open to gravity at a level lower than the lowest level of mix in the plates to ensure that there is no head pressure applied to the raw side of the regenerator on the suction side. With raw and pasteurized mix separated only by a thin plate, a positive pressure differential on the pasteurized side ensures no leakage of raw mix into pasteurized mix, should there be a pin-hole leak in the plates. Initial warming of mix occurs in the raw side of the regenerator, the heat of which is being removed from pasteurized mix on the opposite sides of the plates. From the regenerator, mix flows through the timing pump, the speed of which dictates the holding time in the external holding tube. Location of the timing pump between the raw and pasteurized sides of the regenerator contributes to the required pressure differential. After the timing pump, final heating occurs in the heating section, the heat being provided by an external source of hot water. The holding tube is designed so that the mix flow within the tube ensures the appropriate holding time. Following the holding tube, temperature is measured by the recorded/controller device (Safety Thermal Limit Recorder), which signals the flow diversion device to either divert mix back to the constant level tank, if the temperature is too low, or to open under mechanical pressure to allow mix to proceed in forward flow through the

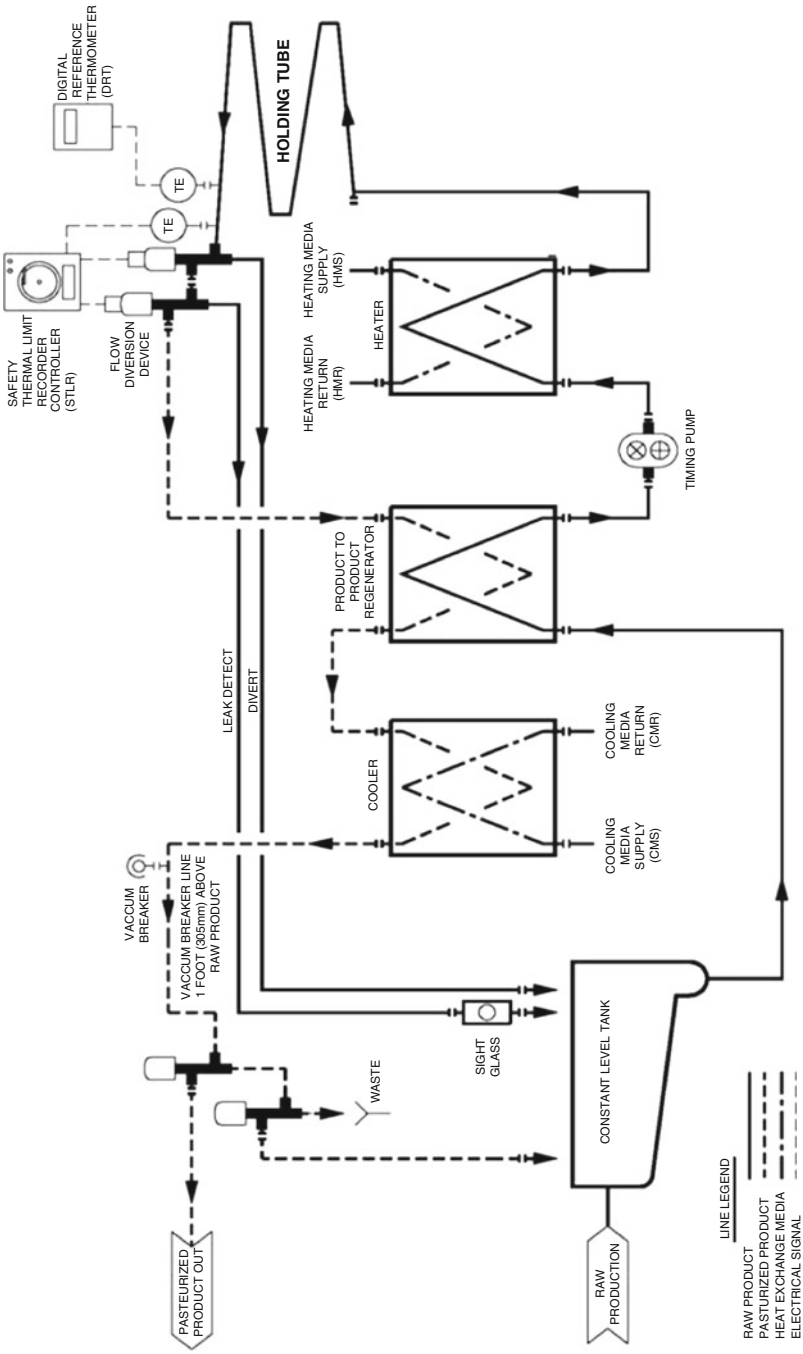

Fig. 5.7 The components of a simple configuration of a continuous HTST pasteurizer with positive displacement timing pump (U.S. Department of Health and Human Services. 2011)

rest of the system. After the flow diversion device, mix is fully pasteurized. Cooling is accomplished through the pasteurized side of the regenerator and the cooling section, where final heat is removed by an external source of cold water or brine or glycol solution. Mix exits the HTST system via a vacuum breaker located above the highest level of mix in the plates, to ensure there is no suction pressure on the discharge side that might affect the pressure differential in the regenerator.

Several advances to this basic system are shown in Fig. 5.8. The first is the addition of a booster pump between the constant level tank and the raw side of the regenerator. As systems become larger, the timing pump has a difficult job to pull mix on its suction side through the raw side of the regenerator. Hence, the booster pump (sometimes referred to as a "stuffing" pump) is added to help fill the raw side of the regenerator and reduce suction pressure on the timing pump. The use of a booster pump, however, then necessitates active monitoring and control of the differential pressure on the sides of the regenerator. This is done with differential pressure measurement and a back pressure valve and controller on the discharge of the system, again with the goal to ensure that a pin-hole leak does not allow contamination of pasteurized mix with raw mix.

The principal outcome of pasteurization is that the mix is rendered free of microorganisms that have the potential to cause disease among consumers. To ensure that pasteurization is accomplished within the parameters of time and temperature needed to kill all potential pathogens, controls are prescribed by regulations. Among them is a requirement that holding tubes be designed to expose mixes to the minimal temperature for the minimal time that matches the temperature (Table 5.1), e.g., 25 s when the minimum is 80°C (175 °F). Determinants of holding time are rate of mix flow, length and diameter of the tube, and amount of mixing of the fluid in the tube. Each continuous-flow pasteurizer must have either a positive displacement-type timing pump or a meter-based timing system to control the rate of flow through the holding tube. The meter-based system consists of a centrifugal pump, a control valve (or the pump must be of the variable speed type), and a magnetic flow meter that uses an electric signal to control the flow rate of the product through the holding tube (Fig. 5.8). The magnetic flow meter must produce a linear signal proportional to the flow through the holding tube. Also, there must be high flow and low flow alarms to signal the flow diversion device to close in the event the rate of flow goes above or below preset limits. The advantage of the centrifugal timing pump/magnetic flow meter system compared to the positive displacement timing pump is the higher initial cost of the positive displacement pump and the higher cost of regular replacement of the rotors within the pump.

Holding tubes must be so designed that the simultaneous temperature difference between the hottest and coldest product in any cross-section of flow at any time during the holding period will not be greater than 0.5°C (1 °F), and the average velocity through the holding tube shall not be less than 1 ft/s (3.05 cm/s) (U.S. Department of Health and Human Services 2011).

Ice cream mixes may be so viscous as to cause flow within the pasteurizer holding tube to be of the laminar type (smooth and stable). In such cases the holding tube must be sized to hold the mix twice as long as would be necessary were the

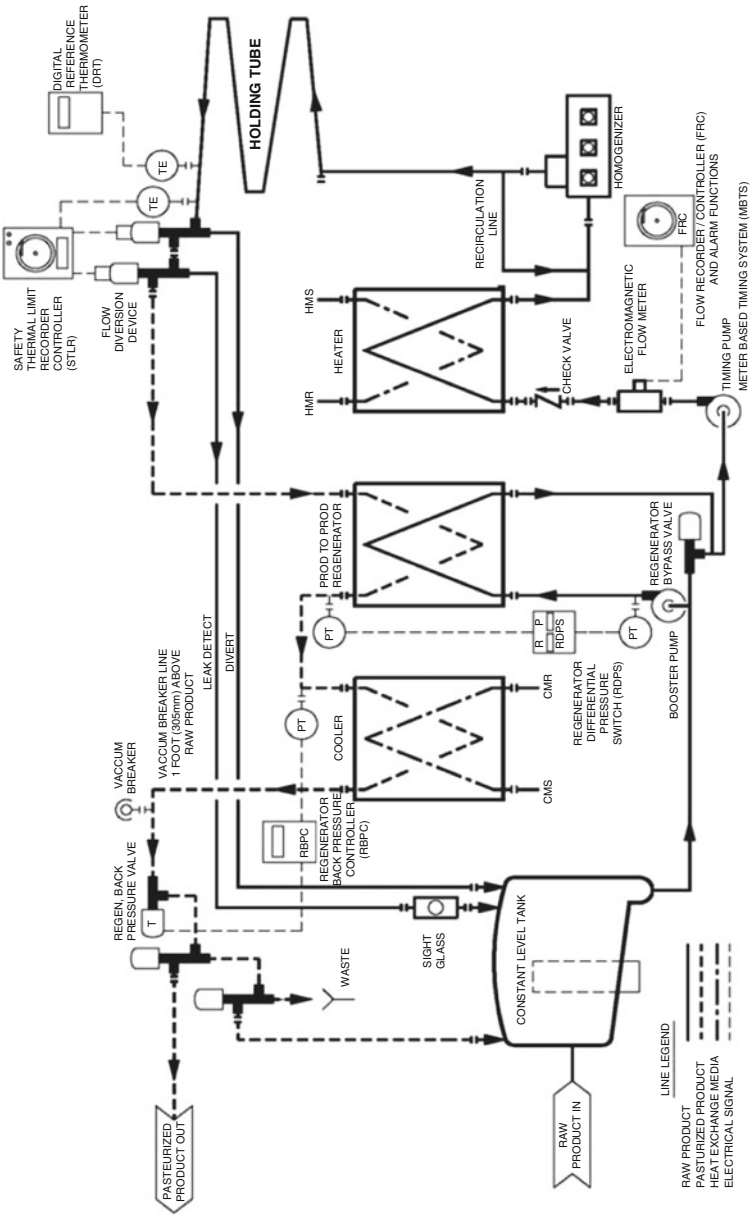

Fig. 5.8 The components of an advanced configuration of a continuous HTST pasteurizer showing, in addition to the components of Fig. 5.7, a centrifugal booster pump before the raw side of the regenerator, a centrifugal timing pump with magnetic flow meter and flow controller, in-line homogenizer with recirculation line located between the end of the heating section and the holding tube, and back pressure controller to maintain positive pressure differential in the regenerator (required due to the presence of the booster pump) (U.S. Department of Health and Human Services. 2011)

flow turbulent (high rate of mixing), due to the lack of cross-sectional mixing of product within the tube. Laminar flow results in streamline flow in which the center streamlines move at up to twice the average flow rate. Goff and Davidson (1992) tested viscosities and flow characteristics of representative ice cream mixes. Many of the mixes to which they added stabilizers showed non-Newtonian flow (apparent viscosities decreased as shear rates increased). This type of viscous mix can create laminar flow in the holding tube, requiring extension of tube length, or can decrease the rate of pumping through the pasteurizer. Additionally, the mix nearest the wall of the holding tube, being held longer than that mix flowing through the center of the tube, may suffer in quality from the extra long application of heat.

Holding times of pasteurizers usually are determined by measuring the rate of flow of a salt solution from the upstream to the downstream end of the holding tube (U.S. Department of Health and Human Services 2011). The low viscosity of the salt solution permits turbulent flow so that mixing within the tube makes the time of passage of each portion of the solution very close to the average flow rate. Denn (1980) reported that the flow pattern is laminar for Reynolds numbers (N_{Re}) < 2,100. Turbulent flow exists when N_{Re} exceeds 4,000, but the International Dairy Federation recommends that an N_{Re} of >12,000 be maintained in HTST pasteurization tubes.

Viscosities of ice cream mixes are affected by the concentration, type, and degree of hydration of the stabilizer, carbohydrates, colloidal salts, and proteins of the mix; type of heat treatment; whether the mix is homogenized prior to holding; and the rate of shear in the holding tube. Shear rates varied from 50 to 180 s^{-1} in experiments by Goff and Davidson (1992), and viscosities at 80°C ranged from 8.7 mPa.s in an unstabilized mix to 103 mPa.s in a mix containing 0.25% carboxymethyl cellulose. The latter was measured at a low shear rate. Mixes contained 14% fat and 41% total solids. Further details on mix viscosity are available in a later section of this chapter.

Continuous pasteurizers are capable of heating mixes to temperatures well above those required to meet pasteurization standards. Furthermore, it is relatively easy to increase the length of the holding tube or to slow the rate of pumping to increase the holding time. Each of these three methods of increasing the heat treatment increases processing cost. Increasing temperature increases costs for heat energy; increasing holding tube length increases resistance to fluid flow, resulting in increased energy costs for pumping and, possibly, requiring a larger pump; reducing rate of flow reduces plant capacity. Reasons for higher heat treatment include the following: (1) it reduces the amount of stabilizer needed by up to 25%, (2) it improves body and texture because of the denaturation of proteins and the consequent increase in their water-holding capacity, and (3) it increases resistance to oxidation because it exposes additional reducing groups as heat causes proteins to unfold.

An important advantage of continuous flow pasteurizers is the capacity to clean them in place (CIP) by circulating rinse water, detergent, and more rinse water through them (see Chap. 13). Systems designed for CIP can be operated automatically in many installations. Thus, computer or microprocessor control is facilitated. To avoid buildup of films of denatured protein on heating surfaces, mixes should be substantially free of entrained air as they enter the heating section of the pasteurizer.

Fig. 5.9 Complete mix processing plant for small to mid-size operations, 600–5,000 L/h, including blending tanks, HTST pasteurization, homogenization, plate cooling, and aging tanks (courtesy of Technogel, Bergamo, Italy)

Several industrial processing companies (e.g., Technogel, TetraPak Hoyer Promix) offer complete mix-making equipment assemblies, including blending, pasteurization (batch or continuous), homogenization, cooling and aging equipment, preassembled as a stand-alone unit (Fig. 5.9). Sizes range from 150 to 600 L/h (batch) and 600–5,000 L/h (continuous) from Technogel and 300–3,000 L/h from TetraPak. It is also possible to find small-scale mix pasteurization equipment (e.g., Technogel Mixtronic, 60 or 120 L batch size) with high-shear blending capability to aid in homogenizing, although the resulting fat globule size distribution would not be comparable to valve homogenization.

Homogenization

The main purpose of homogenization is to make a stable and uniform suspension of the fat by reducing the size of fat globules to less than about 2 μm. When a mix is properly homogenized, the fat will not rise and form a cream layer nor will the frozen product have a greasy or buttery appearance or mouthfeel. Homogenized fat destabilizes very slowly in the freezer so that emulsifiers are usually required to provide the amount of controlled fat destabilization that results in a frozen product that is dry in appearance and slow to melt (see Chap. 11). Homogenization is required for any mix containing a fat or oil that is not in a relatively stable emulsion. The list of sources of such lipids includes butter, butter oil, anhydrous milk fat, fractionated milk fat, plastic cream, frozen cream, and oils from vegetable sources.

Homogenization is usually accomplished by forcing the mix through a very small orifice under suitable conditions of pressure and temperature, using a positive displacement pump to provide the pressure. Homogenizers are piston-type pumps (Fig. 5.10) that move a constant amount of liquid through the very thin orifice of one or two valves. Therefore, homogenizers can be used as timing pumps in HTST systems. Fat globules, which must be in the liquid state, are greatly distorted as they travel at a velocity of about 12,000 cm/s between the parallel walls of the valve and

Fig. 5.10 Industrial five-piston homogenizer (TetraPak Alex), showing flow through the piston pump. The homogenizing valve assembly sits at the exit of the pump (courtesy of TetraPak Hoyer A/S, Hoejbjerg, DK)

valve seat [Fig. 5.11, although some valves differ in design]. The globules experience a sudden release in pressure and rate of flow as they exit the valve and impact a ring that surrounds it. This drop in pressure momentarily lowers the vapor pressure of the mix to a point at which vapor pockets are formed. The extremely unstable and high shear environment in which the globules find themselves causes them to be disrupted. As bubbles of vapor form and collapse, shear forces known as cavitation are highly active.

Natural fat globules are coated with phospholipids to which are adsorbed other lipids and proteins. As fat globules are reduced in size during homogenization, the amount of phospholipid available to be adsorbed becomes limiting, and added emulsifiers are adsorbed to the fat. When the average diameter of the fat globules is reduced to one-half the original diameter, the number of globules increases by eight times and the total surface area is doubled. Thus, the amount of materials adsorbed increases markedly. Usual homogenization treatment reduces globule diameters about tenfold and increases total surface area about 100 times. Since proteins are adsorbed on the outer surfaces of the newly formed membranes, the amount of hydrated surface area is greatly increased by the treatment. This may account for the increased smoothness of texture associated with homogenization of mixes.

Efficiency of homogenization is reduced when the homogenizing valve is worn, the pump does not deliver fluid at the designed rate (usually because the intake or discharge valve is damaged or worn), temperature of mix is low, or air is present in

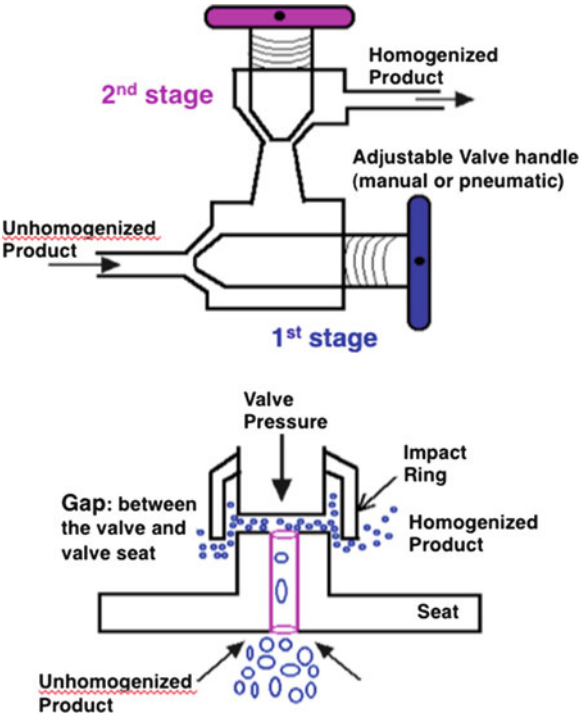

Fig. 5.11 A schematic diagram of the configuration of a two-stage homogenizing valve assembly (*top*) and individual homogenizing valve (*bottom*), which would be located at the end of the pressure-inducing ram of each stage

the mix. Inadequate homogenization can lead to fat churning in the freezer. Evidence of such churning can be seen as greasy appearance of the scraper blades, elbows in pipes and surfaces of extrusion nozzles. Churning is most likely to occur with high fat mixes that are formulated to be extruded in a very stiff and dry form.

To check for adequacy of homogenization, diluted mixes should be examined with light scattering techniques or under an oil immersion objective of a microscope for large globules or excessive clumping (Fig. 5.12; see also Chap. 14 for further details of analyses). An eyepiece micrometer can aid in determining the sizes of the globules. An inexpensive alternative is to place mix in an Erlenmeyer flask, or slender bottle, for several hours then to run tests for fat in the top and bottom portions of the mix. Differences in fat content greater than about 5% of the test of the well-mixed sample indicate that homogenization is not adequate.

Homogenization efficiency increases with increases in temperature up to about 80°C (176 °F). If homogenization precedes pasteurization by several seconds and any part of the mix is composed of raw milk, the minimum temperature for homogenization is 60°C (140 °F). At this temperature, milk lipase is virtually inactivated, ensuring that lipolysis will not take place as the protective membrane is stripped from the fat globules during homogenization. Furthermore, higher temperatures limit clumping of fat globules and reduce the energy needed to run the homogenizer.

Location of the homogenizer in the process line depends on several factors. When the pasteurizer is of the batch type, homogenization follows immediately

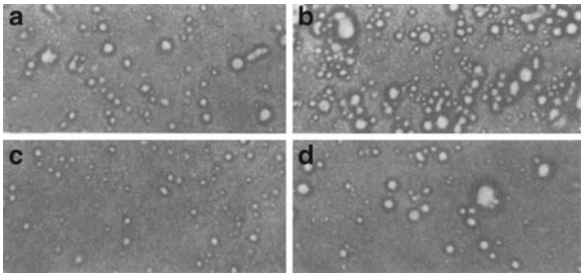

Fig. 5.12 Microscopic appearance (×800) of fat globules in ice cream mix diluted 1:4 with water: (**a**) reference sample homogenized with normal two-stage pressures, 13.8/3.5 MPa on first and second stage, respectively (2,000/500 psig), showing good fat dispersion; (**b**) unhomogenized, showing large and clustered fat globules; (**c**) homogenized at an elevated pressure of 27.6/3.45 MPa (4,000/500 psig), showing very small, well-dispersed globules; (**d**) homogenized at single-stage of 3.45 MPa only (500 psig), showing some size reduction compared to (**b**) but considerable clustering compared to (**a**). Only the reference sample contained emulsifier (0.075%). From Schmidt and Smith 1989

after pasteurization. If the homogenizer is to function as the timing pump in a continuous system, it must be located between the raw side regenerator and the heating section of the pasteurizer (Fig. 5.8). Placed here, it contributes to maintaining the pressure differential in the regenerator, as discussed above. Furthermore, heat produced in the process is recoverable, and less heat is needed to be added in the heating section of the pasteurizer than if the homogenizer were to be placed downstream from the flow diversion valve that is located at the end of the holding tube. Systems in which a second positive displacement pump serves as the timing pump provide greater opportunity for control of volumetric flow rate; however, since the two pumps are highly unlikely to move exactly the same amount of product, a bypass line must be installed around the homogenizer, and the homogenizer must operate at a rate greater than that of the timing pump (Fig. 5.8). The homogenizer is not placed downstream of the flow diversion device, because it must not be allowed to run dry during periods of divert flow.

Undissolved particles passing through the homogenizer in continuous flow lines tend to cause wear on valves. The most difficult of the solid ingredients to dissolve is usually the stabilizer. Placement of the homogenizer as far downstream from the blending tank as possible allows for maximal hydration of such materials. In any case there must be adequate turbulence to keep solids suspended during passage through the processing line. Wear on homogenizer valves should be checked routinely. Increased pressure is not likely to correct problems due to defective valves. Entrainment of air in the mix and leakage of air into the mix on the suction side of the homogenizer must be avoided if efficient homogenization is to be accomplished.

Since several homogenizer valve designs exist and mixes vary in their fat content and other components, pressures necessary to produce adequate dispersion of fat also vary. Commonly accepted pressures for plain mix with 10% milk fat in a two-stage homogenizer are 2,000 psig (13.8 MPa, 136 Atm., 141 kg/cm^2) and 500 psig

Table 5.2 Approximate homogenization pressures for single-stage homogenization, or for the first stage of two-stage homogenization (in which case 3.5 MPa or 500 psig is normally used on the second stage) for mixes of varying fat contents

	Pressure	
Fat (%)	(MPa)	(lb/in^2)
1–8	19.3–20.7	2,800–3,000
8–10	17.2–19.3	2,500–2,800
10–12	15.8–17.2	2,300–2,500
12–14	13.7–15.1	2,000–2,200
14–16	12.4–13.7	1,800–2,000
16–18	10.3–12.4	1,500–1,800

(3.45 MPa, 34 Atm., 35 kg/cm^2) on the first and second stages, respectively. Schmidt and Smith (1989) reported that no emulsifier was needed in a stabilized (0.25%) mix containing 10.2% milk fat that was homogenized at only 500 psig (see discussion of emulsifiers in Chap. 3). In general, as fat content increases to 14–18%, homogenization pressures on the first stage should be reduced to prevent excessive mix viscosity (Table 5.2) while still maintaining sufficient fat structuring.

Chocolate mixes require pressures that are about 500 psig (3.45 mPa) lower than those used for plain mixes containing the same amount of fat. The combination of cocoa fat and nonfat cocoa solids found in chocolate mixes leads to higher mix viscosities, so a reduction in pressure aims to alleviate excess mix viscosity and its consequent increase in back pressure while flowing though heat exchangers. Also, cocoa can contain varying amounts of bean shell that can cause wear on the homogenizer valves. Therefore, an important specification for the cocoa purchaser is a maximal amount of shell.

Under usual conditions, fat globules tend to cluster upon exiting the first homogenizing valve. This is overcome by operating at a low pressure, usually 500 psig, a second valve installed immediately downstream from the first (Fig. 5.11). High fat mixes usually contain reduced amounts of MSNF, therefore reduced protein. This may contribute to excessive clustering of fat globules and, consequently, to excessive mix viscosity. Other factors that promote clustering include the use of non-emulsified fat, low homogenization temperature, the use of only one homogenizing valve, and high mix acidity. Pressure of 500 psig on the second-stage valve is generally satisfactory for cluster breakup regardless of the quantity of fat in the mix.

Minimizing homogenization pressures for higher fat mixes conserves energy and reduces costs of operation. When the practice also reduces requirements for emulsifier, costs can be reduced further.

While it is possible to reduce homogenizing pressures with higher fat contents, the opposite is true for mixes of lower fat contents, when higher pressures are needed to create more fat globules of smaller size. The goal is to spread the lower content of fat out further, allowing it to participate in more fat structuring (see Chap. 11). Current research in high- and ultra-high-pressure homogenization of dairy emulsions and low-fat ice cream mixes has documented the reductions possible in the

emulsion droplet size. Using pressures of 100 MPa (Hayes et al. 2003; Innocente et al. 2008; Biasutti et al. 2010) and up to 300 MPa (Cortes-Munoz et al. 2009), it is possible to reduce emulsion droplet size to about 0.1 to 0.2 μm mean size (compared to 0.8 μm for normal homogenization). The greater number of globules produced have been shown to improve texture and meltdown characteristics in low-fat ice creams (Hayes et al. 2003). However, there are two disadvantages to this approach, one is the higher cost of homogenizer power consumption at higher pressures and the other is the higher level of adsorption of proteins to the smaller fat globules. Thus, to ensure good fat structuring with the limited amount of fat, more emulsifier is needed with higher homogenizing pressure (Hayes et al. 2003).

While not a homogenizing treatment per se, there has also been recent research interest in the application of high hydrostatic pressure to ice cream mixes (Huppertz et al. 2011). Hydrostatic pressure treatment at 200–500 MPa was shown to have little effect on the size of the milk fat globules, but increased the viscosity of the ice cream mix considerably. The viscosity of pressure-treated ice cream mix increased with increasing pressure and treatment time and with increasing fat, milk solids nonfat, and sucrose content of the mix. Transmission electron micrographs showed the presence of a network of casein micellar fragments, arising from pressure-induced disruption of casein micelles, in the pressure-treated mix and ice cream. Ice cream from pressure-treated mix showed a higher resistance to melting than ice cream from untreated mix. The network of micellar fragments was believed to be responsible for the increased viscosity and reduced melting, and was hypothesized to occur as a result of calcium-induced aggregation of caseins on decompression. While hydrostatic pressure treatment of mix may be impractical for ice cream manufacturers, the advantages of this process may give rise to further development of milk protein-based ingredients for ice cream formulations.

Aging

Pasteurization and homogenization change the physical forms of the suspended solids of ice cream mixes. Pasteurization melts all of the fat while homogenization reduces fat globule diameters. New and different fat globule membranes are formed (see Chap. 11). Hydrophilic colloids are hydrated and reduced in size. Cooling to <4°C (<40 °F) subsequent to these processes causes fat to begin to crystallize. However, the mix is not ready to freeze at that point in the process. It is common to age mix for anywhere from 4 to 24 h. Crystallization of the fat in the emulsified state occurs more slowly than when it is in the bulk state (not emulsified). Fat crystallization rate depends on the type of fat and emulsifier used (Adleman and Hartel 2001), but generally requires up to 4 h for complete crystallization (Barfod et al. 1991). Nearly complete lipid crystallization is needed to ensure proper fat destabilization during freezing (see Chap. 11). Further, there is considerable rearrangement of molecules at the fat globule interface. The adsorption of proteins that occurs during homogenization does not lead to the most energetically favorable interface,

particularly in the presence of low molecular weight emulsifiers. At aging temperatures, the emulsifiers displace protein at the fat globule interface (Gelin et al. 1994). As well, some of the hydrocolloid stabilizers require time for full hydration to provide significant increases in viscosity. Sodium carboxymethyl cellulose and guar gum, commonly used stabilizers, hydrate well during processing of most mixes. However, hydration proceeds slowly for the small amount of carageenan that is usually added with these stabilizers to prevent whey separation on long-term storage.

Generally, 4 h is sufficient for these changes to occur. Freezing of improperly aged ("green") mixes leads to ice cream characteristics similar to those found with non-emulsified mixes. Namely, there is less retention of shape and relatively fast meltdown due to less than optimal destabilization of fat during freezing.

Cooling of mixes to 0–2°C increases the rate of crystallization of fat, increases capacities of freezers, and almost completely eliminates the possibility that microorganisms can grow in the mix. Such cold temperatures add several days to the shelf life of mixes sold to other firms for freezing.

Packaging for Sale

Mixes are frequently prepared in a large plant for sale to ice cream retailers who freeze ice cream on the premises where retail sales take place. Depending on the size of operation, mix containers range in capacity from 1/2 to 5 gal (2–20 L). Filling is done on the same equipment used for fluid milk, and the containers are firm-walled plastic, plastic-coated paper, or flexible plastic bags. Each type is distributed in cases or cartons.

UHT processing and aseptic filling of sterilized containers is an important development for mix distributors. The long shelf life, reduction in risk of unexpected spoilage, and almost complete elimination of risk of having pathogens in the product may result in significant savings that offset the higher costs of processing when UHT/AP systems are used.

Flavoring

Most manufacturers process mixes in the plain unflavored form, choosing to add flavoring materials at the freezer. Furthermore, most of these flavorings are purchased in the ready-to-use form from specialists in that field rather than being prepared in the ice cream plant (Chap. 4). Flavoring materials are chosen based on consumer preferences, availability, costs, equipment needed to introduce flavoring into the product, labeling implications (such as the perceived advantage of having "all natural" on the label), stability of flavoring material, and packaging considerations. Chocolate flavorings are usually added to mixes prior to processing. Liquid and pureed flavorings are added to mix in the flavoring tank prior to freezing. Fruits and nuts may be added

to mixes before continuous freezing provided they are finely ground or chopped and are evenly distributed in the mix, although they are generally added after freezing.

In the case of batch freezer operations, the most common practice is to flavor plain mix after it is placed in the freezer, just prior to freezing. For solid ingredients, time of addition in the batch freezer depends on the amount of breakup of the materials that will produce the optimal size and distribution of the flavoring material. For example, the distribution of cookies in cookies-and-cream ice cream will vary from very large chunks to miniature pieces depending on the time and rate of agitation after addition of the cookies to the frozen mix. To control this variable the freezer should be emptied quickly and with minimal agitation once the cookies are broken to the desired size.

Addition of ingredients to pasteurized mix constitutes a Critical Control Point as part of the HACCP plan in ice cream manufacture, because no further lethal process is given the product (see Chap. 13 for further details of product safety systems). Therefore, it is important that all operations at this point be done in a sanitary manner and that ingredients be free of pathogenic microorganisms. The most likely pathogens to be encountered at this point are *Listeria monocytogenes* and salmonellae.

Physical Properties of Mixes

The ice cream mix represents a complex colloidal system. Some of the constituents occur in true solution (sugars, including lactose, and salts), others are colloidally suspended (casein micelles, stabilizers, insoluble sweetener solids, and some of the calcium and magnesium phosphates), and the fat globules are in coarse dispersion. Although the whey proteins are dissolved, they have little effect on the freezing point.

The substances in true solution are small molecules or ions and have a strong affinity for water. The substances in colloidal suspension typically have particles with an opposite electrical charge to that of the solvent, and the mutual attraction stabilizes the suspension. The like electric charges on the particles keep them apart, which helps to maintain the suspension. Occasionally, the substances in suspension may not have sufficient attraction for the solvent and there may not be sufficient viscosity to keep them suspended. Different substances also have differing affinities for water. Some particles of hydrophobic colloids have so little affinity for water that if there is no charge on the particle precipitation occurs. On the other hand, substances with high degrees of affinity for water, the hydrophilic colloids (e.g., stabilizers), may remain suspended even when they have no electrical charge. Substances in coarse dispersion or suspension (e.g., flavoring materials) do not stay uniformly dispersed, but settle or rise depending on their density relative to the suspending medium.

Since ice cream is so complex, many factors have an impact on the physical properties of mix. Mix properties of practical importance include stability, density, acidity, viscosity, interfacial and surface tension, specific heat, and freezing point.

Mix Stability

Mix stability refers to the resistance to separation of the milk proteins in colloidal suspension and the milk fat in emulsion. Instability results in separation of (1) fat globules due to creaming, (2) protein particles as coagulated or precipitated material, or (3) a clear serum or whey from mix or melted ice cream.

Ice cream mix is homogenized to reduce the relatively large fat globules to fine particles with a high degree of dispersion. A normal distribution of fat globules results, with a mean centered around 0.5–1.0 μm and a maximum size of about 2 μm. The fat globules in the homogenized mix are surrounded by an interfacial layer of proteins and emulsifiers. The state of dispersion of milk fat in ice cream depends on the forces that tend to drive the fat globules apart—the emulsifying effects of the homogenizing valve and the mutual repulsion of the globules due to their electric charges. The forces that tend to bring the globules together are the collisions of the globules as they emerge from the valve of the homogenizer, the Brownian movement of the very small globules, the cohesiveness of the adsorbed layers surrounding the globules, the interfacial tension between fat and serum phases, and the concentrating effect of freezing on the proximity of fat globules to each other in the serum.

Fat is less dense than water and an oil-in-water emulsion will normally separate ("cream") as the fat globules rise to the top. According to Stoke's Law, the rate of rise of fat suspended in an aqueous phase is a function of the difference in densities between the fat and water, the size of the droplets, and the viscosity of the continuous phase. The fat droplets in ice cream mix do not cream due to their small size after homogenization (thus preventing collisions and flocculation during creaming, which would enhance the rate), the increased density due to the newly adsorbed surface layer, and the high viscosity in the mix due to the addition of proteins and stabilizers. The emulsion of the mix can be too stable, however, leading to reduced rates of partial coalescence during freezing. Optimum stability is that which allows the mix to pass through the processing stages (especially the plate-type pasteurizer in which plates may be pushed apart by high viscosity mixes) while permitting the whipping and freezing process to destabilize an adequate amount of fat. The displacement of proteins by emulsifiers helps create this optimum in stability by decreasing the interfacial tension of the emulsion.

Protein stability results from the state of the proteins and the appropriate balance in the solution of pH and salts. Excessive heat in pasteurization, for example, may change the conformation of the whey proteins (denaturation), leading to their adsorption to the casein micelle and their eventual precipitation. Likewise, any change in solvent conditions may lead to enhanced protein precipitation. This causes an undesirable increase in mix viscosity, which can negatively affect subsequent operations.

Whey separation from mix or from melted ice cream is another example of mix stability problems. This generally arises from phase separation between milk proteins and polysaccharide stabilizers. All of the stabilizers in common use are

incompatible in solution with the proteins, despite that both are hydrophilic. Hence, they tend to move apart from each other, leading to formation of a clear serum layer in the mix after standing or to the leakage of serum from the ice cream during melting (see Chap. 11 for further discussion of phase separation). Carrageenan is normally added to stabilizer blends to reduce phase separation (see Chap. 3).

Density

The density or specific gravity (density relative to water) of ice cream mix varies with composition. Increased levels of MSNF, sugars, and stabilizers increase density, whereas increased fat decreases mix density (fat has a density of about 0.9 g/mL compared to 1.0 g/mL for pure water). Measurements of specific gravity may be made with a hydrometer and of density by weighing a known volume of mix at a known temperature on a gravimetric balance (see Chap. 14 for analytical techniques). Density can also be calculated based on composition as shown in Chap. 5. The density of ice cream mixes may vary from 1.0544 to 1.1232 g/mL, with an average for a 10% fat mix of approximately 1.1 g/mL (kg/L).

Acidity of Mixes

The normal titratable acidity of mixes varies with the percentage of MSNF contained and may be calculated by multiplying the percentage of MSNF by the factor 0.017. Thus, a mix containing 11% MSNF would have a normal titratable acidity of 0.187%. The normal pH of ice cream mix is about 6.3.[1] The acidity and pH are related to the composition of the mix—an increase in MSNF raises acidity and lowers the pH. The percent titratable acidity and pH values for mixes of various MSNF content are given in Table 5.3.

If fresh milk components of excellent quality are used, the mix can be expected to have a normal acidity. The apparent or natural acidity of ice cream mix is caused by the milk proteins, mineral salts (mostly phosphates and citrates), and dissolved CO_2. Developed acidity is caused by the production of lactic acid by bacterial fermentation of the lactose in dairy products. When the acidity of the mix or ice cream is above normal, developed acidity was probably present in the dairy products used in the mix. A high acidity is undesirable as it contributes to excess mix viscosity, decreased whipping rate, inferior flavor, and a less stable mix. The latter may contribute to "cook on" during processing and pasteurization, because heat and acidity accelerate the denaturation of proteins.

[1] A neutral substance (i.e., neither acidic nor alkaline) would have a value of 7.0, with decreasing values indicating increasing acidity and increasing values indicating alkalinity.

Table 5.3 Approximate titratable acidity[a] and pH values for ice cream mixes containing 7–13% milk solids-not-fat (MSNF)

MSNF (%)	Approximate acidity (%)	Approximate pH
7	0.119	6.40
8	0.136	6.35
9	0.153	6.33
10	0.170	6.32
11	0.187	6.31
12	0.204	6.30
13	0.221	6.28

[a]As lactic acid

Mix Viscosity

Rheology is a branch of physics concerned with the composition and structure of flowing and deformable materials. For liquids, viscosity becomes the most important aspect of rheology, whereas for solids, it is their deformation behavior under force that becomes more critical. Many food systems exhibit behavior part way between liquids and solids, and this is referred to as viscoelasticity. Ice cream mix is primarily a viscous system whereas ice cream is primarily a viscoelastic system. Considerable attention has been given to factors affecting mix viscosity since it has such a large impact on processing and product characteristics.

Viscosity, the resistance of a liquid to flow, is the internal friction that tends to resist the sliding of one element of fluid over another. It is defined as the shear stress (the imposed force per area, N/m^2 or Pa) divided by the rate of shear (the velocity gradient resulting in the liquid as a result of the applied shear stress, in m/s/m, or s^{-1}). The standard unit of viscosity is the milliPascal-second, mPa.s, (which is equivalent to the older unit centiPoise, cP). The viscosity of water at 20°C (68 °F) is 1.005 mPa.s (cP). If the shear stress-shear rate relationship is linear, i.e., if viscosity is constant regardless of applied stress, the liquid is said to be Newtonian with a viscosity given by the ratio of shear stress to shear rate. Examples of Newtonian fluids include water and sugar syrups (e.g., corn syrup). Ice cream mix, however, is not a Newtonian fluid. It is pseudoplastic, where the viscosity decreases as shear rate increases. Thus, to characterize the viscous behavior of an ice cream mix, knowledge of the shear rate dependence is necessary. The term "apparent viscosity," still defined as the ratio of shear stress to shear rate but at a specified shear rate, is often used to describe the viscosity of a pseudoplastic material, e.g., 25 mPa.s at 100 s^{-1}. For a pseudoplastic (shear-thinning) fluid like ice cream mix, apparent viscosity decreases as shear rate increases (it seems thinner at higher shear rates). This is important in mix handling since pump size is strongly influenced by fluid viscosity.

Ice cream mix also exhibits thixotropy, which means that its apparent viscosity decreases with time of applied (and constant) shear stress. This time-dependent

decrease in apparent viscosity with shearing is due to rupture of interactions and associations (weak bonding) among the different components of mix. Thixotropy is common in colloidal-type liquids. Because of the importance of thixotropic behavior on accurate measurement of viscosity, a defined pre-shearing time is required to release these interactions before the apparent viscosity can be measured. The measurement of viscosity is discussed in greater detail in Chap. 14.

A certain level of viscosity is essential for proper whipping and retention of air, and for good body and texture in the ice cream. The viscosity of a mix is affected by:

Composition—viscosity increases with increasing concentration of stabilizer, protein, corn syrup solids, fat and total solids, with the contribution of each decreasing in that order (i.e., stabilizer has more influence on mix viscosity than does fat). Also, heat and salts (such as calcium, sodium, citrates, phosphates) can affect the viscosity due to their effect on casein and whey proteins.

Processing and handling of the mix—elevated pasteurization temperatures, increasing homogenization pressures, and aging for up to about 4 h will each increase mix viscosity.

Temperature—as with all fluids, viscosity is temperature dependent, so decreasing storage temperature will result in increased mix viscosity.

Although much has been written about the causes and effects of differences in viscosity, there has been no final answer to the question of what viscosity is most desirable in ice cream mixes. A high viscosity was believed essential at one time, but for fast freezing (rapid whipping) in modern equipment a lower viscosity seems desirable. In general, as the viscosity increases, the resistance to melting and the smoothness of texture increases, but the rate of whipping decreases. The mix should be properly balanced (in regard to composition, concentration, and quality of ingredients) and then properly processed to produce the desired whipping ability, body, and texture. Under these conditions, a desirable viscosity is assured.

Viscosity values of ice cream mix are useful as indicators of whether there are any factors that may be influencing the mix unduly. Although mix viscosity varies greatly, especially due to stabilizer addition, values between 0.1 and 0.8 Pa.s are normally found at 4°C, after aging (Stanley et al. 1996). Hagiwara and Hartel (1996) reported viscosity values of 0.58–0.69 Pa.s at a shear rate of 115 s^{-1} for ice cream mixes containing 12% milk fat, 11% MSNF, 16.5% sweetener, 0.1% emulsifier, and 0.3% locust bean gum/carrageenan blend. Aime et al. (2001) reported viscosity values ranging from 0.02 to 0.15 Pa.s at 100 s^{-1} and 4°C in low fat mixes containing 0.3% commercial stabilizer blend.

Interfacial Characteristics

The interfacial characteristics between fat globule surfaces, air bubble surfaces, and serum are critical for converting ice cream mix into ice cream. Interfacial tension in ice cream mix refers to the force acting at the interface between fat and

water, which is largely determined by the type and quantity of material adsorbed at the fat interface. Surface tension refers to the force acting at the interface between water and air, which is also determined by the type and quantity of material adsorbed at the air interface. Both parameters are important in ice cream mix, with interfacial tension important to partial coalescence of the fat phase and surface tension important to aeration of the mix during ice cream manufacture. In both cases, adsorption of various molecules to the interface has a significant effect on stability and physical characteristics of importance in ice cream.

The interfacial tension between a liquid oil and pure water is approximately 30 mN/m, whereas the surface tension between pure water and air is approximately 72 mN/m (Walstra 2003). These values are considerably reduced in the presence of certain surface-active components. Adsorption involves substances migrating to the interface, forming a layer or film, and hence reducing the interfacial or surface tension. Good "surfactants" (surface active agents) are amphiphilic, with both hydrophilic and hydrophobic aspects on the same molecule, and sufficient molecular flexibility to rearrange at interfaces. The hydrophilic portion resides in the aqueous phase while the hydrophobic portion resides in the fat or air phase. Examples are proteins and emulsifiers (mono- and diglycerides, polysorbate 80, etc.). Addition of emulsifiers in ice cream mix lowers the interfacial tension significantly. Goff and Jordan (1989) measured the interfacial tension of anhydrous butter oil at 70°C (to ensure complete melting of the fat) in the presence of milk proteins (MSNF) with and without emulsifiers. An 11% MSNF solution without emulsifier reduced interfacial tension to 6.2 mN/m. Upon addition of monoglycerides, interfacial tension decreased slightly (to 5.0 or 5.5 mN/m depending on the saturation of the fatty acid), whereas addition of polysorbate 80 (PS-80) decreased interfacial tension to 2.2 mN/m. Although it is unclear how these values of interfacial tension apply at lower temperatures where a portion of the fat has crystallized, it is believed that a similar decrease in interfacial tension is observed in refrigerated ice cream mix. A similar decrease in surface tension is observed due to the addition of proteins and emulsifiers although very little data on ice cream mix is available. Walstra (2003) states that protein solutions decrease the surface tension of water against air from 72 to about 50 nM/m at 25°C.

Furthermore, substances accumulate at a surface in the order of their abilities to lower the interfacial tension. Thus, emulsifiers displace proteins adsorbed to fat globules. Therefore, interfacial tension, with regard to emulsifier action, is a predictor of protein adsorption/displacement, which, in turn, is primarily responsible for controlling the extent of fat destabilization (see Chap. 11). This is complicated, however, by the ease with which proteins can be displaced: casein micelles are easier to displace than whey proteins, due the nature of their conformation at the interface, surface tension provides an indication of the ease of air incorporation into the mix and the stability of the resulting air bubbles.

To be most enjoyable on eating, most frozen desserts must contain air that has been whipped in as minute bubbles. The rate of incorporation of these bubbles and their individual stabilities determine the overall whipping rate. Mixes with lower surface tension values tend to produce higher overrun and smaller air bubbles. Increasing the surface tension above that of the freshly processed mix made from

fresh ingredients is difficult; however, the surface tension may be readily decreased by the addition of emulsifiers. Mixes with too low surface tension values caused by the addition of emulsifier have shown excessive rates of whipping, fluffy and short body characteristics, and high susceptibility to shrinkage.

The major factors at work during the freezing process that affect whipping rate are (1) effective agitation, (2) the presence of a controlled volume of air, and (3) concomitant freezing of the mix. It is vital that the mix contains surface-active components that will quickly migrate to the surfaces of the formed air cells to stabilize them. This function is performed by proteins, phospholipids, and added emulsifiers. It is also important that fat globules and ice crystals do not mechanically interrupt and weaken the lamellae of the air cells. Therefore, as freezing starts, it is required that fat globules be small and well dispersed. However, to prevent collapse of the foam, especially during storage, and to produce dryness and stiffness, it is vital that fat globules be partially destabilized.

The size, number, and physical condition of fat globules in an ice cream mix determine the rate of whipping and the stability of the whipped product. Small fat globules and limited clumping enhance whipping. Nonfat mixes whip more rapidly than those containing fat, but when frozen, they possess a foam structure that is susceptible to shrinkage. Partial coalescence of the fat globules in ice cream during freezing produces a bridging structure that provides resistance to shrinkage (see Chap. 12). Protein from MSNF is important for whipping. Factors that lead to loss of protein functionality, such as excessive heat and denaturation or poor solvent quality from ethanol addition, for example, may adversely affect the whipping properties of the protein. Added sodium caseinate improves whipping properties and affects air cell and ice crystal distribution to an extent hardly expected of any other commonly used ice cream constituent. However, high levels of caseinate may lead to insufficient fat destabilization, due to its excessive adsorption at the fat interface. Egg yolk solids and buttermilk solids from sweet cream improve whipping ability, presumably due to lecithin existing as a lecithin-protein complex. Emulsifiers also improve whipping ability. Finally, the design and operation of the freezer determine whether the maximum whipping ability of a given mix is obtained.

Freezing Point

The freezing point of ice cream is dependent on the concentration of the soluble constituents and varies with the composition. The freezing temperature can be calculated with considerable accuracy (see Chap. 6) and can be determined in the laboratory with a cryoscope or a vapor pressure osmometer (see Chap. 14).

An average mix containing 12% fat, 11% MSNF, 15% sugar, 0.3% stabilizer, and 61.7% water has a freezing point of approximately −2.5°C (27.5 °F). The initial freezing point of ice cream mix is highly dependent on the sweetener content and MSNF of the mix, specifically the lactose and mineral salts content. With more use of blended MSNF ingredients with higher concentrations of lactose and salts,

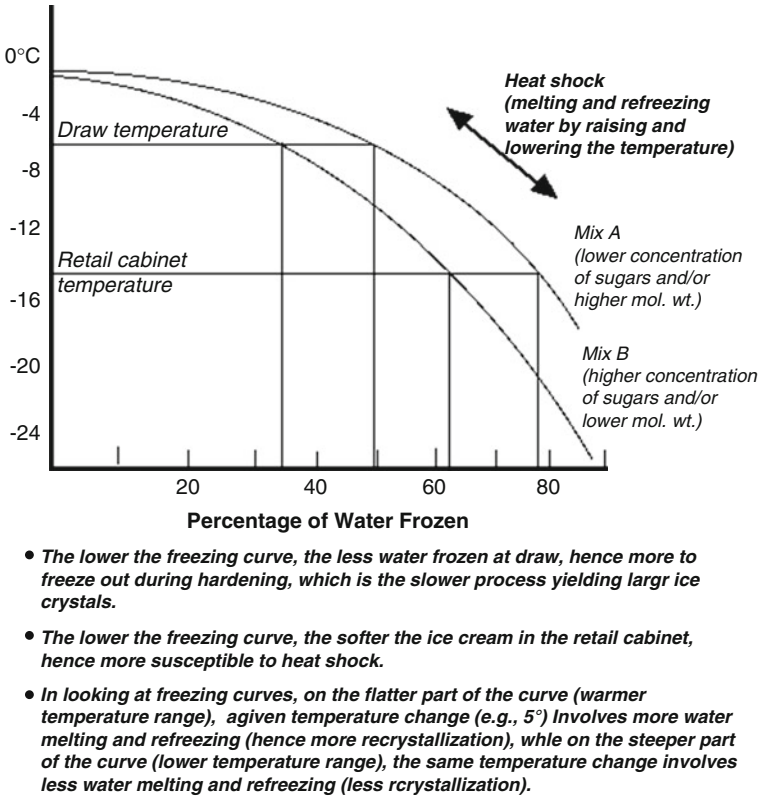

Fig. 5.13 Typical freezing curve for ice cream mixes of different composition showing percentage of water frozen at various temperatures

especially those derived from or making high use of whey powder, the effect on freezing point can be extreme (see Chap. 3). The freezing point of mixes with high sugar and lactose content may range downward to −3°C (26.5 °F) while for mixes with high fat, low lactose, or low sugar content it may range upward to −1.4°C (29.5 °F).

During freezing, a freeze concentration effect is observed. When latent heat is removed from water and ice crystals are formed, a new, lower, freezing point is established for the remaining solution since it has become more concentrated in respect to the soluble constituents. If freezing occurs slowly enough (quasi-equilibrium), the temperature-concentration profile of the unfrozen phase follows the freezing point depression curve. A typical freezing curve for ice cream shows the percentage of water frozen at various temperatures (Fig. 5.13). As seen, small changes in temperature between the initial freezing point of the mix and about −10°C cause significant changes in percentage of water frozen, whereas similar changes in temperature have much less effect at temperatures less than about −20°C. Calculations for generating such a curve are demonstrated in Chap. 6.

Specific Heat

The ability of mix to transfer and absorb heat is important in both pasteurization and freezing of mix. Differences in specific heat capacity (usually denoted C_p in equations, for heat capacity at a constant pressure) arise from differences in composition since each of the ingredients contributes to specific heat according to its own inherent value.

Specific heat capacity can be measured, usually by using calorimetry, or can be calculated based on the composition of the ingredients. These calculations are usually based on specific heat contributions of each ingredient $(C_p)_i$ on a weight basis, W_i. One such equation for calculating specific heat is given below.

$$C_p = \sum_i (C_p)_i W_i$$
$$= (C_p)_{water} W_{water} + (C_p)_{MSNF} W_{MSNF} + (C_p)_{sug/stab} W_{sug/stab} + (C_p)_{fat} W_{fat}$$

Here, the contributions for water, MSNF, sugar/stabilizer, and fat are separated.

The following specific heat values work well with ice cream: fat 2.09 kJ/kg°C, MSNF 1.93 kJ/kg°C, sugar or stabilizer 1.47 kJ/kg°C, and water 4.187 kJ/kg°C. The specific heat of water varies little with temperature, for example, from 4.195 kJ/kg°C at 10°C to 4.224 kJ/kg°C at 0°C. In comparison, the specific heat of MSNF varies from 1.503 kJ/kg°C at 10°C to 1.164 kJ/kg°C at 0°C, or nearly 12 times as much as that of water. It must also be noted that within MSNF, protein and lactose would have differing values, so if the ratio differed in an ingredient from the traditional ratio found in milk, then the specific heat value for MSNF would have to be corrected for true accuracy.

Using the values of specific heat given above, one can calculate the expected specific heat of different ice cream mixes as shown in Table 5.4. As these calculations show, even substantial changes in mix composition do not change specific heat of the mix very much. A typical value of specific heat for ice cream mix often used for calculations is 3.35 kJ/kg°C. Although differences in specific heat among mixes are rather small, accurate values are needed for pasteurizer and freezer calculations.

Ice Cream Defects Originating from Mix Composition

Mix quality is of utmost important to ice cream quality, both from a physical and sensory standpoint. The sensory analysis of ice cream is discussed in detail in Chap. 14. Defects in flavor associated with mix ingredients will be discussed here, whereas those associated with flavoring ingredients were discussed in Chap. 4. Some of the main flavor defects and their causes and remedies are summarized in Table 14.3. Defects in body and texture are described in Chaps. 11 and 12. Some of the main body and texture defects and their causes and remedies are summarized in Table

Table 5.4 Calculated specific heat values for ice cream mixes based on composition

Component	Specific heat (kJ/kg°C)	Concentration (g/g mix)	Calculated product
Standard mix: 10% fat, 38% total solids			
Fat	2.09	0.10	0.209
MSNF	1.93	0.10	0.193
Sugar/Stab	1.47	0.18	0.265
Water	4.187	0.62	2.596
Specific heat			3.26 kJ/kg°C
Reduced fat mix: 4% fat, 35% total solids			
Fat	2.09	0.04	0.084
MSNF	1.93	0.13	0.251
Sugar/stab	1.47	0.18	0.265
Water	4.187	0.65	2.722
Specific heat			3.32 kJ/kg°C
Premium mix: 16% fat, 40% total solids			
Fat	2.09	0.16	0.334
MSNF	1.93	0.10	0.193
Sugar/stab	1.47	0.18	0.265
Water	4.187	0.60	2.512
Specific heat			3.30 kJ/kg°C

14.4. Further details on ice cream mix and ice cream flavor and texture defects can be found in Alvarez (2009).

Defects in flavor of frozen desserts are conveniently placed in the following categories:

1. Dairy products of poor quality—sour (acid), oxidized, stale, lipolyzed, unclean, and excessively cooked.
2. Sweetener(s)—unnatural, excessive, or deficient.
3. Flavoring—unnatural, excessive, or deficient.
4. Blend—unpleasant balance of ingredients.
5. Storage—stale or absorbed flavor.

The acid flavor is imparted by dairy ingredients made from sour milk or cream due to lactic acid bacteria that grow in raw milk that has been inadequately refrigerated and reduce lactose to lactic acid during their growth and metabolism. Souring can occur in milk held a long time in dairy plants, but temperatures above 4°C (40 °F) are necessary, and the contaminating bacteria must be able to produce lactic acid. The common spoilage bacteria in pasteurized liquid dairy products, such as concentrated milk, are proteolytic and lipolytic rather than fermentative. Because bacteria counts must reach into the millions before significant lactic acid is produced in milk, it is highly undesirable that sour products ever reach the dairy plant.

Cooked flavor is the "Flavor of Assurance" in ice cream, and, provided it is mild, the flavor is not objectionable. The rationale for the preceding statement is that heat breaks disulfide bonds (-S-S-) in whey proteins, exposing sulfhydryl (-SH) groups that are considered to contribute significantly to the cooked flavor. If the cooked

flavor has dissipated beyond recognition, there is good reason to believe that the -SH groups have been oxidized back to the original -S-S- linkage. When cooked flavor becomes strong enough to be described as "scalded milk, caramel-like, scorched, or burnt," there is reason to be concerned. The main contributors of such high intensity cooked flavors are dried products, especially high heat types. Of course, the relatively high temperature and long time of pasteurization of ice cream mixes compared with those used for milk mean that cooked flavors are likely to be stronger in ice cream than in milk. Those manufacturers that give extra holding time to their ice cream mixes with the intent of denaturing proteins so that they will hold maximal water run the risk that cooked flavor will be excessive for at least a segment of consumers. The advantages that offset this potential defect must be weighed in the balance when the decision is made to use such a treatment.

Lacks freshness is a mild form of "old ingredient," stale, or lipolyzed flavors. When the term is correctly applied, either a defect has not developed to the point of being positively identifiable in the finished mix, or an ingredient that may have had an identifiable defect has been used in low enough concentration that identification is not possible.

Ice creams that have the old ingredient defect suffer from staleness, oxidation, or fermentation of one or more ingredient. Often this defect is not readily tasted initially but develops as the product melts and is expectorated. The mouth is left with an unclean feeling.

Oxidized flavor in ice cream can be common and is usually associated with the fat component. Often it may have been present in the source of fat before mix manufacture and was undetected. Oxidation of milk is sometimes spontaneous and present immediately after milking, due to intrinsic factors during milk secretion. It can also result from contamination with copper ions. Oxidized flavor sensations vary through a series of intensities and types, including papery, cardboardy, metallic, tallowy, fishy, and painty. The flavor is generally noted as the ice cream starts to melt and it persists after expectoration.

Oxidation of milk fat proceeds by the well-known autoxidation reaction in three stages: initiation, propagation, and termination. In milk, the initiation reactions involve phospholipids present in the fat globule membrane. Free radicals formed from phospholipids are then able to initiate oxidation of unsaturated triglycerides, especially in the presence of copper, iron, other metal ions, and proteins. During propagation, antioxidant compounds such as tocopherols and ascorbic acid are depleted while peroxide derivatives of fatty acids accumulate. Peroxides, which have little flavor, undergo further reactions to form a variety of carbonyls, some of which are potent flavor compounds, especially some ketones and aldehydes (Walstra et al. 2006). Most methods available to monitor lipid oxidation are unsuitable as an early index of oxidized flavor development in milk: measurement of peroxides is not useful because peroxides are unstable intermediates; tests based on colorimetric reaction of thiobarbituric acid with malonaldehyde show some correlation to sensory values but are rather insensitive; and direct measurement of oxygen uptake is only suitable for controlled experimental conditions.

Another milk chemistry problem causing similar flavor, but more like the odor of wet cardboard, is the breakdown of proteins to form aldehydes due to exposure to UV light. This "light-induced" flavor is often present in fluid milk at the retail level but has little chance to occur in frozen desserts, because they or their ingredients are seldom exposed to UV light. An exception is found with ice cream in packages that have transparent film over a window in the lid through which the color and appearance of the product can be seen. Even in these packages ice cream seldom gets exposed to UV rays from fluorescent lights with enough intensity to produce the off flavor.

Lipolytic rancidity is caused by the hydrolysis of the ester bonds that hold fatty acids onto the glycerol moiety of milk fat. The flavor defect is known as lipolyzed or rancid. The natural lipase of milk can catalyze the reaction if the protective fat globule membrane is broken by foaming and churning of raw milk. Prevention measures for this type of fat degradation are usually applied at the farm; however, the pumping and agitation of milk or cream before pasteurization, especially if temperatures are allowed to rise above 4°C, will increase the rate of release of fatty acids. After pasteurization, the source of the catalyst is lipase-producing bacteria. These are usually post-pasteurization contaminants, especially Pseudomonas fluorescens. Frequently these bacteria produce heat-stable lipases that can cause cream and butter to become rancid if these products are held a long time before use. These microbial enzymes are not significantly active at temperatures used to store ice cream, so ice cream is not expected to develop lipolyzed flavor during storage. However, use of rancid butter or cream in a mix is likely to impart the flavor to the finished product. Taste receptors adapt slowly to lipolyzed flavor. The sensation may be similar to the pungency of blue cheese if the short-chain fatty acids, such as butyric acid, predominate, or to soapiness, if the longer chain fatty acids, such as lauric acid, are highly abundant. Rancidity typically leaves an unclean and unpleasant aftertaste. Products containing perceptible free fatty acids are highly undesirable and should not be marketed.

Salty flavor is unusual in ice cream, but some formulas call for salt, making it possible that too much may be added. Additionally, overuse of dried whey or salted butter can cause a product to taste salty. Saltiness is quickly perceived on tasting a sample.

Whey flavor often reminds analysts of graham crackers. It is imparted to ice cream when poor quality whey solids are added or when excess whey is used. The U.S. federal standards permit up to 25% of the MSNF of a formula to be replaced with whey solids, and this may be too much if the quality of this component is not satisfactory. Dry whey stored an excessive time may be oxidized, rancid, or unclean. Whey used in ice cream should be light in color, free flowing, absent of lumps, and clean tasting.

Egg yolk is the characterizing ingredient in French vanilla or custard ice cream. Thus, the egg yolk flavor is desired if it is clean and pleasant. However, overuse of eggs can lead to undesirable flavor notes in some products, and eggs are subject to the development of off flavors similar to those of milk products, especially oxidized and lipolyzed flavors. When used at concentrations up to 1%, egg yolk solids are

compatible with most ice cream flavors. The high emulsifying properties of egg yolk solids (high phospholipid content) recommends them for use in vegetable fat type frozen desserts.

Stabilizer/emulsifier components may impart off flavors, because they are prone to oxidation if not kept in a dry and cool environment. The high concentrations of these ingredients used in products low in fat and in ice cream novelties make these products the most likely ones to exhibit this defect.

Food solids from nondairy sources should be considered potential sources of off flavors. Each laboratory should have a table of expected or potential off flavors for each ingredient, a description of the ingredient, an expected storage life, and optimal storage conditions. Every shipment of ingredients should be examined on receipt and periodically thereafter if they are held more than about 20% of their expected shelf life.

The sweetener system is characterized by defects in both quantity and quality. Lacks sweetness is sensed as flatness or blandness, and, severe deficiency of sweetener can lead to body and texture defects. A high ratio of corn syrup solids to sucrose can cause the syrup flavor.

Too sweet results from overuse of sweetener, especially nonnutritive types. The product is likely to take on a candy-like taste. When ice cream is too sweet, other flavors tend to be subdued. Furthermore, too much nutritive sweetener is often associated with low freezing point and rapid melting.

Syrup flavor is described as malty or caramel-like. Corn syrups and maltodextrins may impart off flavors when they are inadequately refined or have been fermented. Use in high concentrations causes the syrup flavor to dominate other flavors. Syrup tends to mask delicate flavors such as vanilla. Cooked flavor enhances syrup flavor. Together they may engender the sensations of “toasted coconut” or “marshmallow.” High syrup flavor is often associated with gummy or sticky body.

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Chapter 6
Calculation of Ice Cream Mixes

Introduction

Manufacturers of frozen dairy desserts need to know the quantity of ingredients required to make the desired amount of product; the freezing characteristics of their mix; how much ice cream can be made from a volume of mix; and how much it costs to make each package of ice cream. Answers to such questions can be obtained only if it is known how to perform mix calculations. Knowledge of calculations is also helpful in properly balancing a mix to provide uniform quality and to meet legal standards. The method and procedures of making mix calculations are demonstrated by a few typical problems along with some detail to aid in understanding. Standardizing of components in milk or milk products, mix formulation calculations, freezing point depression calculations, and overrun calculations are all shown. Much practice is usually necessary to develop speed and accuracy in making such calculations. This practice can be obtained by using the examples demonstrated here as patterns for setting up and solving similar problems.

Mix Formulation Software

Computer software programs provide a quick and reliable way to calculate mix recipes, and are frequently used to assist in calculations and solve the mathematics. It is possible to have the computer calculate the amounts of each available ingredient to prepare a mix at a minimal cost. With a wide variety of mix formulations and product lines, daily or weekly compositional variation of ingredients (e.g., fat content in cream), availability of several sources of components that can be chosen at any time (e.g., cream or butter; concentrated skim or skim milk powder), very high production capacities, many new ingredients with which to work, and consumer demand for special products with complex formulations, the number of variables that must be considered is not limited to sources of milk fat and MSNF and becomes impossible

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to manage on paper. Hand calculation of formulas becomes more and more cumbersome with each increase in complexity of product line. Limitations imposed by government regulations, availability and costs of raw materials, storage capacity, inventory, shipping schedules, and other such variables argue for computerization of each aspect of control of the processes. Although computerized formulation is a great time saver, the computer merely serves as a tool for the process. Therefore, to produce valid formulas, information fed into the system must be current and accurate.

Many types of computerized systems for ice cream formulations and processing exist. In large, industrial situations, the entire software program has likely been custom designed. In large plant situations, software programs for formulation of ice cream mixes can provide significant savings of time, make optimal use of ingredients, maintain quality by use of limitations set by the firm, and provide these benefits on a least-cost basis. For smaller operations, general mathematical software that can solve algebraic equations, such as Microsoft Excel, can be set up to solve mix recipe calculations. Spreadsheet software can also be used to generate freezing curves, as will be demonstrated later in this chapter. The user must know and understand what is required of the computer in order to program it correctly. Thus, an understanding of the art of problem solving is still required and the techniques and examples shown here will be helpful in setting up the program.

Several programs have been written to supply specific software for mix calculations for ice cream makers, such as the TechWizard® (Owl Software, Columbia, MO, www.owlsoft.com). This program can do formulation calculations with multiple ingredients, least cost formulations, nutrition labels, generate freezing curves, and do several other types of analyses based on mix formulations. In the case of least cost formulation software, the program will specify the cost range within which it is possible to use each ingredient. The quantities of ingredients available and their composition are entered into the computer along with the acceptable compositional range for each element of the finished product. When all ingredients are available in unlimited quantities, the program chooses materials that solve the formula constraints at the lowest cost. The computer will then calculate the amount of each ingredient that will minimize the cost of the mix within the specified compositional and quality restrictions. This low cost does not mean quality is sacrificed provided quality was considered in setting limitations in the program. If not all ingredients are available at all times or some ingredients must be forced into use, the program solves the same formulas based on additional restrictions.

Mathematical Processes most Frequently Used

Even though the discussion on calculations to follow assumes a working knowledge of arithmetic, it may be helpful to review the following mathematical facts that will be used frequently:

1. When a percentage figure is used in division or multiplication, the percent sign is dropped and the decimal point is moved two places to the left. *Thus 94% = 0.94 and 2.25 × 94% indicates that 2.25 is multiplied by 0.94, or 2.25 × 0.94 = 2.11. Likewise 2.25/94% indicates that 2.25 is divided by 0.94, or 2.25/0.94 = 2.39.*
2. When the amount of milk (kg or lb) and the percentage of a constituent (e.g., % fat) are given, the amount of that constituent in the milk is obtained by multiplication: *50 kg milk × 4% milk fat = 50 × 0.04 = 2.0 kg fat supplied by 50 kg milk @ 4%.*
3. When the desired amount of a constituent (e.g., kg or lb of fat) and the percentage of that constituent in milk are known, the amount of milk needed to supply that constituent is obtained by division: *2.0 kg fat required/4% fat in milk = 2.0/0.04 = 50 kg milk required to supply 2 kg fat @ 4%.*
4. When the amount of fat and milk (kg or lb) are known, the percentage of fat is obtained by division: *2.0 kg fat/50 kg milk = 0.04 = 4% fat in milk.*

Standardizing Milk and Cream

For convenience in calculating mixes, it may be desirable to use an easy method for standardizing milk and cream so that stocks are always of the same fat content. Either of the following two methods is satisfactory.

Algebraic Mass Balance

Example Problem 1
If 120 kg of 18% fat cream is required, how much 40% fat cream and 4.2% fat milk must be combined?
Answer:

$$\text{Let} = 40\%\ \text{cream}, Y = 4.2\%\ \text{milk}$$

$$\text{Mass balance}: \text{mass in(both streams)} = \text{mass out(single stream)}$$

$$X + Y = 120\ \text{kg}$$

$$\text{Component balance}: \text{fat in(both streams)} = \text{fat out(single stream)}$$

$$\text{fat in 40\% cream} + \text{fat in milk} = \text{fat in 18\% cream}$$

$$0.4X + 0.042Y = 0.18(120)$$

$$Y = 120 - X \quad \textit{rearranging mass balance}$$
$$0.4X + 0.042(120 - X) = 21.6 \quad \textit{substituting into component balance}$$
$$0.4X - 0.042 = 21.6 - 5.04$$
$$0.358X = 16.56$$
$$X = 46.3 \text{ kg of } 40\% \text{ cream}$$
$$Y = 120 - 46.3 = 73.7 \text{ kg milk}$$

Proof: $\dfrac{(46.3 \text{ kg cream} \times 0.4 \text{ kg fat / kg cream}) + (73.7 \text{ kg milk} \times 0.042 \text{ kg fat / kg milk})}{120 \text{ kg}} = 0.18$

Use of the Pearson Square for Standardizing Cream and Other Milk Products

The Pearson Square is a simple way to easily solve an algebraic two-component mass balance such as the one shown above. To set up a Pearson Square, draw a rectangle and in the center place the percentage of fat desired. At the upper left hand corner place the percent of fat in the cream that is to be reduced (i.e., the high fat stream). In the lower left hand corner put the percentage of fat in the milk that is to be used to standardize the cream (i.e., the low fat stream). Working diagonally across the rectangle, subtract the smaller number from the larger and place the differences at the opposite corners. The number at the upper right-hand corner represents the proportion of cream of the % fat indicated by the number at the upper left-hand corner. The number at the lower right-hand corner indicates the proportion of milk of the % fat indicated by the number in the lower left-hand corner, i.e., the ratios of each to combine to get the desired fat content. By mixing the milk and cream in these proportions, the desired fat content will be obtained.

Example Problem 2
35% fat cream and skim milk (0% fat) are to be mixed to produce 20% cream. The weights to be used are determined as follows:

(% fat in cream) 35		20 (parts cream)
	20	
(% fat in skim milk) 0		15 (parts skim milk)
		35 (total parts)

20 parts of 35% cream mixed with 15 parts of skim milk will produce 35 parts of 20% cream.

Suppose 220 kg of 20% cream are needed. The weight of cream required will be found as follows: $220 \times 20/35 = 125.71$ kg.

The weight of skim milk required will be $220 - 125.71 = 94.29$ kg.

Example Problem 3
Given 367 kg of 38% cream to be reduced by skim milk to an 18% cream, the figures will be:

38		18
	18	
0		20

367 kg × 20/18 = 407.77 kg of skim milk required.

Example Problem 4
Suppose that 110 kg of cream testing 16% fat is required and that 26% cream and 4% milk are available for preparing this cream.

26		12
	16	
4		10
		22

Thus, by mixing 12 parts of 26% cream and 10 parts of 4% milk there will be obtained 22 parts of 16% cream. We require 110 kg of 16% cream. Therefore the weight of 26% cream to use will be 110 × 12/22 = 60 kg and the 4% milk needed will be 110 − 60 = 50 kg.

Mix Formulation Calculations

The general objective of calculating ice cream mixes is to turn the formula, which is based on the desired components, into a recipe, which is based on the actual ingredients to be used to supply the components and the amount of mix desired. The formula is given as percentages of fat, milk solids-not-fat (MSNF), sugar, corn syrup solids (CSS), stabilizers and emulsifiers, and by default water, since 100-Total Solids (the sum of the components) = water (see Chap. 2). The ingredients to supply these components are chosen on the basis of availability, quality, and cost (see Chap. 3). It must be remembered, however, that most ingredients supply more than one component. For example, cream, milk, and condensed whole milk products contain milk fat, MSNF, and water. Skim, condensed skim, and liquid sweeteners also contain water, in addition to the MSNF or sugar they are used to supply. Even dried ingredients usually contain some percent of water.

The first step in a mix calculation is to identify the composition of each ingredient. In some cases the percentage of solids contained in a product is taken as constant (e.g., 3% moisture in skim milk powder) or provided by an ingredient supplier, while in others the composition must be obtained by analysis (e.g., the fat content in milk or cream).

Ice cream mixes can be divided into simple and complex groups. Simple mixes are those for which each ingredient quantity can be readily calculated based on the

fact that it supplies only one component to the mix. For example, fat could be supplied from cream only or butter only for a simple mix. Once the amount of cream required is known, its contribution to MSNF would be readily known and if skim milk powder was the only other source of MSNF, the quantity of it could be readily calculated. Water would be used to balance such a formulation. Simple mixes can be calculated with basic arithmetic. If there is only one source of the component needed for the formula, for example the sugar, it is determined directly by multiplying the percentage needed by the amount needed, e.g., 100 kg of mix @ 10% sugar would require 10 kg sugar.

Complex mixes include at least two constituents that are obtained from two or more ingredients. For example, fat could be supplied by milk, cream, and whole concentrated milk for a complex mix. If there are two or more sources, then an algebraic method may be utilized. The algebraic method involves either simultaneous equations or matrix algebra, and hence rather lengthy calculations and a thorough knowledge of setting up and solving these. Computer programs developed for mix calculations generally solve simultaneous equations based on mass and component balances. For manual calculations, a shortened procedure known as the "Serum Point" method has been derived. This method has solved the algebraic simultaneous equations in a general way so that only the equations need to be known and not resolved each time. The Serum Point method is basically identical to the algebraic method; however, the use of formulas simplifies the procedure. In the Serum Point method, a constant content of MSNF is assumed in the aqueous (serum), nonfat portion of all milk ingredients, e.g., 9%. Thus, the MSNF content of milk or cream is calculated as (100 − percent fat) × 0.09. The 9% MSNF can be substituted by an actual composition, e.g., 8.8%, if known and more accuracy is desired. This section will illustrate solutions of complex mix calculation using algebraic techniques and the Serum Point method.

Mix Decisions

The following are key decisions an ice cream manufacturer must make before calculating an ice cream mix:

- *Composition of the mix formulation*: the proportionate amount of each constituent must be specified, e.g., the % fat.
- *Size of batch*: batch size is usually constant within a factory. Calculation on a 100 kg (or lb) basis permits easy conversion to larger batches.
- *Choice of ingredients*: decisions should be based on qualities, functions, costs, and availabilities.
- *Composition of ingredients*: although tables offer general information about composition, best results are obtained when calculations are based on analyses of the ingredients used.
- *Classification of the mix*: having the above information permits classification of the mix as simple or complex, and calculations can be made accordingly.

Simple Mixes

Simple mixes require minimal calculations and include such mixes as one made of cream, concentrated skim milk or skim milk powder, sugar, stabilizer/emulsifier, and balanced with water.

Example Problem 5
Desired:100 kg mix testing 14% fat, 10% MSNF, 15% sucrose, 0.4% stabilizer/emulsifier (39.4% Total Solids, T.S.).

Ingredients on hand: Cream @ 40% fat, skim milk powder @ 97% MSNF, water, sucrose, stabilizer/emulsifier.

Solution:
1. Find the amount of cream required to supply 14 kg of fat/100 kg mix,

$$14 \text{ kg fat} \times \frac{100 \text{ kg cream}}{40 \text{ kg fat}} = 35 \text{ kg cream}$$

2. Find the amount of skim milk powder needed to supply a *total* of 10 kg of MSNF/100 kg mix.

$$\text{The cream contributes } 35 \text{ kg} \times \frac{5.4 \text{ kg MSNF}^{1}}{100 \text{ kg cream}} = 1.89 \text{ kg MSNF}$$

Skim milk powder must contribute 10 kg MSNF needed - 1.89 kg from cream
= 8.11 kg MSNF

$$8.11 \text{ kg MSNF} \times \frac{100 \text{ kg skim milk powder}}{97 \text{ kg MSNF}} = 8.36 \text{ kg skim milk powder}$$

[1] Milk or cream can be considered as a mixture of fat and skim milk. In this problem, the MSNF content of the cream was calculated as follows: cream at 40% fat, remaining 60 kg skim milk at 9% MSNF, therefore MSNF in cream = 60 kg × 9% = 5.4 kg. In the manufacture of butter, fat is churned from cream. If no washing of the butter is performed after churning and no salt is added, the non-fat portion is also skim milk (e.g., 20% skim (at 9% solids) in 80% fat butter). However, the skim milk content could be substituted wholly or in part with wash water, which would reduce the MSNF level to anywhere between 1.8% and 0%. Therefore, butter either needs to be analyzed for solids or an assumption of no MSNF should be made to assure that at least the required MSNF is supplied from other ingredients.

3. Sucrose required will be 15.0 kg/100 kg mix.
4. Stabilizer/emulsifier required will be 0.4 kg/100 kg mix.
5. The amount of water required will be equal to 100 minus the sum of the weights of the other ingredients, thus,

$$100-(35+8.36+15+0.4)=41.24 \text{ kg water}$$

Proof: It is very important to always check your calculations to ensure you have the right answer. This can be done with a proof table, such as the one below. In this order list all the ingredients you have just calculated, calculate the components contributed by each ingredient based on its % composition, and sum the columns to ensure you have the right quantity of mix and the right percentage of fat, MSNF, and total solids. The total mass of each component divided by the total mass of mix should yield the desired percentage.

Proof Table

Ingredients	Weight (kg)	Fat (kg)	MSNF (kg)	T.S. (kg)
Cream	35	14	1.89	15.89
Skim milk powder	8.36	–	8.11	8.11
Sucrose	15.0	–	–	15.0
Stabilizer/emulsifier	0.4	–	–	0.4
Water	41.24	–	–	–
Total	100.0	14	10.0	39.40[a]

[a]Note: The Total Solids (T.S.) desired is the sum of the components: 14% fat, 10% MSNF, 15% sucrose, 0.4% stabilizer/emulsifier = 39.4% T.S

If mix size is other than 100 kg (or lb), it is suggested to nevertheless do the calculations on the basis of 100 and then scale up the mix by multiplying by the appropriate factor. For example, if 3,500 kg of the above mix is to be made, then the weights of ingredients could simply be multiplied by 35.

Complex Mixes

Complex mixes contain more than one source of at least two components, hence require the use of an algebraic method or the Serum Point method to solve. Both methods are demonstrated and utilized in this section.

Example Problem 6
Mix made from cream, skim milk, and skim milk powder (*three sources of MSNF, three sources of water*): solution shown by both the Algebraic and Serum Point Methods.

Desired: 1,200 kg mix @ 13% fat, 11% MSNF, 12% sucrose, 3% CSS, 0.5% stabilizer, 0.15% emulsifier (39.65% T.S.).
On hand: Cream @ 40% fat, skim milk, skim milk powder @ 97% MSNF, sugar, CSS, stabilizer, emulsifier.

(Note: *only one source of fat, sugar, stabilizer, and emulsifier, but three sources of MSNF*)

Solution of problem 6 via an algebraic method:
(solve on the basis of 100 kg)

$$\text{Cream}: 100\text{ kg mix} \times \frac{13\text{ kg fat}}{100\text{ kg mix}} \times \frac{100\text{ kg cream}}{40\text{ kg fat}} = 32.5\text{ kg cream}$$

$$\text{Sucrose}: 100\text{ kg mix} \times \frac{12\text{ kg sucrose}}{100\text{ kg mix}} = 12\text{ kg sucrose}$$

$$\text{CSS}: 100\text{ kg mix} \times \frac{3\text{ kg CSS}}{100\text{ kg mix}} = 3\text{ kg sucrose}$$

$$\text{Stabilizer}: 100\text{ kg mix} \times \frac{0.5\text{ kg stabilizer}}{100\text{ kg mix}} = 0.5\text{ kg stabilizer}$$

$$\text{Emulsifier}: 100\text{ kg mix} \times \frac{0.15\text{ kg emulsifier}}{100\text{ kg mix}} = 0.15\text{ kg emulsifier}$$

Skim milk and skim milk powder: two sources of the MSNF and water

Now, let X = skim milk powder, Y = skim milk

Mass balance: (All the components add up to 100 kg, so skim milk powder + skim milk = 100—mass of other ingredients)

$$X + Y = 100 - (32.5 + 12 + 3 + 0.5 + 0.15) = 51.85$$

MSNF balance: (Equal to 11% of the mix and coming from the skim milk, skim milk powder, and cream, so the portion from the skim milk powder and skim milk = 11 kg—the contribution from the cream). The MSNF portion of the skim milk and cream are taken as 9% of the nonfat portion, i.e., 9% in the case of the skim milk and $(100-40) \times 0.09 = 5.4\%$ in the case of the cream.

$$0.97X + 0.09Y = 0.11(100) - (0.054 \times 32.5)$$

Once the appropriate equations have been written, they need to be solved algebraically.

$X + Y = 51.85$ so, $Y = 51.85 - X$ *from the mass balance*

$0.97X + 0.09Y = 9.245$ *from the MSNF balance*

$0.97X + 0.09(51.85 - X) = 9.245$ *substituting*

$0.97X - 0.09X + 4.67 = 9.245$

$0.88X = 4.58$

$X = 5.20$ kg skim powder

$Y = 51.85 - 5.20 = 46.65$ kg skim milk

The above shows the simultaneous solution of two equations with two unknowns. Likewise, if there were three unknowns, e.g., fat, MSNF, and the total weight, then three equations could be written, one for each of fat, MSNF, and weight.

However, the above problem could be solved also with the Serum Point method, and the solution of the above example by that method, along with the derivation of the equations, follows. The Serum Point calculation assumes constant content of MSNF in skim milk and the skim portion of all dairy ingredients, e.g., 9%. It then solves the calculation beginning with the most concentrated source of MSNF. It is advisable to solve a problem with the Serum Point method on the basis of 100 kg, and then to scale up to the desired mix quantity by multiplying by the appropriate factor, e.g., solution for each component for 100 kg × 12 = solution for 1,200 kg.

Solution of problem 6 via the Serum Point method:

1. The amount of skim milk powder needed is found by the following formula:

$$\frac{\text{MSNF needed} - (\text{serum of mix} \times 0.09)}{\%\ \text{MSNF in powder} - 9} \times 100 = \text{kg skim milk powder}$$

(The derivation of the above equation is shown at the end of the problem.)

The serum of the mix is found by summing the desired percentages of fat, sucrose, stabilizer, and emulsifier (i.e., the weights of *all* of the ingredients other than serum) and subtracting from 100 [i.e., "serum" = MSNF (or "serum solids") + water]. In the present problem then,

$$100 - (13 + 12 + 3 + 0.5 + 0.15) = 71.35 \text{ kg serum.}$$

Substituting, we have:

$$\frac{11 - (71.35 \times 0.09)}{97 - 9} \times 100 = \frac{4.58}{88} \times 100 = 5.20 \text{ kg skim powder}$$

2. The weight of cream (since there is only one source of fat) will be

$$13\ \text{kg} \times \frac{100\ \text{kg cream}}{40\ \text{kg fat}} = 32.5\ \text{kg cream}$$

3. The sucrose will be 12 kg/100 kg mix.
4. The CSS will be 3 kg/100 kg mix.
5. The stabilizer will be 0.5 kg/100 kg mix.
6. The emulsifier will be 0.15 kg/100 kg mix.
7. The weight of mix supplied so far is,

Cream	32.50 kg
Nonfat dry milk	5.20 kg
Sucrose	12.00 kg
CSS	3.00 kg
Stabilizer	0.50 kg
Emulsifier	0.15 kg
	53.35 kg

The skim milk needed therefore is 100 − 53.35 = 46.65 kg.

It is always important to check your solutions to ensure that they give the desired result. Such a proof is shown below, where the quantities of each ingredient and the quantities of each component in each ingredient are laid out in a table and summed. The total mass of each component divided by the total mass of mix should yield the desired percentage.

Proof Table

Ingredients	Weight (kg)	Fat (kg)	MSNF (kg)	T.S. (kg)
Cream	32.50	13.0	1.75	14.75
Skim milk	46.65	–	4.20	4.20
Skim milk powder	5.20	–	5.05	5.05
Sucrose	12.00	–	–	12.00
CSS	3.00	–	–	3.00
Stabilizer	0.50	–	–	0.50
Emulsifier	0.15	–	–	0.15
Total	100.0	13.0	11.0	39.65

Now the ingredients can be multiplied by 12 to scale up to 1,200 kg. While the calculations could have been solved initially for 1,200 kg, solving on the basis of 100 kg generally simplifies the mathematics.

Cream	32.50 kg/100 × 1,200 kg = 390 kg
Skim milk	46.65 kg/100 × 1,200 kg = 560 kg
Skim milk powder	5.20 kg/100 × 1,200 kg = 62.4 kg
Sucrose	12.00 kg/100 × 1,200 kg = 144 kg
CSS	3.00 kg/100 × 1,200 kg = 36 kg
Stabilizer	0.50 kg/100 × 1,200 kg = 6 kg
Emulsifier	0.15 kg/100 × 1,200 kg = 1.8 kg

The sum of which is 1,200 kg.

Derivation of the Serum Point equations:
Example problem 6 is resolved again using simultaneous equations in a general way to show the source of the serum point equations.
On hand:

Cream @ 40% fat (supplies fat, water, and MSNF, therefore can be thought of as a mixture of fat and skim milk)
Skim milk @ 9% MSNF (supplies water and MSNF)
Skim milk powder @ 97% MSNF (supplies water and MSNF)
Sucrose
CSS
Stabilizer
Emulsifier

Solution:
There is only one source of fat, sucrose, CSS, stabilizer, and emulsifier.

$$\text{kg fat} = 100\text{ kg mix} \times \frac{13\text{ kg fat}}{100\text{ kg mix}} = 13\text{ kg fat(This assumption is explained below).}$$

$$\text{kg sucrose} = 100\text{ kg mix} \times \frac{12\text{ kg sucrose}}{100\text{ kg mix}} = 12\text{ kg sucrose}$$

$$\text{kg CSS} = 100\text{ kg mix} \times \frac{3\text{ kg CSS}}{100\text{ kg mix}} = 3\text{ kg CSS}$$

$$\text{kg stabilizer} = 100\text{ kg mix} \times \frac{0.5\text{ kg stab.}}{100\text{ kg mix}} 0.5\text{ kg stabilizer}$$

$$\text{kg emulsifier} = 100\text{ kg mix} \times \frac{0.15\text{ kg emul.}}{100\text{ kg mix}} = 0.15\text{ kg emulsifier}$$

There are two sources of MSNF.

Let X = skim milk powder (kg)
Let Y = skim milk (kg) + skim milk in cream (kg)

$$\text{Mass balance :} \qquad X+Y=\text{Total mix}-\text{components already}$$
$$X+Y=100-(13+12+3+0.5+0.15)$$
$$(\textit{the}''\textit{Serum of the Mix}'')$$

$$X+Y=71.35$$
$$(\text{so},Y=71.35-X)$$

$$\text{MSNF balance :} \qquad \underset{\substack{\textit{Serum solids}\\ \textit{fraction}\\ \textit{in powder}}}{0.97X} + \underset{\substack{\textit{Serum solids}\\ \textit{fraction}\\ \textit{in skim}}}{0.09Y} = \underset{\substack{\textit{Serum solids}\\ \textit{fraction}\\ \textit{in mix}}}{(0.11\times 100)}$$

$$0.97X+0.09(71.35-X)=11$$
$$0.97X+(0.09\times 71.35)-0.09X=11$$
$$0.97X-0.09X=11-(0.09\times 71.35)$$
$$X=\frac{11-(0.09\times 71.35)}{0.97-0.09}$$

Which is equal to:

$$\text{kg skim milk powder} = \frac{\text{MSNF needed - (0.09} \times \text{serum of mix)}}{\text{\% MSNF in powder - 9}} \times 100$$

(This is the serum point equation!)

$$X=\frac{4.58}{0.88}=5.20 \text{ kg powder}$$

$$\text{kg cream} = 13 \text{ kg fat} \times \frac{100 \text{ kg cream}}{40 \text{ kg fat}} = 32.5 \text{ kg cream}$$
$$\text{kg skim} \quad = 100-32.5-15-0.5-0.15-5.2=46.65 \text{ kg}$$

Calculating mixes with the Serum Point method:

When solving mix formulation calculations using the Serum Point method, you always solve for the most concentrated source of MSNF first. To calculate the amount of the most concentrated source of MSNF needed, the formula is:

$$\text{Amount of conc. milk} = \frac{(\text{MSNF needed})-(\text{serum of mix}\times 0.09^{\text{a}})}{(\text{MSNF / kg conc. milk})-(\text{serum / kg conc. milk}\times 0.09)}$$

[a] The figure 0.09 represents the % MSNF of skim milk, in this case 9%. However, if skim milk tests 8.6% MSNF (or other %), use the appropriate figure.

If there is any fat or sugar in the concentrated milk[b], it/they must be calculated:

$$\text{Fat} = (\text{amount of conc. milk}) \times (\%\ \text{fat})$$
$$\text{Sugar} = (\text{amount of conc. milk}) \times (\%\ \text{sugar})$$

The serum of the mix is found by adding the desired percentages of fat, sugars, stabilizer, emulsifier, and others (i.e., the weights of *all* of the other ingredients) together and subtracting from 100 [i.e., "serum" = MSNF (or "serum solids") + water].

Calculate the amount of milk and cream needed by subtracting the total of all other ingredients from the total amount of the mix:

$$\text{Milk and cream} = (\text{total amount of mix}) - (\text{total amounts of other ingredients})$$

The amount of cream needed is then calculated as follows:

$$\text{Cream(kg)} = \frac{(\text{fat needed}) - [(\text{milk and cream needed}) \times (\%\ \text{fat in milk})]}{(\%\ \text{fat in cream}) - (\%\ \text{fat in milk})} \times 100$$

Note: this equation for fat is derived from a generalized fat balance, in much the same way that the MSNF equation was derived above.

Example Problem 7

Mix containing cream, milk, and skim milk powder (three sources of MSNF, three sources of water, and two sources of fat); solved by both the Algebraic and Serum Point Methods.

Desired: 100 kg mix containing 14% fat, 9.5% MSNF, 15% sucrose, 0.4% stabilizer, 0.5% frozen egg yolk solids (39.4% T.S.).

On hand: Cream 30% fat, milk 3.5% fat, skim milk powder @ 97% MSNF, sucrose, stabilizer, and egg yolk (50% solids).

The solution to this problem will be shown by the simultaneous solution of three equations, since there are three sources of MSNF, three sources of water, and two sources of fat, and by the Serum Point method. Both produce the same results. Follow whichever method you prefer. Computer programs exist that solve simultaneous equations; writing the equations, however, requires an understanding of the objectives of the problem.

[b] The general term *concentrated milk* as used here refers to plain concentrated milk, which is often called condensed milk in the industry, to sweetened condensed milk and to dried milk. Additionally, usage of the term in these illustrations is meant to apply to all concentrations of fat.

Solution of problem 7 via the algebraic method:

$$\text{Sucrose}: 100 \text{ kg mix} \times \frac{15 \text{ kg sucros}}{100 \text{ kg mix}} = 15 \text{ kg sucrose}$$

$$\text{Stabilizer}: 100 \text{ kg mix} \times \frac{0.4 \text{ kg stabilizer}}{100 \text{ kg mix}} = 0.4 \text{ kg stabilizer}$$

$$\text{Egg yolk}: 100 \text{ kg mix} \times \frac{0.5 \text{ kg egg yolk solids}}{100 \text{ kg mix}} \times \frac{1.0 \text{ kg egg yolk}}{0.5 \text{ kg egg yolk solids}} = 1 \text{ kg egg yolk}$$

Now, let X = skim powder, Y = milk, Z = cream.

Mass balance: All the components add up to 100 kg, so the sum of the three unknowns = 100—the sum of the known mass of the other components.

$$X + Y + Z = 100 - (15 + 0.4 + 1) = 83.6$$

MSNF balance: Equals 9.5% of the mix and comes from the milk, skim milk powder, and cream. Assume 9% in the skim portion of the milk and cream so that the MSNF of the milk = $0.09 \times (100 - 3.5)$ and of the cream = $0.09 \times (100 - 30)$

$$0.97X + 0.08685Y + 0.063Z = 0.095(100)$$

Fat balance: Equal to 18% of the mix and coming from the milk and cream

$$0.035Y + 0.3Z = 0.14(100)$$

These equations could now be solved simultaneously or with matrix algebra or with mathematical software to produce the final outcome:

X = 3.7 kg skim milk powder
Y = 37.7 kg milk
Z = 42.3 kg cream

Solution of problem 7 via the Serum Point method:

1. Determine the amount of skim milk powder required by using the Serum Point equation above:

$$\frac{\text{MSNF needed} - (\text{serum of mix} \times 0.09)}{\%\ \text{MSNF in skim milk powder} - 9} \times 100 = \text{skim powder}$$

$$\text{Serum of mix} = 100 - (14 + 15 + 0.4 + 1.0) = 69.6.$$

Substituting we have,

$$\frac{9.5-(69.6\times 0.09)}{97-9}\times 100=\frac{3.236\times 100}{88}=3.68\text{ kg skim milk powder}$$

2. The amount of sucrose required is 15.0 kg.
3. The amount of stabilizer required is 0.4 kg.
4. The amount of egg required is 1.0 kg.
5. Determine the amount of milk and cream needed.
   Materials supplied so far are 3.68 kg skim milk powder, 10 kg sucrose, 5 kg CSS, 0.4 kg stabilizer, and 1 kg egg yolk: a total of 20.08 kg. 100 – 20.08 = 79.92 kg milk and cream needed.
6. Determine the amount of cream by following formula:

$$\frac{\text{kg fat needed}-[\text{kg cream and milk needed}\times(\%\text{ fat in milk}/100)]}{\%\text{ fat in cream}-\%\text{ fat in milk}}\times 100$$

Substituting we have,

$$\frac{14-\left[79.92\times\left(\frac{3.5}{100}\right)\right]}{30-3.5}\times 100=\frac{11.20}{26.5}\times 100=42.26\text{ kg cream.}$$

7. The amount of milk needed = 79.92 – 42.26 = 37.66 kg of milk.

Proof Table

Ingredients	Weight (kg)	Fat (kg)	MSNF (kg)	T.S. (kg)
Cream	42.26	12.68	2.66	15.34
Milk	37.66	1.32	3.27	4.59
Skim milk powder	3.68	–	3.57	3.57
Sucrose	10.00	–	–	10.00
CSS	5.00	–	–	5.00
Stabilizer	0.40	–	–	0.40
Egg yolk	1.00	–	–	0.50
Total	100.00	14.00	9.50	39.40

Example Problem 8

Mix containing cream, milk, skim milk powder, and whey solids to supply 25% of the MSNF (four sources of MSNF, three sources of water, and two sources of fat); solved by the Serum Point Method although it could also be solved by the algebraic method above.

Desired: 100 kg mix containing 10% fat, 10% MSNF (of which 25% is from whey solids), 12% sucrose, 4% CSS, 0.4% stabilizer/emulsifier blend (36.4% T.S.).

Hence, we can calculate this as 7.5% MSNF and 2.5% whey solids, along with the other components.

On hand: Cream 40% fat, milk 3.9% fat, skim milk powder @ 97% MSNF, whey powder @ 97% solids, sucrose, CSS, stabilizer/emulsifier blend. Note: assume 9% MSNF in the skim portion of the milk and cream, as above.

Solution of problem 8 via the Serum Point method:

1. Determine the amount of skim milk powder required by using the Serum Point equation above:

$$\frac{\text{MSNF needed} - (\text{serum of mix} \times 0.09)}{\%\ \text{MSNF in skim milk powder} - 9} \times 100 = \text{skim powder}$$

$$\text{Serum of mix} = 100 - (10 + 2.5 + 12 + 4 + 0.4) = 71.1.$$

Substituting we have,

$$\frac{7.5 - (71.1 \times 0.09)}{97 - 9} \times 100 = \frac{1.10}{88} \times 100 = 1.25 \text{ kg skim milk powder}$$

2. The amount of whey powder required is 25% whey solids of 10 kg MSNF = 2.5 kg/97% = 2.58 kg.
3. The amount of sucrose required is 12.0 kg.
4. The amount of CSS required is 4.0 kg.
5. The amount of stabilizer/emulsifier blend required is 0.4 kg.
6. Determine the amount of milk and cream needed.
   Materials supplied so far are 1.25 kg skim milk powder, 2.58 kg whey solids, 12 kg sucrose, 4 kg CSS, and 0.4 kg stabilizer/emulsifier: a total of 20.23 kg. 100 − 20.23 = 79.77 kg milk and cream needed.
7. Determine the amount of cream by following formula:

$$\frac{\text{kg fat needed} - [\text{kg cream and milk needed} \times (\%\ \text{fat in milk} / 100)]}{\%\ \text{fat in cream} - \%\ \text{fat in milk}} \times 100$$

Substituting we have,

$$\frac{10 - [79.77 \times (3.9 / 100)]}{40 - 3.9} \times 100 = \frac{6.89}{36.1} \times 100 = 19.09 \text{ kg cream.}$$

8. The amount of milk needed = 79.77 − 19.09 = 60.68 kg of milk.

Proof Table

Ingredients	Weight (kg)	Fat (kg)	MSNF (kg)	T.S. (kg)
Cream	19.09	7.64	1.04	8.68
Milk	60.68	2.36	5.25	7.61
Skim milk powder	1.25	–	1.21	1.21
Whey powder	2.58	–	2.50	2.50
Sucrose	12.00	–	–	12.00
CSS	4.00	–	–	4.00
Stabilizer/emulsifier	0.40	–	–	0.40
Total	100.00	10.00	10.00	36.40

Example Problem 9
Mix containing sweetened condensed milk, which is principally used to supply MSNF but also provides sugar to the mix that needs to be accounted for.

Desired: 100 kg mix testing 14% fat, 10% MSNF, 15% sucrose, 0.5% stabilizer/emulsifier (39.5% Total Solids).

On hand: Cream 32% fat, milk 3.5% fat, sweetened condensed skim milk @ 28% MSNF and 40% sugar, sucrose, and stabilizer/emulsifier.

Solution of problem 9 via the Serum Point method:

1. Find the amount of sweetened condensed skim milk required by the following formula:

$$\frac{\text{MSNF needed} - (\text{serum of mix} \times 0.09)}{\%\ \text{MSNF in cond.} - (\text{serum of cond.} \times 0.09)} \times 100 = \text{sweet condensed skim milk(kg)}$$

Note: Serum of condensed skim milk is calculated the same as serum of mix, i.e., 100 – (fat + sugar + stabilizer/emulsifier)
Substituting we have:

$$\frac{10 - (70.5 \times 0.09)}{28 - (60 \times 0.09)} \times 100 = 16.17 \text{ kg sweet condensed skim milk}$$

2. Find the amount of sucrose needed:

$$16.17 \times 0.40 = 6.47 \text{ kg of sucrose in the condensed milk.}$$
$$15 - 6.47 = 8.53 \text{ kg of sucrose still needed.}$$

Note: if sweetened condensed skim milk is being used and the quantity required to provide all the MSNF, as determined by the serum point method, contains too much sugar for the formula, then the amount of sweetened condensed skim milk would need to be reduced to just that sufficient to supply all the sugar. The

remainder of the MSNF would have to be provided by an additional source, such as skim milk powder.
3. The amount of stabilizer/emulsifier required is 0.5 kg.
4. Find weight of milk and cream needed.
   Material so far supplied is, 16.17 kg condensed milk, 8.53 kg sugar and 0.5 kg stabilizer, a total of 25.2 kg.

$$100 - 25.2 = 74.8 \text{ kg milk and cream required.}$$

5. Find the amount of cream by the following formula:

$$\frac{\text{Fat needed} - [\text{kg milk and cream required} \times (\%\text{ fat in milk} / 100)]}{\%\text{ fat in cream} - \%\text{ fat in milk}} \times 100 = \text{kg cream}$$

Substituting we have:

$$\frac{14 - (74.8 \times 0.035)}{32 - 3.5} \times 100 = 39.93$$

6. Find milk required:

$$74.8 - 39.93 = 34.87 \text{ kg milk.}$$

Proof Table

Ingredients	Weight (kg)	Fat (kg)	MSNF (kg)	Sugar (kg)	T.S. (kg)
Cream	39.93	12.78	2.44	–	15.22
Milk	34.87	1.22	3.03	–	4.25
Sweetened condensed milk	16.17	–	4.53	6.47	11.00
Sucrose	8.53	–	–	8.53	8.53
Stabilizer/emulsifier	0.50	–	–	–	0.50
Total	100.00	14.00	10.00	15.00	39.50

Example Problem 10
Mix containing sweetened condensed whole milk, providing MSNF, fat, and sugar.

Desired: 100 kg mix testing 14% fat, 10% MSNF, 15% sucrose, 0.5% stabilizer/emulsifier.

On hand: Cream 30% fat, milk 4% fat, sweetened condensed milk 8% fat, 20% MSNF, 42% sugar, stabilizer/emulsifier, and sucrose.

Solution of problem 10 via the Serum Point method:

1. Find the amount of sweetened condensed milk by formula:

$$\frac{\text{MSNF needed} - (\text{serum of mix} \times 0.09)}{\%\ \text{MSNF in condensed} - (\%\ \text{serum in condensed} \times 0.09)} \times 100 = \text{kg condensed milk}$$

Substituting we have:

$$\frac{10 - (70.5 \times 0.09)}{20 - (50 \times 0.09)} \times 100 = 23.58 \text{ kg sweetened condensed milk}$$

2. Stabilizer/emulsifier required will be 0.5 kg.
3. Find the amount of sucrose needed.

$$23.58 \times 0.42 = 9.90 \text{ kg sucrose in condensed milk.}$$
$$15 - 9.90 = 5.1 \text{ kg sucrose still required.}$$

4. Find the amount of milk and cream needed.

$$100 - 29.18(\text{condensed milk, sugar, and stabilizer}) = 70.82 \text{ kg.}$$

5. Find the amount of cream required.

$$23.58 \times 0.08 = 1.89 \text{ kg fat in the condensed milk.}$$
$$14 - 1.89 = 12.11 \text{ kg fat still needed.}$$

Use the following formula:

$$\frac{\text{kg fat needed} - [\text{kg milk and cream required} \times (\%\ \text{fat in milk} / 100)]}{\%\ \text{fat in cream} - \%\ \text{fat in milk}} \times 100$$

= kg cream needed
Substituting we have:

$$\frac{12.11 - (70.82 \times 0.04)}{30 - 4} \times 100 = 35.69 \text{ kg cream}$$

6. Find the amount of milk required:

$$70.82 - 35.69 = 35.13 \text{ kg milk.}$$

Proof Table

Ingredients	Weight (kg)	Fat (kg)	MSNF (kg)	Sugar (kg)	T.S. (kg)
Cream	35.69	10.71	2.25	–	12.96
Milk	35.13	1.40	3.03	–	4.43
Concentrated milk	23.58	1.89	4.72	9.90	16.51
Sucrose	5.10	–	–	5.10	5.10
Stabilizer/emulsifier	0.50	–	–	–	0.50
Total	100.00	14.00	10.00	15.00	39.50

Example Problem 11
This is an example of a mix being formulated with "leftover" cream and milk.

Desired: Make 2,000 kg of mix testing 11% fat, 10.5% MSNF, 10% sucrose, 5% CSS, 0.5% stabilizer/emulsifier (37.0% Total Solids).

On hand: Use all of 450 kg of 30% cream and 300 kg skim milk.

They contain $450 \times 0.30 = 135$ kg fat and $(450 - 135) \times 0.09 = 28.35$ kg MSNF from the cream plus $300 \times 0.09 = 27$ kg MSNF from the skim milk.

Obtain the balance from unwashed, unsalted butter @ 84% fat, milk @ 4% fat, skim milk powder @ 97% MSNF, sucrose, CSS, and stabilizer/emulsifier.

Solution of problem 11 via the Serum Point method:

1. Find skim milk powder needed.
   Use the following formula:

$$\frac{\text{MSNF needed} - (\text{serum of mix} \times 0.09)}{\%\ \text{MSNF in skim milk powder} - 9} \times 100$$

   Substituting we have:

$$\frac{210 - (1{,}470 \times 0.09)}{97 - 9} \times 100 = 88.3 \text{ kg skim milk powder}$$

   Note: in this case, the quantity of mix desired was 2,000 kg, so the quantity of MSNF needed and the serum of the mix were both multiplied by 20. Furthermore, multiplying the amount of serum by the concentration of MSNF contained therein and subtracting that value from the total MSNF needed (numerator of the equation) accounts for the MSNF contributed by all of the milk and cream.
2. Find sugar, CSS, and stabilizer/emulsifier needed.
   $2{,}000 \times 0.10 = 200$ kg sucrose
   $2{,}000 \times 0.05 = 100$ kg CSS
   $2{,}000 \times 0.005 = 10$ kg stabilizer
3. List the materials supplied so far:

Ingredient	Weight (kg)
Cream	450.00
Skim milk	300.00
Skim milk powder	88.30
Sucrose	200.00
CSS	100.00
Stabilizer	10.00
Total	1148.30

4. Find the amount of butter and milk needed.

$$2{,}000 - 1148.3 = 851.7 \text{ kg butter and milk required.}$$

5. Find the amount of fat that still has to be made up. Total fat required = 2,000 kg × 11% = 220 kg. 220 − 135 (fat in 450 kg 30% cream) = 85 kg
6. Find the amount of butter needed by the following formula:

$$\frac{\text{kg fat needed} - [\text{kg butter and milk needed} \times (\%\text{ fat in milk} / 100)]}{\%\text{ fat in butter} - \%\text{ fat in milk}} \times 100$$

Substituting we have:

$$\frac{85 - (851.7 \times 0.04)}{84 - 4} \times 100 = 63.66 \text{ kg butter}$$

7. Find the amount of milk needed.

$$851.7 - 63.66 = 788.04 \text{ kg milk}$$

Proof Table

Ingredients	Weight (kg)	Fat (kg)	MSNF (kg)	T.S. (kg)
Cream	450.00	135.00	28.35	163.35
Milk	788.04	31.50	68.09	99.59
Butter	63.66	53.50	0.92	54.39
Skim milk	300.00	–	27.00	27.00
Skim milk powder	88.30	–	85.65	85.65
Sucrose	200.00	–	–	200.00
CSS	100.00	–	–	100.00
Stabilizer/emulsifier	10.00	–	–	10.00
Total	2,000.00	220.00	210.00	750.00
Percent		11.0	10.5	37.0

Example Problem 12
Calculate a mix containing liquid sweeteners, which requires an adjustment to the calculation of the serum of the mix, since the liquid sweetener also contributes water.

Desired: 100 kg of mix testing 12% fat, 11% MSNF, 14% sucrose, 3% CSS, 0.35% stabilizer, 0.15% emulsifier.

On hand: Cream @ 40% fat, milk @ 3.5% fat, concentrated skim milk @ 35% MSNF, liquid sucrose @ 66% solids; regular conversion corn syrup @ 80% solids, stabilizer, emulsifier.

Solution of problem 12 via the Serum Point method:

1. Calculate the weight of concentrated skim first, but determine the serum of the mix as follows:

   (a) Find the amount of liquid sucrose that must be added to provide 14 kg of sucrose solids:

$$14 \text{ kg sucrose} \times \frac{100 \text{ kg liquid sucrose}}{66 \text{ kg sucrose}} = 21.21 \text{ kg.}$$

   (b) Find the amount of corn syrup that must be added to provide 3 kg of CSS:

$$3 \text{ kg solids} \times \frac{100 \text{ kg liquid CSS}}{80 \text{ kg solids}} = 3.75 \text{ kg.}$$

   Serum of the mix is found by adding together the amounts of fat—12.00 kg, liquid sucrose—21.21 kg, liquid corn syrup—3.75 kg, stabilizer—0.35 and emulsifier—0.15 and subtracting from 100:

$$100 - 37.46 = 62.54 \text{ kg} = \text{the serum of the mix}$$

   Use the following formula:

$$\frac{\text{MSNF needed} - (\text{serum of mix} \times 0.09)}{\%\ \text{MSNF in concentrated skim} - 9} \times 100$$

   Substituting we have:

$$\frac{11 - (62.54 \times 0.09)}{35 - 9} \times 100 = 20.65 \text{ kg of concentrated skim milk}$$

2. Liquid sucrose required = 21.21 kg.
3. Liquid corn syrup required = 3.75 kg.
4. Stabilizer required = 0.35 kg.
5. Emulsifier required = 0.15 kg.
6. Find the amount of milk and cream needed:

$$100 - (20.65 + 21.21 + 3.75 + 0.35 + 0.15) = 53.89 \text{ kg}.$$

7. Find the amount of cream needed by formula:

$$\frac{\text{Fat needed} - [\text{kg milk and cream required} \times (\%\text{ fat in milk} / 100)]}{\%\text{ fat in cream} - \%\text{ fat in milk}} \times 100 = \text{kg cream}$$

Substituting we have:

$$\frac{12 - (53.89 \times (3.5 / 100)}{40 - 3.5} \times 100 = 27.69 \text{ kg of cream}.$$

8. Find the amount of milk required:

$$53.89 - 27.69 = 26.20 \text{ kg of milk}.$$

Proof Table

Ingredients	Weight (kg)	Fat (kg)	MSNF (kg)	Sweetener (kg)	T.S. (kg)
Cream	27.69	11.08	1.50	–	12.58
Milk	26.20	0.92	2.27	–	3.19
Conc. skim	20.65	–	7.23	–	7.23
Sucrose	21.21	–	–	14.00	14.00
Corn syrup	3.75	–	–	3.00	3.00
Stabilizer	0.35	–	–	–	0.35
Emulsifier	0.15	–	–	–	0.15
Total	100.00	12.00	11.00	17.00	40.50

Restandardizing Ice Cream Mixes

There are times when, for a variety of reasons, a mix is incorrectly calculated or ingredients are incorrectly measured or its composition has to be changed; therefore, the mix needs to be adjusted with the addition of further ingredients to arrive at the exact composition to meet the desired formulation. However, adding further

mass also changes the proportions of all solids, hence some recalculations need to be done. Restandardization problems involve the formulation of a new mix of such a composition that when it is added to the old mix, the two will balance. A suitable volume of new mix is chosen to ensure standardization while not adding too much additional product. Thus the volume of the additional mix is somewhat arbitrary and flexible. The additional mix can be formulated with whatever ingredients are required and available, e.g., cream or butter, skim milk powder, sugar, CSS, stabilizer/emulsifier, and water.

For example, if a mix is low in fat but all other ingredients are satisfactory, a new mix can be formulated to supply the additional required fat while maintaining the composition of all the other constituents, including the content of original fat. Suppose we have 1,200 kg of mix that contains 12% fat rather than the required 13%. An additional 150 kg of mix could be made. The fat required for 1,350 kg mix would be $1{,}350 \times 0.13 = 174.50$ kg. Fat present in the original mix is $1{,}200 \times 0.12 = 144.00$ kg. The additional fat to be supplied would thus be 31.50 kg. This could be supplied by cream or butter and the amount of that ingredient determined by division by its fat content. The additional 150 kg must also supply the correct proportion of all other components according to the original mix. After all ingredient weights are determined, the balance of the 150 kg is made up with water.

Likewise if a mix is high in fat, the volume chosen should be sufficient to dilute the mix to the needed fat content. That volume must also supply the correct proportion of all other components according to the original formula. For example, if there is 1,000 kg of mix testing 13% fat and it should have tested 12%, a surplus of 10 kg of fat is contained. Therefore, an additional $10/0.12 = 83.3$ kg of fat-free mix is needed: 130 kg fat/1083.3 kg of mix provides 12% fat. This 83.3 kg of new mix must supply the correct proportion of MSNF, sugar, CSS, and stabilizer/emulsifier, according to the original formula.

Other mixes low or high in any component can be recalculated in the same manner.

Freezing Point Depression Calculations

The solutes (sugars and milk salts) in an ice cream mix depress its freezing point. As water progressively freezes out of an ice cream mix in the form of pure ice crystals, the concentration of solutes in the unfrozen water continues to go up and the freezing point continues to go down. This gives rise to a freezing curve, the plot of unfrozen water vs. temperature. This has great importance in ice cream since unfrozen water is directly related to firmness. Hence, the sugars and milk salts are responsible for the softness and scoopability of ice cream. It is very important to know how firm or soft ice cream will be at any given temperature (especially so for ice cream scooping operations). This section provides an example of the calculation of the freezing curve. See Chap. 11, Ice Cream Structure, for a greater discussion of the relationship between solutes, ice, and the unfrozen phase.

Freezing point depression is the difference between 0°C and the temperature at which an ice cream mix first begins to freeze. The freezing point depression of solutions is calculated based on principles of thermodynamics; however, experience has shown that deviations from chemically "ideal" systems occur at the high concentrations of solutes encountered in ice cream mix. Thus, methods have been worked out that determine freezing point depression of ice cream mix by comparison to well-established tabulated freezing point depression data for sucrose solutions (Livney et al. 2003). In ice cream mix, the sum of each of the components that impact freezing point depression is needed. It is the combination of sweeteners (mono- and disaccharides) and milk ingredients (lactose and salts) used in the formulation that leads to the specific freezing point depression curve for any mix. Fat, proteins, large molecular weight carbohydrates such as the starch fragments found in CSS, stabilizers, and emulsifiers do not contribute to freezing point depression because fat is immiscible with the aqueous phase, and proteins and polysaccharides are very large molecules. However, as these substances are increased in concentration, there is less water in which solutes can dissolve, so the presence of these materials will result indirectly in depression of the freezing point. The important compositional data, therefore, are % sugar(s), % MSNF, and % water.

This chapter will present freezing point depression calculation of an ice cream mix by taking the sucrose equivalents of all the mono- and disaccharides that influence freezing point. The contribution of salt on freezing point is calculated and the two values are summed to obtain the initial freezing point of the mix. This method is based on work by Leighton (1927) and subsequently modified by Smith and Bradley (1983) and Bradley and Smith (1983). The tabulated data was generated by a German scientist Pickering by accurately measuring the freezing point of a series of sucrose solutions of increasing concentration (Leighton 1927; Whelan et al. 2008). Baer and Keating (1987) showed that this method correlated very well with actual freezing points of standard ice cream mixes measured by an osmometer. However, in a comparison of this method to actual measurements with an osmometer on 110 mixes formulated to contain a wide variety of ingredients and concentrations; Jaskulka et al. (1993) suggested that this method underestimated or overestimated freezing point depression by as much as 0.18°C, depending on the choice of ingredients.

Jaskulka et al. (1995) developed a method for predicting freezing points for a wider variety of formulations using an empirical model, based on actual measurement with an osmometer of freezing point of 110 mixes with a wide variety of ingredients and composition. The quadratic model contained as many as 19 terms, based on composition. With some ingredients present in a mix, their model was claimed to be more accurate than the one presented here.

The method presented here can also be used to calculate the amount of water frozen into ice for a given ice cream at any temperature by varying the solute concentration since freeze concentration of the unfrozen phase occurs during freezing. For a typical ice cream, a relationship between temperature and the amount of water frozen into ice, the freezing curve, is obtained (see Chaps. 7 and 11). Based on the freezing point curve and the assumption of an equilibrium ice content, the amount of water converted to ice at any temperature can be calculated by a mass balance (Bradley 1984).

Livney et al. (2003) measured freezing curves using a novel DSC technique for ice cream mixes containing different combinations of sweeteners, stabilizers, and MSNF and compared results to calculated values using the method described here. They showed that freezing temperature calculations and measurements were similar, regardless of formulation, and were independent of stabilizer addition. Calculated and measured freezing curves from freeze concentration, however, were seen to deviate beyond 50–60% of water frozen, and stabilizers were seen to produce lower values of frozen water than unstabilized solutions in some cases. Whelan et al. (2008) modified the DSC method used by Livney et al. (2003) and found closer agreement to calculated freezing curves. They also showed that the measured freezing curve corresponded closely with the calculated curve up to 55–60% of total water frozen after which the calculated method overestimated the amount of water frozen in the system. At high levels of freeze concentration, specific solute–solvent interactions account for the nonideal behavior (Livney et al. 2003). Therefore it should be recognized that the calculated method for the freezing curve is quick, easy, and suitable for relative comparisons, but for precise absolute values, measurement may be required (see Chap. 14 for methods).

Freezing Point Depression of a Mix

To calculate the freezing point of a given mix, the first step is to determine the equivalent content of sucrose in the mix, based on all the mono- and disaccharides that are present. This is referred to as the sucrose equivalence (SE) in g/100 g of mix.

$$\begin{aligned} SE = {} & (MSNF \times 0.545) + (WS \times 0.765) + S + (10DE\ CSS \times 0.2) + (36DE\ CSS \times 0.6) \\ & + (42DE\ CSS \times 0.8) + (62DE\ CSS \times 1.2) + (HFCS \times 1.8) + (F \times 1.9) \end{aligned}$$

Where:

MSNF = milk solids-not-fat, 0.545 is the percentage of lactose typical of MSNF.
WS = whey solids (from dry or condensed whey), 0.765 is the percentage of lactose typically found in whey solids.
S = sucrose or other disaccharides such as maltose or lactose (if added directly as a separate ingredient, otherwise it is accounted for in the MSNF or whey solids calculations) or disaccharide alcohols such as maltitol or lactitol.
DE = dextrose equivalence of the CSS, the various factors convert the carbohydrates in the starch hydrolysate to sucrose equivalents.
HFCS = high fructose corn syrup, which is mostly monosaccharide, hence the factor of 1.8 to convert it to equivalent sucrose content.
F = pure fructose or other pure monosaccharides such as dextrose or monosaccharide 6-carbon alcohols such as sorbitol, the factor of 1.9 to convert it to equivalent sucrose content based on molecular weight ratios; all in g/100 g mix (or %).

Table 6.1 Freezing point depression (°C) below 0°C of sucrose solutions (g/100 g water)

g Sucrose/100 g water	FPD (°C)	g Sucrose/100 g water	FPD (°C)	g Sucrose/100 g water	FPD (°C)
3	0.18	63	4.10	123	9.19
6	0.35	66	4.33	126	9.45
9	0.53	69	4.54	129	9.71
12	0.72	72	4.77	132	9.96
15	0.90	75	5.00	135	10.22
18	1.10	78	5.26	138	10.47
21	1.29	81	5.53	141	10.72
24	1.47	84	5.77	144	10.97
27	1.67	87	5.99	147	11.19
30	1.86	90	6.23	150	11.41
33	2.03	93	6.50	153	11.63
36	2.21	96	6.80	156	11.88
39	2.40	99	7.04	159	12.14
42	2.60	102	7.32	162	12.40
45	2.78	105	7.56	165	12.67
48	2.99	108	7.80	168	12.88
51	3.20	111	8.04	171	13.08
54	3.42	114	8.33	174	13.28
57	3.63	117	8.62	177	13.48
60	3.85	120	8.92	180	13.68

Data were extrapolated from Leighton (1927), which were originally derived from Pickering (1891 as cited by Leighton)

If blended protein, lactose, and mineral ingredients are used as a source of MSNF, the lactose and salts in those ingredients should be included directly in the calculation rather than using the factors for MSNF or WP. Simply ensure that all lactose and salts are accounted for and none are double-counted. If xylitol (5-carbon sugar alcohol, molecular weight 152), erythritol (4-carbon sugar alcohol, molecular weight 122), or other such low molecular weight sweeteners are included in the formulation, the molecular weight of sucrose (342) divided by their molecular weight could be used as the appropriate factor.

The equivalent concentration of sucrose in water (g/100 g water) is then determined by dividing the SE by the water content.

g sucrose/100 g water = SE × 100/*W*

where: *W* is the water content (100 − total solids, %).

To obtain the freezing point depression associated with this concentration of SE in water, FPD_{SE}, Table 6.1 is used.

The contribution to freezing point depression from salts in MSNF and WS is found using the following equation:

$$FPD_{SA} = \frac{(MSNF + WS) \times 2.37}{W}$$

Here, FPD_{SA} is the freezing point depression for salts (°C) contained in MSNF and WS, and the constant 2.37 is based on the average molecular weight and concentration of the salts present in milk. For computation in °F, the factor 4.26 is used. To obtain the freezing point depression of the ice cream mix, FPD_T, the two contributions are summed.

$$FPD_T = FPD_{SE} + FPD_{SA}$$

Example Problem 13
Calculate the initial freezing point of an ice cream mix containing 10% MSNF, 2% whey solids, 12% sucrose, 4% 42DE CSS, and 60% water (40% total solids).

First, calculate the sucrose equivalents:

$$SE = (10 \times 0.545) + (2 \times 0.765) + 12 + (4 \times 0.8) = 22.18$$

The equivalent concentration of sucrose in water is,

$$\frac{\text{g sucrose}}{100 \text{ g water}} = 22.18 \times 100 / 60 = 36.97$$

Now, by interpolation find the freezing point depression for this level of sucrose equivalent from Table 6.1.

$FPD_{SE} = 2.27°C$

For salts:

$$FPD_{SA} = \frac{(10+2) \times 2.37}{60} = 0.47\ ^{\circ}C$$

Find the total freezing point depression for the mix:

$$FPD_T = 2.27^{\circ} + 0.47^{\circ} = 2.74\ ^{\circ}C$$

Thus, the initial freezing point temperature for this ice cream mix is –2.74°C.

Freezing Curves

The initial freezing point can then be used to compute a freezing curve, where the percent of water frozen in the mix (removed as ice) is plotted against freezing temperature. This is done by continually reducing the water content (W) in the mix and recalculating the FPD_T as above, since the remainder of the water is converted to ice and no longer acting as a solution.

Table 6.2 Freezing point depression values[a] applicable to the formula in Example Problem 13 when 10–80% of the water in the ice cream is frozen

% Water frozen	*W*	g Sucrose/100 g water	FPD_{SE}	FPD_{SA}	FPD_{T}
10	54	41.07	2.53	0.53	3.06
20	48	46.21	2.86	0.59	3.45
30	42	52.81	3.33	0.68	4.01
40	36	61.61	3.97	0.79	4.76
50	30	73.93	4.92	0.95	5.87
60	24	92.42	6.45	1.18	7.63
70	18	123.22	9.21	1.58	10.79
75	15	147.87	11.26	1.90	13.16
80	12	184.83	14.27	2.37	16.61

[a]FPD_{SE} freezing point depression of sucrose equivalents; FPD_{SA} freezing point depression of salts; FPD_{T} total freezing point depression

Example Problem 14

Calculate the freezing curve for ice cream, based on a mix containing 10% MSNF, 2% whey solids, 12% sucrose, 4% 42DE CSS, and 60% water (40% total solids).

From above, we calculated that the initial freezing point (0% water frozen) was −2.74°C. When 20% of the water is frozen, 80% is still liquid, so *W* is now (60% × 0.8) = 48%. The g sucrose/100 g water is now 22.18 × 100/48 or 46.21 g/100 g water. From Table 6.1, this (FPD_{SE}) corresponds to 2.86°C. For the milk salts, $FPD_{SA} = (10+2) \times 2.37/48 = 0.59$°C. Thus, FPDT = 2.86° + 0.59° = 3.45°C. At −3.45°C, we conclude that 20% of the water in this mix will be frozen.

Similarly, a series of ice contents can be used, sufficient to plot a freezing curve. Such values are shown in Table 6.2 and plotted in Fig. 6.1.

Table 6.3 shows an adaptation of the above freezing curve calculation that, when fed into an Excel spreadsheet, will give the predicted FPD_{Total} (freezing point) and theoretical freezing curve, plotted as % water frozen in the mix (first column) graphed against the FPD_{Total} (last column).

Overrun Calculations

Overrun is the industrial calculation of the air added to frozen dessert products, and it is calculated as the percentage increase in volume of mix that occurs as a result of the air addition, i.e., air volume/mix volume. Tight control over overrun is essential in ice cream operations, since it is directly tied to yield. If all costing calculations are done on the basis of 100% overrun but ice cream is made at an average of 95%, the loss in volume of ice cream will be 5 L of ice cream per 100 L of mix. This loss in finished product can be substantial over the course of a day of production. For the same reason, tight control over the rate of incorporation of inclusions is also important, as it is also tied directly to yield and profit. On the other hand, if overrun is higher than desired, this could lead to loss of desired quality or even to product that

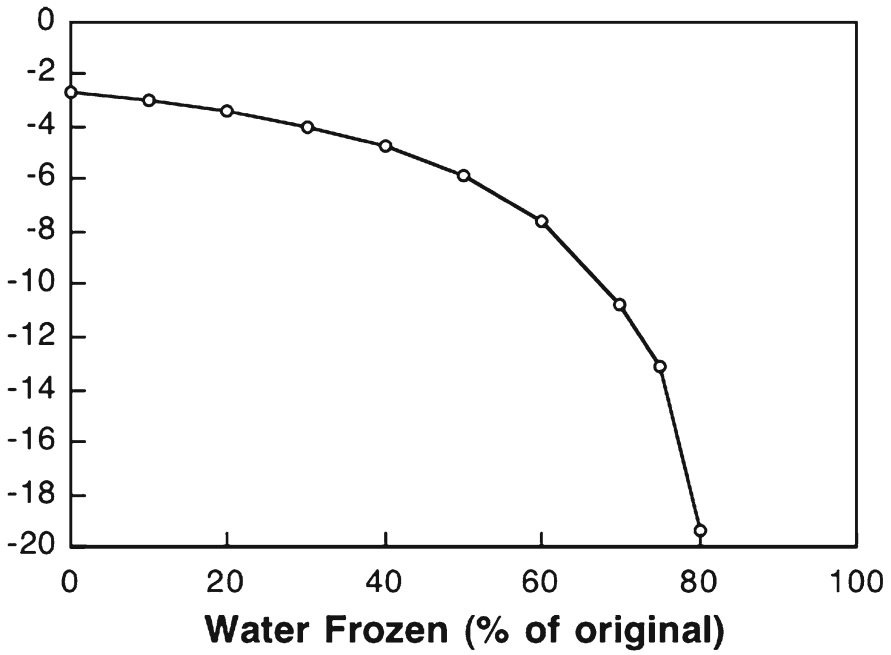

Fig. 6.1 Freezing point depression curve for a mix with 10% MSNF, 2% whey solids, 12% sucrose, 4% 42DE CSS, and 60% water (40% total solids)

does not meet the legal requirements for weight of food solids. Therefore good knowledge of overrun calculations is critical. Even if a continuous freezer in which the overrun is automatically set is in operation, it is important to monitor whether it continues to perform accurately. The following examples will show calculations of overrun by volume and by weight, without and with the addition of particulates, and will also show calculations of target package weights. When packages are being filled on a processing line, package weights should be closely monitored. Deviations can be attributed to variations in the overrun of the ice cream (which would require freezer barrel adjustment), variations in the ratio of ice cream to particulate addition (which would require ingredient feeder or ripple pump adjustment), or variations in the fill level of the package (which would require packaging machine adjustment).

Determining Manufacturing Overrun by Volume, no Particulates

The equation for overrun determination of a production run, based on the definition of overrun given above, is as follows:

$$\%\ \text{Overrun} = \frac{\text{Vol. of ice cream produced} - \text{Vol. of mix used}}{\text{Vol. of mix used}} \times 100\%$$

Table 6.3 Excel spreadsheet method for calculation of initial freezing point and freezing curve plotted as % water frozen in the mix (first column) graphed against the FPD_{Total} (last column)

WF[a] (%)	WNF (g)	g Suc/100 g water	FPD[b, c] $_{Sweetener}$	FPD_{Salt}	FPD_{Total}
0–90 in increments of 5	(% W[d] * (1 − (WF[a] (%)/100)))	((SE * 100)/WNF[e] (g))	=((−9 * 0.00001) * (g Suc/100 g water)^2 − (0.0612) * (g Suc/100 g water))	(% MSNF[f] * 2.37[g])/(g) water not frozen	$FPD_{Sweetener}$ + FPD_{Salt}
Example: % water frozen in mix = 0; (g) water not frozen = 62.85; % SE = 21.86; % MSNF[f] = 12					
% SE[h] = the sum of all carbohydrate (carbohydrate * FPD[b] potential compared to sucrose) sources in the mix; e.g., sucrose (15 * 1) + lactose (6.86 * 1) = 21.86					
0	(62.85 * (1 − (0/100)) = 62.85)	(21.86 * 100)/62.85 = 34.78	=((−9 * 0.00001) * (34.78)^2 − (0.0612) * (34.78)) = −2.23	(12 * 2.37)/62.85 = −0.45	2.14 + 0.45 = −2.68
5	(62.85 * (1 − (5/100)) = 59.71)	(21.86 * 100)/59.71 = 36.62	=((−9 * 0.00001) * (36.62)^2 − (0.0612) * (36.62)) = −2.36	(12 * 2.37)/59.71 = −0.48	2.29 + 0.48 = −2.84
10 etc.…					

[a] WF = Water frozen in the mix
[b] FPD = Freezing point depression
[c] Polynominal equation with intercept through zero derived from regression model where g sucrose/100 g water is graphed against FPD °C. Data was extrapolated from Leighton (1927)
[d] W = Water in the mix
[e] WNF = Water not frozen
[f] MSNF = Milk solids not fat
[g] The constant 2.37 is based on the average molecular weight and concentrations of salts present in milk
[h] SE = Sucrose equivalent

Example Problem 15
500 L mix gives 950 L ice cream:

$$\frac{950-500}{500}\times 100\% = 90\%\ \text{Overrun}$$

Any added flavors, such as chocolate syrup, that become homogeneous with the mix can incorporate air and are, therefore, accounted for in the following way.

Example Problem 16
800 L mix plus 100 L chocolate syrup (900 L chocolate mix) gives 1,700 L chocolate ice cream:

$$\frac{1{,}700-(800+100)}{(800+100)}\times 100\% = 88.9\%\ \text{Overrun}$$

Determining Manufacturing Overrun by Volume, with Particulates

Example Problem 17
40 L mix plus 28 L pecans gives 110 L butter pecan ice cream. Therefore: 110 − 28 = 82 L actual ice cream surrounds the nuts.

$$\%\ \text{Overrun} = \frac{\text{Vol. of ice cream} - \text{Vol. of mix used}}{\text{Vol. of mix used}}\times 100$$
$$= \frac{82-40}{40}\times 100\% = 105\%$$

The pecans do not incorporate air. This type of a determination might be useful if, for example, defects in a given mix were known to show up at >115% overrun. Otherwise, in a calculation of total output, a calculation similar to the one above, with no particulates, may be more useful. Remember in accounting for the volume of the pecans that some spaces among the pecans when measured before addition to the ice cream is occupied with air.

Determining Package Overrun by Weight, no Particulates

Overrun in ice cream can also be determined by weight in the following equation, which computes the decrease in weight of a given volume of mix due to the addition of air. It is mathematically identical to the equation above.

$$\%\ \text{Overrun} = \frac{\text{Wt. of mix} - \text{Wt. of same vol. of ice cream}}{\text{Wt. of same vol. of ice cream}} \times 100$$

Must know density of mix (wt. of 1 L), usually 1.09–1.1 kg/L *(see example below)*

Example Problem 18
If 1 L of ice cream weighs 560 g net weight (exclusive of package) and the assumed mix density is 1.09 kg/L,

Then:

$$\%\ \text{Overrun} = \frac{1{,}090 - 560}{560} \times 100\% = 94.6\%$$

Note: the 560 g of mix that produced this 1 L of ice cream had a volume of 560/1.09 = 514 mL, so as above, (1 L ice cream—0.514 L mix)/0.514 L mix = 94.6%.

Determining package overrun by weight if the ice cream has particulates in it gives very little information because both the ratio of ice cream to particulates and the air content of the ice cream affect the final weight.

An overrun chart is useful during manufacturing so that monitoring of overrun can be made by weighing a small, standardized volume, such as a metal cup with a flat top, and alternatively, monitoring the weight of the actual consumer package. The overrun chart establishes the overrun percentage in the ice cream for various weights of a specific container of ice cream. To develop such a chart, select a cup or consumer package for use, then apply the following formula:

$$\begin{aligned}&\text{Gross weight at desired overrun}\\&= [(\text{net weight of cup of mix} \times 100 / 100 + \text{desired overrun})] + \text{weight of cup}\end{aligned}$$

Make the same calculation at 5% overrun increments (or smaller increments if desired) to complete the chart. For example, if a cup contained 500 mL and its net weight was 35 g, then for a mix density of 1.1 kg/L the chart would be as follows:

$$\begin{aligned}&0\%\ \text{overrun} : 585\ \text{g}\ [\text{determined as}\ (500\ \text{mL} \times 1.1\ \text{g/mL}) + 35\ \text{g}]\\&5\%\ \text{overrun} : 559\ \text{g}\ [\text{determined as}\ (500\ \text{mL} \times 1.1\ \text{g/mL} / 1.05) + 35\ \text{g}]\\&10\%\ \text{overrun} : 535\ \text{g}\ [\text{determined as}\ (500\ \text{mL} \times 1.1\ \text{g/mL} / 1.1) + 35\ \text{g}]\\&.\\&.\\&.\\&100\%\ \text{overrun} : 310\ \text{g}\ [\text{determined as}\ (500\ \text{mL} \times 1.1\ \text{g/mL} / 2) + 35\ \text{g}]\\&.\end{aligned}$$

and so on to complete the chart through the normal operating range.

Determining Mix Density

The density of ice cream mix at any temperature is determined by the reciprocal of the sum of the volumes per unit mass of its three components: fat, total nonfat solids and water (Steinberg, 1963). The equation below uses the density of milkfat at 20°C=0.93 kg/L, the density of total nonfat solids (sugars and proteins)=1.58 kg/L and the density of water at 20°C=1.00 kg/L (note: 1 kg/L=8.33 lbs./US gal.). Density varies with temperature, so using the volumes of fat and water at different temperatures than 20°C would provide the mix density at that temperature. However, it is difficult to accurately predict the density of partially crystalline fat at temperatures below 20°C.

$$\frac{1}{\frac{\%\ \text{fat}}{100}\ /\ 0.93\ \text{kg/L} + \left(\frac{\%\ \text{total solids}}{100} - \frac{\%\ \text{Fat}}{100}\right) /\ 1.58\ \text{kg/L} + \frac{\%\ \text{Water}\ /\ 1.00\ \text{kg/L}}{100}} = \text{kg/L of mix}$$

Example Problem 19
Calculate the weight per liter of mix containing 12% fat, 11% MSNF, 10% sugar, 5% CSS, 0.30% stabilizer, and 38.3% total solids:

$$\frac{1.0}{(0.12 / 0.93\ \text{kg/L}) + ((0.383 - 0.12) / 1.58\ \text{kg/L}) + (0.617\ /\ 1.00\ \text{kg/L})} = 1.0959\ \text{kg / L of mix}$$

Determining Target Package Weights, no Particulates

Use the following formula:

$$\text{Weight of given vol. of ice cream} = \frac{\text{Wt. of same vol. of mix}}{(\text{Desired overrun} / 100) + 1}$$

Example Problem 20
Desired overrun is 90%, mix density is 1.09 kg/L

$$\text{Net wt. of 1 L} = \frac{1{,}090\ \text{g}}{\left(\frac{90}{100}\right) + 1} = 573.7\ \text{g}$$

Table 6.4 Mix density, ice cream density, and food solids per gallon of ice cream when frozen at 50 and 100% overrun from mixes containing 10 or 14% fat and varying amounts of total solids

Mix				Frozen product					
TS	Fat	Density		50% overrun			100% overrun		
(%)	(%)	(kg/L)	(lb/gal)	(g/L)	(lb/gal)	(FS[a])	(g/L)	(lb/gal)	(FS[a])
32	10	1.079	9.00	719	6.00	1.92	540	4.50	1.44
34	10	1.088	9.08	725	6.05	2.06	544	4.54	1.54
36	10	1.096	9.15	731	6.10	2.20	548	4.58	1.65
38	10	1.108	9.25	739	6.17	2.34	554	4.63	1.76
38	10	1.084	9.05	723	6.03	2.29	542	4.53	1.72
40	***14***	1.114	9.30	743	6.20	2.48	557	4.65	1.86
40	***14***	1.093	9.12	729	6.08	2.43	547	4.56	1.82
42	10	1.124	9.38	749	6.25	2.63	562	4.69	1.97
42	***14***	1.102	9.19	735	6.13	2.57	551	4.60	1.93

[a]Food solids in lb/gal with 1.6 lb/gal being the minimum in the United States

Also, the density of ice cream can be calculated in a similar manner.

$$\text{Density of ice cream} = \frac{\text{Density of mix}}{(\text{Overrun}/100)+1}$$

Example Problem 21
Assume a mix density of 1,100 g/L,

$$@100\%\ \text{Overrun, density of ice cream} = \frac{1{,}100\ \text{g/L}}{(100/100)+1} = 550\ \text{g/L}$$

Determining Target Package Weights, with Particulates

Example Problem 22
Ice cream with candy inclusion: density of mix is 1.1 kg/L; overrun in ice cream is 100%; density of candy is 0.75 kg/L*; candy added at 9% by weight, i.e., 9–100 kg final product.

*Note: density of particulate pieces containing void spaces must be determined by first crushing the material to eliminate void spaces, given that ice cream will fill in the voids after incorporation.

In 100 kg final product, we have:

$$9 \text{ kg of candy or} \frac{9 \text{ kg}}{0.75 \text{ kg / L}} = 12.0 \text{ L}$$

$$91 \text{ kg of ice cream or} \frac{91 \text{ kg}}{(1.1 \text{ kg / L}) / [100 / 100) + 1]} = 165.45 \text{ L}$$

So, 100 kg gives a yield of $12 + 165.4 = 177.4$ L

$$1 \text{ L weighs} \frac{100 \text{ kg}}{177.4 \text{ L}} = 564 \text{ grams}$$

In many cases, ice creams of different flavors are manufactured to provide the same weight per package for the consumer. As a result, overrun of the actual ice cream in the product varies from flavor to flavor, depending on the density and the ratio of the particulates to the frozen mix.

Density of mixes vary significantly with the amounts of fat, nonfat solids, and water they contain. These factors and the overrun determine the amount of food solids per unit volume as illustrated in Table 6.4.

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Chapter 7
Freezing and Refrigeration

Introduction

Freezing the mix is one of the most important operations in making ice cream, since the quality, palatability, and yield of the finished product depend on proper freezing. Typically, freezing of ice cream is accomplished in two steps: (1) dynamic freezing, where the mix is frozen quickly while being agitated to incorporate air and to limit the size of ice crystals formed; and (2) static freezing, where the partially frozen product is hardened without agitation in a special low-temperature environment designed to remove heat rapidly. During dynamic freezing, where ice crystals are formed, both the dispersion of air bubbles and rearrangement of fat globules also occur. During static freezing (often called hardening and discussed in detail in Chap. 10), previously formed ice crystals grow larger in accordance with the decrease in temperature, but in general, no new nuclei are formed.

The general procedure of the dynamic freezing process involves movement of the previously prepared and aged mix into the freezer, operation of the freezer, and removal of frozen product from the freezer. Mastering the details of freezer operation, however, to produce a uniformly high-quality product requires considerable practice. Several variables must be controlled simultaneously, and even with highly sophisticated programmable control on the freezers, there are still slight variations in product characteristics from day to day.

General Freezing Operations

In the dynamic freezing step, cold, flavored ice cream mix enters the cylindrical freezer barrel and is chilled with a liquid refrigerant, as shown schematically in Fig. 7.1. The mix is whipped with a dasher, a mixing device with sharp scraper blades that contact the very smooth surface of the freezing cylinder. Freezing of ice cream mix occurs on the inside of the barrel wall as the liquid refrigerant vaporizes

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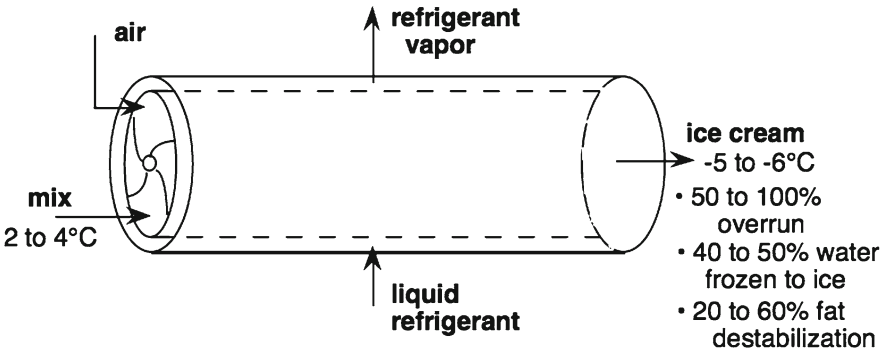

Fig. 7.1 Schematic drawing of scraped-surface freezer used for ice cream manufacture

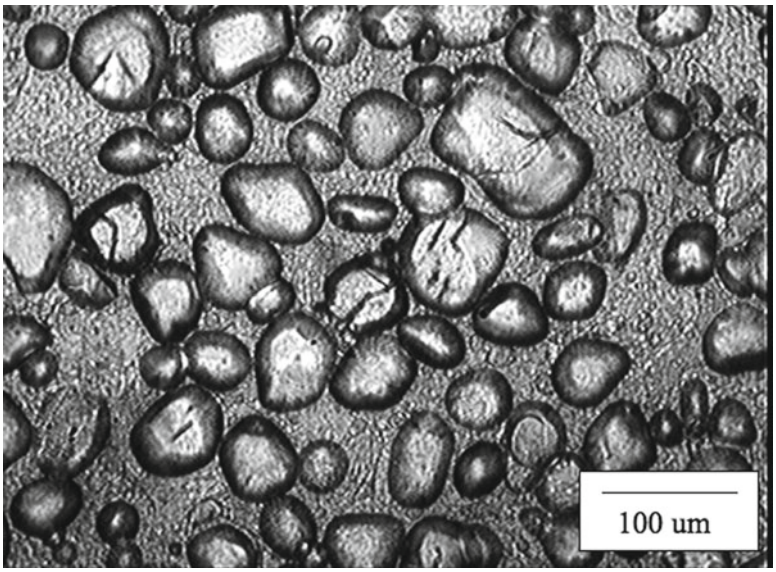

Fig. 7.2 Ice crystals in ice cream

on the other side of the wall. As the dasher rotates within the freezing barrel, typically at speeds of 100–200 rpm, the blades scrape an ice layer from the cylinder wall. The small crystals contained in the ice layer mix with the rest of the ice cream within the freezing barrel, where complex heat and mass transfer processes lead to formation of the disk-shaped ice crystals that ultimately exit the scraped-surface freezer. These ice crystals should be small (preferably less than about 30 μm) with a smooth surface (Fig. 7.2). Further details of this process are available in a recent review article (Cook and Hartel 2010), and discussed in more detail in Chap. 11.

Ice cream can be frozen in either batch or continuous freezers. The distinction is often based on the size of the company, with larger operations generally processing

ice cream in continuous freezers. Regardless of the type of freezer used, the general mechanisms that occur to transform ice cream mix into a high-quality ice cream product are much the same. In addition to formation of ice crystals, air is traditionally incorporated in the dynamic step, although sometimes the ice cream mix may be pre-whipped prior to freezing. At the same time that ice crystals are forming and air is being incorporated, the fat globules undergo destabilization, which leads to partial coalescence and formation of clumps of fat globules. These fat clumps help to promote air incorporation and stabilization of the small air bubbles incorporated during whipping of the mix.

At the end of the freezing process, whether batch or continuous, the ice cream is only partially frozen. Unless a soft-serve product is being produced, the ice cream exiting the scraped-surface freezer is filled into packages, which are then sent through a hardening step (or secondary freezing) where additional ice is frozen and the ice cream becomes hard. Further details on hardening of ice cream can be found in Chap. 10 and on the changes that take place during dynamic freezing in Chap. 11.

Types of Freezers

Freezers for frozen desserts are designed to perform specific tasks under a variety of conditions and at varying costs. The soft-serve freezer must continue to deliver frozen product intermittently over several hours of operation. Batch freezers are designed to freeze a quantity of mix for delivery in a short time period. Continuous freezers receive mix continuously from positive displacement pumps and discharge the partially frozen product continuously.

Freezing times are affected by numerous factors, including mechanical and physical factors related to the freezer as well as the properties of the mix. The mechanical and physical factors include:

- *Type and construction of freezer*. Freezer construction determines heat transfer rates between the refrigerant and the freezing ice cream mix.
- *Condition of cylinder walls and blades*. Heat transfer through the freezer wall is strongly influenced by the nature of the heat transfer surface. Oil build-up on the refrigerant side and an ice layer build-up on the product side significantly decrease heat transfer rates and increase freezing times. Uneven or dull scraper blades lead to larger ice crystal sizes.
- *Speed of dasher*. Faster dasher rotational speeds help promote heat transfer and nucleation of ice, but also generate increased frictional heat energy. For this reason, dasher speeds are usually limited to 100–200 rpm.
- *Temperature of refrigerant* (governed by suction pressure). Lower refrigeration temperatures promote faster freezing as heat is removed more rapidly.
- *Velocity of refrigerant* as it passes around the freezing chamber. The convective heat transfer rate between the refrigerant and the barrel is an important component of the overall heat transfer coefficient.

- *Overrun desired*. More air incorporated into the ice cream during freezing reduces the effective heat transfer rate into the product, slowing down the freezing rate.
- *Temperature at which the ice cream is drawn from the freezer*. Draw temperature determines how much ice is frozen in the process. Lower draw temperatures require longer freezing times.

The second aspect that affects freezing time is the nature of the mix itself. Mix characteristics that affect the freezing time include:

- *Composition*. The composition of the mix contributes to its heat capacity and viscosity, both factors that affect heat transfer from the freezing mix to the refrigerant. Choice of stabilizer in particular has a strong effect on mix viscosity. For example, mixes made with higher levels of guar gum have higher viscosity and require greater energy (and longer times) to freeze (Smith et al. 1985).
- *Freezing point*. Freezing does not begin until the mix has cooled below its freezing point. However, a mix with a lower freezing point temperature will produce less ice when drawn to the same temperature as a mix with higher freezing point and thus, will have a shorter freezing time.
- *Methods of processing*. Pasteurization and homogenization can influence the nature of the proteins and fat globules, both of which can have an influence on viscosity of the mix.
- *Kind and amount of flavoring materials*. Certain types of flavoring (e.g., cocoa in chocolate) potentially influence heat capacity and viscosity of the mix, thereby affecting heat transfer rates and freezing.

The Continuous Freezer

The continuous freezer process was first patented in 1913 but did not become widely used until the 1930s. The process typically consists of continuously feeding a metered amount of mix and air into one end of the freezing chamber. As the mix passes through this chamber, it is agitated and partially frozen before being discharged in a continuous stream at the other end of the chamber. This product is dispensed into packages that are placed in a hardening unit to complete the freezing process.

Capacities of continuous freezers range from about 100 to 4,500 L/h (30–1,200 gal per hour) per freezer barrel. Some freezers have two or three freezer cylinders mounted on a single frame that are operated by the same controller. Freezer capacity ratings are generally based on nominal conditions such as:

1. Machine in new or excellent condition.
2. Refrigerant is clean, free of oil, and noncondensable gases.
3. Full fat ice cream mix is used with approximately 38% TS.
4. Temperature of mix entering the freezer is 4.4°C (40°F), and it is drawn at −5.6°C (22°F).

5. Evaporating temperature of the ammonia refrigerant (saturated conditions) is −30.6°C (−23°F) or ammonia back pressure at the evaporator is 13.8 kPa (2 psi).
6. The rating is stated in terms of L/h (or gal/h) at 100% overrun.

Freezer ratings are determined under optimal conditions and thus, the user cannot be assured that operations can be maintained at that capacity. Furthermore, mix characteristics significantly affect freezer capacity.

The first continuous freezers had a positive-displacement pump that metered a constant supply of mix to a second pump that displaced two to three times the volume of the first pump. An air inlet valve was positioned upstream of the second pump so a desired amount of air could be admitted to the cylinder for whipping into the ice cream. A hold-back valve located at the distal end of the cylinder was adjusted to keep pressure on the cylinder. Instead of depending on air drawn in by vacuum, today's freezers are supplied with compressed air through a regulator or a mass flow meter.

Freezer manufacturers vary in their approach to controlling the overrun, stiffness, and draw temperature of frozen products. One method is to control the speed of the mix pump, while using an air mass controller to meter the desired percentage of overrun air. The programmable logic controller (PLC) maintains the desired mix flow rate by means of a variable frequency inverter to adjust the speed of the mix pump. Based on the mix flow rate the PLC sends a signal to the air mass controller to meter the proper amount of air to provide the desired percentage of overrun. Most modern freezers utilize variable frequency inverters, but mix pump speed of some freezers may be controlled with mechanical or hydraulic variable speed drives.

The stiffness (viscosity) is measured by monitoring the dasher motor load required to rotate the dasher assembly. The major factor that determines the product stiffness is the temperature, since the ice content is the primary factor affecting stiffness. However, using temperature to measure stiffness and to control the freezing is subject to error. The mix composition affects the freezing point; furthermore, mix viscosity and overrun also affect the product stiffness. Additionally, it is inherently difficult to control the freezing process using temperature as the process variable, because of the low input resolution (small temperature changes create relatively large changes in stiffness) and contamination of the temperature probe.

Back pressure on the freezing cylinder or "cylinder pressure" is important for proper freezer performance. On older freezers, the cylinder pressure can be manually controlled with a product hold-back valve, maintained by the ratio between mix and product pumps, or monitored and controlled by the PLC on fully automatic freezers. Newer commercial continuous freezers utilize a mix and product pump. The mix is fed to the freezing cylinder through a mix pump and the semi-frozen product discharges from the freezing cylinder through the product pump, the speed of which is controlled to maintain a constant pressure in the freezing cylinder. The mix pump feeds mix into the pressurized cylinder, while the discharge (ice cream) pump must overcome the downstream line pressures. To maintain constant barrel pressure and uniform overrun, downstream pressures need to be held relatively uniform. Changes in product viscosity can affect significantly the pressures against

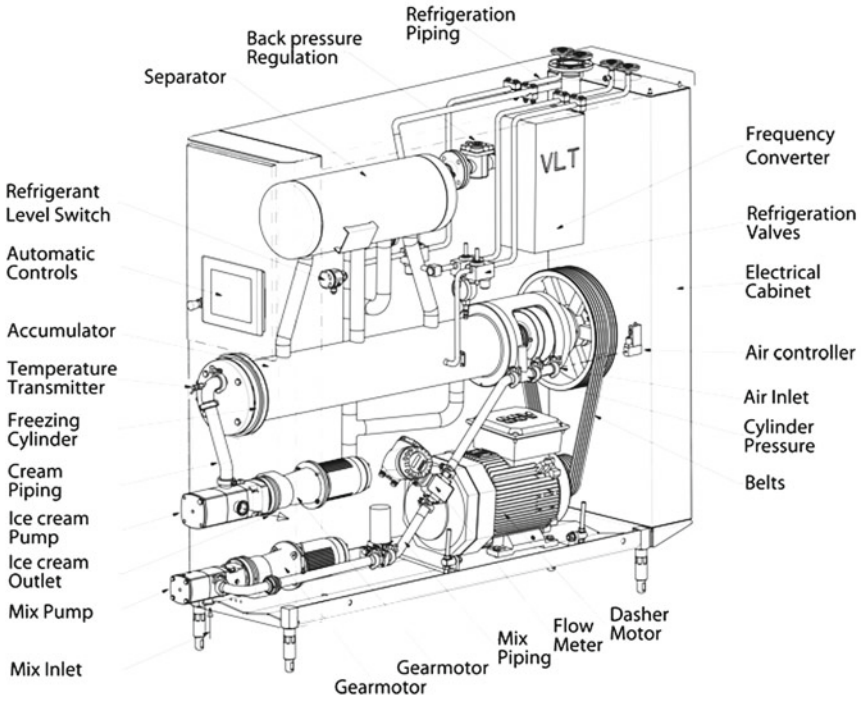

Fig. 7.3 Schematic drawing of a continuous freezer that has both a product pump and a mix pump (courtesy of Tetra Pak Hoyer A/S, Hoejbjerg, DK)

which pumps must work in transporting ice cream from the freezer to the filler. These changes in viscosity can arise from changes in extrusion temperature and from heat conducted through pipelines covered with varying amounts of frost. The two-pump system isolates the freezing cylinder from external pressure changes and tends to yield more constant overrun (Fig. 7.3).

Low-temperature extrusion freezing of ice cream following conventional freezing in a scraped surface freezer (Windhab and Bolliger 1998; Wildmoser and Windhab 2001) has gained in popularity (the so-called slow-churned process) in the past decade. In this system, the ice cream exiting the scraped-surface freezer (at −5 to −6°C) is cooled further (to about −13 to −15°C) in an extruder with slowly rotating screw(s). The product remains pumpable even at this low temperature (and higher ice content) because the shear effects in the extruder prevent ice crystal accretion. The smaller ice crystals, while allowing adequate flow of ice cream from the extruder, also provide smoother texture and greater resistance to ice recrystallization (development of large ice crystals) during storage. The extruder also maintains the finely dispersed air bubble structure by minimizing disproportionation between small and large bubbles, which leads to overall increase in air bubble size. Furthermore, Bolliger et al. (2000) showed that low temperature extrusion generally enhanced fat destabilization, although the additional mechanical shearing minimized

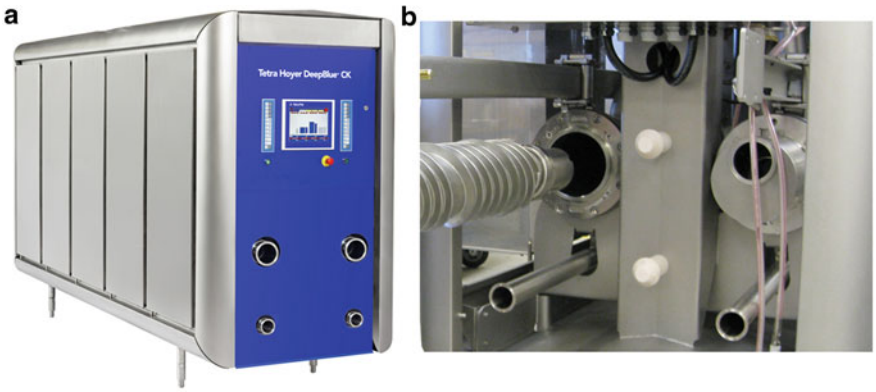

Fig. 7.4 TetraPak Deep Blue second-stage (low-temperature extrusion) freezer: (**a**) external; (**b**) interior of extruder barrel and single-screw (courtesy of Tetra Pak Hoyer A/S, Hoejbjerg, DK)

the size of resulting fat agglomerates. As a result, reduced emulsifier levels were required in the mix to achieve desirable structural and textural characteristics. In addition to these quality characteristic advantages, low temperature extrusion greatly reduces and may even eliminate the need for specific static hardening processes. The advantages of the low-temperature extrusion process in maintaining desirable ice cream microstructures have led manufacturers to introduce reduced-fat products with claims of full-fat creaminess. Tetra Hoyer markets a second-stage freezer (low-temperature extruder) based on this concept, called Deep Blue (Fig. 7.4), with capacities as high as 3,000 L/h (800 gal/min). Special filling units easily accommodate the viscous, low-temperature ice cream product that exits the extruder.

One approach to controlling air incorporation is through pre-aeration of the warm mix ahead of the freezing cylinder. The dasher in the barrel cannot spin fast enough to divide the mass of air injected with the mix until the mix viscosity increases during freezing. Since viscosity increase due to freezing typically starts about one-third of the distance from the entrance end of the freezing chamber in a continuous freezer, most of the small air cells are formed in the distal two-thirds of the chamber. By substantially dispersing the air before mix enters the cylinder, air incorporation is more uniform, particularly in low-fat and nonfat formulations. In consequence, the exiting product appears dryer than when no pre-aeration is done, and smaller variations are seen in overrun and package weight. Frozen desserts made in this way may be comparatively less susceptible to shrinkage in the container. Suppliers recommend testing the device with different formulations to determine the most favorable mixer speed for maximizing benefits of pre-aeration.

Another recent development in ice cream freezer design is product recirculation, generally found in conjunction with pre-aeration in the CREAM (Continuous product Re-circulation with complete Emulsification of overrun Air and Mix) freezer (Fig. 7.5). Here, a portion of the ice cream product from the exit of the scraped-surface freezer is recirculated back into the pre-aeration device. Recirculated product cools

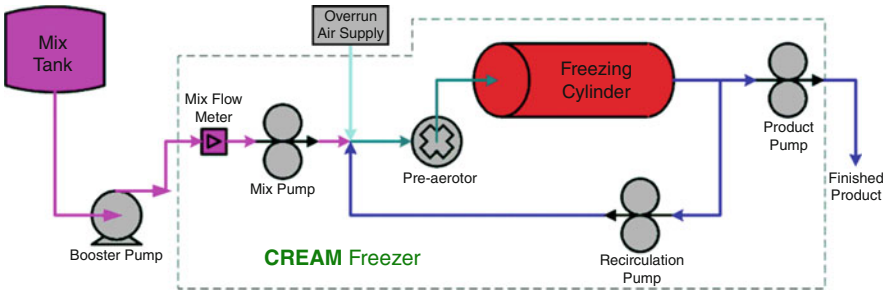

Fig. 7.5 Schematic diagram of CREAM (Continuous product Re-circulation with complete Emulsification of overrun Air and Mix) freezer (courtesy of WCB Ice Cream, Northvale, NJ)

the mix entering the freezer, meaning that more of the freezing cylinder length is devoted to freezing (rather than chilling). This is thought to enhance both ice crystal formation and air cell size reduction.

Dashers function in ice cream freezers to carry the sharp blades that scrape ice from cylinder walls, to agitate the mix and air, forming a finely divided foam, and to partially churn the fat to help stabilize the foam. Dashers come in many different types, from solid (high volume displacement of the cylinder) to open (low volume displacement) (Fig. 7.6). The latter contain beaters within the dasher assembly. High-displacement dashers, those with a solid core that rotate at a high speed, tend to produce a stiffer product than the open dasher that is driven more slowly.

High-displacement dashers, which displace about 80% of the volume in the freezer barrel, have a high speed of rotation and tend to produce ice creams with very small ice crystals. However, these products tend to be highly churned and have slow melting rate. This type of dasher action is desirable for producing extruded products like ice cream bars that are to be enrobed in chocolate. Here, product shape must be maintained long enough for effective hardening, and shape must be maintained when the bar is covered with the warm chocolate. However, the combination of solid dasher with a small annular space between the dasher and the freezer cylinder wall limit the volume of mix in the chamber. As the surface to volume ratio increases, so do chances of freeze-up within the cylinder.

By increasing the diameter of the freezing cylinder and reducing the displacement of the dasher, the freezer becomes much less sensitive to variations in refrigerant supply. Mix tends to act as a buffer against physical changes within the system, and the output is increased in uniformity of temperature and overrun. However, less fat destabilization is likely to occur in such freezers so that the ice cream tends toward a wetter appearance and decreased time of meltdown. In addition, the ice crystals in ice cream made with an open dasher tend be larger, with a broader size range, as the average residence time within the barrel is increased. Currently supplied open dashers displace 15–50% of cylinder volume and can be purchased with or without beaters.

Internal microstructure of frozen desserts is highly dependent on freezer design and operation. The design and state of repair of the cylinder dasher and blades as well as the capacity of the freezer to carry away heat are important determinants of

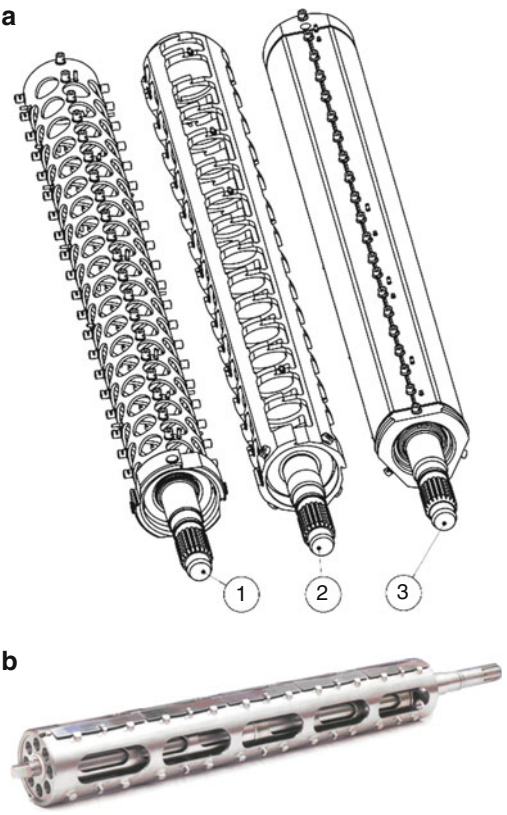

Fig. 7.6 Dashers designed for producing specific types of products in continuous freezers: (**a**) left-open with open beater, center-open with closed beater, right-closed (courtesy of Tetra Pak Hoyer A/S, Hoejbjerg, DK).
(**b**) Open dasher (courtesy WCB Ice Cream, Northvale, NJ)

finished product quality. The ice cream manufacturer is advised to gain full knowledge of these parameters from the manufacturer of the freezer before making a purchase. See Chap. 11, for details on structure development in the ice cream freezer.

Operating the Continuous Freezer

The principal responsibilities of the freezer operator are (1) to regulate the amount of air being introduced into the mix to produce the desired overrun and (2) to control the temperature of the refrigerant on the freezing chamber to give the desired stiffness to the product as it leaves the machine. These two variables need consistent monitoring either manually or by means of a microprocessor, but changes are usually minimal once the system has been brought to a stable condition. Stability is achieved when temperatures of the equipment have been lowered to a steady state by removal of the heat stored in them and the rate of flow of mix and air have been

stabilized. A source of error in overrun control is entrained air in the mix. This can result from adding incompletely melted rerun (mix that previously went through the freezer) to the mix tank, air leaks on the suction side of the mix pump, or from air left over from blending operations.

To achieve optimal freezer operation, mixes must consist of the intended composition and be processed as planned. Air incorporation prior to the freezing process must be minimized, as entrained air coming into the freezer makes it difficult to maintain preset overrun values, and unintended aeration could induce fat destabilization or other structural changes before they should be occurring. At start-up, semi-frozen ice cream is sometimes recirculated back to the entrance of the freezer as rework. If so, this may need to be deaerated prior to entering the freezer. Better practice would be to send all rework back to the mix operation to be repasteurized and blended with fresh mix. Deaeration at that step may also be necessary. An exception to this statement regarding entrained air would be pre-aeration systems that are specifically designed to enhance structure, as discussed in the previous section. Further, mix should be supplied to the freezer pump at a low and constant temperature and at a constant pressure.

Care and maintenance of the freezer and refrigeration system must be given priority if freezing is to be optimal on a daily basis. The following are the chief requisites for keeping the system operating properly:

1. Keep the refrigerant jacket clean and free from oil, water, and nonvolatile refrigerant fractions. Routinely check and drain water, oil, etc., from refrigerant side of freezer, as needed.
2. Keep the scraper blades sharp, clean, and straight. Utmost care should be exercised in handling the blades to avoid bending or damaging.
3. Keep mix pumps in proper working condition.
4. Make certain there is an adequate supply of refrigerant at the freezer. This requires that the entire refrigerant system be maintained.
5. Provide steady suction pressure at about 7 kPa (1 psi) lower than the pressure at which the freezer was designed to operate. An insufficient supply of liquid refrigerant or a significant rise in the suction pressure will soon show up as softness of the discharged product.

Freezer Controls

Automatic process control systems are designed to improve production efficiency and product quality by eliminating the variables of manual operation. An example of the control elements incorporated into modern ice cream freezers is shown in Fig. 7.7. Fully automated freezers offer even greater improvement in production efficiency and product quality. Automatic PLC-operated freezers and process control systems are designed to improve production efficiency and product quality by eliminating the variables of manual operation and by shortening adjustments for optimal start-up and

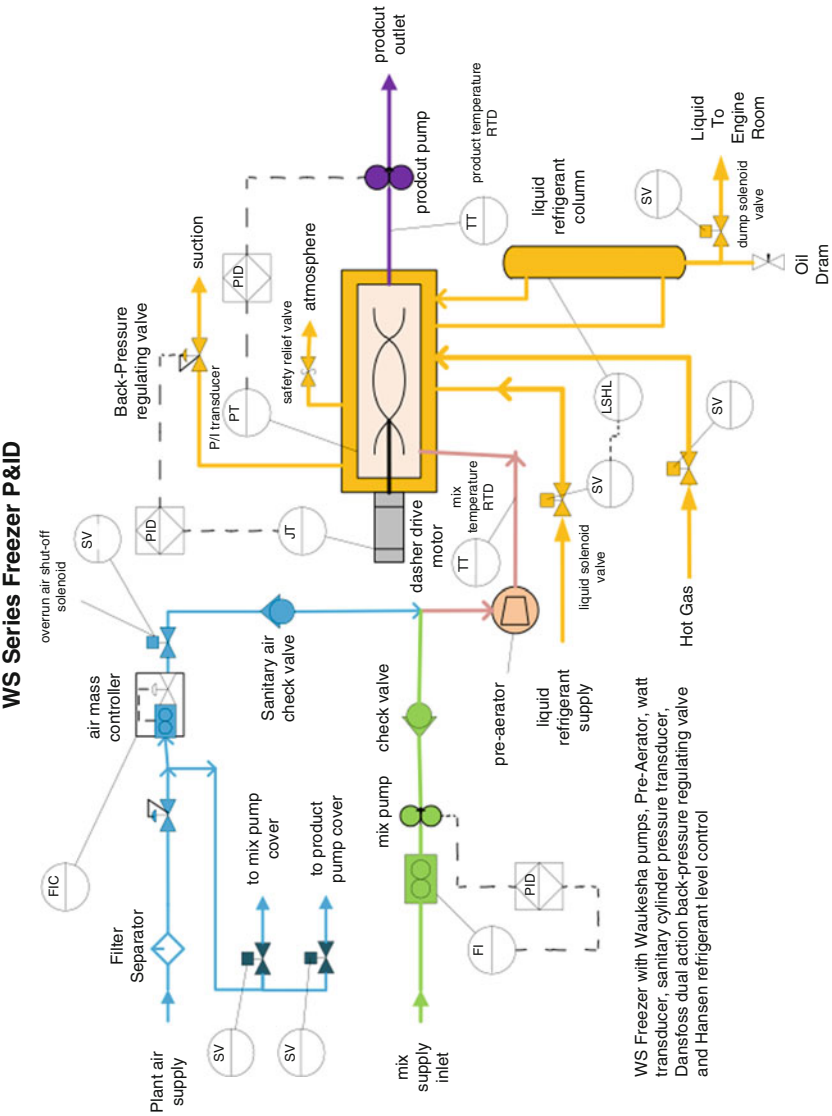

Fig. 7.7 Basic programming elements (P&ID) for continuous ice cream freezing systems (courtesy of WCB Ice Cream, Northvale, NJ)

shut-down sequences and, as a result, reducing start-up and shut-down loss of ice cream. However, as loss of ice cream cannot entirely be avoided during start-up, systems for reworking of ice cream have been developed. In one such system, a rerun tank melts and deaerates ice cream so it can be added to the mix vat or reprocessed. An air purge or blow-down feature clears much of the material from the lines.

Automatic freezers have an advanced control system with predefined start-up, shut down, and production sequences. This control improves production efficiency and product quality by minimizing product losses and securing accurate and constant ice cream outlet flow. This enables filling and portioning of ice cream products with uniform quality, overrun, and product weight. To achieve precise and immediate adaption to preselected production parameters and supply changes, the mix inlet flow, air addition (for overrun), freezing, and cylinder pressure must be rapidly and accurately controlled.

The ratio between the mix pump speed and the ice cream pump speed is automatically adjusted to obtain and hold the desired cylinder pressure, ensuring the desired overrun and ice cream texture. In addition to the normal regulation of the mix flow via the speed of the positive displacement gear pump, exact regulation is carried out by means of an advanced magnetic flow-metering device. The computer compensates automatically for the internal backflow in the mix pump by regulating the speed of the mix pump. As the ice cream contains air and therefore is compressible, small changes in the ice cream viscosity will lead to flow fluctuations of the ice cream and ice cream products of various sizes. Thus, air metering is critical and is based on mass flow metering. The airflow is automatically metered into the mix, which means that the overrun of the frozen ice cream is kept at a predetermined value. Together with the compensation to overrun for barometric air pressure changes, optimal overrun accuracy can be achieved.

Controls of the dasher drive and the refrigeration system are networked to assure proper viscosity control and final product temperature. The desired ice cream viscosity or ice cream temperature is achieved by adjusting the pressure (evaporation pressure) of the refrigerant in the freezer by means of the refrigerant back pressure valve. The product viscosity (stiffness) is measured in percent of dasher motor load (which is continuously monitored), with the full horsepower draw of the motor being 100%. The actual product viscosity or motor load is compared to the desired set point. Motor load below the set point indicates that the product is too soft or too warm, so the controller instructs the refrigeration backpressure valve to open. This will lower the temperature around the freezing tube and lower the product temperature. If the motor load is high, indicating that the product is too stiff or too cold, the temperature on the jacket is automatically raised by means of closing the refrigeration backpressure valve.

Some programmable freezers can be linked to the ingredient feeder and the filler machine to permit the freezer to control the mix flow rate and hence, to adjust rate of production to rate of inclusion addition and package fill. Graphic displays of output of the freezer and the ingredient feeder can be produced with some control units.

The control panel, often now a touch screen, provides easy operation and monitoring of the freezing process. All functions of the machine are operated from the panel. Refrigeration, air, and mix flows are controlled according to computer calculations and advanced control loops, based on the operator's preselected values for ice

Fig. 7.8 Gram (GIF 1200) freezer with rated capacity of 1,500 L/h (courtesy of Gram Equipment Company of America, Inc., Tampa, FL)

cream viscosity or temperature, overrun, and capacity. The control panel provides clear and easily understood information to the operator by means of graphic displays and written text. Full production data for up to 100 products can be stored in the computer memory, facilitating start-up and enabling optimum production conditions to be attained quickly. Essential production data (i.e., ice cream flow, viscosity, and overrun) are displayed constantly during production and at the touch screen the operator is able to bring other data to the screen (for example, mix and ice cream temperature, accumulated mix and ice cream flow, pump speed curves of recent production parameters, etc.). A manual operation mode is available if desired. If disturbances

occur during production, these will be indicated on-screen so that action can be taken. In the case of serious disturbances, the instant stop/hold procedure will automatically be activated. For easy maintenance in stop-mode, a service screen appears automatically to remind which service work has to be done according to preset schedule.

Commercial Freezers

The ice cream equipment manufacturing industry has followed the general industry trends over the past decade with consolidations reducing the number of manufacturers that offer large continuous freezers. There are now four major global companies that manufacture ice cream freezers for commercial-scale operation. These include Gram Equipment Co. (www.gram-equipment.com), TetraPak Hoyer (www.tetrapak.com), WCB Ice Cream (formerly Waukesha Cherry Burrell, www.wcbicecream.com), and Technogel (www.technogel.com).

Gram Equipment Company of America, Inc. offers a series of fully automated freezers with maximum capacities from 420 to 4,000 L/h (110–1,060 gal/h). The GIF models (Fig. 7.8 shows the GIF 1500 model) enable automatic control of production. The smaller models are self-contained, with Freon as refrigerant, while the larger models can be set to use either ammonia or CO_2.

TetraPak Hoyer offers several models of continuous ice cream freezers. The Frigus KF series provides full automation and comprehensive monitoring of all main production parameters (Fig. 7.9). Six KF models are available with capacities from 100 to 4,300 L/h (26–1,150 gal/h). Several of the KF models are available as manually controlled freezers. The Frigus SF series are self-contained Freon units with maximum capacity values from 300 to 1,200 L/h (80–317 gal/h). The Frigus SF freezers are available as manually controlled or PLC-controlled. The KF 80 XC model freezer is a laboratory unit with capacity from 10 to 100 L/h. The Hoyer Deep Blue, as noted earlier, is a second-stage freezer capable of reducing temperature to −12 to −15°C (10 to 5°F) at a maximum capacity of 3,000 L/h.

WCB Ice Cream offers four series of industrial continuous freezer, which includes the WS (standard freezer), EE (energy efficient freezer), and CREAM (this freezer utilizes the patented CREAM process to improve product quality). These freezers are offered in capacities ranging from 500 to 4,500 L/h. The customer may select manual, semiautomatic and automatic controls, with the automatic version providing PLC control of six modes of freezer operation and PID control of the mix flow, overrun air, viscosity (product stiffness), and cylinder pressure. Figure 7.10a shows the standard WS freezer while Fig. 7.10b shows the CREAM freezer, with the ice cream recirculation line at the bottom left of the unit.

Technogel (Fig. 7.11) offers a line of continuous ice cream freezers (Explorer models) with a maximum capacity range from 100 to 1,500 L/h. The freezers are self-contained with Freon refrigerant and are equipped with modern control options.

Fig. 7.9 Tetra Hoyer Frigus-KF freezer (courtesy of Tetra Pak Hoyer A/S, Hoejbjerg, DK)

Sanitary Design of Ice Cream Freezers

3-A Sanitary Standards, Inc. (McLean, VA) provides the guidelines for manufacture and accepted practices related to batch and continuous ice cream freezers (see www.3-A.org). The latest standard entitled "Batch and Continuous Freezers for Ice Cream, Ices, and Similarly Frozen Dairy Foods" was issued as Document Number: 3A 19-07 on December 1, 2008. The purpose of this standard is to describe the sanitary features of batch and continuous freezers for ice cream, ices, and similarly frozen dairy foods and equipment integral therewith. This includes pumps, equipment for incorporating air or flavoring material into the product and mix supply tanks attached to and

Fig. 7.10 WCB Ice Cream freezers. (**a**) WS series. (**b**) CREAM freezer (courtesy of WCB Ice Cream, Northvale, NJ)

made as a part of the freezer. Soft-serve freezers are not covered under this standard. Permitted materials are described, as are features of sanitary design and fabrication.

Start-Up and Shut Down of a Continuous Freezer

During start-up operations, a significant amount of waste is generated before the freezer reaches steady state and high-quality product is produced. Prior to start-up of a continuous freezer, the operator must ensure that it is sanitized properly (see Chap. 13) before starting flow of mix into the freezer.

During start-up, mix is pumped into the barrel to push out any remaining sanitizer solution. Once the barrel is operating with mix, refrigerant is allowed to flow into the evaporator and freezing begins. As the product in the barrel begins to freeze, its viscosity increases as measured by the torque on the dasher motor. When the viscosity set point for the freezer is reached, mix and product pumps are started to allow flow of ice cream. Air injection is started at the same time. Cold product then flows through the warm pipes into the ingredient feeder and filler. It is not until steady state operation is reached that quality product is packaged for sale. Prior to

Fig. 7.11 Technogel Explorer model continuous freezer (courtesy of Technogel, Greensboro, NC)

that, any material exiting the fillers is treated as waste. Modern freezers are designed to minimize the amount of waste generated during start-up.

Once the freezer is started, the refrigerant is shut off from the freezing chamber only when the machine is to be stopped. Usually the refrigerant is turned off a few minutes before the last of the mix is to enter the chamber. This permits the machine to warm to an extent that the rinse water that follows the last of the mix can pass through without being frozen. The rinse water temperature should not exceed 38°C (100°F) to avoid heat stress damage to the very cold cylinder. To avoid high wear due to friction, freezer operation should be minimized during rinsing. Once the water passing through the freezer has flushed out most of the solids, the freezer should be shut down. It then goes through a proper cleaning and sanitizing protocol as described in Chap. 13.

Freezer Outlet/Ice Cream Piping

The product exiting the scraped-surface freezer is ready for further processing. The design and dimensions of the exit piping are important to efficient operation since the product pump must be sized to overcome the frictional losses as the product

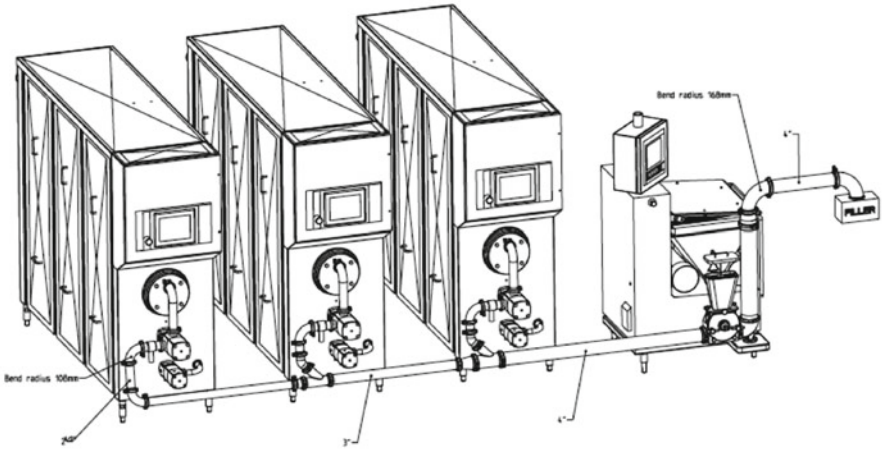

Fig. 7.12 Three freezers in series feeding one ingredient feeder (courtesy of Tetra Pak Hoyer A/S, Hoejbjerg, DK)

moves toward the fillers. Some general guidelines for efficient design of the piping include:

1. Minimize restrictions.
2. Maintain the pipe diameter given by the outlet pump.
3. Keep piping to no longer than needed, typically between 5 and 10 m.
4. Minimize bends and turns, use large radius bends.
5. Avoid all sharp flow changes.
6. Avoid valves in the outlet piping; if needed, select valves with "straight" flow through.
7. Use pipe fittings/bends to connect the freezer between two different filling machines instead of using a "change-over valve."
8. Do not isolate the outlet pipe as this leads to high back pressure in the ice cream pipe.
9. Use stainless steel piping instead of rubber housings.

In large-scale operations, multiple freezers feed into a single pipe for filling, as seen in Fig. 7.12. If inclusions are to be added, the single large-diameter product pipe goes through an ingredient feeder prior to filling. See Chap. 10 for more details on packaging and filling operations.

Continuous Ingredient Feeders

Solid materials, fruits, nuts, candies, etc., are usually added to soft frozen product as it exits the continuous freezer. Fruit and ingredient feeders (Fig. 7.13) are made to

Fig. 7.13 Continuous ingredient feeder (courtesy of Tetra Pak Hoyer A/S, Hoejbjerg, DK)

distribute these materials at the rate chosen for the particular product. An augur-style device is used to continuously feed pieces or chunks into ice cream after the scraped-surface freezer. Older ingredient feeders were more prone to breaking of particulate pieces, but newer designs in ingredient feeders allow for larger inclusions to be incorporated into flowing ice cream with less damage to the integrity of the piece. Newer ingredient feeders can also be automatically programmed to allow for accurate dosing of the ingredient depending on the flow rate of ice cream from the continuous freezer. This requires accurate flow rate measurement of the inclusion itself, which can be difficult depending on its shape and bulk density. Gear-type positive displacement pumps are used to force syrups, jams, or purees through small orifices into flowing streams of soft-frozen desserts to make variegated, ripple or swirl-type products. Depending on the distribution pattern desired, the nozzle, which usually has multiple orifices, may be rotated at speeds controlled by the operator.

The Batch Freezer

The batch freezer is a less complicated machine than the continuous freezer. Each batch of product is measured, flavored, colored, and frozen separately. Batch freezers are often used in small manufacturing plants and in product development laboratories. They are less costly to install than small continuous freezers and they allow small volumes of particular flavors to be made. Packaging remains a manual operation.

Batch freezers generally consist of a horizontally oriented cylinder of capacities ranging from 15 to 40 L (4–10 gal), a dasher, designed to propel the product toward the discharge port, the refrigeration unit (compressor, condenser, expansion valve, and evaporator—in this case the freezer cylinder), a cabinet, and in some models a mix supply tank. The refrigerant is typically a halocarbon type, usually R22 or R502, although with the environmental concerns over chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), new refrigerants are continually being developed. Further details on halocarbon refrigerants and their use in ice cream manufacturing plants are provided later in this chapter.

The temperature of the refrigerant should fall in the range of −23 to −29°C (−10 to −20°F) to provide for rapid formation of small ice crystals while permitting development of desired overrun. Freezing too slowly causes large ice crystals to form, whereas freezing too rapidly limits time for incorporation of air. The drawing temperature of ice cream from the batch freezer, −5 to −6°C (23–25°F), is slightly higher than that used for continuous freezers and residence times in the freezer barrel are substantially longer for batch processing (5–6 min). This results in batch-frozen products having slightly larger ice crystals than continuous-frozen products. Typically, air cells are larger as well due to the nature of aeration. Precise overrun control is difficult with a range of 10–15% being experienced during emptying of the barrel. This occurs because the dasher continues to operate during unloading of the freezer. Whippability of mixes must be high because air is present at atmospheric pressure.

Although freezers for soft-frozen products, including milk shakes and frozen beverages operate on the same general principles as batch freezers, they have some unique characteristics. They must be capable of holding the product frozen while avoiding churning and significant variation in overrun. This subject is discussed in Chap. 8.

Numerous companies produce batch freezers for a variety of operations. These include Emery Thomson (http://www.emerythompson.com) (Fig. 7.14), Taylor (www.taylor-company.com) (Fig. 7.15), Carpigiani (carpigiani-usa.com) (Fig. 7.16), Stoelting (www.stoelting.com) (Fig. 7.17), SaniServe (www.saniserv.net) (Fig. 7.18), and Technogel (www.technogel.com) (Fig. 7.19), among others.

Operation of the Batch Freezer

In preparation for use, freezer parts should be examined for cleanliness and state of repair. After the operator's hands have been thoroughly washed, the freezer should

Fig. 7.14 Emery Thompson 44-quart capacity batch freezer (courtesy of Emery Thompson Machinery and Supply Co., Brooksville, FL)

be assembled according to manufacturer's instructions. Sanitization can be accomplished with hot water, but in doing so the final temperature must be 82°C (180°F) to achieve adequate sterility. Since that heat must be removed from the cylinder during freezing, chemical sanitizers are recommended instead (see Chap. 13). It is important to drain the sanitized freezer well to avoid contamination of the first batch of product. While sanitizing, the dasher should be turned no more than a few revolutions to minimize wear.

The second step in freezing is to add a measured amount of flavored and colored mix. The total volume of these components should take into consideration the desired overrun by leaving sufficient headspace for whipping of air to occur; for example, about one-half the capacity of the freezer if 100% overrun is desired, or more mix if less overrun is desired. After the mix is added into the freezer, the dasher is started and the refrigerant is turned on. This order of operation is important in the avoidance of damage to the machine. Scraper blades will dull rapidly if the dasher is operated with no mix in the cylinder. Refrigerant must never be turned on unless the dasher is in motion. Starting a dasher that is frozen to the cylinder wall can cause damage to the dasher or the drive mechanism.

Incorporating particulate flavoring and coloring materials to batch-frozen ice cream can be done either by adding them into the freezer through the mix hopper (if of large-diameter opening) near the late stages of freezing or by incorporating them manually into the ice cream after it is drawn from the freezer (into a large mixing

Fig. 7.15 Taylor freezer Model 220, 20 quart capacity (courtesy of Taylor Co., Rockton, IL)

bowl) before packaging. If added into the freezer while it is still operating, there must be enough time before emptying of the freezer to become uniformly distributed, but the order and moment of adding them varies with the product. The mixing action of the dasher may be sufficient to disrupt and damage product integrity to the point where it becomes unacceptable, so ingredients should be added only after mix has begun to thicken. Nuts, fruits, cookies, and baked goods will remain in larger pieces, and candies will be less likely to dissolve if they are added late in the freezing cycle. Manufacturer's suggestions serve as general guides, but each operator should determine the proper time for adding such ingredients based on the specific conditions and product ideal.

The time to shut off the refrigeration may be determined by the operator drawing a small portion of ice cream and checking temperature. Experience and training are

Fig. 7.16 Carpigiani freezer LB-502 series, 20-quart capacity (courtesy of Carpigiani, Winston-Salem, NC)

necessary to learn the appearance of the partially frozen mix that dictates stopping the refrigerant from flowing into the chamber around the barrel. Much of the whipping takes place after the refrigerant is turned off. Some freezers have automatic shutoff controls that respond to selected amperage of the circuit that supplies electricity to the dasher motor.

Shutting off the refrigeration too soon can result in (1) an extended whipping time with possible failure to obtain desired overrun, (2) soft ice cream, and (3) coarse texture. Likewise, failure to turn off the refrigerant soon enough can result in (1) extended whipping time to obtain desired overrun, (2) stiffer ice cream with a lower temperature, (3) inability to remove all of the product from the barrel, and (4) smoother texture provided the product does not have to warm excessively to produce desired overrun. The main consideration, then, is selection of the optimal consistency for whipping the mix. This property will vary with composition of the mix, flavorings added, construction of the freezer, rate of freezing, and temperature in the freezer. During whipping, air bubbles form but some burst, yet there is a net gain in

Fig. 7.17 Stoelting batch freezer, model VB25, 25-quart capacity with a vertical freezing barrel (courtesy of Stoelting, Kiel, WI)

air content until maximal overrun is reached. With continued whipping and a rise in temperature there is a net decrease in air cells. For this reason, it is important to empty contents of the freezer quickly. When the ice cream is drawn from the freezer, it should be stiff enough to form a "ribbon," yet soft enough to slowly settle into the container and to lose its shape in a minute or two. If a small amount of ice cream becomes too soft to package, it may remain in the barrel and be refrozen with the next batch provided the color and flavor will blend well. Pieces of residual fruit and nuts cannot be removed without taking the freezer apart, so it is best to plan the sequence of freezing starting with plain ice creams and progressing to those that contain particulates. It should always be the practice that nut-containing products be frozen last to avoid carryover of nuts to containers that do not show on the label the type of nut that might be contained.

Fig. 7.18 SaniServe model B-10, 10-quart capacity (courtesy of SaniServe, Mooresville, IN)

Filling Containers from a Batch Freezer

The freezer should be emptied as rapidly as possible to prevent wide fluctuations in overrun among packages, since the ice cream will continue to whip while being drawn out. As mentioned above, ice cream may need to be drawn into a large pre-cooled mixing bowl if that proves to be the only way to adequately incorporate particulate ingredients and maintain their shape and integrity. If filling directly into packaging, caution is in order to prevent formation of air pockets that leave the container partially filled. This problem is experienced when the ice cream is so stiff as to not flow readily. Well-frozen ice cream is desired from a quality standpoint, but some compromise in freezing temperature endpoint may be necessary to permit efficient and adequate fill.

Large containers are usually filled directly from the freezer. Small containers are best filled from a packaging machine fed through a hopper; otherwise, it may be necessary to fill them manually after discharging the ice cream from the freezer.

Fig. 7.19 Technogel Mantogel-30 batch freezer, 30–40 quart capacity (courtesy of Technogel, Greensboro, NC)

Other Freezer Types

Over the years, a variety of other methods of producing frozen desserts and similar products have been developed. These include direct cryogenic freezing (e.g., liquid nitrogen) and shaving a previously frozen product into finely dispersed elements to create a smooth frozen product (e.g., Pacojet). It may also be possible to make frozen dessert-like products from specially formulated mixes that can be stored at ambient temperatures and frozen by the consumer by simply placing the package in a home freezer.

Cryogenically Frozen Products

Liquid nitrogen (LN_2), with a boiling temperature of −196°C at atmospheric pressure, provides rapid freezing of ice cream mix or ice cream. LN_2 can be used for

rapid hardening of ice cream containers in small-scale operations. It can also be used to rapidly freeze ice cream bars to very low temperatures in some novelty manufacturing operations (see Chap. 9). However, the most common use of LN_2 has been for the freezing of small drops or pellets of ice cream mix to create a novel means of serving. Allowing ice cream mix to drop into LN_2 causes the drop to solidify almost immediately. Finely dispersed, dendritic crystals are formed due to the rapid rate of cooling (Hindmarsh et al. 2007), although because of the excessively low temperatures, full ice crystallization is inhibited. Ice cream mix, when cooled below approximately −35°C, turns into a glassy state (Goff et al. 1993; Goff and Sahagian 1996) where ice crystallization is inhibited due to the lack of mobility of the water molecules at that low temperature. As the drop falls into the LN_2, dendritic ice crystals form initially in the freezing zone, but as temperature falls further, below the glass transition temperature, molecular mobility inhibits further freezing. The result is a solidified drop in the glassy state that contains dendritic crystals distributed randomly throughout. As long as the drop remains below the glass transition temperature, the unfrozen portion remains in the glassy state. As soon as the drop warms up to temperatures above this point, the mobility of water molecules is now sufficient to allow further ice crystallization, which is accompanied by a release of latent heat. For this reason, such products must be held at very low temperatures or else they are prone to melting and agglomeration.

When a cryogenically frozen product warms up to normal freezer storage temperatures of −20 to −10°C, ice crystallization continues to occur, potentially causing deleterious effects on product quality. For example, if beads of cryogenically frozen product are placed in a normal home freezer (−20°C or above), sufficient ice crystallization and latent heat generation occurs to actually melt the surface of the bead and cause it to become sticky. Beads will thus clump together rather than remain free-flowing. Thus, these products are highly sensitive to storage conditions (e.g., temperature fluctuations) and have very short shelf life at normal frozen-chain distribution conditions. One means of enhanced stability of these beads has been to further coat the bead in a layer of ice, thereby protecting the product itself from becoming sticky and clumping.

Because of the freezing method, cryogenically frozen products generally have very low air incorporation, making each drop fairly dense. Since they are eaten in the form of small beads, however, air incorporation during freezing is not needed to produce an acceptable product.

Shaving Devices

One unique approach to creating a frozen dessert (although the process is not limited to desserts) is a device that shaves fine bits off a previously frozen block of product (see www.pacojet.com). A high-precision blade spinning at 2,000 rpm shaves a micro-thin layer of the frozen food into the container below. For example, a block of frozen fruit inserted into this shaving device would create a smooth,

creamy frozen product, similar in nature to a smoothie, but made of pure fruit. This system does not allow air incorporation, unless pre-whipping of the product is done prior to freezing. However, even if not pre-aerated, the finely shaven pieces embed space that provides some aeration.

Consumer-Frozen Shelf Stable Products

Over the years, an elusive goal of frozen dessert manufacturers has been a product that is contained in a shelf stable package that the consumer places in the home freezer prior to consumption and that freezes into an acceptable frozen dessert. The problem has been that freezing in such an environment (static with relatively warm freezing temperature) leads to formation of low numbers of large and typically dendritic, ice crystals (similar to a quiescently frozen popsicle). Previous unsuccessful attempts at such a convenience product have required the consumer to periodically remove the package from the freezer and massage it vigorously to break up the large ice crystals. If a food-grade ice nucleating agent was added to the premix, this could help induce small crystals and smoother texture, but thus far such an ingredient has not yet become available.

Refrigeration

Refrigeration in food processing is the removal of heat from a substance to lower its temperature and/or change the state of water to ice. In an ice cream manufacturing plant, refrigeration is used for various cooling duties (e.g., cooling of ice cream mix) or, most importantly, for freezing of ice cream. At the same time the product is being cooled or frozen, the transfer of heat during refrigeration involves the cooling medium gaining energy (heat). Thus, "refrigeration" is the reverse of "heating," with both occurring simultaneously and being dependent on the same principles and factors of heat exchange. The ice cream industry typically uses the term "refrigeration" to mean the process of cooling to temperatures between 4.4 and −34°C (40 and −30°F). "Chilling" is a term typically used for lowering temperature without freezing being involved (as in cooling the pasteurized mix), but often the terms refrigeration and chilling are used synonymously.

Refrigeration Principles

The removal of heat from a substance in chilling or refrigeration means an equal amount of heat energy is absorbed by the cooling medium. This energy transfer may result in either a change in temperature of the cooling medium or an endothermic

(requires heat energy input) change in state. In some refrigeration systems, both types of heat transfer (temperature increase and change in state) might occur. For example, water can cause a cooling effect by absorbing heat from another material so that the temperature of the water increases. In this case, the cooling is due to the change in sensible heat (change in temperature) of the refrigerant and the amount of heat lost by the product is essentially the same as the amount of energy absorbed by the water. In other cases, the heat absorbed by the refrigerant is used to cause a phase change, like melting of ice or evaporation of water. For example, cooling due to evaporation of water (evaporative cooling) occurs in many places, including certain types of air conditioners ("swamp coolers") used in the American Southwest. In this system, as the water evaporates, the energy needed for water to become vapor (vapor molecules have more energy than liquid molecules) must come from the environment in which the water is sprayed; thus, that environment is cooled by the amount of energy needed for vaporization. It is the energy required to cause water to evaporate (change phase from liquid to vapor) that provides the bulk of the cooling effect in this case. The energy associated with the phase change is the latent heat (in this case, the latent heat of vaporization).

The total heat content of a material can be considered as a combination of the temperature of that material and the energy associated with its state (vapor, liquid, or solid). The change in this heat content relative to some arbitrary condition is called the enthalpy. The enthalpy change of a refrigerant (ΔH) as it heats from one temperature, T_1, to another, T_2, is given as

$$\Delta H = mC_p(T_2\text{-}T_1)$$

where, m is the mass of material being heated, and C_p is specific heat. Since C_p of water is approximately 4.18 kJ/kg K (1 Btu/lb°F), the enthalpy change associated with heating 1 kg of water by 10°C would be

$$\Delta H = (1\text{ kg})(4.18\text{ kJ / kg K})(10\ ^{\circ}\text{C}) = 41.8\text{ kJ}.$$

If there is a change of phase, the amount of enthalpy change is found as the product of the mass of material that changes state (m_r) and the latent heat (λ) for the phase change. That is,

$$\Delta H = m_r\lambda$$

In the case where both latent heat and sensible heat are important in a refrigeration system, the change in enthalpy associated with the refrigerant would be the sum of the two terms. For the case where a refrigerant is first heated from T_1 to T_2 and then undergoes a phase change, the change in enthalpy is written as

$$\Delta H = mC_p(T_2\text{-}T_1) + m_r\lambda$$

The enthalpy change of the refrigerant ultimately goes into cooling down the product. The amount of energy change in the product (Q_{cooling}) as it is cooled by the refrigerant, assuming no heat losses to the environment, is essentially equivalent to the enthalpy change of the refrigerant, or

$$Q_{\text{cooling}} = \Delta H$$

However, the change in the product depends on the refrigeration process in question. In chilling operations, the product decreases in temperature according to the amount of heat removed by the refrigerant. In freezing operations, the latent heat of fusion as ice crystallizes must also be taken into account.

In the production of ice cream, a refrigeration effect is needed to remove the heat necessary to freeze ice and cool the product. In the dynamic freezing process (Fig. 7.1), mix enters the freezing chamber at a temperature just slightly above its freezing point. Initially, the mix must be cooled to a temperature below the freezing point to initiate ice crystal formation. The amount of sensible heat removed in cooling the mix is dependent on the thermal properties of the mix, which depends on its composition (heat capacity). Once freezing occurs, the refrigeration system must remove the latent heat associated with forming ice in the barrel of the freezer. At the same time as ice is forming, the unfrozen mix (containing a slurry of ice crystals) continually cools to the draw temperature at which ice cream is removed from the freezer barrel. Thus, in the dynamic freezing step, the refrigeration system must remove heat associated with cooling the mix, formation of ice and further cooling of the ice cream slurry to the draw temperature as well as frictional heat input from the dasher. In the static freezing step (hardening), additional heat is removed as temperature is lowered further and additional ice is formed. The refrigeration system in the hardening room must remove the heat associated with reduction in temperature along with that released as additional ice is formed.

Commercial continuous ice cream freezers are supplied with liquid refrigerant, usually ammonia, from the in-plant refrigeration system. High pressure, liquid refrigerant is throttled through an expansion and enters the chamber surrounding the freezing cylinder (Fig. 7.20) through an electrically controlled solenoid valve and a float valve that maintains the proper refrigerant level around the freezing cylinder. This cylinder is flooded with low-pressure liquid refrigerant, which, on absorbing heat from the ice cream mix, boils and vaporizes. Flooded barrels are preferred over direct expansion refrigeration systems to enhance heat transfer from the liquid refrigerant to the ice cream mix. The vaporized refrigerant exiting the freezer is carried to the compressor, where it is recompressed back to high pressure. The high pressure refrigerant gas passes through a condenser, where it is liquefied. The high-pressure liquid refrigerant is then again circulated through the expansion valve to the freezer. For protection against freeze-up, continuous freezers have a hot gas line, equipped with a solenoid valve, to carry hot gas into the chamber surrounding the freezing cylinder. This unit can be activated manually or automatically. For example, if the ammeter (for measuring electric current), because of high demand for

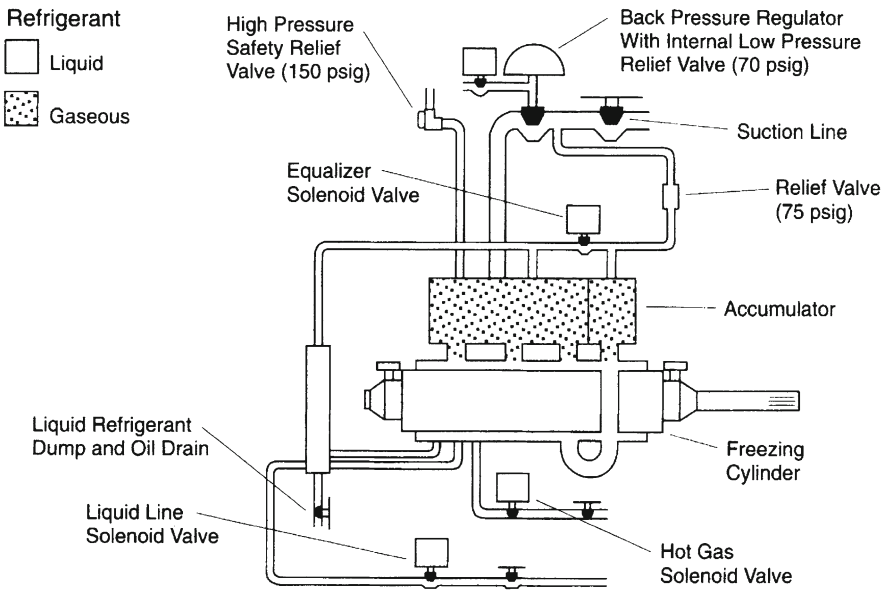

Fig. 7.20 Schematic diagram showing the refrigeration system for an ice cream freezer in the "on" mode (courtesy of WCB Ice Cream, Northvale, NJ)

current, were to indicate the torque on the dasher motor to be exceeding a set point, the solenoid valve could be automatically opened so hot gas would flow into the chamber with the liquid refrigerant. The temperature would immediately rise, and defrosting of the freezer cylinder would occur.

Types of Refrigerants

Refrigerants may be distinguished by their main mode of action. A primary refrigerant is one in which the latent heat associated with its phase change provides the bulk of the refrigeration effect. In contrast, a secondary refrigerant is a fluid used for providing cooling and that has been cooled by a primary refrigerant. Primary refrigerants of importance in ice cream manufacture include ammonia and the class of refrigerants called "halocarbons," whereas secondary refrigerants used in ice cream facilities typically include chilled water, brine, and glycol solutions.

Primary Refrigerants

For the best heat transfer, a primary refrigerant should be a fluid (not a solid or vapor) when in contact with the material to be cooled. The best primary refrigerants

Table 7.1 Comparison of properties of primary refrigerants for 1 kW cooling load for a refrigeration cycle with −15°C evaporating temperature and 30°C condenser temperature

	CO_2	Ammonia	Freon (R-12)
Evaporating pressure (kPa gage)	2,191	137.8	81.3
Condensing pressure (kPa gage)	7,084	1,068	640.9
Refrigeration effect (kJ/kg)	131.8	1,104	118.6
Refrigerant circulated per ton (g/s)	7.6	0.90	8.4
Vapor density at −15°C (kg/m^3)	59.8	3.2	10.7

Note: 1 atmosphere of pressure (14.7 psi) is 101.3 kPa

are those that give a large refrigeration effect (high latent heat) under conditions of high heat transfer (fluid phase). Several compounds exhibit this behavior, including ammonia and the halocarbons. Some important comparisons among three primary refrigerants are shown in Table 7.1.

Ammonia has been used for a long time and is the most common refrigerant used in large-scale ice cream operations. From Table 7.1, the most important advantages of ammonia are that it absorbs a large amount of heat when vaporizing (large refrigeration effect) and its operating pressures are reasonably convenient for freezing cycles with typical operating temperatures between −15°C (5°F) and 30°C (86°F). Other advantages of ammonia are that leaks are easily detected and its toxicity is not great in low concentrations despite its pungent odor. Ammonia does, however, have some disadvantages, including the relatively low density (Table 7.1). This low density means that relatively large pipes and compressors are needed to handle the volume of vapor flow generated. Another major disadvantage is the health hazard associated with ammonia leaks. Even minor leaks produce the objectionable odor and result in a pronounced irritating effect on mucous membranes and wet skin.

The halocarbons, including CFCs, hydrofluorocarbons (HFCs), HCFCs, and hydrofluoroolefins (HFOs), are often used as primary refrigerants in the ice cream industry. These refrigerants come in many different chemical compositions, as both pure component fluids and mixtures of various pure components. Halocarbons such as R-12 (dichlorodifluoromethane) and R-502 (a mixture of R-22 and R-115) are two refrigerants that have been widely used for many years in small ice cream freezers and freezer cabinets. However, these refrigerants were banned by an international agreement of developed countries as outlined in the 1987 Montreal Protocol. The Montreal Protocol led to the promulgation of the Clean Air Act (CAA) in the United States. In the CAA, Congress adopted time lines for the phase-out of CFC-based refrigerants consistent with the Montreal Protocol. The CAA permitted continued use of CFC refrigerants in existing equipment; however, it outlawed the manufacture of new CFC refrigerants on January 1, 1996. In addition, time lines for the phase-out of HCFC refrigerants were established as part of the CAA. On January 1, 2010, the use of R-22 began phasing down, starting with a ban on manufacturing and shipping new equipment with R-22. The refrigerant itself will continue to be manufactured, but in progressively reduced quantities until is completely phased out by 2020.

The main disadvantages of halocarbon refrigerants, other than the relatively low refrigeration effect (Table 7.1), are (1) leaks are not easily detected (a special Halide torch that gives a pink flame in the presence of Freon can be used to detect leaks), (2) the system must be tighter than for ammonia to avoid leaks (small leaks are not noticeable), and (3) they are less satisfactory than ammonia for very low temperatures. Environmentally, these compounds have been shown to cause depletion of the ozone layer and most contribute to global warming. They are currently categorized by their ozone depletion potential (ODP) and global warming potential (GWP).

A new, more environmentally friendly set of refrigerants that do not contain CFC or HCFC constituents are currently available, many of which can be used for chilling and freezing in an ice cream facility. One alternative for R-502 is R-404A, an HFC mixture containing 44% pentafluoroethane (CF_3CHF_2), 52% 1,1,1-trifluoroethane (CF_3CH_3), and 4% 1,1,1,2-tetrafluoroethane (CH_2FCF_3). R-404A has no ODP and has been approved for long-term use in refrigeration systems. Another approved refrigerant with potential application to freezing of ice cream is R-507A, an HFC mixture containing equal amounts of pentafluoroethane (CHF_2CF_3) and 1,1,1-trifluoroethane (CH_3CF_3). A comparison of the physical properties of R-507A and R-502 is given in Table 7.2. Although these refrigerant mixtures may be used to replace R-502, they are not without problems. First, environmental issues still exist with HFC refrigerants in that they are recognized as greenhouse gases. Also, the conversion to the new refrigerant requires considerable modification of existing refrigeration system designs. Typically, the systems using the new refrigerants require larger condensers and more airflow over the condenser to remove sufficient heat. Furthermore, use of R-404A and R-507A requires a polyester type oil, neither of which is compatible with the oils commonly used in refrigerant systems.

Because HFC refrigerants have considerable GWP, the quest for potential refrigerant alternatives that do not deplete the ozone but have lower GWP continues. This desire has led to the development of the newest class of halocarbon refrigerants known as hydrofluoroolefins (HFOs). HFO refrigerants are in the very early stages of development, but initial applications have targeted the replacement of HFC-134a refrigerants in automotive air conditioners (Minor and Spatz 2008; Tanaka and Higashi 2010). Refrigerant HFO-1234yf has thermodynamic properties very similar to HFC-134a but early assessment suggests that it will not be suitable as a "drop-in"

Table 7.2 Comparison of R-507 and R-502 refrigerants for 1 kW cooling load for a refrigeration cycle with −15°C evaporating temperature and 30°C condenser temperature

	R-507	R-502
Evaporating pressure (kPa gage)	279.1	247.2
Condensing pressure (kPa gage)	1,364.0	1,217.6
Latent heat of vaporization (kJ/kg)	175.3	156.5
Net refrigeration effect (kJ/kg)	112.9	104.4
Coefficient of performance (COP)	4.25	4.35
Specific volume of suction vapor (m^3/kg)	0.051	0.050
Refrigerant circulated per kW (g/s)	8.85	9.58

replacement for HFC-134a (Reasor et al. 2010). Because HFO-1234yf has a very short atmospheric lifetime (11 days) compared to HFC-134a (14 years), it has a very low GWP (4) compared to the GWP of HFC-134a (1,430). Because HFO refrigerants generally include hydrocarbons as a blend component, they are classified as "slightly flammable," whereas their HFC counterparts were completely nonflammable. Managing flammability will be a concern in the near future for HFOs.

In recent years, particularly in Europe, there has been renewed interest in CO_2 (R-744) as a primary refrigerant. In fact, in the early twentieth century, CO_2 was an important refrigerant for a variety of applications (storage systems, displays, kitchen and restaurant coolers, and even comfort cooling systems) (Kim et al. 2004). For a variety of reasons, CO_2 was replaced by the halocarbons when CFCs were introduced in the 1930s and 1940s. With the growing environmental concerns surrounding the halocarbons, there was renewed interest in CO_2 as a primary refrigerant in the 1980s and 1990s (Lorentzen 1994). CO_2 in vapor compression systems, whether alone or in tandem with another refrigerant, has potential to help resolve some of the safety and environmental concerns of other primary refrigerants.

Secondary Refrigerants

The most common secondary refrigerants used in ice cream manufacture are chilled water, brine, and glycol solutions. In each case, the refrigerant provides a cooling effect at the same time as it warms up. The warmed secondary refrigerant is cooled again for reuse by expansion of a primary refrigerant in a mechanical refrigeration system. Secondary refrigerants are used mainly for chilling operations (i.e., in plate coolers after pasteurization or maintaining temperature in mix storage tanks), although they may also be used for freezing of frozen novelties.

Chilled water. Chilled water is widely used as a refrigerant in dairy plants because it is inexpensive and stores considerable heat. However, temperatures below 0°C (32°F) cannot be attained with a chilled water system, and it can only be used for chilling operations.

A chilled water system is made up of an ice builder, where a primary refrigerant is used to cool water into ice, and a circulation system for pumping chilled water around the plant. A layer of ice is formed on the evaporator coil of a mechanical refrigeration system and the water in contact with that ice at the freezing point of water is the chilled water that is circulated through the plant.

Brine. The addition of salt to water lowers the freezing point of the mixture sufficiently so that freezing of an ice cream mix can be induced (see Chaps. 5 and 6 for more details on freezing point depression and its calculations). Under usual conditions, it is not practical to obtain temperatures below −15°C (5°F) by this method, although it is possible to cool brine to temperatures well below −30°C (−23°F). Table 7.3 shows freezing temperatures for solutions of sodium chloride (NaCl) and calcium chloride ($CaCl_2$) at different concentrations.

Table 7.3 Freezing point temperature for sodium chloride (NaCl) and calcium chloride ($CaCl_2$) salt solutions of different concentration

Weight %	NaCl	$CaCl_2$ (anhydrous basis)
1	−0.59°C (31.2°F)	−0.44°C (31.2°F)
2	−1.2°C (29.9°F)	−0.88°C (30.4°F)
4	−2.4°C (27.7°F)	−1.8°C (28.7°F)
6	−3.7°C (25.3°F)	−2.9°C (26.7°F)
8	−5.1°C (22.8°F)	−4.3°C (24.3°F)
10	−6.6°C (20.2°F)	−5.9°C (21.5°F)
12	−8.2°C (17.3°F)	−7.7°C (18.1°F)
15	−10.9°C (12.4°F)	−11.0°C (12.2°F)
20	−16.5°C (2.4°F)	−18.3°C (−0.9°F)

Source: Haynes (2011)

Brine is less efficient than a direct expansion system since the heat removed for refrigeration must be transferred to the brine and then to the mechanical refrigeration system. Although low temperatures can be achieved with high salt concentrations, the increased viscosity of brine solutions at low temperatures limits their use for very cold requirements. Other disadvantages are the corrosiveness of the brine and the more bulky installation. The most important advantages are that brine solutions permit storing refrigeration (a cold reservoir) and can be used where ammonia leaks would be dangerous. Brine continues to find application in certain operations such as in making ice cream novelties and in making artificial ice in rinks and arenas.

The care of brine systems is important and may be summarized as follows:

1. Test the brine every month for concentration, alkalinity, and ammonia.
2. Keep the concentration of the brine high enough to give a freezing point at least 5.6°C (10°F) lower than the lowest temperature to which it will be cooled. Otherwise, brine will freeze onto the expansion coil, and this ice will act as insulation preventing the heat in the brine from penetrating the expansion coil.
3. Adjust the alkalinity by adding a solution of sodium hydroxide (caustic soda) or of lime until the brine is neutral to litmus or phenolphthalein. If the brine is acid to litmus, it will be too corrosive.
4. Use only one metal, preferably a pure grade of cast iron, in contact with the brine. The use of different metals in a system favors corrosive action.
5. Immerse a bar or strip of zinc in the brine to decrease the corrosion when different metals are used in a system.
6. Add a solution of sodium dichromate and caustic soda to reduce corrosion; however, this will cause irritation of the skin. Care must, therefore, be used in handling the dichromate, as well as the brine containing it. To make the solution, thoroughly dissolve, by stirring, a mixture of 2.3 kg (5 lb) commercial dichromate and 0.64 kg (1.4 lb) caustic soda in 3.8 L (1 gal) of water. This amount will be sufficient to treat 1,420 L (375 gal) of brine the first time. Once a year it will be necessary to add from one-fourth to one-half the original amount.

7. Avoid air coming in contact with the brine since air makes the brine acid and more corrosive. Keep the brine tank covered, and avoid bubbling air through the brine or spraying the brine.
8. Avoid ammonia leaks from the expansion coils, which cause the brine to become more alkaline. Leaks can be detected by boiling a sample of brine in a narrow-necked flask and testing the vapors with red litmus paper. If the red litmus paper turns blue, the steam from the boiling brine contains ammonia.

Glycol. Glycol solutions (or antifreeze) also can be used as secondary refrigerants in an ice cream facility. Either ethylene or propylene glycol mixtures with water have a sufficiently low freezing point that they can be cooled (again by using a primary refrigerant system) and circulated for use in chilling operations. Although it is possible to cool glycol solutions to very cold temperatures (a 50% solution of ethylene glycol has a freezing temperature of −35.8°C (−32.5°F) and a 50% solution of propylene glycol has a freezing point of −37.0°C (−25.5°F)), the use of glycol refrigerants below about −10°C (15°F) is limited by the high viscosity. At lower temperatures, pumping requirements increase and heat transfer rates decrease significantly.

Combined Refrigeration

In some cases, as with a home ice cream freezer, it is actually a combination of the two effects (latent heat and sensible heat changes) that provides the refrigeration effect to freeze the ice cream. The combination of ice and salt, for example, will make a very cold brine solution that can be used to freeze ice cream. As heat is transferred out of the ice cream mix to freeze ice in it, ice in the brine will melt, so it has to be continually renewed to maintain low temperature.

Mechanical Refrigeration

A mechanical refrigeration system is based on the principle that a high-pressure refrigerant in its saturated liquid state can absorb considerable heat from the surroundings (cooling effect) when it vaporizes upon depressurization. In an enclosed mechanical refrigeration system, the refrigerant vapor is recompressed to high pressure and cooled to condense the refrigerant back into the liquid state. The refrigeration cycle repeats as the high-pressure liquid refrigerant is once again depressurized to provide cooling. The choice of primary refrigerant to be used in a mechanical refrigeration system depends on many factors, including (1) the boiling point of the liquid, (2) the pressures needed for efficient operation, (3) the latent heat of vaporization (amount of heat absorbed when the refrigerant vaporizes), (4) heat transfer rate capability, (5) transport properties, (6) efficiency (work input per unit of cool-

ing output), (7) the ease with which a leak can be detected, (8) its corrosive action on metals used in the system, (9) its toxicity, (10) cost and availability, and (11) environmental impacts.

Operating Principles

The mechanical refrigeration system has four essential parts: (1) the compressor, (2) the expansion valve, (3) the evaporator, and (4) the condenser and receiver (see Fig. 7.21). The compressor, typically of the twin screw-type, consists of two mating screw threads that mesh together to pressurize the low-pressure vapor refrigerant originating from the evaporator. The purpose of the compressor is to compress the vapor to a higher pressure to allow subsequent heat removal. It takes the vapor from the low-pressure side, in large volume at low pressure and low temperature, compresses it to higher pressure, and discharges it into the high-pressure side of the system. Thus, the compressor occupies a position dividing the two sides of a mechanical refrigeration system. The high-pressure side of the system extends from the compressor discharge to the expansion valve and includes the condenser, a receiver, and the interconnecting piping.

Compression of the refrigerant vapor causes its temperature to increase according to the ideal gas law (increasing pressure in a compressor causes the volume to decrease and the temperature to increase), resulting in a superheated high-pressure vapor leaving the compressor, which is directed to the condenser. The vast majority of ice cream plants use evaporative condensers to reject heat from the system to the

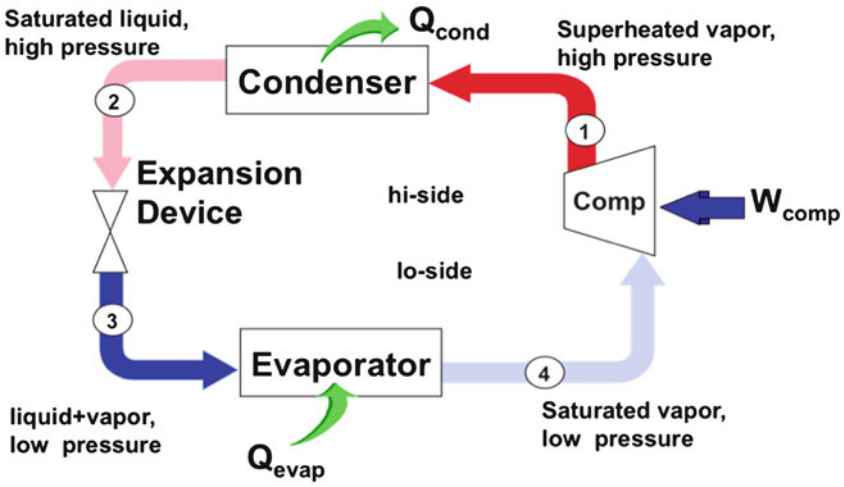

Fig. 7.21 Basic mechanical refrigeration system (courtesy of D. Reindl, University of Wisconsin)

outdoors. An evaporative condenser consists of a series of serpentine tubes through which the refrigerant passes with water being sprayed over the outside surfaces of the condenser tube bundle (see later section). As the refrigerant traverses through the heat exchanger tube bundle, it gives up its heat to the environment (outdoors) and changes state from a vapor back to a liquid. It remains at high pressure in the condenser.

High-pressure liquid refrigerant is drained by gravity to a reservoir known as a "high pressure receiver." From the high-pressure receiver, liquid is supplied to plant loads—throttling from high pressure to low pressure and causing a portion of the high pressure liquid to flash to a vapor. This expansion cools the entire refrigerant liquid–vapor mixture to a low temperature. The cold liquid refrigerant is then able to absorb heat from product being chilled or frozen as it undergoes a change in state back to a vapor. The low-pressure side of the system extends from the downstream side of the expansion valve to the compressor suction. The expansion valve is usually an ordinary needle valve permitting fine adjustment, either manually or through a process controller. The expansion valve derives its name from the fact that the high pressure, liquid refrigerant passes through the valve and then expands into a vapor at lower pressure. The expansion of the refrigerant in the evaporator (i.e., coils of pipes or a freezing chamber located where refrigeration is to be produced) requires heat to be removed from the environment surrounding the evaporator. This provides the refrigeration effect. The refrigerant vapors exiting the evaporator are channeled back to the compressor. In this way, the refrigerant is used repeatedly, being compressed, condensed, and expanded in a continuous cycle. The refrigerant never wears out, although slight leaks invariably occur, making it necessary to periodically replenish the supply of refrigerant in the system. The refrigeration or cooling effect is obtained in the evaporator as the liquid refrigerant absorbs heat while vaporizing. The pressure in the evaporator dictates the evaporating temperature for a given refrigerant. If lower refrigerant temperatures are required, the pressure in the evaporator must be lowered. The lower that pressure, the greater the cooling effect, but the greater amount of work required by the compressor to recompress the vapor. The evaporation coils may be located in the hardening room, in a tank of water or brine, in the ice cream freezer, or any other operation requiring refrigeration.

A diagram of a simple mechanical refrigeration system with two evaporators is shown in Fig. 7.22. Each of the elements described above is evident, along with other necessary components. These include a suction trap to prevent liquid refrigerant from entering the compressor and a high-pressure receiver tank as a reservoir for the liquid refrigerant prior to expansion. In this system, with flooded evaporators (see next section), liquid refrigerant vaporizes directly in the evaporator (i.e., the barrel of a scraped surface freezer) and promotes excellent heat transfer.

A large amount of heat is absorbed as the liquid changes to a vapor (latent heat), and a smaller amount of heat is absorbed by the vapor when it expands further (sensible heat). This absorbed heat is carried in the vapor to the compressor and on to the condenser, where it is transferred from the hot refrigerant vapor to the cooling water or air around the condenser coils. Sometimes this cooling water is used only once and wasted; in other places, it is more economical to reuse this water. In these

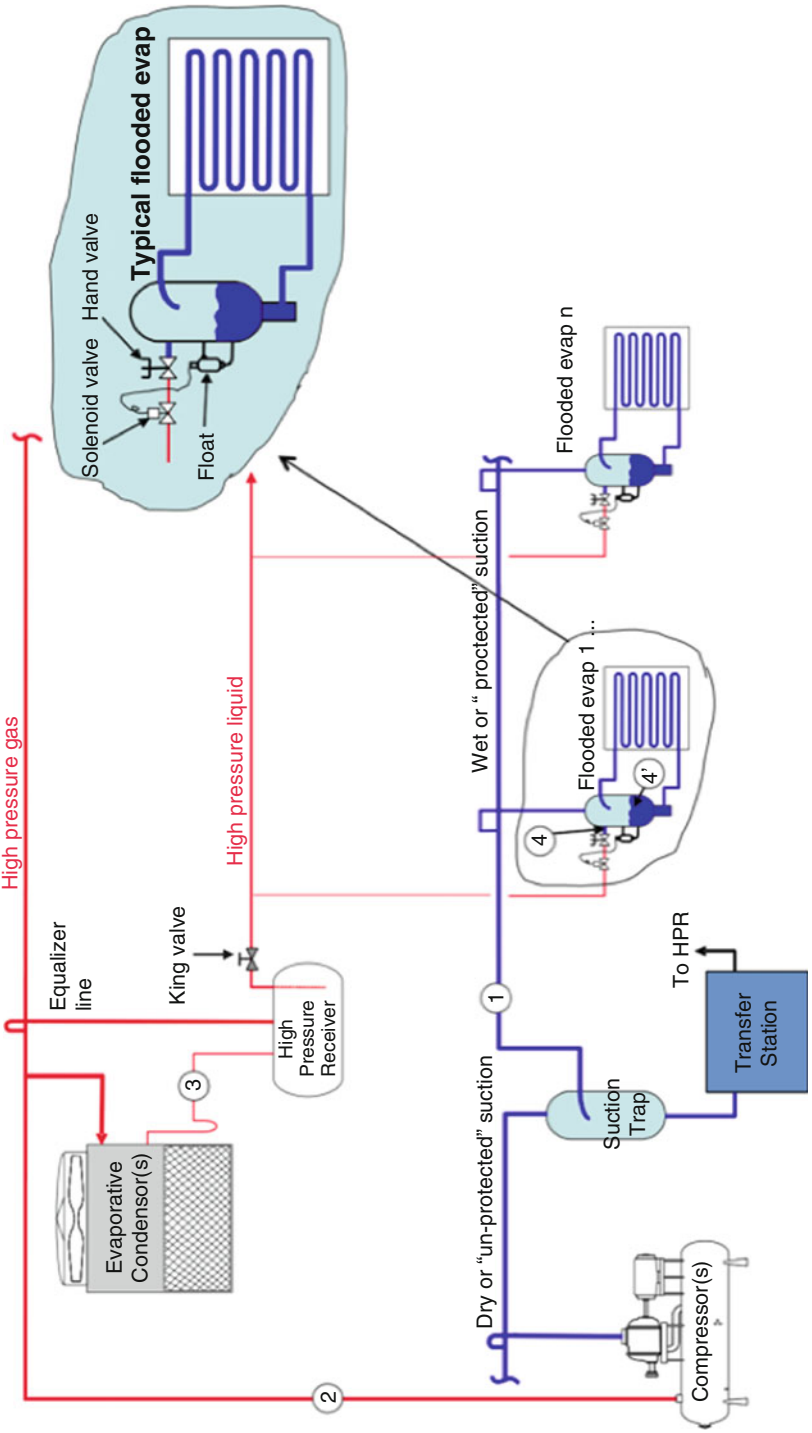

Fig. 7.22 Single stage mechanical compression refrigeration system with flooded evaporation (courtesy of D. Reindl, University of Wisconsin)

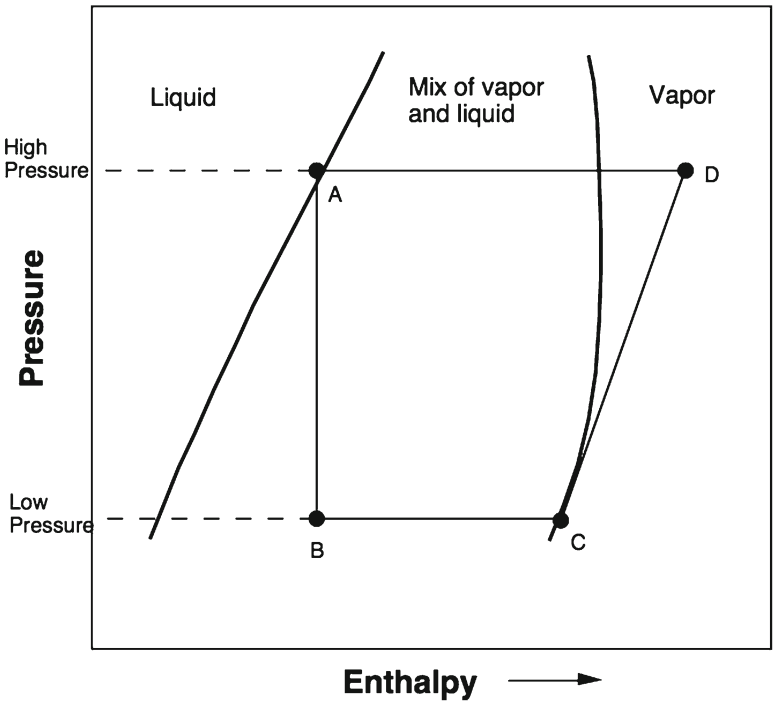

Fig. 7.23 Typical refrigeration cycle for ammonia on a pressure-enthalpy diagram

cases, the water is pumped to the top of a cooling tower (usually on the roof) and allowed to trickle down over the tower, cooling by partial evaporation in the process. This proves very economical where the cost of water is high. In some halocarbon systems, the condenser is air cooled, usually by a fan blowing air around condenser coils that have fins to facilitate radiation of the heat. In a home freezer, ambient air circulation across the condenser coils on the back of the unit is sufficient to condense the Freon in the system.

For an ammonia system, the enthalpy changes through the cycles of an ammonia system are characterized very well. For a typical cycle involving high and low temperatures of −15°C (5°F) and 30°C (86°F), the change in ammonia through the system is shown on a pressure-enthalpy diagram (Fig. 7.23). Liquid ammonia at 30°C (86°F) and 1,064.7 kPa gage pressure (154.5 psig) (point A in Fig. 7.23) is allowed to expand to low pressure in an evaporator in an ice cream plant. As the ammonia expands, its pressure decreases to 135.1 kPa gage pressure (19.6 psig) and temperature decreases to −15°C (5°F). In order for the liquid ammonia to vaporize, it must remove energy from the environment to provide the latent heat of vaporization and its enthalpy increases from 323.1 kJ/kg (138.9 Btu/lb) to 1,427 kJ/kg (613.3 Btu/lb). This large latent heat provides a substantial refrigeration effect in the evaporator. When the ammonia vapors exit the evaporator (point C in Fig. 7.23),

they are at low temperature and low pressure. In order to reuse the ammonia, the vapor must be recompressed to high pressure by a compressor. The vapor also increases in temperature as it is compressed (point D in Fig. 7.23). Now the vapor must be cooled in the condenser to bring it back to the form of a high pressure, liquid refrigerant (point A in Fig. 7.23) ready for reuse in the evaporator. From this approach, it can be seen that ammonia removes about 1,104 kJ (474 Btu) from the environment in the evaporator for every kg (lb) of ammonia vaporized. In comparison, a similar cycle for Freon (R-12) gives an energy change of only about 118.6 kJ/kg (51 Btu/lb) of refrigerant vaporized. It is this large ΔH that makes ammonia such an excellent primary refrigerant.

Another important parameter in refrigeration systems is the coefficient of performance (COP). This is defined as the ratio of the refrigeration effect to the work required. That is, COP is the ratio of heat removed in the evaporator to the energy (or work) required by the compressor. A high COP indicates an efficient system since the amount of cooling is large compared to the amount of work required by the compressor. The heat removed in the evaporator is the refrigeration effect caused by expansion of the refrigerant (line B–C in Fig. 7.23). The work of the compressor is the energy required to compress the refrigerant vapor exiting the evaporator at low pressure to the high pressure side. This compression follows a path of constant entropy, resulting in a vapor at high pressure and also high temperature (line C–D in Fig. 7.23). Thus, COP is the ratio of enthalpy change of the refrigerant (B–C) to the work requirement by the compressor (C–D).

Evaporator Systems

There are several methods of introducing the high pressure, liquid refrigerant into the evaporator coils. Since this is where the main refrigeration effect takes place, the most efficient use of refrigerant is desired, which means that the best heat transfer conditions must be used. In an ice cream factory, evaporators can be the ice cream freezer barrel, ice builder coils (for chilled water), coils in storage freezers or hardening tunnels, and brine tank coils.

Direct expansion. The direct-expansion method of cooling involves directing the effluent of the expansion valve directly into the evaporator (either coils in the freezer or the barrel of the ice cream freezer itself). This effluent is vaporizing refrigerant and, although it may still be somewhat fluid as the refrigerant contacts the evaporator, the refrigerant is primarily vaporized by the time it contacts the evaporator coils. Thus, heat transfer is not as high as possible.

Flooded system. In a flooded system (as shown in Fig. 7.22), the liquid refrigerant collects in and nearly fills the expansion coils or chamber. The compressor draws off the vapor as the absorbed heat vaporizes the liquids in the operation of this flooded system. The liquid refrigerant under high pressure and at room temperature passes through a valve (usually controlled by a float) to the expansion coils or

chamber, where it is a liquid under a lower pressure and lower temperature. As heat is transferred to the liquid refrigerant, evaporation takes place. The vapor from this evaporative process is constantly removed by the compressor, and the liquid level is maintained by the float.

The important advantages of the flooded system are: (1) it is more efficient, because heat is more readily transferred between liquids than between vapors, gas, or liquid to gas; (2) less cooling surface or coil surface is needed; and (3) there is less fluctuation in temperature. The fact that float valves occasionally stick, causing liquid refrigerant to enter and damage the compressor, is the main disadvantage.

Defrosting Methods

Over time, humidity in the air of a freezer or hardening room gradually builds up on the external surfaces of the evaporator coils. The common methods of defrosting evaporator coils in a freezer are as follows:

1. Brushing the coils with a stiff or wire bristled brush. This is not a very effective method as it may leave a thin layer of ice that gradually increases in thickness.
2. Melting/scrubbing with hot water or steam. This is a wet, messy operation that leaves much moisture in the room and causes the entire freezer or hardening room to warm up. Despite that, it is nearly always used when the expansion coils are in a separate cabinet through which the hardening room air is circulated.
3. Passing hot liquid refrigerant through the coils. This requires extra valves and pipes in the installation, but does not raise the temperature of the room much. The frost and ice are easily removed from the quickly heated coils before temperature in the environment rises significantly.
4. Passing hot refrigerant vapor or gas through the coils. This is similar to the use of hot liquid refrigerant.
5. Using a brine drip or spray over the coils. A trough containing calcium chloride crystals is placed above the coil so that as the crystals absorb moisture and the brine drips down over the coil to collect in a vessel at the bottom.

Compressors

The function of the compressor is to draw low-temperature, low-pressure refrigerant vapors from the evaporator to maintain the desired suction-side pressure. This pressure must be low enough to allow the liquid refrigerant to vaporize at the required temperature for the desired refrigeration effect. The vapors are compressed in the compressor and the high-pressure refrigerant discharge gas is directed to the condenser where it is cooled and condensed back into a liquid.

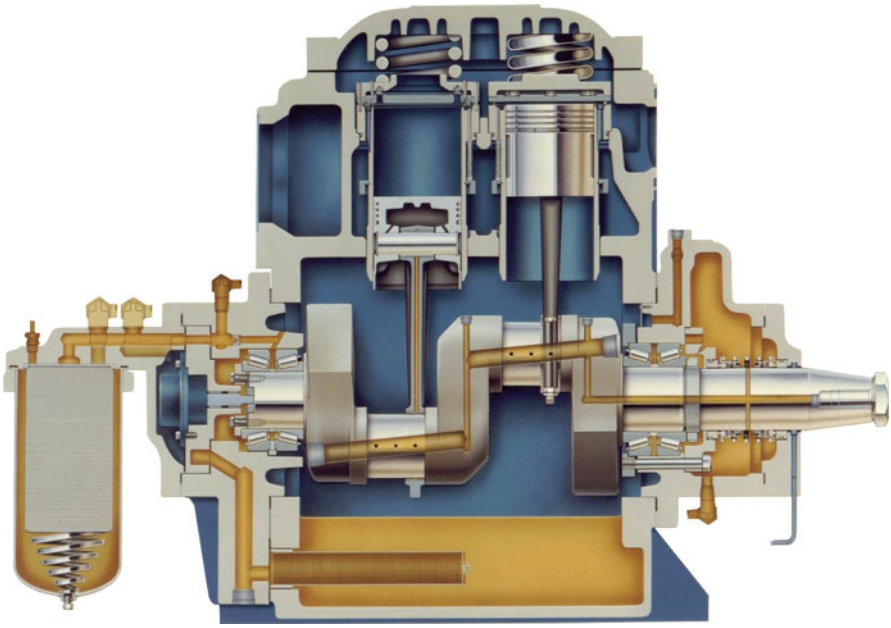

Fig. 7.24 Cross section of a reciprocating compressor (courtesy of Vilter Manufacturing, Sidney, OH)

Historically, ice cream plants and other food processing operations used reciprocating or piston type compressors. Today, the majority of plants use screw-type compressors. Reciprocating compressors, such as the one shown in Fig. 7.24, consist of multiple cylinders that draw vapor into the cylinder through an intake valve as the piston moves downward. When the piston reaches the bottom end of its stroke and begins to move upward, the gas within the cylinder begins to increase in pressure; thereby, forcing the intake valve closed. As the piston continues its upward travel, the cylinder volume decreases causing the gas pressure to rise. As the piston approaches the top end of its travel, the pressure of the refrigerant within the cylinder becomes high enough to push open a discharge valve that allows the gas to leave the cylinder. A limitation associated with reciprocating compressors is their ability to develop pressure lift during the compression process. For operating temperatures below −22.2°C (−8°F), the compression process needs to be staged. In this case, one compressor (known as a booster compressor) will raise the pressure of the refrigerant vapor from the evaporating pressure to an intermediate pressure. A second compressor (known as a high stage compressor) will then take the intermediate pressure vapor and raise its pressure high enough to reject heat from the system to the ambient environment.

Through the last 25 years, screw compressors have progressively dominated the market. A cross-section of a twin-screw compressor is shown in Fig. 7.25. The twin screw consists of a driven male rotor with lobes that mates with a female rotor with

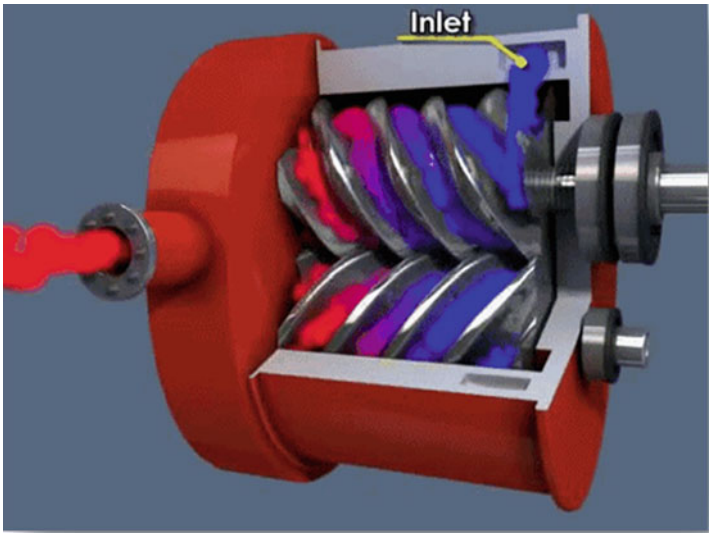

Fig. 7.25 Twin-screw compressor (courtesy of Howden Compressors, Inc., Plymouth Meeting, PA)

gulleys or pockets. Vapor flows into the pocket of a screw thread on the suction side of the machine. As the screw rotates, the pocket of low-pressure vapor becomes trapped and begins to traverse down the access of the screw thread. As the gas traverses the screw thread, its volume is decreased causing the gas pressure within the screw's pocket to increase. As the pocket reaches the end of the screw thread, the high-pressure gas is forced out of the pocket through a port in a housing surrounding the compressor's screw threads.

In addition to the twin-screw compressor technology, a single-screw compressor is available and used in the industrial refrigeration marketplace. A cut-away of a single screw compressor is shown in Fig. 7.26. Conceptually, a single screw compressor develops compression in a manner similar to the twin screw; however, the actual implementation of the compressor is different. Rather than having a mating male rotor, the single screw consists of a single female rotor with two intermeshing gate rotors. The gate rotors provide a seal to the pockets created in the female main rotor.

Both twin- and single-screw compressors are capable of developing considerably higher pressure lift (compression ratio) compared to a reciprocating compressor. Screw compressors have good full-load operating efficiency and they are available in large capacities for a given footprint. This makes them ideal for use in large plants.

Compressor manufacturers provide performance data for their equipment in terms of the machine's capacity in tons of refrigeration and the corresponding power input required (expressed in terms of horsepower HP) for a given suction pressure/temperature and discharge pressure. Refrigeration system design engineers consider

Fig. 7.26 Single-screw compressor (courtesy of Vilter Manufacturing, Sidney, OH)

the requirements of the process in terms of temperature and loads and then select compressors that individually or collectively have sufficient capacity (tons) to meet a design plant load. Based on the owner's requirement for operating efficiency, the designers will also consider the comparative performance, HP/ton, for different compressor options. This entire process has been simplified and improved by the introduction of computerized selection programs by the compressor manufacturers. These selection programs allow engineers to quickly evaluate rated performance of a variety of options at both full-load and part-load operating conditions.

Condensers

The function of the condenser is to remove the heat from the compressor discharge gas. Sufficient heat must be removed from the high-pressure discharge gas to condense the vapors back to the liquid state. For a single stage compression system, the condenser must remove the aggregate heat load absorbed by the evaporators and the mechanical power input by the compressor. The primary type of condenser used in industrial refrigeration systems, including ice cream manufacturing, is the evaporative condenser (Fig. 7.27). These units are usually housed on the roof of the manufacturing facility, as seen in Fig. 7.28.

High-pressure discharge gas flows to the inlet of the evaporative condenser's tube bundle. The tube bundle is located within a cabinet where a fan moves ambient air across the heat exchanger. Water is sprayed over the outside of the heat exchanger tube bundle to enhance the rejection of heat from the refrigerant to the ambient environment by itself undergoing a phase change from water to vapor.

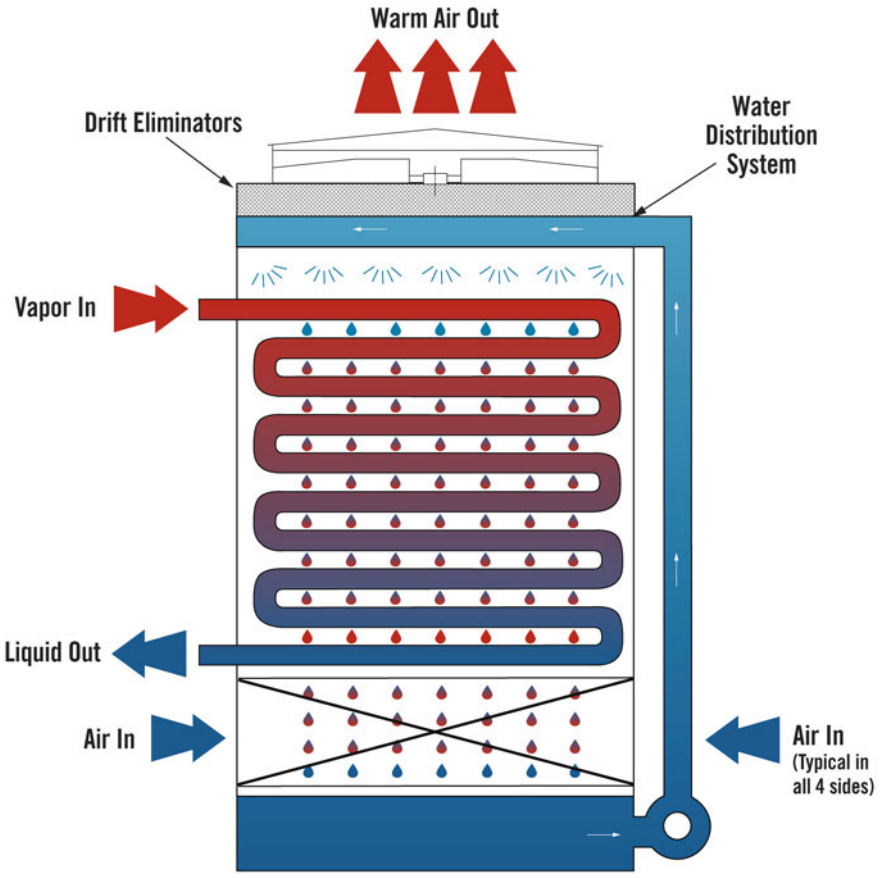

Fig. 7.27 Cross section of an evaporative condenser (courtesy of Baltimore Air Coil, Jessup, MD)

Figure 7.29 shows a relatively new condenser technology being used in industrial refrigeration systems. The condenser consists of a serpentine bundle heat exchanger near the top of the unit operating like an evaporative condenser but it also includes fill media located below the evaporative condenser. As water flows over the evaporative condenser portion of the unit, a portion of the water will evaporate as it absorbs heat from the condensing refrigerant within the heat exchanger. The water then proceeds to flow down through a cross-corrugated fill media exchanging energy with ambient air. A portion of the water flowing through the fill media evaporates and further cools. The cooler water is then pumped to the top of the unit to again flow over the tube bundle of the condenser. One advantage of this design is that the tube bundle is less susceptible to scale formation because the water tends to operate at lower temperatures than a traditional evaporative condenser.

Fig. 7.28 Field installation of an evaporative condenser on an industrial ammonia refrigeration system (courtesy of Baltimore Air Coil, Jessup, MD)

Indirect heat exchangers may be of the double tube, shell and tube, or coil types. In these systems, a secondary refrigerant (chilled water, brine, or glycol) is circulated on one side of the heat exchanger and the hot vapors enter the other side. Sufficient heat is transferred from the hot vapors to the refrigerant to allow condensation of the refrigerant. The warmer secondary refrigerant is then recirculated back to the source (ice builder, brine, or glycol tank) to be cooled once again by a primary refrigerant. One of the simplest condensers is the coil on the back of a home refrigerator. Due to the temperature cycles in the Freon system within the refrigerator, ambient air is sufficient to cause condensation of the Freon vapor within the coil.

Operating Precautions

Some precautions to observe in operating refrigeration systems are as follows:

1. When opening valves on refrigerant lines, open them slowly.
2. Keep the suction pressure as high as possible. However, pressure must be sufficiently low to give the desired temperature. The pressure on the low side should correspond to an ammonia boiling point 5.6°C (10°F) lower than the temperature of the medium surrounding the expansion coils or within the chamber for maximum efficiency. A lower back pressure than this reduces the refrigeration capacity. There is a temperature drop of about 5.6°C (10°F) between the medium being cooled and the ammonia due to the wall of the expansion coil. This is the same principle as in a milk cooler. The cooling medium must always be cooler than the temperature to which it is desired to cool the milk. Table 7.4 shows the boiling point of ammonia at different gage pressures.

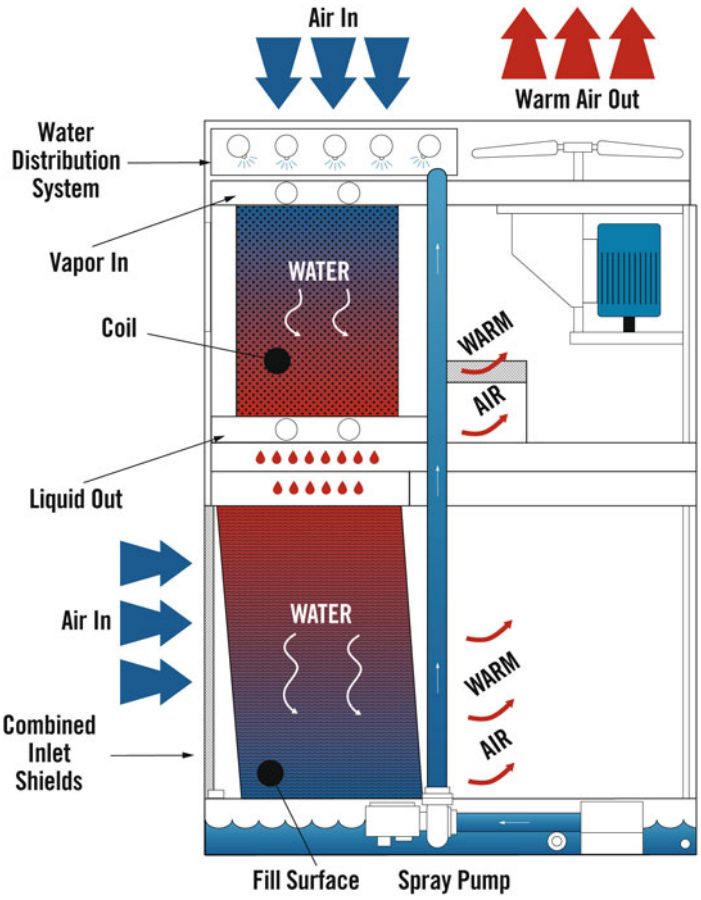

Fig. 7.29 Hybrid evaporative condenser/cooling tower (courtesy of Baltimore Air Coil, Jessup, MD)

To illustrate, if a minimum temperature of −23.3°C (−10°F) is wanted in the medium being cooled, the pressure on the low-pressure gage should be that at which ammonia will boil at −28.9°C (−20°F) or 0.53 kg/cm^2 (3.45 lb/in.^{2}). Table 7.4 shows that it is not necessary to carry a vacuum on the low side unless extremely low temperatures are desired; head pressures (pressures on the high side) are determined by the temperatures of the refrigerant in the condenser. Because liquids transfer heat more efficiently than gases, lower temperatures can be obtained in the cooled product if equally cold liquid refrigerant, rather than vapor, is in direct contact with the surface of the heat exchanger.

3. Keep the head pressure as low as possible to save power. The head pressure depends on (a) size of the condenser, (b) temperature of water used for cooling the condenser, (c) amount or volume of water flowing through the condenser, (d) impurities in the refrigerant (mainly oil and air), and (e) cleanliness of the inside and outside of the condenser.

Table 7.4 The relation of gage pressure to boiling point of ammonia and minimum temperature produced in the refrigerated medium where vapors are the recipients of the heat

Gage pressure		Boiling point of ammonia		Minimum temperature	
(kg/cm^2)	($lb/in.^2$)	(°C)	(°F)	(°C)	(°F)
0.18	1.17	−31.7	−25	−26.0	−15
0.53	3.45	−28.9	−20	−23.3	−10
0.75	5.99	−26.1	−15	−20.6	−5
1.36	8.77	−23.3	−10	−17.8	0
1.69	10.93	−20.6	−5	−15.0	5
2.38	15.37	−17.8	0	−12.2	10
2.97	19.17	−15.0	5	−9.4	15
3.65	23.55	−12.2	10	−6.7	20
4.33	27.93	−9.4	15	−3.9	25
5.11	32.95	−6.7	20	−1.1	30
5.96	38.43	−3.9	25	1.7	35
6.88	44.41	−1.1	30	4.4	40

4. Inspect and drain all oil traps regularly. Some oil always passes along with the refrigerant and collects at low spots in the system, especially in ammonia systems. Valves at these points permit the oil to be drained out, thereby improving the efficiency of the heat transfer. Worn piston rings favor oil passing into the refrigerant.
5. Keep air out of the system. Air and some other gases do not condense into a liquid, but collect on the high-pressure side of the system. Air not only decreases the efficiency of the condenser, but also the overall system because the presence of air increases the operating pressure on the condensing side of the system; thereby, making the compressors work harder. Usually the air is removed from the top of the liquid drain pipe leaving the condenser through a process known as "purging."
6. Keep the evaporator coils as free from frost as possible. This is especially important in hardening rooms, because frost and ice reduce the rate of heat transfer.

Multistage Refrigeration Systems

Single-stage mechanical refrigeration systems as described above give a low temperature side of about −15°C (5°F). In freezing ice cream, temperatures as low as −30 to −40°C (−22 to −40°F) are needed, which means that multistage refrigeration systems are common in ice cream plants. With multistage systems, temperatures as low as −73 to −101°C (−100 to −150°F) can be obtained.

When colder temperatures are needed, a single-stage mechanical refrigeration system may not be possible (limited by compression ratio of the compression technology being used) or it may not be efficient. As noted above, reciprocating compressors are limited to a compression ratio on the order of 8:1. This means that a system operating with ammonia as the refrigerant would only be capable of operating at a

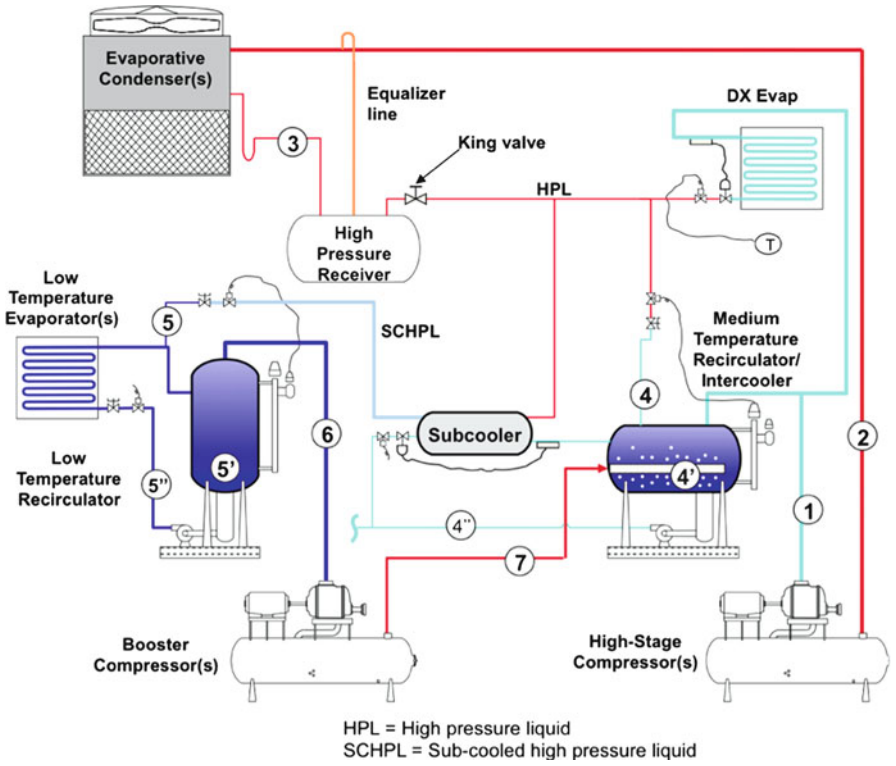

Fig. 7.30 Two-stage mechanical refrigeration system with two temperature levels (courtesy of D. Reindl, University of Wisconsin)

saturated suction temperature of −22.2°C (−8°F). If colder temperatures are required, designers have two choices: (1) select a screw compressor technology that has greater compression ratio capability or (2) configure the system for multistage compression. Screw compressors are capable of operating at 18:1 compression ratios, which means that a given system would be capable of operating in a single stage to a saturated suction temperature of −40°C (−40°F). In such cases, a compound or two-stage compression system is used that allows more efficient compression of the vapors. A two-stage compression system with low and medium temperature evaporators is shown in Fig. 7.30. When refrigerant vapors are compressed, the temperature increases substantially according to the ideal gas law. In a two-stage compression system, the first stage of compression is accomplished by a "booster compressor." The discharge gas from a booster compressor is cooled by the use of an intercooler before entering the second compressor in series known as the "high stage compressor." The high stage compressor is used to raise the refrigerant pressure sufficiently high to reject heat from the system to the ambient environment. The vapors exiting the high-stage compressor are then cooled and condensed in the condenser.

In multistage systems, the same refrigerant must operate at both high and low temperatures, leading to some inefficiency. Cascade refrigeration systems utilize

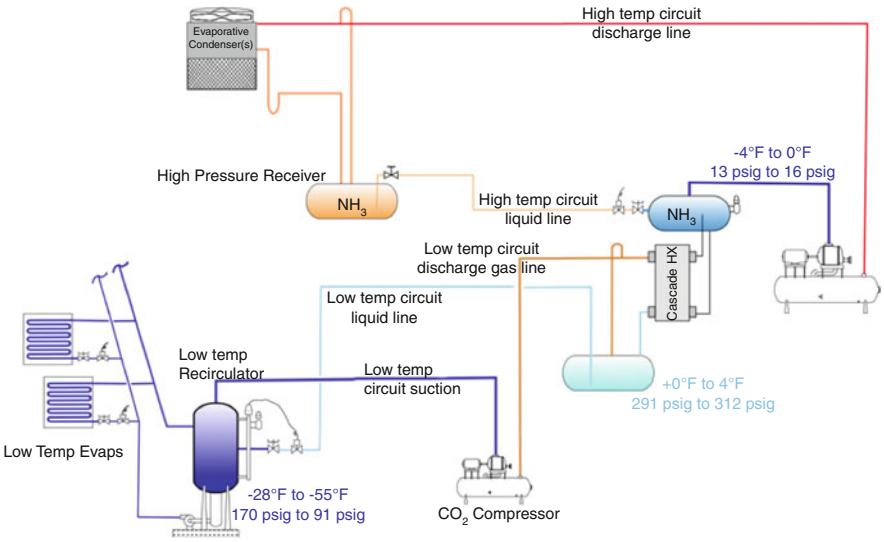

Fig. 7.31 Cascade refrigeration system with ammonia and CO_2 (courtesy of D. Reindl, University of Wisconsin)

two different refrigeration systems to efficiently attain very low temperatures. A cascade system using ammonia and CO_2 to provide low temperature refrigeration is shown in Fig. 7.31. Here, the CO_2 is used on the low temperature side and ammonia on the high temperature side. The refrigeration effect of the ammonia is used to condense the CO_2 for the low temperature side system.

Calculation of Refrigeration Loads

Modern ice cream plants have a mechanical refrigeration system designed to meet the needs of the entire plant operation. The total refrigeration needs of a plant are determined by the number and size of ice cream freezers employed in the plant, the type of refrigerant used (generally ammonia or an environmentally friendly halocarbon), and whatever other ancillary cooling requirements there are in the plant (i.e., hardening room, storage freezer, chilled water system, etc.). Calculating overall refrigeration loads requires evaluating each unit individually and then summing the individual loads to arrive at a total refrigeration requirement. Here, the refrigeration needs for the dynamic freezing step are used as an example.

The objective in the dynamic step in freezing ice cream is to produce the maximum number of ice crystals by dropping the temperature of the mix well below its freezing point to promote nuclei formation. The amount of ice formed in the dynamic freezing step depends primarily on the freezing point of the mix and the temperature at which the ice cream is removed (draw temperature), although the thermal properties

Table 7.5 Enthalpy change of ice cream over the temperature range of freezing (data estimated from Cogne et al. 2003)

Temperature (°C)	Enthalpy change (kJ/kg)	Temperature (°C)	Enthalpy change (kJ/kg)
0	–	−8	148
−1	2.5	−9	156
−2	32.5	−10	165
−3	65	−15	189
−4	92	−20	212
−5	109	−25	228
−6	126	−30	241
−7	139	−35	251

of the mix can also impact refrigeration needs. Compared with mixes with low freezing points those with higher freezing points require the formation of a greater amounts of ice for a given draw temperature and require a greater refrigeration effect. Lower draw temperatures also result in both more ice being formed and the need for more refrigeration. Mixes vary in composition, so they vary in freezing point. Furthermore, composition affects heat capacity, or specific heat, which governs the amount of energy needed to reduce the temperature of the mix. The freezing point and specific heat of a mix are determinants of the amount of ice that will be formed with any given amount of heat energy removed (refrigeration effect).

The amount of heat to be extracted from an ice cream mix in the dynamic freezing step is affected by composition of the mix and the temperature to which it is frozen. Extraction of heat occurs in three steps, viz., (1) sensible heat from the liquid mix, (2) latent from the water as it solidifies, and (3) sensible heat from the semisolid slush. Variations in mix composition affect heat removal through effects of (1) specific heat, which affects the sensible heat requirements, (2) freezing point depression, which affects the amount of water frozen into ice at any temperature, and (3) fat content and type, which affects the heat required to crystallize additional fat. Table 7.5 illustrates for one mix (milk 11.5%; fat 9%; sugar 18.33%; emulsifier 0.3%; total solids 41.13%) the enthalpy change as temperature decreases. A substantial release of latent heat occurs as temperature decreases below the freezing point of the mix. As temperature reaches −8 to −10°C, the latent heat terms begin to taper off since less ice forms at these temperatures. Enthalpy continues to decrease even below −20°C primarily due to the change in heat capacity of the frozen product since most of the freezable water has frozen by this temperature. The difference in enthalpy between a typical draw temperature (ca. −5.5°C) and freezing point temperature of this mix (ca. −1°C) gives the enthalpy change associated with ice formation in the scraped surface freezer. From Table 7.5, this is approximately 116 kJ/kg. Mixes with higher freezing point depression freeze more ice at any temperature and require greater heat removal from the refrigerant.

The energy requirement during freezing can also be estimated from the contributions of each part of the freezing, as noted above. The latent heat of fusion of ice is 334.2 kJ/kg (144 Btu/lb; 80 cal/g), so when a kg of ice melts, 334.2 kJ of energy is removed from the environment surrounding the ice (a cooling effect) and to freeze

a kg of ice requires that a refrigeration system remove the same amount of heat from the vicinity of the growing ice crystal. In contrast, the latent heat of fusion of milk fat is 81.5 kJ/kg (35.1 Btu/lb; 19.5 cal/g); therefore, it contributes only a small amount to the refrigeration needs during freezing of ice cream.

The following example illustrates a simplified method of estimating the heat removed from a mix containing 12% fat, 11% MSNF, and 16% sugar. The mix enters the freezer at 4.4°C and is drawn at −5.6°C. Specific heat of the mix is estimated at 3.35 kJ/kg°C; specific heat of the semi-frozen ice cream is 2.72 kJ/kg°C; latent heat of fusion of water is 334.2 kJ/kg; water in the mix is 60.7%; freezing point of mix is −2.63°C; and water frozen at this draw temperature is 48%. Latent heat of fusion of milk fat is ignored because most of its solidification takes place during aging of the mix.

Therefore:

	kJ/kg
Sensible heat of mix = [(4.4) − (−2.6) °C] × (3.35 kJ/kg°C)	=23.5
Latent heat of fusion = (334.2 kJ/kg) × (0.48 kg ice/kg water) × (0.607 kg water/kg mix)	=97.4
Sensible heat of slush = [(−2.6) − (−5.6) °C] × (2.72 kJ/kg°C)	=8.2
Total kJ absorbed per kg mix	=129.1
(Total Btu absorbed per lb mix)	=(55.6)

Thus, 129.1 kJ (55.6 Btu) of energy must be removed for every kg (or lb) of mix frozen in the continuous freezer. Note that the sum of latent heat and sensible heat for cooling the slush (97.4 + 8.2) add to 105.6 kJ/kg, in good agreement with the data of Cogne et al. (2003) given in Table 7.5. For 1 kg/s (132 lb/min) of mix being frozen into ice cream, the total heat to be removed by the refrigeration system is

$$(129.1\ \text{kJ/kg}) \times (1\ \text{kg/s}) = 129.1\ \text{kJ/s (or kW)}$$

or

$$(55.6\ \text{Btu/lb}) \times (132\ \text{lb/min}) = 7{,}340\ \text{Btu/min}$$

The main component of refrigeration is removal of the latent heat of formation of ice, which constitutes greater than 75% of the specific energy requirements for freezing of mix, although as mentioned above, friction energy from the dasher can account for up to half of the energy to remove from the freezer barrel. Heldman (1966) and Heldman and Hedrick (1968) presented a slightly more accurate (and more complicated) method for predicting the total refrigeration requirements for freezing ice cream to any temperature above 0°F (−19°C). He divided the total heat required into four portions, viz., (1) sensible heat above the initial freezing point, (2) sensible heat of the unfrozen portion during freezing, (3) latent heat of ice, and (4) sensible heat of ice below the initial freezing point. Calculations confirmed that latent heat is the largest portion of the total requirement; however, sensible heat of

unfrozen and frozen portions accounted for 8–10% of the total heat at normal freezing temperatures. Obviously, the more heat removed from the mix prior to its entry into the freezer, the higher the capacity of that freezer given a constant drawing temperature. Uniformity in temperature and rate of flow of mix increases the probability that overrun and freezing rate will be uniform.

The amount of refrigeration needed for dynamic freezing requires knowledge of how much energy can be removed by the refrigerant. The essential unit of refrigeration traditionally has been defined as the "ton," or the amount of energy needed to convert one ton (2,000 lb) of water into ice in 24 h. In SI units, the measure of refrigeration is the kW. Both sets of units will be developed here since many refrigeration engineers still use the traditional refrigeration units of tons.

For a ton of refrigeration, the energy needed to produce 2,000 lb of ice in 24 h can be calculated from the latent heat. In this case, the latent heat of fusion of ice is 144 Btu/lb. So, if 2,000 lb of ice is formed in 24 h, the energy released will give off

$$(2000\ \text{lb}) \times (144\ \text{Btu / lb}) = 288{,}000\ \text{Btu of energy in a 24h period}$$

or

$$(288{,}000\ \text{Btu}) \div \{(24\ \text{h})(60\ \text{min/ h})\} = 200\ \text{Btu / min} = 3.33\ \text{Btu / s}$$

In SI units, 1 ton of refrigeration is equivalent to 3.517 kW (or 3.517 kJ/s) of energy. One kilowatts of refrigeration means 1 kJ (1,000 J) of energy are removed every second.

Returning to the calculation of heat removal in dynamic freezing, the amount of heat to be removed for freezing of 1 kg/s of mix under specific conditions was 129.1 kJ/s (7,340 Btu/min). To obtain the refrigeration load needed for this freezer, the energy needed for freezing is divided by the energy needed per kilowatts or ton of refrigeration.

$$(129.1\ \text{kJ / s}) \times (1\text{k W / (kJ / s)}) = 129.1\ \text{kW of refrigeration needed}$$

or

$$(7{,}340\ \text{Btu / min/ ton}) \div (200\ \text{Btu / min}) = 36.7\ \text{tons of refrigeration needed}$$

Dividing the refrigeration requirements by the latent heat of vaporization of the refrigerant gives the required ammonia flow rate needed to meet this refrigeration load. For example, 1,104 kJ/kg (474 Btu/lb) of heat is removed when using ammonia.

$$(129.1\ \text{kW}) \div (1{,}104\ \text{kJ / kg}) = 0.12\ \text{kg / s}\ (15.5\ \text{lb / min})\ \text{ammonia}$$

Knowing the density of ammonia at the conditions of the refrigeration system allows determination of the volume of ammonia for this flow rate. From calculations such as these, refrigeration engineers are able to size heat exchangers and other components of the mechanical refrigeration system. Of course, these calculations are dramatically simplified to demonstrate the principles. Refrigeration engineers utilize software that account for all energy inputs and outputs to calculate more accurate values of refrigeration needs.

Terms Used in Refrigeration

COP: Coefficient of performance of the compressor system. The ratio of the refrigeration effect in the evaporator to the work required to recompress the refrigerant.

Condenser: The unit in a mechanical refrigeration system that condenses refrigerant to high pressure liquid.

Evaporator: The unit in a mechanical refrigeration system where the refrigerant is expanded to lower pressure causing evaporation of the refrigerant, which provides the cooling effect.

Latent heat of evaporation: The amount of heat (in kiloJoules) required to change 1 kg of liquid into l kg of vapor without changing the temperature or pressure.

Latent heat of fusion: The amount of heat (in kiloJoules) required to change 1 kg of liquid into a solid without changing the temperature or pressure.

Ton of refrigeration: 288,000 Btu per 24 h, or the amount of heat required to melt 1 ton of ice per day at 32°F without changing the temperature or pressure. Also equivalent to: 12,000 Btu/h and 200 Btu/min.

Ton refrigeration machine: A compressor or machine that will produce 1 ton of refrigeration during 24 h of continuous operation under a particular set of conditions.

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Chapter 8
Soft-Frozen Dairy Desserts

Introduction

Soft-frozen dairy desserts appeal to many consumers because of their creamy and smooth texture. These dessert products are typically frozen on the retail premises from manufactured and distributed mix and are consumed in the soft-frozen state soon after being prepared, without hardening, in the form of cones, sundaes, parfaits, banana splits, milk shakes, and related items. Soft-frozen desserts became popular in the 1950s and remain popular with customers of shops focusing on these products and in fast-food-style restaurants. Less capital is needed by the retailer to get into the soft-serve ice cream business than to make and sell hard-frozen ice cream. Although vanilla is by far the most common flavor, chocolate or other flavors are also available and opportunities to add flavored syrups and/or mix-ins and to enrobe cones with chocolate have greatly increased the consumer's options for soft-serve products. Soft-frozen desserts include ice cream, light or low-fat ice cream, ice milk, frozen custard, and frozen yogurt. Milk shakes are also included in this category, as most foodservice operations would operate a milk shake freezer to make shakes from a prepared dairy mix in much the same way as they would for soft-serve cones. Ice cream parlors that scoop hard ice cream might continue to make milk shakes in the more traditional manner by blending hard ice cream, milk, and flavor syrups with a milk shake blender (e.g., Hamilton Beach).

Production of soft-serve products in the United States is shown in Table 8.1. Significant trends can easily be seen. Low fat is three to four times as popular as full fat and has been so over most of the past 20 years. It is interesting to note, however, that since this market is all foodservice, Nutrition Facts labels are not as obvious to consumers as with packaged goods, so it is not necessarily a conscious choice to select low fat rather than a manufacturer's or retailers choice to serve products with more optimal eating quality for this mode of consumption. Soft-frozen yogurt has been quite cyclical with peaks in 1991 and 2000 and valleys in the mid-1990s and mid-2000s. In 2009, it was showing increasing popularity again. In years during which soft-frozen yogurt production has been high, low-fat soft-serve production

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Table 8.1 Soft-serve frozen dessert production (million US gallons) in the United States in selected years 1991–2009 to show significant trends in the market

Year	Full fat	Low fat	Frozen yogurt
1991	45.5	217.5	74.6
1997	59.7	280.1	28.2
2000	97.6	284.8	52.0
2002	132.5	235.9	34.1
2005	62.0	249.2	37.0
2008	54.3	239.4	49.9
2009	63.5	232.9	50.9

Source: USDA, National Agricultural Statistics Service, as reported by the International Dairy Foods Association, Washington, DC, in Dairy Facts, 2010

has been low and vice versa, showing the effect of frozen yogurt trends on consumer choice. Frozen yogurt is discussed in more detail in Chap. 15.

Soft-Serve Mix Composition

The way soft-serve products are marketed makes it possible to use formulas that differ considerably from formulas for hard-frozen products. Although some ice creams made in soft-serve shops are hardened after being packaged or are formed into novelties or cakes, the principal forms in which they are marketed are as soft-frozen products and shakes.

Soft-serve mixes are unique in composition, stability, and whippability. A fat content below about 4% increases risks of having a coarse or icy texture and weak body. A fat content above about 12% is associated with significant risk of churning in the freezer and a greasy mouth coating. Much of the soft-serve mix in the market is 4–7% fat (ice milk or light ice cream). According to their respective websites in 2011, McDonald's vanilla soft-serve cones were 4% fat while Dairy Queen vanilla soft-serve cones were 5% fat. Typical formulas for full-fat ice cream used as soft serve contain 2–3% less sugar than do formulas for regular ice cream. The MSNF content varies inversely with fat content and may be as high as 14% for a low-fat formula. Generally, while the fat content is kept lower, the MSNF content is higher than for hard-frozen products. Lactose crystallization is not a problem in these products, as they are consumed immediately after freezing. The sugar content ranges from 13 to 15%, which is somewhat lower than for regular ice cream. Sweetener content has to be balanced with the amount of lactose from the MSNF to provide the right consistency (freezing point and ice phase volume are affected) at the appropriate draw temperature, so higher MSNF contents suggest lower sugar contents. Corn syrup solids are often used, but overuse can lead to an enhanced sensation of gumminess.

Stabilizers and emulsifiers are used in amounts ranging from 0.2 to 0.3% and from 0.1 to 0.2%, respectively. Stabilizers are required for viscosity enhancement

and mouthfeel, but their function in ice recrystallization is not needed since hardening and storage are not involved. Thus a different choice of stabilizing agents than for hard ice cream may be more appropriate. Dryness and shape retention, however, are a big concern in soft-serve products; hence the emulsifier content is generally kept high. Whipping is also done under conditions closer to batch than continuous freezing, so emulsifiers are needed to help produce finely distributed air cells. All of these properties contribute to the smoothness of the final product. Calcium sulfate may be used at about a rate of 0.1% to enhance dryness and stiffness. Most stabilizer/emulsifier suppliers have blends specially prepared for soft-frozen products. Some typical formulas for soft-serve products are shown in Table 8.2.

Soft products are usually drawn from the freezer at −6 to −8° C (18–20° F). Fat separation and large ice crystal sizes are likely defects that result from cycling of the freezer to maintain temperature during extended holding times. Overrun of soft-serve products ranges from 30 to 60%, depending on the TS content. The higher the TS content, the higher the overrun may be while maintaining desirable body and texture characteristics.

Frozen custard mixes may be of moderate- or high-fat content and by definition in the USA are required to contain 1.4% egg yolk solids for the plain flavors and 1.12% for bulky flavored products. Example formulas for soft-serve frozen custards are shown in Table 8.3. Total solids generally range from 32 to 37%. Herald et al. (2008) studied the use of egg alternatives and showed that modified corn starch, whey protein concentrate, or soy protein isolate can each contribute some of the textural properties of eggs or egg yolks in custard-style ice creams, but none of them matched the control for flavor characteristics.

Milk shake mixes for foodservice fall outside the Standard of Identity for ice cream in the USA and are not defined in regulations of many states. However, in the USA they should contain at least 3.25% fat and 8.25% MSNF as does whole milk. In Canada, milk shake mixes must contain not less than 3% milk fat and 23% total solids. Compared with ice cream they are low in fat, high in MSNF, and low in sugar. The total solids content is characteristically 25–30%. For the best quality of milk shakes, overrun should be kept below 20%. This means that it is not desirable to use emulsifier in these products. Serving temperatures are typically −2°C to −3°C, depending on composition, so as to have an ice: unfrozen ratio conducive to consumption of these drinks typically through a wide-diameter straw. Two representative formulas for milk shake mixes are shown in Table 8.4.

Malted milk formulas are typically slightly higher in fat but lower in sugar than milk shake formulas. They are characterized by the added malt syrup and malt base or cocoa. The product is served in a flowable but highly viscous soft-frozen state. Some typical formulas for soft-serve malted milk products are shown in Table 8.5.

Smoothies are viscous frozen dessert drinks made usually from fruit or fruit juice at the site of consumption. They can be made with freshly cut fruit or freshly squeezed juice or a combination of fresh fruit with frozen fruit or juice concentrates. The usual practice is to blend the fruit/juice with frozen yogurt, sherbet, nonfat ice cream, and/or ice and serve immediately.

Table 8.2 Example formulas for soft-serve ice creams

Constituents[a]	%						
Milk fat	3.0	3.0	4.0	5.0	6.0	6.0	10.0
MSNF	14.0	14.0	14.0	13.0	12.5	13.0	11.0
Sugar	10.0	14.0	11.0	12.0	12.0	13.0	12.0
CSS	4.0	–	4.5	4.0	4.0	–	3.0
S/E	0.5	0.5	0.5	0.4	0.4	0.5	0.4
TS	31.5	31.5	34.0	34.4	34.9	32.5	36.4

[a]*MSNF* milk solids-not-fat, *CSS* corn syrup solids, *S/E* stabilizer plus emulsifier, *TS* total solids

Table 8.3 Example formulas for frozen custards

Constituents	%	
Fat	5.0	10.0
MSNF	12.0	11.0
Sugar	14.0	14.0
Egg yolk solids	1.4	1.4
Stabilizer	0.4	0.4
TS	32.8	36.8

Table 8.4 Example formulas for milk shake mixes

Constituents	%	
Fat	3.5	4.0
MSNF	12.0	14.0
Sugar	10.0	8.0
Corn syrup solids	–	3.5
Stabilizer	0.4	0.35
TS	25.9	29.85

Table 8.5 Example formulas for soft-serve malted milk products

Constituent	%			
Fat	4.0	6.0	4.0	5.0
MSNF	13.0	12.0	12.0	12.0
Sugar	10.5	10.5	10.0	10.5
Corn syrup solids	4.5	4.5	–	4.5
Malt syrup solids	–	–	0.75	0.75
Cocoa	–	–	3.0	3.0
Malt base	3.0	3.0	–	–
TS	35.0	36.0	29.75	35.75

Gelato is an Italian-style ice cream that is lower in fat and total solids than regular ice cream but typically higher in sugar content, to give it a soft, scoopable texture. It carries abundant rich flavor and has very low overrun. While gelato is not typically extruded directly for consumption as is soft serve, gelato typically is frozen in a batch freezer and not hardened as such, but rather drawn into shallow tubs from

which it can be scooped with a characteristic gelato paddle-shaped scoop. These are kept at appropriate temperatures at which the frozen product is pliable and sticky. Gelato is discussed in more detail in Chap. 15 with Specialty Products.

Freezers for Soft-Serve and Shakes

Few changes in the basic design of soft-serve freezers have occurred since they were first introduced. Although advances in electronics and mechanics have allowed them to be made smaller and more efficient, they still operate in basically the same way: they receive a cold liquid mix from either an integrated or remotely located storage vessel, feed it into a cylinder surrounded with refrigerant, freeze it while beating in air and scraping a thin layer of frozen product from the cylinder wall, and after sufficient temperature is achieved, dispensing it on demand through a dispensing head into a cone or serving container. However, advances in technology have allowed for electronic monitoring of ice cream viscosity and consequent regulation of refrigeration to maintain consistent quality. Examples of manufacturers of soft-serve freezers include Taylor (http://www.taylor-company.com), Carpigiani (http://www.carpigiani.com), SaniServ (http://www.saniserv.com), and Stoelting (http://www.stoelting.com/foodservice-equipment).

Several functional types of soft-serve freezers are available. These include models for the countertop or the floor; single- and twin-barrel freezers for multiple flavors; freezers with built-in syrup rails and cone dispensers for easy logistics of serving; models for milk shakes, soft serve, or both together; low-overrun machines; and frozen drink machines. Examples include a single-cylinder counter model (Fig. 8.1), a floor model with two chambers from which two flavors can be dispensed separately or in combination as in a twist (Fig. 8.2), and a combination four-flavor milk shake or single-flavor soft-serve combination machine with syrup rail (Fig. 8.3). High-volume freezers are designed to produce as many as 7–10 cones per minute. Capacities of the refrigerated mix reservoir generally range from 8 to 60 L, although some freezers provide option to draw directly from bag-in-box mix containers through a special nozzle and pump apparatus.

The freezer cylinder capacity ranges from 1.5 to 4 L for ice cream and 5 to 7 L for shakes. Compressors are sized from 1 to 3 hp per dispenser head on the machine with capacities for heat exchange of 1–3 kW (3,000–9,000 BTU/h). The dasher(s) is driven by a separate motor rated at 0.5–2 hp. Most freezers require 208–230 V with smaller one-phase (10–15 amp) or larger three-phase (20–30 amp) versions. Some smaller units can run on 110 V (15 amp). It is important that there be an adequate and steady power supply to prevent failure of the major electrical components. Most units are available in either air- or water-cooled condenser versions. Ventilation or adequate water for cooling is, therefore, important for proper operation. Another consideration related to efficient operation is locating freezers out of direct sunlight and away from openings of heat ducts.

Because temperatures of dispensing are higher for shakes and frozen beverages than for soft-frozen desserts, motors are smaller in freezers designed for these

Fig. 8.1 Single-cylinder, counter model Taylor Crown Series Model 706 soft-serve freezer

products. In contrast, motors for frozen custard machines are considerably larger than those of shake machines. Frozen custard mixes contain more total solids and are frozen to lower overrun (15–40%) than are the typical low-fat, light, and nonfat soft-serve mixes (40–70%). Therefore, more power is required to turn the dasher and to deliver the product at the lower drawing temperature demanded by the lower freezing point of the typical frozen custard mix. Figure 8.4 shows a model of freezer for frozen custard that provides for regulation of mix flow to permit continuous removal of product into a separate portable dipping cabinet. The freezer can be operated in either the batch or continuous mode.

There are two types of air handling systems for soft-serve freezers. Gravity-fed machines are the most simple. The mix tank is located above the freezing cylinder, and the mix flows into the cylinder through a metering orifice at the base of the mix feed tube. As mix enters the cylinder, air is simultaneously dawn in through the top of the tube. Whipping then occurs at atmospheric pressure. Control over the mix:air ratio is imprecise, and overrun is typically 20–40%. The other system employs

Fig. 8.2 Double-cylinder, floor model soft-serve freezer with center spigot to dispense "twist"—a combination of two flavors being dispensed through the two spigots (Carpigiani Model U253)

pressurized air. It is more complex to operate and maintain, but it allows for precise control of overrun. Machines with air/mix pumps create pressures above atmospheric in the freezing cylinder and thus permit overrun up to 80% to be obtained, if desired.

Freezers used to make soft-serve ice cream or milk shakes are designed to dispense product on demand. Thus, dispensing may be done in rapid succession or at infrequent and varied time intervals. Sometimes the frozen product remains in the barrel for several hours and is subjected to agitation and successive refrigeration cycles. To maintain high quality under such circumstances requires specially formulated mixes and a well-insulated freezer barrel that will minimize the frequency that refrigerant is needed. Churning is the most frequently observed defect. Efficient homogenization and proper emulsifying agents are the usual corrective actions for overcoming this problem. Product that is obviously churned should be emptied from the freezer. The freezer should then be cleaned and sanitized and a new batch made.

Fig. 8.3 A combination four-flavor milk shake/single-flavor soft-serve machine with four-compartment syrup rail for heated and room-temperature sundae toppings. This freezer also has heat treatment capabilities (Taylor Crown Series Model 606)

Soft-serve products are usually drawn at −7°C (19 °F) and shakes at −3°C (27 °F) with some variance due to differences in freezing points of mixes. Some freezers are equipped to maintain viscosities of shakes and soft-serve products within acceptable ranges for high quality when dispensed.

Many soft-serve retailers now offer the consumer the choice of adding mix-ins, e.g., the Dairy Queen Blizzard or McDonald's McFlurry. Taylor offers an integrated mix-in blender called the Razzle. Another example of flavored product options utilizes an injection device that can be attached to certain soft-serve freezers to apply flavoring both internally and externally (Fig. 8.5). The manufacturer (http://www.flavorburst.com) offers more than 40 concentrated flavors to use with the machines.

Fig. 8.4 Continuous batch freezer with mix flow regulator allowing the operator to set the correct amount of mix flowing into the freezing cylinder for desired consistency. In front is a portable dipping station (Taylor Model C002)

Cleaning and Sanitizing Soft-Serve Freezers

Managers and operators must continually emphasize to employees the great importance of proper cleaning and sanitizing of freezers. The fact that much of the help in retail ice cream stores consists of inexperienced persons and that employee turnover is typically frequent means that training is usually needed on a consistent basis. Freezer manufacturers generally provide specific instructions for cleaning and sanitizing, and these should be followed closely unless they prove to be inadequate. Thorough and adequate cleaning is essential to eliminate possible microbial contamination. Some of the larger soft-serve freezers can now be cleaned-in-place

Fig. 8.5 Soft-serve freezer with attachments to deliver a specially formulated flavoring as a swirl on soft-serve frozen desserts (Courtesy Flavor Burst, Danville, IN)

without tear down of equipment while others require complete dismantling of all parts for thorough manual cleaning.

The following procedure for daily manual cleaning of most simple freezers is suggested:

1. Turn off refrigeration and turn beaters on to expel remaining product.
2. Rinse freezer with about 2 L (2 qt) of cool tap water.
3. Prepare 8 L (2 gal) of chlorinated alkaline detergent solution at 52–55°C (125–130 °F) at the concentration recommended by the detergent manufacturer (usually 1–1.5%).
4. Remove the hopper cover and mix tube assembly. Pour about 4 L (1 gal) of detergent solution into the hopper and brush thoroughly as the solution flows into the freezer cylinder. Be sure to brush the mix feed tube.

5. Run dasher for 30 s, then draw off the detergent solution. Rinse with warm water. (Caution: Running the agitator with no mix in the chamber causes excessive wear on the blades and cylinder.)
6. Remove the freezer door and disassemble all freezer parts. Ensure that gaskets and *o*-rings are removed to provide for cleaning behind them. Brush all parts, including the hopper cover and feed tube assembly, using the remaining detergent solution.
7. Rinse all parts thoroughly. Inspect all gaskets and o-rings for cracks or hard deposits and replace if necessary (at least every 90 days). Lubricate seals and valves as directed by the manufacturer and with approved lubricant before reassembly of the freezer.
8. Just prior to use, sanitize the freezer with a solution of 200 ppm (mg/L) of hypochlorite solution. Drain completely but do not rinse with unchlorinated water, because that action may reintroduce contaminants to the machine.

The Heat Treatment Freezer

Some freezer manufacturers offer soft-serve-type freezers and milk shake machines that need minimal daily cleaning because the major freezer components and the mix remaining in the freezer at the end of the day are heated daily to destroy microorganisms (Fig. 8.3). Components that are hand-washed and sanitized each day are those that cannot be subjected to the heating to 66°C (151 °F) for 30 min. The machine must be completely disassembled and cleaned every 14 days to meet National Sanitation Foundation (NSF) certification. Temperatures are monitored in the mix hopper, the freezing cylinder, and the glycol coolant. They can be read from a display monitor, and failure of the machine to provide required temperatures of cooling or heating within prescribed times will result in “hard lock-out” so that automatic operation of the freezer is not possible until the freezer has been disassembled and cleaned. Failure to disassemble and clean within 14 days will also result in “hard lock-out.” If a heating cycle has not been initiated within 24 h of the previous cycle, a “soft lock-out” will occur, and a heating cycle or full cleaning must be initiated before operations can be resumed. The heating cycle is completed within 4 h.

Records of types of system failure are retained in the memory of the microprocessor, and these can be accessed by inspectors or operators. This type of freezer has the advantages of reducing the time and cost of cleaning, saving mix, and enhancing safety in operations where novice employees are used frequently. Thus, they are very popular with the large fast-food chain restaurants. At the same time the capital investment is increased so that they may not be preferred by owner/operator restaurants whose incremental labor cost might be very low.

Heat treatment freezers require use of low-fat (ice milk) based products, 3–5% fat, rather than mixes with higher milk fat content (>8% fat). This is because the hopper has a continuous agitator that can cause churning (evident by visible butter

granules). Furthermore, churning can be evident in the product remaining in the barrel that has been subjected to the heat treatment.

Soft-Serve Blended Products

Soft-serve desserts can also be created by specially designed high shear dispensing machines or blenders that whip a hard-frozen product into a soft slurry and extrude it in the flowable state. This enables the dairy manufacturer to freeze mix in continuous freezers, add inclusions such as fruit, candies, and dough particles, then hard freeze the product for delivery to the retail store where it is to be sold. The hard ice cream, yogurt, or sorbet is tempered in a special cabinet. The frozen product, in the form of portion-size blocks or in bags or cartridges, is then placed in the extrusion cabinet for whipping and serving to customers. Three to four different flavors may be dispensed from such machines. The dispensing machine has minimal parts to be cleaned.

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Chapter 9
Novelty Products and Ice Cream Cakes

Introduction

Since early in the history of the ice cream industry, small manufacturers with imagination and initiative realized the potential for making profit by making and marketing unusual ice cream and frozen dessert products in the form of fancy shapes and/or single-serving products. Ice cream hand-packed into single-serving molds of all shapes for various holidays, etc., perhaps became the forerunner of our modern ice cream novelty industry. The word "novelty" conveys the qualities of freshness, uniqueness, and cleverness in creation and marketing. Novelties have included quiescently frozen bars, special combinations of ice cream with flavors and confections, cup items, and fancy molded items. They can be made of many types of frozen desserts, including ice cream with its various fat contents, frozen yogurt, sherbet, sorbet, puddings, fruit ices, and nondairy, for example, soy or other plant-based formulations. Items such as chocolate, wafers, cookies, nuts, and caramel sauces are frequently incorporated into novelty items.

Much of the creative work in the manufacture of these products was done with considerable manual labor, for example, hand decorating, but recent advances in equipment have made possible mass production at relatively low costs. Some firms have dedicated one or more plants solely to novelty product manufacture. Because the investment in equipment is high, the industry has tended to concentrate into a few plants strategically located to serve large population centers and where there is easy access to a major transportation system.

Factors that determine success in frozen novelty production are ingredients used in the mix, efficiency and effectiveness of the equipment, proper operation of the freezers and packaging equipment, and control during the operations. Marketing, of course, plays a much bigger role for these products than for take-home ice cream, in part due to the impulse purchase nature of the products and high levels of competition. Major areas of production control include portion control and hence yield, rate of freezing, stick insertion, extraction from the molds, yield of coating, wrapping or bagging, packing, sealing cartons, and storage.

H.D. Goff and R.W. Hartel, *Ice Cream*, DOI 10.1007/978-1-4614-6096-1_9,

Most of the products discussed in this chapter are produced as individual servings. The following are some reasons they are in demand in the marketplace: (1) their quality can be especially high because they are frozen rapidly as small individual units, (2) they are easy and convenient to purchase and consume (often being an impulse purchase), and (3) they can take on many unique forms, flavors, and compositions that attract persons who desire variety in eating.

During the first 50 years of their production, novelties were marketed principally to children. However, in the 1980s novelties broke out of their "moderate price/moderate quality" image when superpremium novelties transformed the entire frozen desserts industry. New, indulgent, upscale, adult-oriented novelties, including Dove Bar and Magnum, drove the market upward. The current trend for distribution is increasingly through vending machines. The International Dairy Foods Association, Washington, reported that vending machine sales of frozen novelties in 2009 totaled US $886 million, a substantial rise over the last decade.

Global and regional market share of impulse products by production and value in 2010 are shown in Tables 1.3 and 1.4, relative to take-home products and the artisanal and parlor markets. As was discussed in Chap. 1, there are very large regional differences in the size of the impulse market, impacted in large part by the presence of home freezers. By volume, this category of products makes up 85%of the market in Asia Pacific, 38%in Western Europe, and 25%in North America. It is also obvious from these data that these products demand higher price per unit volume, so their share by monetary value is typically much higher than their share by volume, for example 44%in Western Europe and 36%in North America.

The impulse category can be subdivided into multipack or single-portion purchases, and by dairy-based products or water ices. Global sales by volume and by value for these categories are shown in Table 9.1 and regional sales in Table 9.2. All categories have seen strong growth in volume and value from 2006 to 2010. Globally, single-portion dairy products comprise the largest subcategory, followed by multipack dairy and single-portion water ice products. However, large regional differences can be seen. Water ice products occupy a much more significant share of the impulse product market in Asia Pacific, for example, than they do in Western Europe. Multipacks occupy a much larger share of the market in North America and Western Europe than they do elsewhere.

Single-serving sundae cups, individually wrapped cones, and sandwiches of ice cream within baked wafer layers are perhaps the earliest of the "modern" novelty products, available for at least the last 50–60 years. Shaped novelties, either handheld or on a stick, are manufactured by either molding or extruding. In the molding method unfrozen water ice mixes or ice cream that has been lightly whipped and partially frozen in the continuous freezer is transferred to refrigerated molds. After partial freezing, sticks are inserted and frozen into the product. The frozen novelty is then lifted from the mold and may be dipped in a coating. The extrusion method involves freezing the ice cream in a continuous freezer to a dry, stiff extrusion at a temperature of about −6°C (21°F). Ice cream is then pumped through a specialty-shaped nozzle and cut upon exit with an electrically heated taut wire. Sticks may be inserted and the product is passed through a freezing tunnel refrigerated to −40°C

Table 9.1 Global size of the impulse product market by volume (million L) and by value (million US$) for various categories of product in 2006, 2008, and 2010

	2006		2008		2010	
	Volume	Value	Volume	Value	Volume	Value
Multipack dairy	7148.1	1731.2	8569.2	1830.8	9145.2	1934.0
Multipack water ice	1922.3	489.2	2080.4	479.7	2130.8	482.3
Single-portion dairy	16,613.9	3586.0	20,658.5	3834.6	21,619.2	3936.0
Single-portion water ice	4617.9	1528.9	5370.2	1647.0	5650.0	1700.0
Total impulse products	30,302.1	7335.3	36,678.3	7792.1	38,545.2	8052.4

Source: Euromonitor, 2011

Table 9.2 Regional size of the impulse product market by volume (million L) and by value (million US$) for various categories of product, 2010

	Multi-pack dairy		Multi-pack water ice		Single-portion dairy		Single-portion water ice	
	Volume	Value	Volume	Value	Volume	Value	Volume	Value
North America	629.3	2513.3	238.9	961.7	164.8	2068.4	65.6	603.3
Latin America	34.3	136.2	6.8	26.9	307.4	2923.9	94.5	655.3
Western Europe	706.8	3976.8	142.2	685.5	376.0	4814.0	88.8	1023.9
Eastern Europe	14.2	22.0	0.5	0.7	589.1	2858.9	31.4	157.5
Asia Pacific	467.9	2026.9	73.0	370.9	2276.5	7276.6	1338.0	2841.1
Australasia	72.5	433.0	16.3	71.1	37.4	684.9	9.1	116.3

(−40°F) where they are hardened to about −15°C (5°F) or lower. Finally, they may be dipped in a coating. Other products of this category include multi-portion cakes or logs, which are often prepared with the same type of extrusion equipment as for single-serving items although at the small-scale level, hand packing and hand decorating of cakes is still quite common.

Cup, Cone, and Sandwich Products

Single-serving cups of 100–250 mL size are perhaps not novel, but are within the category of handheld or impulse products. Cups are usually plastic or paper, although sometimes Styrofoam cups have also been used. In the latter case, care must be taken to ensure good freezing since the Styrofoam cup itself will act as a heat transfer barrier to the freezing process. Traditionally cups have been packaged with a wooden or plastic spoon, sometimes incorporated into the lid. Cups can be packed in multiple flavors. Sundae cups contain syrups such as chocolate, butterscotch, strawberry, or

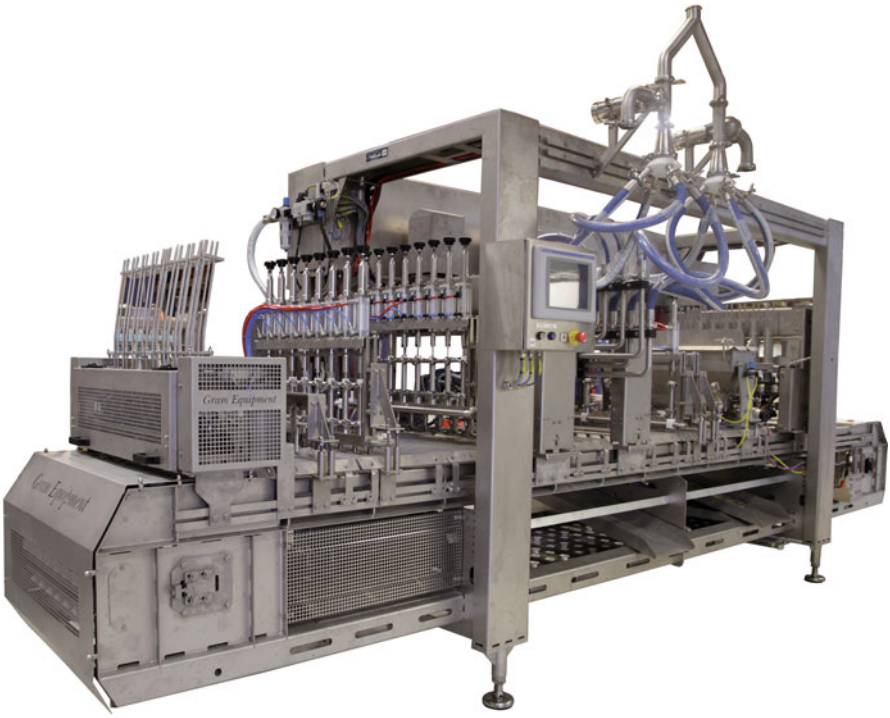

Fig. 9.1 An in-line filling machine capable of filling cones or cups with plain or variegated ice cream with various toppings (model GMF, courtesy of Gram Equipment of America, Tampa, FL, USA)

other fruit flavors deposited on the top of a fluted extrusion. Nuts or dry crumb can also be added. Cups are packed on filling equipment similar to that shown in Fig. 9.1, which are available from several companies. For example, Gram Equipment (http://www.gram-equipment.com) has two cup-filling machines, the GMF in-line filling machine for cups and cones that can produce 2,500–13,500 pieces per hour, and the ILF modular design for cups or cones in 4-, 6-, or 8-wide configurations designed to produce 6,500–31,000 pieces per hour. Norse Dairy Systems of Columbus, Ohio, USA (http://www.norse.com) produces a four-lane high-speed cup filler capable of producing 14,000–17,000 cups per hour, requiring a freezer output of 1,500–5,000 L/h, depending on cup volume. They also produce a two-lane filler for up to 9,000 pieces per hour, requiring a freezer output of 1,200 L/h. Various valving options at the filler head with input from more than one freezer barrel allow for multiple flavors in various shape configurations (e.g., striped, swirled, fluted, center core) within the cup. Cups of ice cream with fancy decorations or multiple flavors can also be produced (Fig. 9.2) and capped with a clear plastic-fitted lid. Another similar option is a push-tube type of filler (e.g., Norse Dairy Systems), in which the bottom of the tube is pushed up to continually reveal the product for consumption.

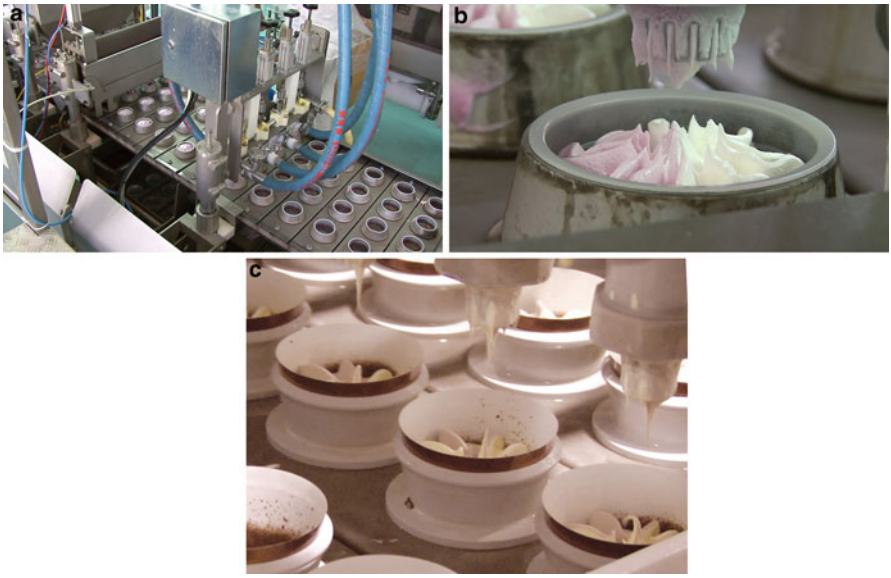

Fig. 9.2 Cup filling on a four-wide cup and cone filler (**a**), close-up view of the cup-filling nozzle filling a two-flavor product (**b**) and close-up view of the cone-filling nozzle (**c**) (model ILF, courtesy of Gram Equipment of America, Tampa, FL, USA)

A variation on cup-filled products are those cups that are designed to be dispensed through an extrusion-type nozzle (e.g., star) on the cup itself at the retail level (e.g., Unilever's Cornetto Soft). Disposable, single-service specially designed cups with various flavors of ice cream are filled at the manufacturing plant and distributed to retailers. At the retail level, the cup is tempered to an optimum serving temperature and then is placed in a machine that squeezes the ice cream from the cup onto a cone, which is then served to the customer. The ice cream does not contact the machine but is squeezed directly through a nozzle on the cup, making clean-up very simple. This type of dispensed cup provides a convenient alternative to soft-serve machines or to scooping of bulk ice cream for the retailer.

Cups can be replaced in many cup-filling machines with baked cones in paper sleeves to produce conventional cone items (Fig. 9.2). These can also be topped with syrups and or nuts. Chocolate sprayed on the inside of the cone acts as an edible barrier to slow down moisture migration from the ice cream to the cone. Norse Dairy Systems produces a cone filler with up to five stations for depositing of multiple layers of ice cream within the cone, syrups and sauces, and toppings. Various size fillers are capable of up to 9,000 pieces per hour requiring a freezer output of 1,100 L/h. Fancy cone items with, for example, raised and rounded scoops above the cone ("ball-top" or "round-top" cones) are produced on specialty-filling machines (e.g., Norse Dairy Systems has an eight-wide machine capable of producing 9,600 pieces per hour) from which product is conveyed into a hardening tunnel. These cones can have multi-flavor center cores and inclusions and a

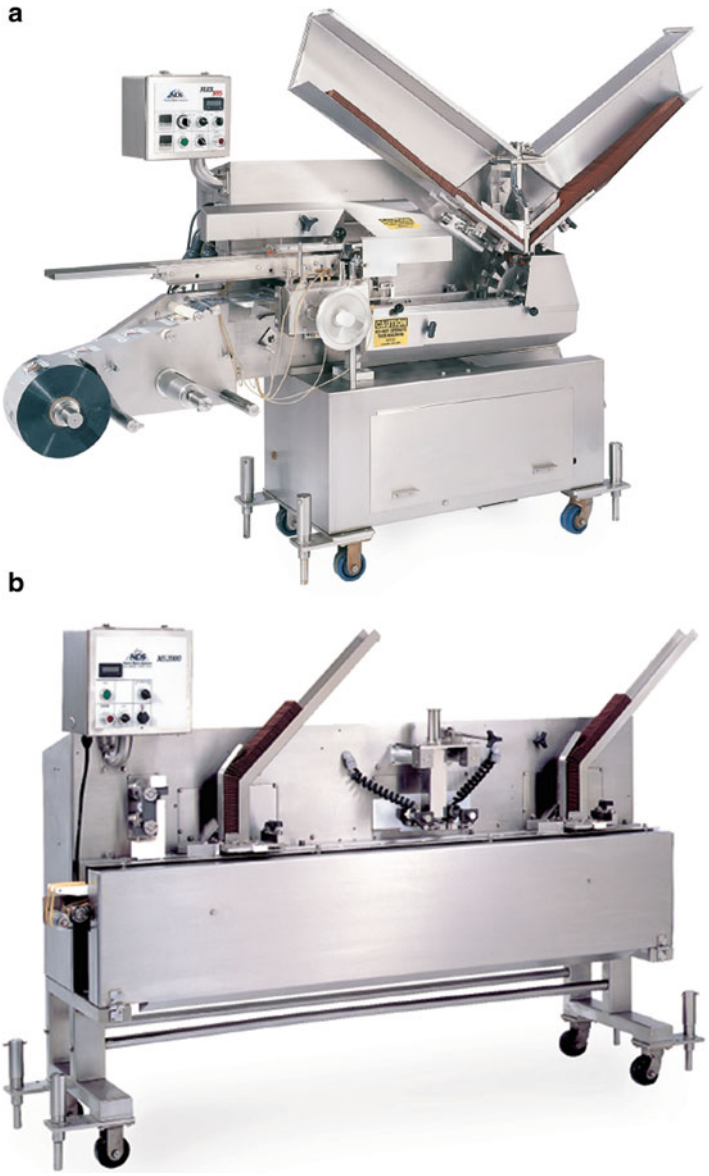

Fig. 9.3 Ice cream sandwich machines: (**a**) conventional and (**b**) "Extrude and Cut" (courtesy of Norse Dairy Systems, Columbus, OH, USA, http://www.norse.com)

variety of toppings. These products can also be made on extrusion manufacturing equipment, described below.

Ice cream sandwiches have traditionally been produced by extruding ice cream through a rectangular vertical nozzle, applying wafer biscuits to each surface, and

using the equipment indexing and edge of the wafer to cut the flow of ice cream (Fig. 9.3a). Sandwiches are then wrapped, boxed, and hardened. Ice cream for sandwich manufacture must be dry and stiff to retain shape. A higher concentration of emulsifier can be used in the mix if the extrusion is too wet for good shape retention in the slice and sandwich. Overrun should be kept below 100%for good product quality. Moisture migration from the ice cream to the wafer has resulted in a somewhat gummy wafer, but edible barriers on the wafer itself can be used to reduce moisture migration. Norse Dairy Systems produces various size sandwich machines capable of up to 9,000 pieces per hour, requiring up to 1,600 L/h freezer output.

Modern sandwich machines incorporate more flexibility in terms of shape (rectangular, square, or round), ice cream deposition (one, two, or three flavor stacked horizontally or vertically, with or without inclusions or syrups), and wafer composition and width, allowing for products like whole chocolate chip cookies to be used for wafers. On these "Extrude and Cut" (EC) machines, the bottom wafer is deposited onto a conveyer; dry, stiff ice cream is extruded through a vertical nozzle, sliced horizontally with a hot-wire cutter, and deposited on the bottom wafer; and then the top wafer is applied to the slice (Fig. 9.3b). The product is then conveyed into a hardening tunnel before packaging. Gram Equipment, WCB Ice Cream (http://www.wcbicecream.com), Technogel (http://www.technogel.com), and Norse Dairy Systems, for example, all offer such EC Sandwich machines in various sizes up to 9,000 pieces per hour requiring a freezer output of 1,500 L/h. Tetra Pak Hoyer (http://www.tetrapak.com) offers a sandwich module for their "DeepBlue" low-temperature extrusion ice cream machine for slicing of highly viscous low-temperature ice cream for deposition onto biscuits. Fancy sandwich items can be also be produced on the type of extrusion equipment described below.

Molded Products

Molded frozen novelty products always contain sticks for hand-holding. Items commonly frozen quiescently on sticks include water ice, fudge, and creams. Modern equipment makes possible the production of a wide variety of styles (Fig. 9.4). The molding type of production operation has mix being pumped into molds that are immersed in or are sprayed with chilled brine or glycol (Fig. 9.5a). The mix may, in the case of ice cream bars, or may not, in the case of water ice bars, have been whipped and partially frozen in continuous freezers prior to filling in molds. After partial freezing, sticks are inserted and frozen into the product (Fig. 9.5b). The frozen novelty is then lifted from the mold (Fig. 9.5c) and may be dipped in a coating (Fig. 9.5d). These machines are of the straight-through (in-line) (Figs. 9.6, 9.7, and 9.8) or rotary (Fig. 9.9) types. Rotary equipment occupies a much smaller floor space and, by design, eliminates any opportunity for brine contamination into the mold, but straight-through lines offer the advantages of easier changes in mold shape and cleaning of molds after each use.

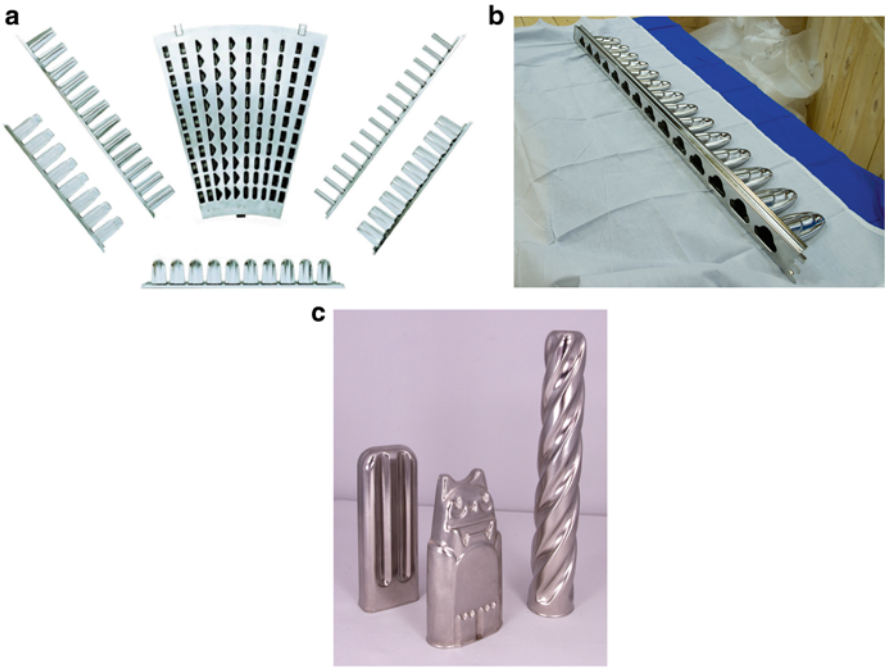

Fig. 9.4 Pictures of various mold shapes for in-line or rotary molding machines (**a**) courtesy of WCB Ice Cream, Northvale, NJ, USA; (**b**, **c**) courtesy of Gram Equipment of America, Tampa, FL, USA

Ice cream molding equipment is available from several companies. As examples, Gram Equipment offers straight-through molding machines (Polo) of various sizes from 4 to 24 rows wide and three machine sizes up to 12,000, 24,000, or 36,000 pieces per hour and rotary carousel molding machines (Ria) of various sizes from 10 to 28 rows wide and up to 30,000 pieces per hour. WCB Ice Cream offers straight-through molding equipment (Versa-Line) capable of processing 7,000–40,000 pieces per hour. They also offer design-on-surface capabilities to apply stripes of various colors, shapes, or combinations to molded water ice novelty items. Tetra Pak Hoyer offers rotary carousel molding machines (Rollo) of various sizes from 8,000 to 36,000 pieces per hour. Technogel offers both rotary and manual molding equipment (Technostick). The latter consists of a refrigerated brine tank and removable, fillable mold baskets that provide opportunities for small-scale manufacturers to produce molded stick bars.

The usual procedure for producing ice cream bars on a stick is to freeze the ice cream in a regular freezer to the desired overrun and a flowable consistency (e.g., 70%at −3°C) and deposit into the molds with top filling (hence the prefrozen ice cream still has to be flowable). Freezing occurs at the inner surface of the mold first and progresses inward. A recent advance in potential product quality comes from

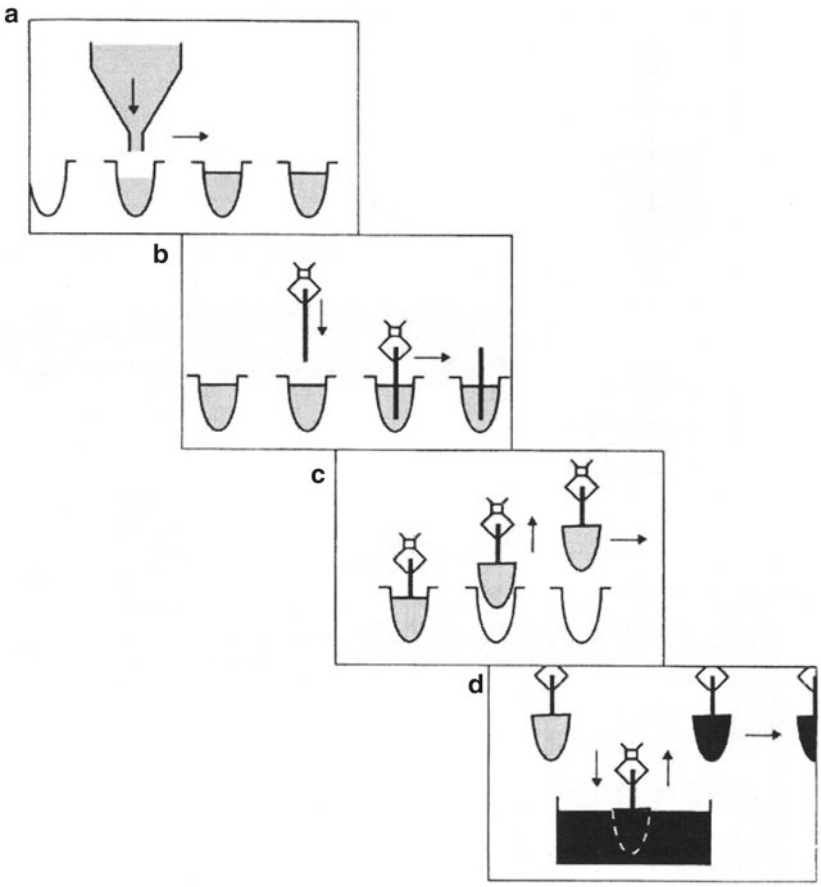

Fig. 9.5 Schematic diagram of the manufacture of coated stick novelties by the molding method

the offering of bottom-up fillers for molded items (Fig. 9.10) by several companies (e.g., Profill by Tetra Pak Hoyer or BUF by Gram Equipment). This allows for ice cream to be frozen in the continuous freezer to a higher overrun than possible for top filling and to a temperature of −5°C or less, resulting in smaller ice crystal size and better texture than that obtainable by the slower freezing in brine when filled at −3°C. The bottom-up configuration eliminates air pockets that would otherwise result from the filling of stiff ice cream. It also allows for inclusions in the ice cream and prevents settling when inclusions are incorporated at −3°C.

Mixes such as water ice or fudge can be deposited directly into molds without prior aeration/freezing. Multiple deposits of mixes of various flavors or colors allow for various horizontal layers to be built up (Fig. 9.8b). To make "splits," water ice is filled into the mold, and once the water ice has been partially frozen in the mold (from the outside in), it is possible to withdraw the unfrozen core of the product by

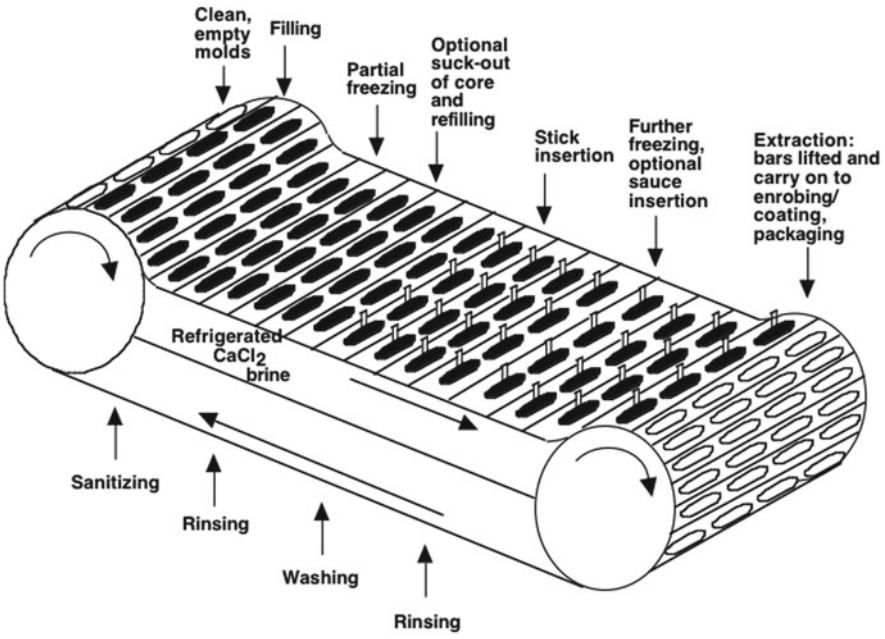

Fig. 9.6 An illustration of a straight-through machine for making molded novelties

vacuum and to redeposit another material to be frozen in the core, for example a soft-frozen ice cream. This produces, for example, the typical split with a water ice outside layer and inner core of ice cream. After sufficient core freezing, sticks are inserted and freezing is completed in the molds.

The molds then progress to a section where they are briefly exposed to heat (warm brine or water) to loosen the bar, and an extractor picks up the novelty by the stick and passes it to the next station. This station can be an enrober, decorator, or packaging apparatus. Chocolate enrobing is usually followed by after-cooling, which ensures solidification of the surface coating before packaging. Individual packaged items are placed typically in bags or boxes, which may be packed in cartons. Because they typically are very hard when packaged, it is unnecessary to transfer them through a hardening tunnel before sending them to cold storage.

Molds are characteristically made of stainless steel and must be both straight-sided and contoured to permit removal of the bar from the mold. Recent advances, however, permit further shape definition on molded novelty equipment. Soft polymeric molds are obtainable with defined 3-dimensional shapes (e.g., cartoon characters). After freezing and release from the mold, the bar is extracted and the polymeric mold is peeled off the surface and inverts as a result. It needs to be re-inverted before refilling. Two-piece, pneumatic-operated hinged molds are also available that can release 3-dimensional shapes by opening the mold. In this case, freezing in brine solution is not possible due to potential for brine contamination. However, freezing of the molds in low-temperature, high-velocity air or in liquid nitrogen in specially

Fig. 9.7 Filling end (**a**) and extraction and wrapping end (**b**) of an in-line (straight-through) molded novelty machine (Versa-Line, courtesy of WCB Ice Cream, Northvale, NJ, USA)

designed equipment (e.g., using WCB's Zero Adhesion Technology (ZAT) process) provides sufficient freezing.

Molded items always contain sticks. These are usually of beech or birch wood. Recent research by Jiamyangyuen et al. (2002) has shown that flavor can be transferred from the stick to the ice cream and that sticks of varying origin also vary in their flavor contribution, some being assessed as more woody or papery than others. Thus, care must be taken to ensure that the stick itself produces a clean, bland flavor that does not negatively affect the ice cream flavor.

Principles and Guidelines for Frozen Dessert Novelty Equipment is a publication that resulted from a joint project of the International Dairy Foods Association (http://www.idfa.org) and the International Association of Food Industry Suppliers (IAFIS) in cooperation with the Milk Safety Branch of the US Food and Drug Administration. The document sets forth criteria for the design and construction of equipment used to produce novelties. The document is not intended to be a regulation but to be used in conjunction with other documents that deal with product safety.

The principles and guidelines are intended to provide design criteria that will result in equipment that:

1. Is easily exposed for cleaning and inspection.
2. Can be cleaned and sanitized efficiently.

Fig. 9.8 Filling of a water ice mix into molds (**a**) and extraction of a multilayer water ice product from molds (**b**) on an in-line or straight-through molding machine (Gram Polo, courtesy of Gram Equipment of America, Tampa, FL, USA)

3. Avoids materials that may deteriorate.
4. Isolates the product from contact with contaminants.
5. Contains no areas where contaminants or vermin may be trapped.
6. Inhibits undesired microbial growth in ingredients.
7. Prevents spillage of ingredients and packaging materials.
8. Prevents unnecessary air movements and formation of aerosols.

Fig. 9.9 Rotary type machine for making molded novelties. (**a**) Overview showing the brine tank with rotary mold tabletop and stations for filling (perhaps in stages), partial suck-out, stick insertion and extraction of the bars for enrobing and/or wrapping at the rear (Hoyer Rollo, courtesy of Tetra Pak Hoyer A/S, Hoejbjerg, DK). (**b**) Close-up of filling heads on a 10-wide rotary tabletop

Ice and Fudge Stick Items

A formula suitable for producing 10,000 ices on sticks (120 mL, 4 fl oz) has the ingredients shown in Table 9.3. The procedure for mix preparation involves mixing the stabilizer with a portion of the sugar, adding the stabilizer, sugar, citric acid, and flavoring to a vat while agitating, and continuing agitation until the sugar is completely

Fig. 9.10 Bottom-up filling machine for molded novelty machines (Hoyer Profill, courtesy of Tetra Pak Hoyer A/S, Hoejbjerg, DK)

dissolved and the stabilizer is suspended. Molds should be filled to 0.5 cm (3/16 in) of the tops to allow for expansion during freezing.

Fudge bars are produced with varying concentrations of fat, and the formulas in Table 9.4 are representative of three of these.

Enrobing

Chocolate Coatings

Along with chocolate-flavored ice cream and chocolate inclusions in ice creams used in novelty products, there are novelty items to which the chocolate is applied as a coating (Fig. 9.11). Combinations of vanilla ice cream with dark chocolate coating have a long history of popularity. Such coatings should have a true chocolate flavor, melt readily in the mouth (melting point near 33°C), so it does not feel waxy, solidify rapidly with minimal drip during application, adhere well to the ice cream, and form a thin layer that resists cracking or breaking during handling.

The usual composition of coatings for frozen desserts is vegetable fat, cocoa, sugar, milk (including skim milk and buttermilk), lecithin, and flavors. The quantity of fat in the coating varies with the product, but 55%is considered minimal. Replacement of cocoa butter with vegetable fats is done for two reasons, viz., economy and function. A fat chosen to replace cocoa butter should have virtually no solid fat at 35°C. If more than 3%solid fat is present, a waxy mouthfeel will likely result.

Table 9.3 Ingredients needed to make 10,000 water ices on sticks in both metric and US measure

Ingredient	Metric measure	US measure
Water	986 L	260 gal
Sugar	190 kg	415 lb
Corn syrup solids	47 kg	104 lb
Stabilizer	4.7 kg	10.4 lb
Citric acid	9.8 L	2.6 gal
Flavoring[a]	977 mL	86 fl oz

[a]Amount of flavoring varies with type and source

Table 9.4 Formulas for making fudge bars containing varying amounts of milk fat

	Amount (%)		
Ingredient	Nonfat	3% Fat	5% Fat
Milk fat	–	3.0	5.0
Milk solids-not-fat	11.0	10.0	9.0
Whey solids	1.5	1.0	1.0
Sugar	15.0	15.0	15.0
Corn syrup (62 DE, 80%TS)	5.0	5.0	4.5
Fudge powder	3.5	3.5	3.5
Stabilizer	0.5	0.4	0.4
Water	63.5	62.1	61.6

Additionally, the amount of solid fat should be as constant as possible in the range of 20–25°C, to avoid softening of the coating at ambient temperatures during consumption, and in this temperature range the fat should be hard and brittle, so it retains a snap. If cocoa butter is removed from the chocolate liquor, it should be replaced with an oil high in lauric acid, such as coconut or palm kernel oil. Lauric acid-based coatings should be processed at a temperature of 35–39°C (95–105°F).

Flexibility of the coating is important to provide resistance to cracking. Soft coconut oil makes coatings flexible while hardened coconut and palm kernel fats reduce flexibility but cut the tendencies for the coating to drip as bars are removed from the enrobing bath. The logical choice, then, is a blend of the three. The addition of 5–10%of non-lauric oil, such as peanut, sunflower, or soybean, provides the protection from smearing often required during packaging. Furthermore, these non-lauric oils do not cause a soapy flavor if they become hydrolyzed. Finally, 0.5%lecithin added to the coating reduces the tendency for viscosity to increase as ice melts producing an aqueous phase in the enrobing vat.

A major requirement of the cocoa for such a coating is that it be finely ground. Furthermore, it should be low in moisture (less than 1 %) and have no residual lipase activity to avoid the tendency for the lauric acid to saponify, producing a soapy taste. This means that there must be no residual lipase from contaminating bacteria of either the cocoa or added oils. For prevention of oxidized flavors, cocoa

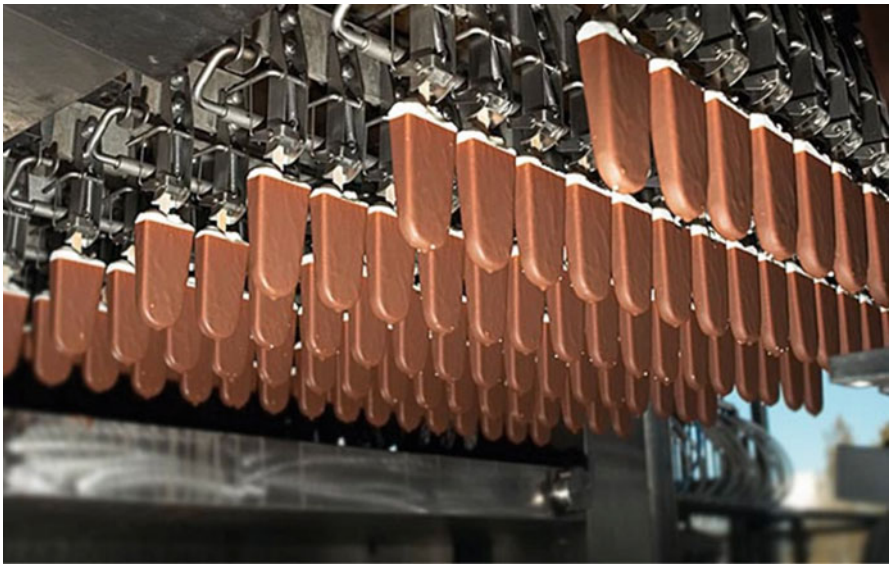

Fig. 9.11 The coating of ice cream bars in a thermostatically controlled dip tank

butter contains a relatively high concentration of antioxidants that many substitute fats do not contain. Fortunately, cocoa powder also contains antioxidants.

It is important to recognize that the amount of cocoa butter and the flavor-carrying nonfat component of these chocolate products vary. Approximate quantities of nonfat cocoa solids in various cocoa-containing ingredients are as follows: chocolate liquor, 45 %; 10–12%fat cocoa powder, 85 %; 22–24%fat cocoa powder, 70 %; sweet chocolate, 6.8 %; and milk chocolate, 4.6 %. The formulations in Table 9.5 are suggested by a major cocoa supplier for making chocolate coatings.

Depending on the ingredients combined with the chocolate liquor or cocoa, there could be different legal requirements for naming of the products used for coatings, for example, "imitation" or "filled" chocolate or "chocolate coating" or "chocolate with vegetable fat coating." It is recommended to check regulations for each legal jurisdiction for imitation or compound coatings before use.

Application of Coatings

Several factors determine the temperature and procedures for coating ice cream novelties:

1. The higher the temperature, the less the amount of coating deposited on the ice cream. However, melting of the product must be avoided.
2. The lower the temperature of the ice cream, the warmer must be the temperature of the coating to obtain minimal thickness.

Table 9.5 Formulas for light and dark chocolate coatings

	Light milk chocolate	Dark chocolate
Ingredients	%	
Natural process cocoa	6	–
Dutch process cocoa	–	10
Sugar	28.5	33
Lauric fat[a]	55	56.5
Nonfat dry milk	10	–
Lecithin	0.5	0.5
Vanillin[b]	0.03	0.03

[a]Usually the fat added is palm kernel oil or coconut oil
[b]Flavoring is optional

3. High overrun in the ice cream promotes rapid melting at the surface; therefore, coating temperature must be adjusted when overrun is changed significantly.
4. The higher the coating temperature the longer the time for solidification. Setting time can be adjusted by changing the ratio of soft oil to hard fat. The chocolate is kept in an electrically heated container with a water jacket controlled with a thermostat (Fig. 9.8).
5. Fast dipping is important, because coating thickness is proportional to residence time in the coating basin.
6. Moisture must be excluded from the coating to avoid increases in viscosity that will lead to thickening of the coating.

Coatings for molded novelties should have a slightly higher sugar (34%vs. 29 %) and lower fat (55%vs. 60 %) content than coatings for extruded novelties. Furthermore, the lauric fat needs to be somewhat harder for coatings used in dipping than for extruding.

Sometimes coatings are sprayed onto surfaces of cones. This coating needs to be quite thin, so the formula calls for about 65%fat, the remainder being 6%cocoa, 20.5%powdered sugar, 8%nonfat dry milk, and 0.5%lecithin. Coatings for ice cream cakes and pies can be more viscous than those used for cones, because the excess is usually removed by forced air or rapid vibrations. A typical formula contains 12%lightly alkalized cocoa, 37%powdered sugar, 50.5%lauric fat, and 0.5%lecithin.

Extruded Products

In the extrusion production operation, ice cream mix is prepared (Fig. 9.12a), frozen in a continuous freezer (Fig. 9.12b) to a temperature of about −6°C (21°F), and pumped through a specialty-shaped nozzle. A mix is chosen that will freeze into dry and stiff ice cream that can be sliced into portions upon exit from the nozzle with an electrically heated taught wire (Fig. 9.12c). Sticks may be inserted (Fig. 9.12d) and

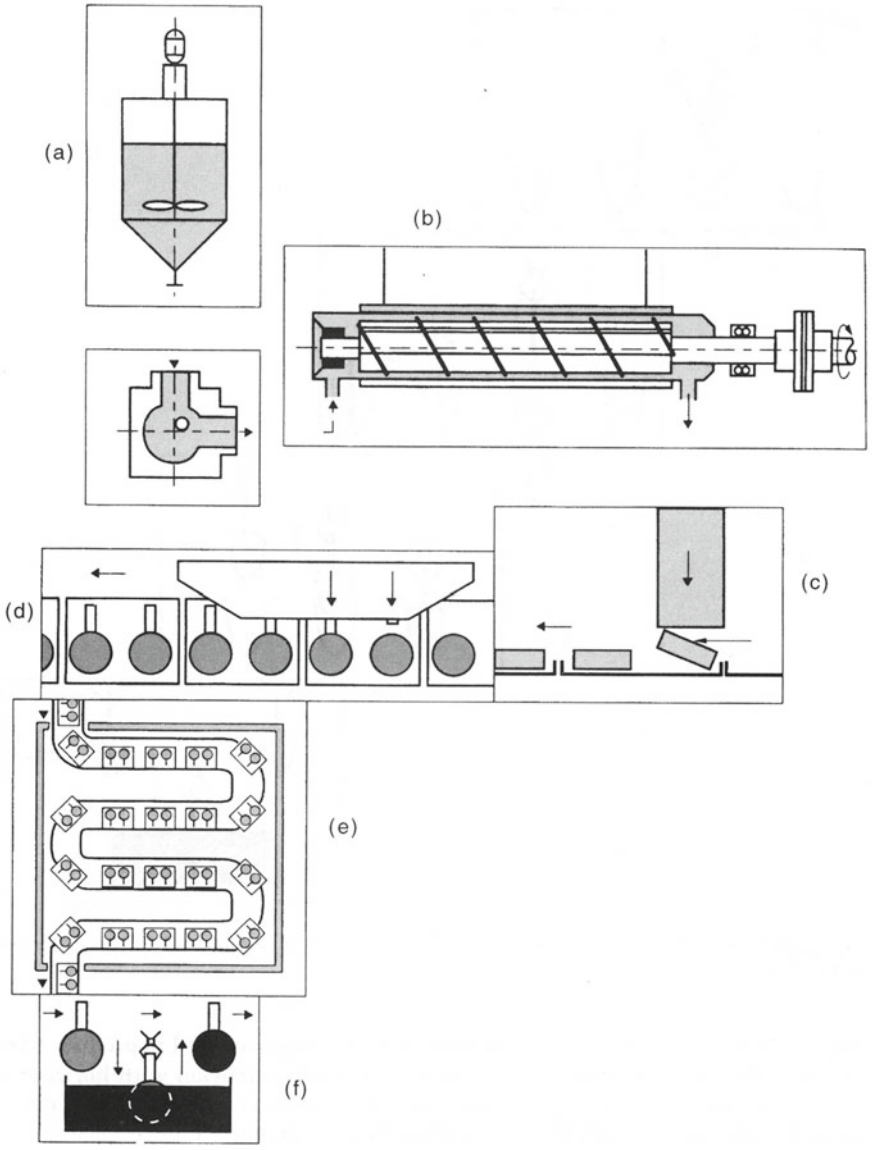

Fig. 9.12 Schematic diagram of the manufacture of coated ice cream novelties by the extrusion method

the product is dropped onto trays that pass through a freezing tunnel (Fig. 9.12e) refrigerated to −40°C (−40°F) where they are hardened to about −15°C (5°F). Finally, they may be dipped in a coating (Fig. 9.12f). Versatile equipment that can produce ice cream novelties in virtually any shape is available, and equipment developments in this area are continuing.

Extrusion equipment is available from several manufacturers. As examples, Tetra Pak Hoyer offers the Straightline Extrusion and Cutting machine capable of handling 7,000–9,000 pieces per hour single lane or 18,000–36,000 pieces per hour multilane. They also offer an Extrusion and Cutting module for their "DeepBlue" low-temperature extrusion ice cream machine for slicing of highly viscous low-temperature ice cream. Gram Equipment offers various Extrusion and Cutting modules for a high-capacity extrusion tunnel (Gram BT) for up to 36,000 pieces per hour and a low-capacity extrusion tunnel (Gram TT) for up to 9,000 pieces per hour, for stick and stickless pieces, sandwiches, bars, and ball-top cones. WCB Ice Cream offers two models of glacier tunnels for up to 12,000 or up to 27,000 pieces per hour, with accompanying Extrusion and Cutting modules and product handling and wrapping systems. Technogel offers an extrusion and tunnel system for 5,000–8,000 pieces per hour.

The extruder may take on a horizontal (Figs. 9.13 and 9.14) or vertical form (Figs. 9.13, 9.15, and 9.16). Horizontal extrusion with vertical cutting is used to produce bars that are often chocolate-bar-style novelties. Vertical extrusion with horizontal cutting, on the other hand, produces slices of variable shape, depending on the shape of the outlet of the extruder pipe (Fig. 9.17). If a stick item is desired, the stick is inserted horizontally in the extruded ice cream slice (Fig. 9.16a). Stick inserters are available from the suppliers of Extrusion and Cutting equipment. The product shape for stick bars is not limited to those that can be withdrawn from a mold, as it is in molding equipment. From either process, the pieces are formed on or dropped onto carrier plates (Figs. 9.15 and 9.16b) that pass through a freezing chamber at −40°C (−40°F) with rapid air circulation for flash freezing. Some candy bar-type extrusion systems are more than 100 m (300 ft) long. Each piece is removed from the carrier plate as it emerges from the freezing chamber. Portions to be coated with chocolate or other coating are then transferred to an enrober, thence through a chill tunnel to set the coating. The colder the bar, the more extensive is the pick-up of coating. Premium bars dipped in pure chocolate need to be very cold as the chocolate coating needs to be kept warm and molten (35°C), and it is essential to prevent melting of the ice cream in the chocolate during enrobing. Bars that are coated in pure fruit juice can be pre-dipped in liquid nitrogen before dipping in the coating. Often this needs to be repeated multiple times to get sufficient pick-up of the coating due to the high sugar content and thus low freezing temperature of the coating.

Capabilities exist for extruding single-flavor, multi-flavored, decorated, chocolate-coated, and dry-coated stickless slices; coated and uncoated ice cream sandwiches; single-portion and large horizontally extruded fancy decorated logs; bite-sized chocolate-coated miniatures; and more. With vertical extrusion equipment, the external contour of the slice (2-dimensional) may be almost any desired shape as is dictated by the shape of the extruder nozzle. Everything from simple designs such as a square or circle to very complex designs such as a baseball glove or a Christmas tree are possible. Ice creams of different flavors and colors, coming from different continuous freezers or different barrels within the same continuous freezer, can be used to create designs within the shape. The ice creams are routed through a complex filler head that directs the flow of each ice cream to the appropriate part of the extruder head (Fig. 9.17). By placing different extrusion nozzles inside

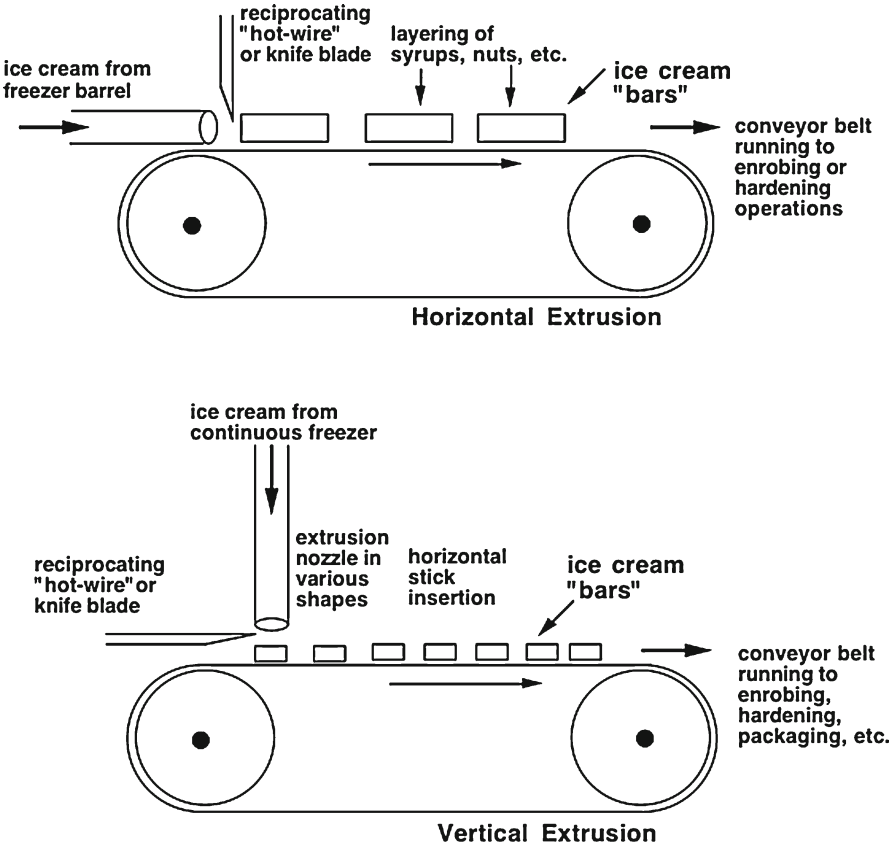

Fig. 9.13 Schematic illustration showing the principle differences between *vertical* and *horizontal* extrusion of ice cream novelties and specialty products

each other, intricate designs, such as faces with eyes, nose, mouth, and ears, can be formed. A large inclusion cutter is available for extrusion nozzles that is capable of cutting through whole pieces of fruit or large pieces of chocolate, for example, without distortion of the product (Fig. 9.18) as the wire moves through it (e.g., WCB Ice Cream Large Inclusion Former and Extruder (LIFE) System). Dynamic extrusion, in which the cutting device moves variably with time, allows for rippled products to be extruded to give 2½-dimensional shapes (e.g., Gram Equipment). Regular and ball-shaped cones can be produced with the addition of cone-filling equipment.

Further cold forming of extruded novelties is also possible. This might, for example, emboss a name or character imprint on the surface of the extruded novelty or change the surface contours (Fig. 9.19). Cold-pressing uses the patented Cryo-ZAT™ process (Zero Adhesion Technology, by WCB Ice Cream). The process takes advantage of the principle that precooling the embossing mold to temperatures below −50°C causes such a difference in rate of contraction between the molded item and the mold that adhesive bonds between the two break, allowing the frozen product to be removed easily. The system employs liquid nitrogen to cool the molds

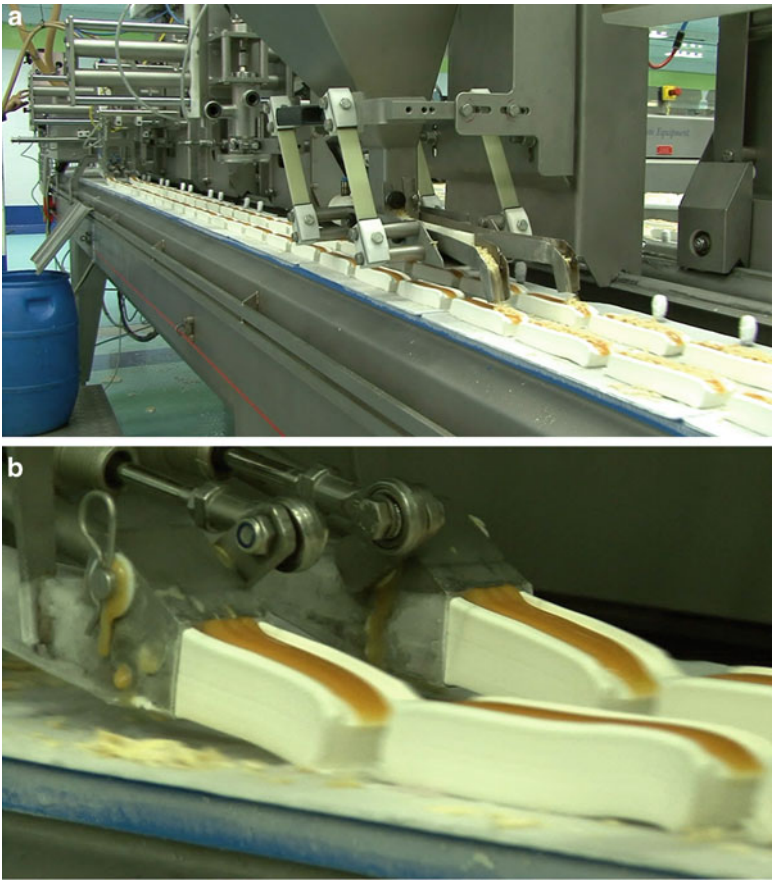

Fig. 9.14 A horizontal extrusion line with nozzles for layering flavors such as caramel and devices for sprinkling nuts onto bars of ice cream (**a**) and a close-up view of the ice cream extrusion nozzle with caramel layering (**b**) (courtesy of Gram Equipment of America, Tampa, FL, USA)

before the prefrozen ice cream product is cold-pressed with the mold. The ice cream freezes almost instantly, so there is no adhesion to the mold. This permits removal of the molded product without application of heat to the mold. Definition of the pressed surface is excellent, retaining the contours of the mold. Such technology is referred to as 2½ dimensional, since the bottom of the bar is still flat.

Ice Cream Cakes and Multi-Portion Products

Continuous freezers can be fitted with special discharge nozzles and used in pairs or trios to produce combinations of flavors in various shapes in the same package (e.g., a green Christmas tree in a red border, or “checkerboard” chocolate and vanilla).

Fig. 9.15 *Vertical* extrusion machine for ice cream bars showing the filling side (*front*), plate conveyor system running clockwise to move product through the hardening tunnel (entrance to box tunnel shown at the *left* side), and product enrobing and wrapping lines after product exists from the hardening tunnel (*right* side at the rear) (courtesy of Technogel, Bergamo, Italy)

When extruded directly into rectangular packaging, the consumer can cut slices off for serving to retain the embedded shape.

For extrusion nozzles, as described above, split-flavor nozzles can be used to produce fancy centers (Fig. 9.20) on horizontal extrusion equipment. These can then be cut into a fancy dessert, for example, log style, for single- or multi-portion packs. Multilayer fluted products (e.g., Unilever's Vienetta) can be made from horizontally extruded layers operating at different velocities, which result in the fluting effect from higher speed extrusion onto low-speed extrusion.

Ice cream cakes and pies can be made with special freezer attachments or specialized equipment. Cakes sold through retail outlets are increasing in popularity as home dessert items. Although formerly ice cream cake making was a very manual operation, cake lines can now be automated in extrusion equipment designed to deliver up to 600 items per hour, which has greatly increased availability (e.g., WCB Ice Cream). The technology operates with the same principle as extruded single-serving products described above and involves extruding ice cream through a large-diameter round, square, oblong, or sqround nozzle onto a support tray and cutting with electrically heated taut wire cutters. Syrup or dry materials can be added between layers, if desired, followed by addition of second or third layers of

Fig. 9.16 Ice cream bars being extruded *vertically* and cut following stick insertion (**a**). After extrusion, the bars travel directly into a hardening tunnel (**b**) (courtesy of Gram Equipment of America, Tampa, FL, USA)

extruded and cut ice cream. To add decoration, smaller shapes, such as dollops, can be deposited on top of the sliced cakes, or the cake can be post-extrusion molded or pressed using liquid nitrogen cooled molds (cryo-ZAT, see above) to produce defined shapes and contours. Further deposition of toppings can be added as desired, and the final cake can be packaged on an automated pick-and-place line into boxes (Figs. 9.21 and 9.22). For more manual operations, a cake filler is available for regulated deposition of ice cream from continuous freezers into springform molds for hardening (e.g., Technogel) prior to hand decorating. If decorating on the side was not desired, disposable plastic or paperboard packaging could be used. Filling of cake molds or cake packages could also be done manually from a batch freezer. Cakes can also be made by decorating layers of ice cream cut from bulk packages

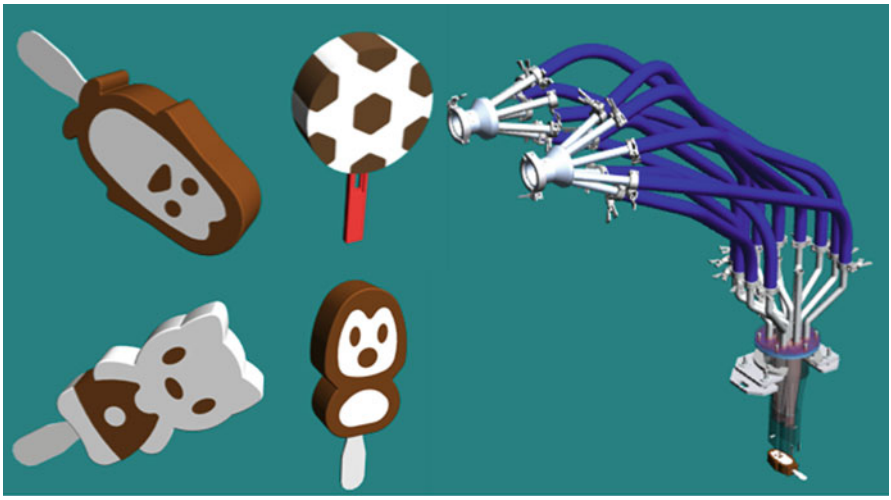

Fig. 9.17 Examples of the types of shapes and designs that are possible using *vertical* extrusion and an example of the filler head that would be required to direct differently colored ice creams to various parts of the design (courtesy of Gram Equipment of America, Tampa, FL, USA)

Fig. 9.18 The incorporation of large inclusions into extruded ice cream bars, made possible by the development of large inclusion cutters (Large Inclusion Former and Extruder (LIFE) System, courtesy of WCB Ice Cream, Northvale, NJ, USA)

by pulling a wire through the tempered ice cream or with the use of a food-grade band saw. Finished cakes are usually inserted into a stiff package to support the form of the cake during handling and delivery. An au fait can be made by placing a layer of fruit between two layers of ice cream. Iciness of the layer of fruit can be prevented by mixing the fruit with sugar and gelatin.

Ice cream pie shells can be made by forming the ice cream about one-half inch thick between two pie pans. The crusts can be filled with a gelatin–fruit–sugar mixture. A more common approach is to use graham cracker mix combined with shortening to make the shells in deep aluminum pie tins. Ice cream can be added directly from the continuous freezer or can be dipped from bulk containers that have been filled directly from a batch freezer. To permit shaping of the top, the

Fig. 9.19 3-D ice cream novelties made by the Cryo-ZAT process (courtesy of WCB Ice Cream, Northvale, NJ, USA)

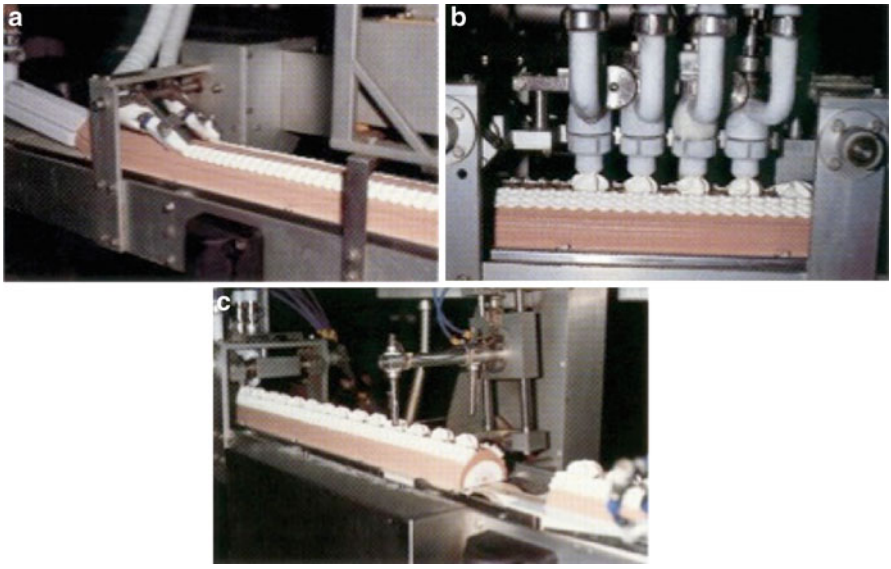

Fig. 9.20 Ice cream log with fancy center produced by *horizontal* extrusion. (**a**) Extrusion nozzles with the top running faster than the bottom to give fluting effect. (**b**) Dollop of ice cream being applied by *vertical* extrusion nozzle. (**c**) *Vertical* slicing to produce multi-portion log reveals that the main *horizontally* extruded log had multiple extrusion nozzles within it

ice cream can be made stiff or the pies partially hardened. Whipped cream, colored to fit the occasion, makes an excellent decorating material for ice cream pies and cakes.

Layered pies are special items. For example a “mud pie” is made with a layer of mocha chip spread on the bottom of a graham cracker crust, and after it has hardened, the top is filled with coffee ice cream. The top is covered with a layer of

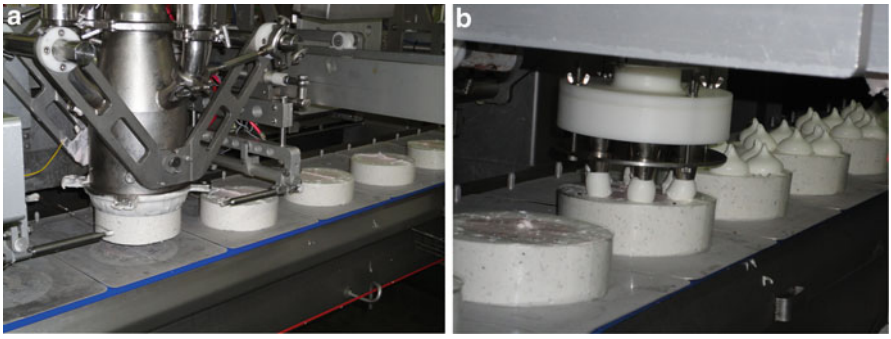

Fig. 9.21 Ice cream cakes being produced by *vertical* extrusion and cutting (**a**) followed by deposition of dollops of ice cream on *top* (**b**)

Fig. 9.22 *Vertical* extrusion and decoration of ice cream cakes on an automated line (courtesy Gram Equipment of America, Tampa, FL, USA)

high-quality chocolate coating, and a decorative circle of frosting is run around the edge. Crushed peanuts are sprinkled on top.

Two examples of Italian-style single-serving ice cream specialty items are spumoni and tartufo. Spumoni (from *foam*) is a fancy molded ice cream that is usually made with three layers of ice cream of different colors and flavors, usually containing candied fruits, usually cherry bits, and nuts as layers between the ice cream. It is prepared in a cup-shaped form in single-serving size. The outside layer is frequently pistachio or sometimes vanilla ice cream. Inside this shell is placed chocolate ice cream or macaroon or chocolate mousse (chocolate ice cream blended with whipped cream), and this is topped with tutti-frutti mousse, a mixture

of fruit, confectioners' sugar, and whipped cream. In serving it is cut into wedge-shaped pieces like cake. Tartufo (from *truffle*) is also an Italian-style single-serving dessert composed of two or more flavors of ice cream with either fruit syrup or frozen fruit, typically raspberry, strawberry, or cherry, in the center. It is typically covered in a shell made of chocolate, but cinnamon or nuts are also sometimes used.

Reference

Jiamyangyuen S, Delwiche JF, Harper WJ (2002) The impact of wood ice cream sticks' origin on the aroma of exposed ice cream mixes. J Dairy Sci 85:355–359

Chapter 10
Packaging, Hardening, and Shipping

Considering the Package

As ice cream is drawn from the scraped-surface freezer, it should be put into containers that give it the desired form, size, and appearance for convenient handling, efficient hardening, consumer appeal, consumer information, convenience, and economy. The label must reveal the ingredients in the order of highest to lowest concentration and the nutrient content in standard format. These labeling considerations were discussed in the context of formulations in Chap. 2.

The ice cream manufacturer is basically interested in using containers that will protect the product, will be desired by potential purchasers, and will cost a minimal amount. However, there are many factors that ultimately determine what package to use. In view of the importance of the subject to the dairy industry, the International Dairy Federation published the third edition of the Technical Guide for the Packaging of Milk and Milk Products (IDF 1995). The Bulletin describes factors that determine the nature of the packages that enter and stay in the marketplace:

1. *Variables that affect choice of raw materials*—such as uniformity of materials, compatibility of product and package, and efficiency of production.
2. *Performance of packages in storage and transport*—how they fit into the overall system of packaging and handling.
3. *Marketing considerations*—suitable consumer units for storage, space savings, stackability, ability to convey a good sales message, and minimal losses or damage.
4. *Consumer acceptance*, *purchase*, *and use*—reasonable price, attractiveness, reliability, safety, information conveyed, and clarity of message.
5. *Public concerns*—energy use, expenditures of nonrenewable resources, public health and welfare, and environmental contamination.

Several of the factors mentioned above are of sufficient public concern that legislation has been passed to control them. Food legislation has two basic objectives—first, to prohibit the sale of foods injurious to health of the consumer, and second, to

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insure that a product of nutritive substance and quality is available to the consumer. Because the majority of today's food packages are either made wholly from or are coated with plastics, there is concern that the polymers are safe and that toxic substances do not migrate from them into the foods. Since plastics consist of a basic polymer plus the auxiliary substances added to achieve desired function, it is required in many countries that manufacturers make a positive list of all polymers, additives, adhesive coatings, and lubricants that are permissible for use in packages for foods. In the United States, that list is published in the Code of Federal Regulations. Part 21, Section 175.105 presents regulations on the use of adhesives. A list of "indirect" additives used in food contact substances is given at the web site of FDA, http://www.fda.gov/Food/FoodIngredientsPackaging/ucm115333.htm. This list references the applicable parts and sections of the Code of Federal Regulations in which the substances listed as indirect food additives are published.

Migration of materials from the package into food, in general, is of major concern (for example, bisphenol-A, BPA, in polycarbonate water bottles). Regulations that address potential outcomes of migration usually address the following concerns (IDF 1995):

1. The taste, smell, or character of the food will not be altered after storage under normal conditions.
2. Total migration from the package, even if completely harmless and not sensorially perceptible, shall not exceed the limit in the "contamination test" limit set by national regulations.
3. The packaging material will contain only substances included on the list of permitted ingredients, and these will not exceed the permitted maximum concentration. Usually the manufacturer guarantees this.
4. If the list of permitted ingredients contains provision that migration of certain components from the packaging material shall not exceed a set level in the food, the packaged food will be checked against that provision. (Important in this regard are monomers of the material that was polymerized and breakdown products that arise from overheating).
5. Fundamental hygiene will be practiced in manufacturing the package and producing the packaging materials.

In general, migration of packaging components into ice cream is minimal, primarily due to the freezing storage temperatures. Molecular diffusion is reduced as temperature decreases, meaning there is little concern for contamination of ice cream through contact with the package.

In recent years, the emphasis on environmental quality has put more pressure on food manufacturers to consider packaging systems that are more environmentally friendly. The frozen desserts industry is no exception, with manufacturers looking for low-cost, yet efficient, "green" alternatives. Most large ice cream companies still use polyethylene-coated paperboard packages; however, greener alternatives are popping up, at least for certain types of applications. For example, biodegradable containers made from wood fiber and corn, and ice cream cups made from bagasse, a by-product of sugar refining, are being used in small ice cream operations.

Whether any biodegradable packages can withstand the rigors of the frozen food distribution and storage system and still deliver a high-quality product remains to be seen.

Another aspect of packaging that has commanded growing attention is the contribution of packaging to greenhouse gases and global warming potential. Life cycle assessment (LCA) is being used more and more to compare the effects of different packaging options, as discussed previous by (Kool and van den Berg 1995). Although no complete LCA has been published for ice cream manufacturing (probably due to the corporate sensitivity of such information), Garcia-Suarez et al. (2008) claim that packaging contributes only 6% of the total carbon footprint (greenhouse gas) for ice cream manufacture. This value included secondary and tertiary packaging but did not include the effects of waste disposal.

The Packaging Operation

The packaging of frozen desserts is of two types: bulk packaging for the sale of dipped products, including cones, and consumer packaging for direct retail sale. Packaging should be done as close to the freezer as possible to limit the backpressure on the freezer cylinder exerted by friction in the pipes. Bends in the line to fillers should be minimized, because they produce several times more friction head than straight pipe of the same size. Short straight pipes from freezers to fillers minimize the amount of energy needed to move the product as well as the amount of rise in temperature from the freezer to the package. The practice recommended is to minimize distance from freezers to fillers and to maximize size of pipes carrying frozen product to containers. See Chap. 7 for more details on piping requirements leading up to the fillers.

Bulk Packaging

Practically all frozen desserts for bulk use are packaged in single-service containers made of paperboard or plastic. Some are packaged in reusable plastic, but little use is made of steel cans. Gelato is often packaged in reusable stainless steel pans for presentation at the scooping shop. It may have been frozen and packed on-site or it may have been delivered to the scooping shop, but as gelato is usually a fresh product, the turnaround time from packaging to scooping should be very short. Containers vary widely in size with many being formed mechanically with multiple spindle machines. Figure 10.1 shows a forming machine for large containers, up to 24 L in size, with operation speeds of up to 480 units per hour. Flattened sidewalls, bottoms, rings to form the bottom and top, and overlapping tops are shipped separately to the ice cream plant for assembly just prior to filling.

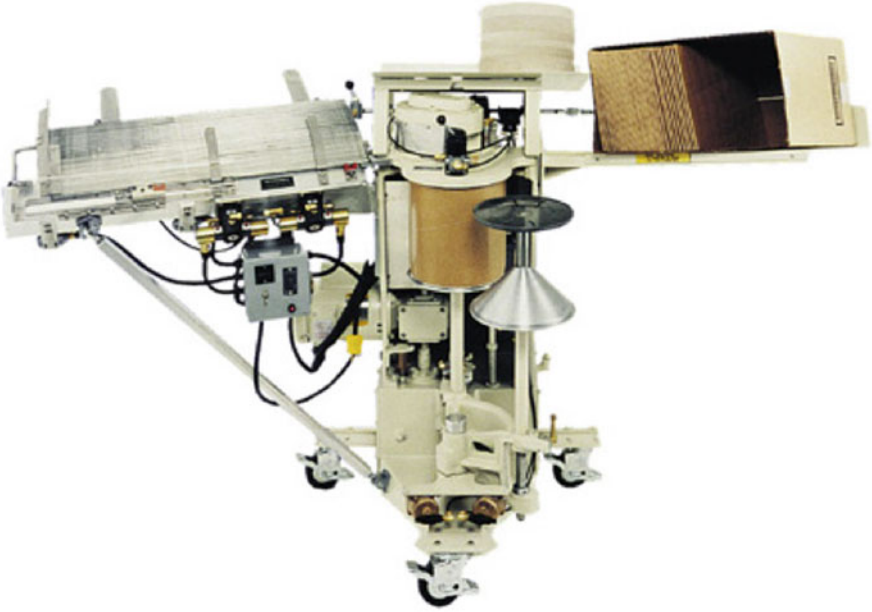

Fig. 10.1 Forming machine for 1-gal (4-L) to 6-gal (24-L) sizes of bulk containers. Produces up to 480/h as it semiautomatically attaches sidewalls and bottom together with seam holders formed from flat metal strips (courtesy of Huhtamaki, Inc., DeSoto, KS)

Once the package is ready, both package and ice cream come together in the filling machine. Figure 10.2 shows the sequence of a bottom-up filler, where the empty package is lifted to near the filler head or "tooling plate," then spun and lowered as product is pumped in. Spinning while filling can be employed and adjusted to help establish elaborate patterns in multi-flavor ice cream products for consumer eye-appeal in dipping cabinets. Weight and stiffness of the product can be used to lower the elevator as the product fills the container. In this case, pressure on the elevator must be adjusted when mix stiffness or overrun changes. Lids are commonly pushed on mechanically as the filled container moves away from the filler on a conveyor. Important functions of filling machines are accurate and precise fill, avoidance of air pockets, maintenance of the distribution of variegates and other inclusions, and freedom from product on the outside of the container.

Proper function and economy of operation of fillers are truly important, but no filler is satisfactory that does not meet strict standards for sanitary construction and operation. To this end, the industry has accepted 3-A Sanitary Standard No. 23–05 (2006), Sanitary Standards for Equipment for Packaging Viscous Products. The standard covers materials and fabrication of equipment used to package frozen desserts. It covers "the sanitary aspects of utilized equipment for holding, opening, forming, dispensing, filling, closing, sealing, or capping containers for viscous products, or wrapping viscous products, and all parts essential to these functions." Manufacturers whose equipment meets the standard may attach a 3-A symbol to

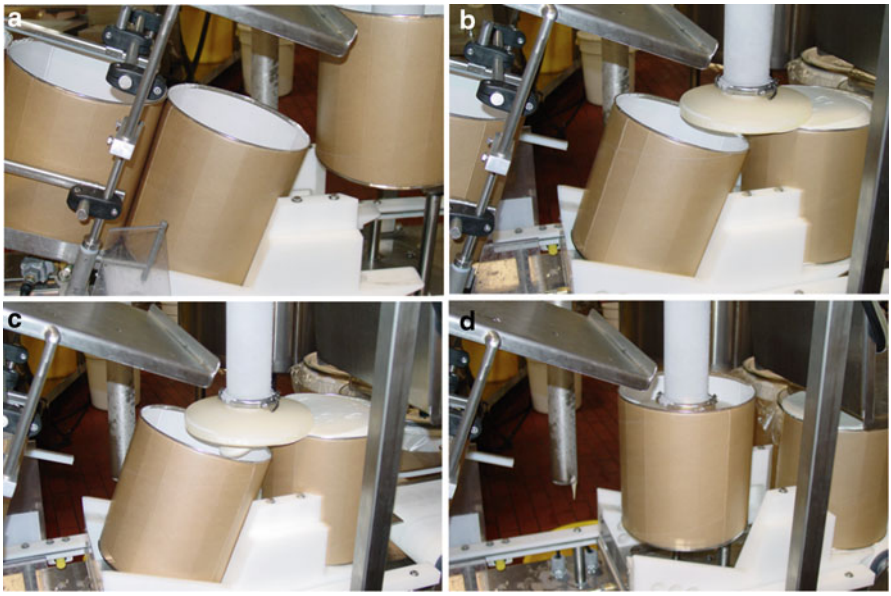

Fig. 10.2 Sequence of filling of bulk containers: (**a**) container staged and ready to load into filling station, (**b**) empty container as it starts transition toward filling station, (**c**) completion of filling of previous container and start of filling of empty container, and (**d**) empty container being raised in the filling station (courtesy of TD Sawvel Co., Inc., Maple Plain, MN)

the packaging machine. The symbol assists sanitarians in inspecting the equipment by letting them know that approved materials and fabrication criteria have been applied. Under this standard, sanitizing means a "process applied to a clean surface which is capable of reducing the numbers of the most resistant human pathogens by at least 5 $\log_{10}$."

Packaging for Direct Sale to Consumers

Packages for sale directly to consumers vary in size from 3 fl oz to 2 gal, or from 100 mL to 8 L. The most common size is 0.5 gal (1.89 L). Shapes are rectangular, cylindrical (round), conical (tapered cylinder), and square-round ("squround" or scround). The latter, a modification of the conical container, is rectangular, tapered, and rounded at the corners. Advantages claimed for the square-round shape include easier scooping than either the round or rectangular container, tighter seal than the rectangular carton, better fit in the freezer than the round container, and stackable with the front forward. In general, consumers prefer two-piece containers (base and lid) over the rectangular one-piece refoldable cardboard type. On a volume basis, ice cream sales in 2010 in the United States had the following distribution of package shape: round, 42.1%, rectangular, 8.8%; square-round, 42.1%; pail/tub, 7.1%

Fig. 10.3 Sequence of freezing, ingredient addition, and filling (courtesy of Tetra Pak Hoyer A/S, Hoejbjerg, DK)

(IDFA 2010). This represents a substantial increase in square-round packages (up from 15% in 2001) and decrease in square/rectangular packages (down from 34% in 2001).

The traditional rectangular half-gallon carton is made of plastic-coated paperboard. It is printed by a paper products firm, folded into a collapsed form, and sealed on one side. Before filling, it is opened and the bottom flaps are closed. The container is then filled and the top flaps are closed with no seal applied. The package is normally opened at one of the ends. A second version of this shape is heat sealed on both ends into its rectangular shape. It is opened on one of the larger sides by breaking the sealed overlapping lid. Conical and square-round type packages are shipped preformed and nested within each other, whereas rectangular and cylindrical types are formed at the location of filling.

A continuous process manufacture and filling line brings the stream of ice cream together with the package. The ice cream side consists of the freezer, ingredient feeder, and filling line (Fig. 10.3). For filling, the package must be fed into the machine and presented to the filling nozzle in the proper sequence. Depending on the package, a forming step may be necessary or preformed containers are fed to the package end of the filler. After the ice cream filler, the packages must be closed and sealed, followed by weighing, passing through a metal detector for quality control purposes, and, sometimes, by overwrapping of the containers. Overwrapping or, less frequently, bagging is done to limit the number of items to be handled and to protect the packages during handling. Overwrapping of single packages provides evidence of tampering, slows transmission of gases, and may improve appearance. Shrink-wrapping by heat is a significant cause of heat shock, but polymers are available that can be applied as "stretch wrap" with no heat used. However, when multiple packages are wrapped together, the surface to volume ratio of the packages is greatly reduced and the rate of hardening can be slowed, depending on the configuration of the bundle and the type of freezer. For example, the package at the center of a bundle, regardless of the size, will experience significantly slower cooling rate than those on the outside. For this reason, bundling of packages and consolidation of bundled packages onto pallets are usually done after hardening to enhance heat removal and retain the smallest possible ice crystal size.

Fig. 10.4 Rotary-type filler for cups and round nested containers (courtesy of Huhtamaki, Inc. DeSoto, KS)

Fillers are available with rotary tables (Fig. 10.4) or in-line configuration (Fig. 10.5) and both are available with multiple parallel lanes (rotary—Fig. 10.6; in-line—Fig. 10.7) for larger operations. These fillers are usually adaptable to a range of volume and package type so that production changes are easily made. Containers in a single lane are filled simultaneously and may be topped and capped at other stations on the stainless steel conveyor. These fillers are computer controlled and can be preprogrammed to fill multiple different products. Fillers can also be linked by computer to a companion freezer, ingredient feeder, and freezing tunnel to provide a fully integrated rate-controlled system. Modern fillers can also deposit multiple flavors simultaneously in multiple lane operations (Fig. 10.8).

Fig. 10.5 In-line filler for square-round packages (courtesy of TD Sawvel Co., Inc., Maple Plain, MN)

Economy in Packaging Operations

In an ice cream manufacturing plant, the economy of packaging can be related to two elements. First, ensuring proper fill weight is critical to meeting legal requirements and satisfying consumers. Second, scheduling the packaging operations should be carefully tied to production rates to minimize bottlenecks and maximize production capacity.

Although ice cream is sold by volume, a minimal weight per gallon is required. Over and above any legal requirements, it is in the interest of the producer to control weight to minimize product losses from overfilling. The three main influences on variation in fill weight are (1) control of overrun from the freezer, (2) variations in particulates from the ingredient feeder, and (3) variations inherent in the filling machine. In general, the better the equipment operation, the better the control over fill weight. Calculations of target package weights based on size, overrun, and particulate density and dosage rate are shown in Chap. 6.

Modern statistical process control (SPC) principles are generally applied, through dedicated software programs, to ensure production optimization so that fill weights are within specifications. Control charts of sample weights showing mean values and standard deviations along with upper and lower control limits are often displayed

Fig. 10.6 Dual-lane rotary type filler for cups and round nested containers (courtesy of WCB Ice Cream, Northvale, NJ)

in real time in the factory control room. Operators monitor these control charts to ensure optimal operation.

Another aspect of importance to packaging economy is scheduling of the entire operation within the factory. Scheduling of production is dependent primarily on rate of sales, amount of product in inventory, production rate possible with the equipment, and the most economical length of a production run. An analysis of the problem of most efficient scheduling can be done using an optimizing lot size formula in which the number of units produced per run, the number of units expected to be shipped or sold per time unit, the cost of holding a unit in inventory (storage) per unit of time, and the cost of setting up and tearing down for a production run are factors. Recently, multistage scheduling models have been applied to ice cream manufacturing with the aim of improving process operations, particularly packaging, and increasing capacity. Bongers and Bakker (2006) used a simplified model of a medium-scale ice cream factory that was able to account for (1) the number of manufacturing lines along with the key equipment of each, (2) flow of material

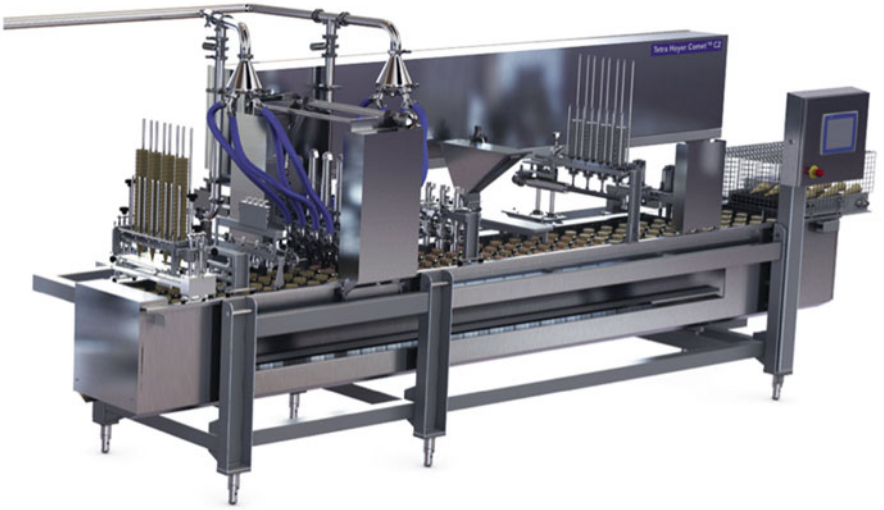

Fig. 10.7 In-line ice cream filler with multiple parallel lanes (courtesy of Tetra Pak Hoyer A/S, Hoejbjerg, DK)

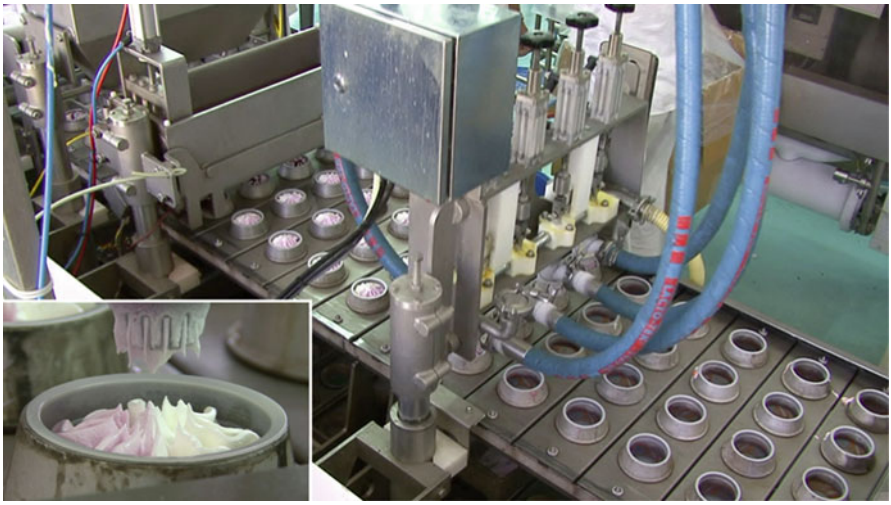

Fig. 10.8 Cup filler with multiple flavors depositing on parallel lanes. Inset shows details of filling station (courtesy of Gram Equipment of America Inc., Tampa, FL)

through the plant, and (3) operating procedures. They showed that capacity could be enhanced by 10–30% by simply better coordinating all operations within the factory (Bongers and Bakker 2006) to reduce bottlenecks to production. More recently, Subbiah et al. (2011) applied a "timed-automata model" to the ice cream scheduling problem of Bongers and Bakker (2006) to develop a weekly make schedule that enhanced production capacity. Kopanos et al. (2012) solved the same ice cream

production scheduling problem using an efficient mathematical framework based on mixed integer programming (MIP) that (1) provided an even shorter make schedule, (2) reduced process line utilization by 10% over the Bongers and Bakker (2006) solution, (3) significantly reduced the total waiting time in the ageing step, and (4) used less computational time than the Subbiah et al. (2011) study. Clearly, such process optimization programs have enormous potential for enhancing packaging operations (and the total manufacturing process) in food factories.

The Hardening Process

In the traditional ice cream process, when ice cream is drawn from a freezer and placed in containers, it is of a semisolid consistency and is not stiff enough to hold its shape. Therefore, the freezing process is continued in containers without agitation until the temperature reaches −18°C (0 °F) or lower, preferably −25 to −30°C. Quick hardening is desirable because slow hardening permits growth of ice crystals and air cells. Stacking of packages before they are hardened (particularly for those containers at the center of the stack) leads to undesirable changes, including deformation of packages, loss of overrun, and surface discoloration because air is pressed out, not to mention growth of ice crystals and air cells.

Time to accomplish hardening has been assumed to be the time for the temperature at the center of the package to drop to −18°C (0 °F). This hardening time for a still air operation may be as short as 30 min for 4-oz (100 mL) packages to as long as 24 h for 2.5-gal (10 L) packages. A shorter time always results in a smoother ice cream. Hardening tunnels and plate type systems remove heat at an accelerated rate. With rapid hardening, a goal should be to achieve a core temperature in the center of the package of −18°C within 4 h, regardless of package size.

Changes During Hardening

During the initial freezing step, a significant amount of energy is expended in making small ice crystals and air cells to produce the highest quality product (see Chap. 11). Proper hardening conditions are necessary to ensure that these fine structures are preserved during subsequent distribution and storage prior to consumption. When ice cream is removed from the primary freezer at draw temperatures of −5 to −6°C, significant changes in the ice crystals and air cells take place until the temperature decreases sufficiently to halt these changes. Thus, optimal control of hardening can have a substantial impact on product quality.

As temperature decreases during hardening, additional ice forms as the system strives to maintain equilibrium between temperature and the amount of ice formed. As long as the temperature decrease during hardening is not excessively fast, as might be

experienced with hardening in liquid nitrogen, for example, the temperature decrease and the amount of ice formed follow the curve shown in Fig. 5.13. Assuming a typical ice cream formulation, about 50% of the water is in the form of ice at draw temperature (−5 to −6°C), and this increases to about 80% when the temperature has decreased to −18°C. Since no new ice crystals are formed during hardening (the constitutive subcooling at any point in the package is sufficiently low and the presence of ice crystals precludes the need for additional nucleation), all of the additional ice formed as temperature decreases appears as an increase in size of the ice crystals already present.

Typically, ice crystal size increases by about 30–40% (from about 25 μm to perhaps 35 μm) during hardening, although not all of this increase is due only to the increase in amount of water frozen to ice. During the time spent at the relatively warm draw temperature, some of the ice crystals that were formed in the scraped-surface freezer melt. In particular, the smaller ice crystals are more sensitive to warmer temperatures and the small ones may even melt away as the large ones grow larger. This process is called ripening, or recrystallization, and it occurs when ice crystals are held at elevated temperatures (near the melting point). Thus, just holding ice cream at constant (but elevated) temperature results in an increase in mean ice crystal size and a decrease in the number of ice crystals present. The decrease in surface area as some crystals melt away is accompanied by increases in volume/size of the remaining crystals as temperature decreases during hardening.

In any packaged frozen dessert in hardening, cooling occurs from the outside, penetrating into the center at a rate depending on thermal diffusivity. Because of the release of heat associated with the phase change during cooling (Ben-Yoseph and Hartel 1998), the reduced thermal diffusivity of ice cream actually provides somewhat of an insulating effect, delaying the rate of cooling at the center of the product. This means that the center of a package can cool at a significantly slower rate than the surface. Hartel (1998) shows temperature profiles at different depths into an individual half-liter package of ice cream during hardening in an air-blast freezer at −30°C. The surface cooled to −18°C in about 13 min, whereas the center took nearly 17.5 min. More importantly, 6 or 7 min elapsed before the center started to cool. This extended time at −6°C led to a substantial increase in ice crystal size at the center due to ice crystal ripening (see Chap. 11 for more details on mechanisms of ripening). The surface had approximately the same ice crystal size as the initial product (median size of 27–28 μm), whereas the median ice crystal size at the center of the ice cream was nearly 10 μm larger. Clearly, rapid hardening is desired to ensure the smallest ice crystal sizes. If such an effect is seen for hardening of individual packages, one can imagine that a stack of containers will show even larger variation in cooling rates and thus, a significant variation in ice crystal sizes.

Air cells also change during hardening, and this can have a significant impact on ice cream quality. During whipping and freezing in the scraped-surface freezer, larger air cells are continually broken down into smaller and smaller bubbles. The small air cells are stabilized by a combination of the partially coalesced fat globules, the ice crystals, and the high viscosity of the continuous phase. However, at draw

temperatures, the small air cells are not stable and can easily coalesce into larger air cells in a process quite similar to ripening of ice crystals. Thus, rapid hardening also is needed to retain the smallest air cells (Chang and Hartel 2002).

These changes during traditional hardening are moderated to a great extent in the cold-extrusion process (see Chap. 7), where product from the draw of the scraped-surface freezer is fed immediately into a low-temperature extruder. The gentle agitation and rapid cooling in the extruder minimize changes to ice crystal ripening and air cell disproportionation. The result is ice cream with smaller ice crystals and air cells than the same ice cream had it been hardened in the usual manner.

Factors Affecting Hardening Time

The governing equation for the rate of heat transfer (Q) is given as:

$$Q = UA\Delta T$$

where U is the overall heat transfer coefficient, A is the exposed surface area, and ΔT is the temperature differential between the hardening room air and the ice cream core. The heat transfer coefficient, U, accounts for (1) conductive heat transfer out of the ice cream and through the package and (2) the convective heat transfer coefficient between the blowing air and the package. To maximize Q, each of the three factors should be as large as possible.

The difference in temperature between the product and the cooling medium defines ΔT. The greater this difference, the faster heat will be removed; consequently, the higher the temperature at drawing for a given hardening tunnel, the longer the time of hardening. This implies the need for very cold hardening temperatures, such as −35 to −40°C, even though it is not necessary to get core ice cream temperatures this low. As freezing proceeds, the ΔT decreases and thus, the rate of temperature decline toward the end of the process is much slower than the rate of temperature decline at the beginning of the hardening process. Very cold hardening temperatures help to maintain a ΔT to speed up the process.

Of the three parameters that influence hardening time, the overall heat transfer coefficient is the most complex since it accounts for both convective and conductive processes. Thermal diffusivity, which influences how fast heat can be removed from the ice cream during hardening, is affected by composition of the product and the overrun. Since fat and air conduct heat more slowly than an aqueous phase, increasing the content of fat or air increases hardening time. The ability of the container and the overwrapping material to transfer heat can also be a significant factor. Packaging of ice cream in material such as corrugated cardboard or styrofoam has not been successful, since the packaging material acts like an insulator and limits the rate of heat transfer during hardening. Plastic conducts heat faster than paper.

(This means also that product can melt faster in plastic than in paperboard containers.) Heat stored in the container at filling causes melting at the interface of the container and product. Therefore, containers that have a high mass would be expected to cause more melting than those of low mass.

Distance for heat to travel from the core to the surface is affected by size and shape of the container as well as by how much separation there is between packages. Thus, overwrapping increases this distance, as does stacking of packages. Doubling the size of the package or of the stack increases the hardening time in the conventional hardening room by about 50%. Overwrapping also affects shape and the amount of surface area per unit volume. The smaller the surface to volume ratio, the slower heat will be transferred. As noted before, for the most rapid hardening and highest quality of product, frozen desserts should be hardened individually.

Once heat gets to the surfaces of the containers, it needs to be removed promptly. Velocity of air movement thus becomes a critical factor. The high velocity of air in air-blast freezers allows for rapid cooling of frozen desserts and minimizes changes in ice crystals and air cells. Again, if individual ice cream containers are cased and palletized, that cold air does not directly contact each container, meaning that the interior containers will cool more slowly. To offset this problem yet allow efficient packaging operations, stacking arrangements within blast-air type freezers now exist that allow controlled air flow between and through cased packages through careful stacking of the cases (Fig. 10.9). This design effectively triples the effective hear transfer rate to individual packages when contained in cases and thereby, reduces freezing time. This design enhances efficiency and reduces cost and greenhouse gas emissions.

In a certain sense, the cold extrusion process is a form of rapid hardening where the temperature of the product exiting the scraped-surface freezer is reduced (at least part way) in a low-temperature extruder. Filling or forming of the product occurs after it exits the extruder and is followed by the same steps of sealing, weighing, and overwrapping. The product then goes into a freezer for further hardening to final temperature.

Another rapid hardening option is immersion of packaged ice cream in liquid nitrogen (LN2) at −196°C (−320 °F) to reduce the center temperature of product in a very short time. For example, in pint packages, temperature was reduced to −34°C (−30 °F) in 5 min (Der Hovanesian 1960). This rapid cooling is most conducive to maintaining the smallest ice crystals and air cells for the highest quality. However, exposure to liquid nitrogen for over 1 min made the texture “salvy” and the body crumbly. Cold shock from LN2 immersion also increased the tendency for shrinkage in the packages. While hardening of packaged ice cream in LN2 may not be economical, use of LN2 hardening for some extruded novelty products is employed, as discussed in Chap. 9.

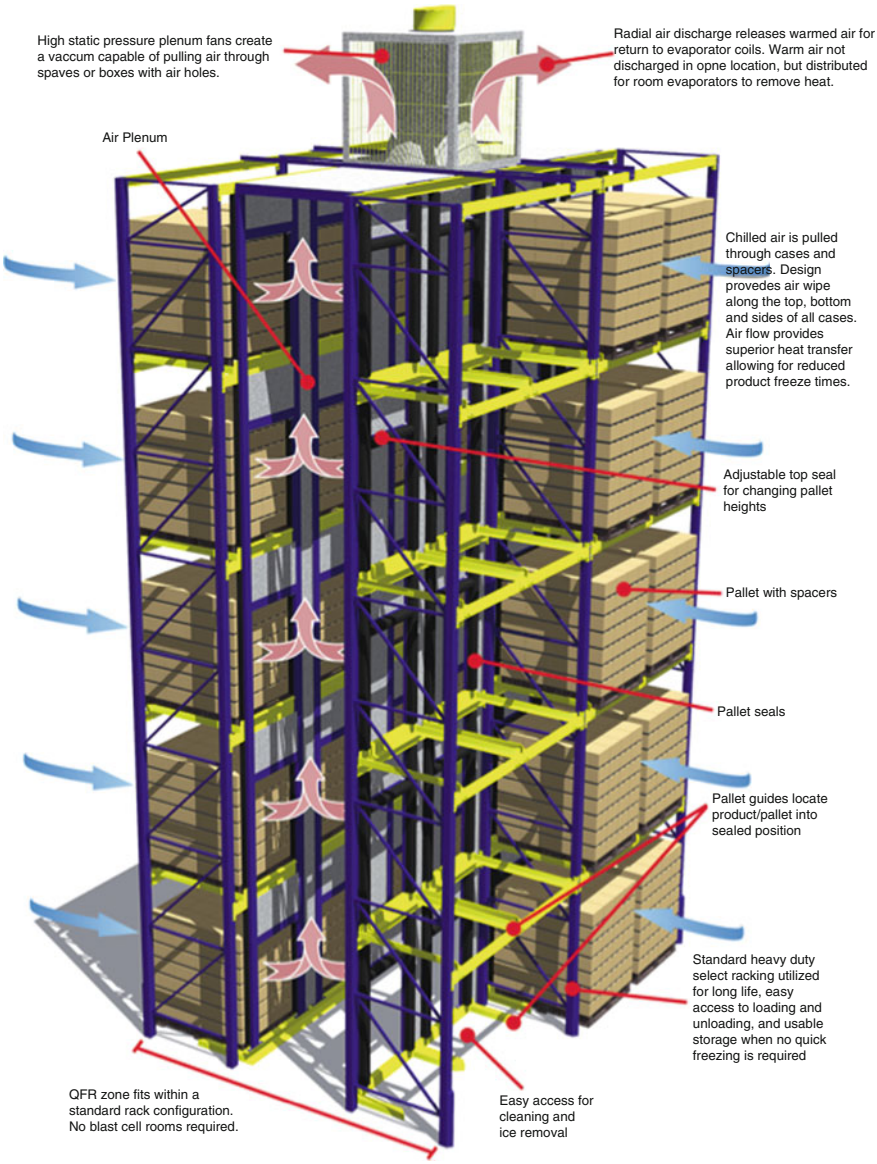

Fig. 10.9 QFR Zone stacking design that allows air flow between packages to promote rapid heat transfer and faster freezing (courtesy of Tippmann Group, Fort Wayne, IN)

Types of Hardening Facilities

Numerous types of facilities have been designed to harden frozen desserts. These include cabinets, cold cells within storage rooms, hardening tunnels, and contact plate freezers.

Cabinets are used only in small operations, for example following batch freezing and hand packing. They resemble retail ice cream cabinets. Air is circulated within these cabinets when the door is closed to speed heat removal. Some cabinets have refrigerant circulating through channels within each shelf: such a design speeds heat removal. At any rate, still air freezers designed for storage should not be used for hardening. If sufficiently cold, small firms may elect to use the hardening room to both harden and store product. In this case compromise is necessary either in the speed with which hardening is done or in costs of keeping the product very cold and moving air rapidly within the room. Cold cells are zones within storage rooms in which chilled air is blown over newly arrived packages as they are conveyed toward the ultimate storage area within the same freezer.

Devices for moving packages through tunnels include conveyors, trays, and belts. Trays may form moving shelves within an enclosed area, each tray being moved stepwise (indexed) from the receiving end, where a row of freshly packaged product is pushed onto the shelf, to the discharge end, where hardened product is pushed off simultaneously.

Hardening tunnels rely on rapid air velocity to increase the convective heat transfer coefficient; hence they are often referred to as convection freezers. Hardening tunnel design may be straight-through or spiral. In a straight-through tunnel, semi-frozen product from the filling station enters the tunnel and is conveyed through to the end with cold air flow providing the cooling effect. More sophisticated in-line tunnels allow variable dwell time for different packages to optimize freezing time and energy use (Fig. 10.10). In a spiral freezer, the conveyor unit gradually inclines and declines within the tunnel and accepts and delivers products at a common point situated at the front of the freezer (Fig. 10.11). The spiral type hardening tunnel typically receives soft product at the bottom of the spiral and discharges hardened product at the top. Operating speeds can be selected to fit manufacturing speeds. Time within a tunnel hardener may vary from 40 to 160 min.

Special tunnels have been constructed to freeze extruded novelties (see further detail in Chap. 9). Product is extruded onto stainless steel plates that are moved mechanically through a cabinet where blasts of frigid air chill the products. As the novelties exit the freezer a hammer-like device taps the steel plate to loosen the hardened piece. It is then swept to another conveyor for passage through process of enrobing, drying, and packaging.

Contact plate freezers chill product rapidly by conducting heat from packages; hence they are often referred to as conduction freezers. They have the additional advantages of requiring minimal floor space and operating with high efficiency. Because they typically have no fans, they do not have to remove the heat of electric motors from the unit. Packages of the same height are contacted on both top and bottom by plates containing circulating refrigerant. Hardening is usually completed within 2 h. A disadvantage of contact plate hardeners is that containers need to be of the same vertical dimension. They work especially well for half-gallon (2 L) rectangular containers. However, since most ice cream manufacturers

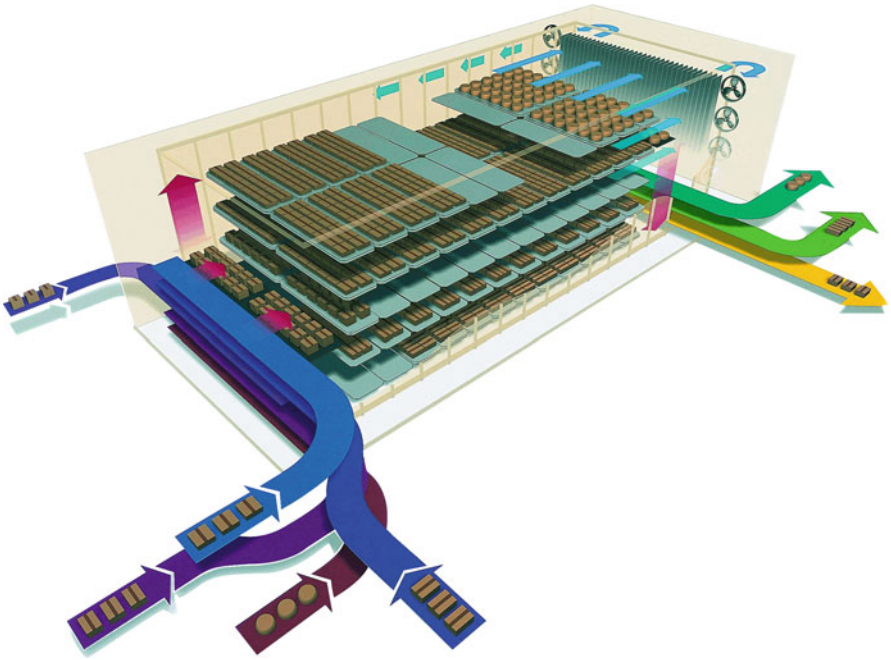

Fig. 10.10 Variable residence time (VRT) freezing tunnel capable of providing different dwell times for different products, separating flavors, and unloading product independent of loading order (courtesy of Odenberg Engineering Ltd., Dublin, Ireland)

are moving away from rectangular shapes, plate freezers are no longer widely used in the industry.

In theory, the rate of product flow through a hardening unit should be just equal to the time it takes to harden the product. The dwell time of product within the unit determines the capacity of the hardening freezer. Factors that influence storage capacity include maximal demand expected, number of different products and container shapes and sizes marketed, capacity of production equipment, time each product can be permitted to stay in storage for reasons of quality, and interest on investment costs. The size and shape of the container as well as the depth of stacking on pallets or shelves are significant factors determining the rate of hardening and thus, the capacity of a hardening unit.

Precautions to Observe in the Operation of Hardening and Storage Rooms

The most commonly used refrigerant in ice cream plants is anhydrous ammonia. Only in small operations are chloroflorocarbon (freon) refrigerants used. Ammonia is a dangerous chemical. It is toxic to humans and animals and is able to penetrate

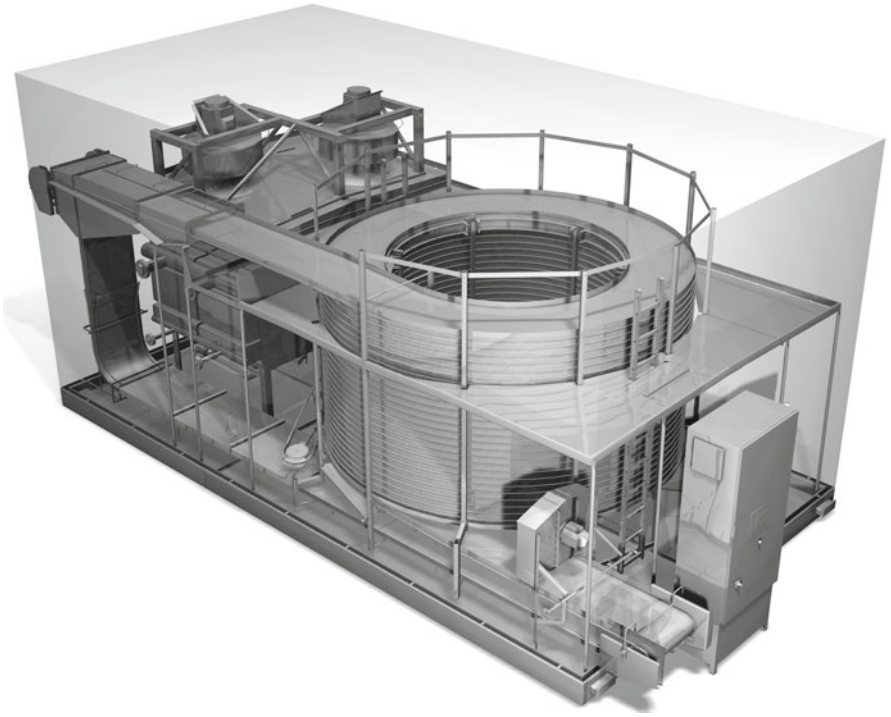

Fig. 10.11 Spiral hardening freezer that employs high air velocity and moves packages along a variable speed, stainless steel track through the freezer from bottom to top (courtesy of JBT FoodTech, Sandusky, OH)

packages readily. Therefore, ammonia leaks from refrigeration systems must be treated as serious occurrences. The US Code of Federal Regulations (29 CFR 1910.120) requires employers in facilities using ammonia to develop and implement a written safety and health program for their employees involved in hazardous waste operations. The requirement is based on Hazardous Waste Site Operations and Emergency Response regulations, which are the responsibility of the US Occupational Safety and Health Administration (OSHA). The program shall be designed to identify, evaluate, and control safety and health hazards, and provide for emergency response. Necessary training includes worker protection requirements, materials handling procedures, compliance with evacuation and containment regulations, responsibilities of the on-scene incident commander, components of the incident command system, personnel roles, facility emergency response planning and audits, the Emergency Planning and Community Right-to-Know Act, spill reporting, and decontamination programs. Obviously, the need is great to protect from hazardous incidents related to escape of ammonia. Although cost of prevention is not insignificant, the costs of an incident can be much higher.

It is not within the scope of this book to treat this subject further, but managers and operators must realize that responsibility for the safe operation of a refrigeration system rests on them. They must be sure to be fully informed of the regulations and to have taken the necessary steps to follow them.

Besides the protective clothing and masks that must be provided for workers in the area of ammonia usage, several other protective measures must be taken in conjunction with walk-in type freezer operations, whether they be refrigerated with ammonia or another chemical. These include the following:

1. Provide a fail-safe latch on the inside of the freezer door(s). It is also necessary to provide an alarm system inside the hardening facility in case someone gets trapped inside. The alarm system should attract help from the outside when regular plant workers are absent.
2. Keep an ax and sledge hammer in a prescribed location inside the door. These can be used as a last resort to break through the door in case assistance cannot be obtained.
3. Avoid use of wood for doors and other components. Moist wood tends to give off odors and is difficult to clean and sanitize.
4. Ensure that the defrost cycles are effective in removing frost and that they do not last so long as to cause significant rise in product temperature.
5. Avoid placing ice cream packages together until hardened unless the apparatus used operates on the principle of removing most of the heat by conductance.
6. Avoid placing newly frozen products close to packages that are already hardened. Heat from the warmer product will migrate to the colder one and cause heat shock.
7. Have all packages dated, and use the first-in, first-out principle of product rotation.
8. Minimize temperature fluctuations. Fluctuating temperatures produce temperature gradients within the frozen product leading to deterioration of product quality.
9. Maintain inventory control.

Handling, Storing, and Shipping

The very cold temperature and high velocity of air flow make it necessary for workers to wear heavy insulated clothing, footwear, and head covers, making the hardening facility and storage freezer a difficult place to work. In part for this reason, completely mechanized handling is becoming more and more common, especially in larger facilities. In such systems, product is conveyed into the hardening device and emerges on a conveyor from which it is mechanically palletized. Containers may be secured on pallets with plastic film that is wrapped mechanically around the containers. The pallet is then moved via forklift truck or conveyor to a forklift type elevator that is programmed to place the pallet at a predetermined location in storage.

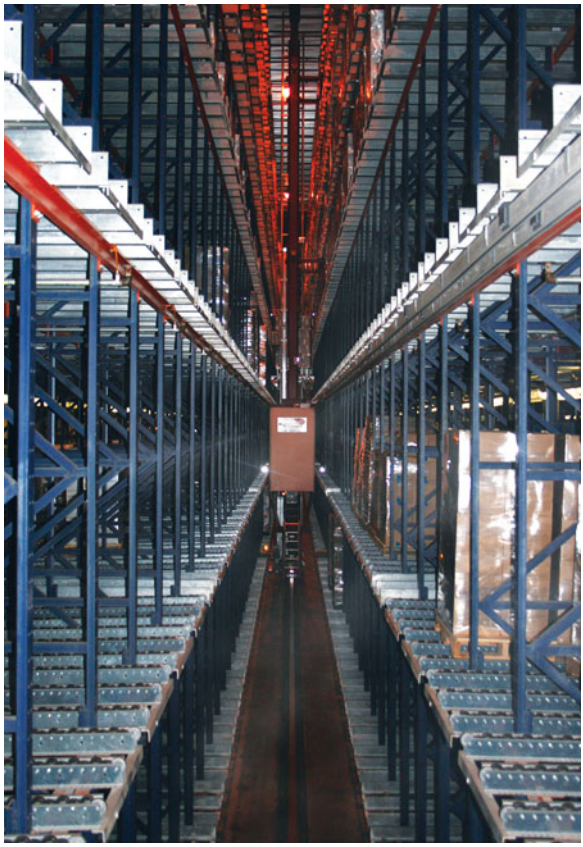

Fig. 10.12 Multiple story storage/retrieval system capable of moving product into and out of storage by computer-controlled vehicles (courtesy of Westphalia Technologies, Inc., York, PA)

Storage/retrieval systems are available that enable one worker to move palletized product into and out of a series of racks to take advantage of vertical storage space (Fig. 10.12). Pallets can be stored and retrieved in multiples on either side of an aisle. Storage racks running perpendicular to the single aisle have been constructed up to 75 ft long. Pallets are raised or lowered to these storage racks by a vertical carriage and are positioned in the racks by an eight-wheel rack vehicle. Both of these electro-mechanical devices are computer-controlled, and positioning is done with the aid of infrared scanners that can position the carriage and rack vehicle within one-eighth inch of any reflective locator pad. The rack vehicle receives single pallets from a forklift on the vertical carriage. One drive in the rack vehicle raises and lowers a platform, and another drive moves the vehicle horizontally.

An inventory system integrated with the hardware provides correct product identity and first-in, first-out inventory control. The location and date of storage of each pallet is stored in computer memory so that management of inventory and proper rotation of product are readily and efficiently accomplished. The operator of the lift is sheltered in an air-conditioned cab equipped with a telephone. The computer can be networked with management, production, and sales so that all information is available at each location.

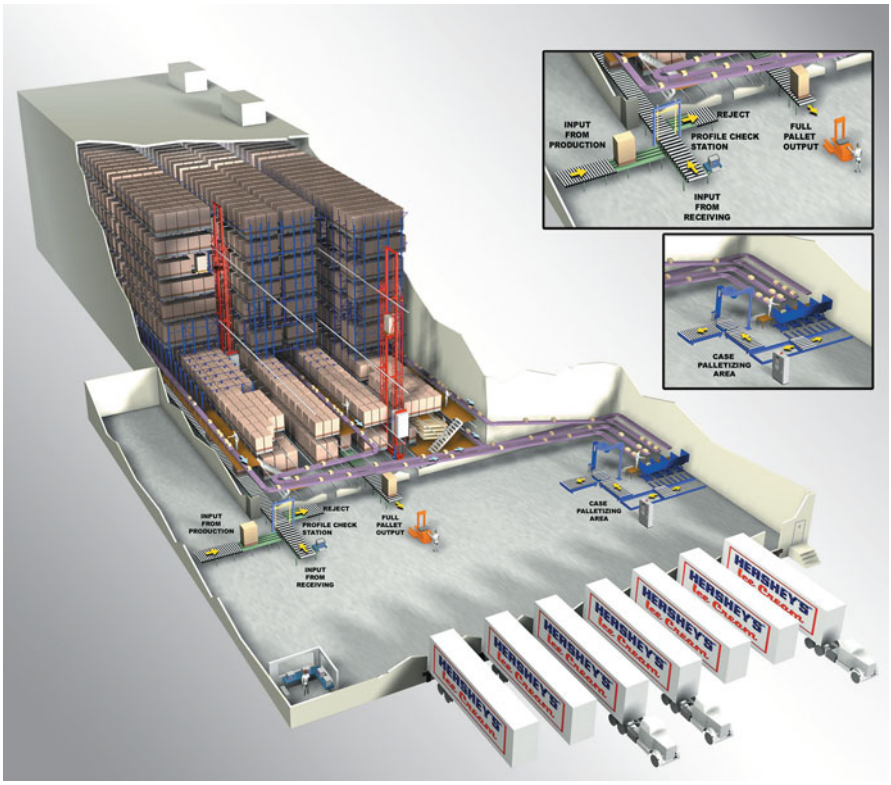

Fig. 10.13 Storage/retrieval system in a facility designed for a large inventory (courtesy of Westphalia Technologies, Inc., York, PA)

Automated storage and retrieval systems are useful where inventories are large (Fig. 10.13). Such systems can result in up to a 40% increase in storage density, a 30% reduction in energy costs for freezer warehouses (due to the higher storage density), increased efficiency of product movement, reduced labor costs, increased productivity and employee safety, and reduced carbon footprint. However, palletized products will need to be broken down into order size lots either at the storage warehouse or later in the distribution chain. In any palletized system it is possible to use gravity flow racks at floor level to feed products to truck load out positions. There the pallets can be loaded directly onto trucks or broken into order size lots for shipment to buyers. Gravity flow racks have wheels or rollers on which pallets roll slowly to a stopping device. Temperature in the load out room can be higher than in the storage room, thus permitting personnel a more worker friendly environment.

Each package should show a product code indicating time of production and lot number in the event it is necessary to trace the product to its origin. All data about each lot must be recorded and retained until there is minimal risk that any of the product remains available for consumption. Inventory control requires a record of

product identity, location in storage, and date of production. Quality control and risk management require records of composition (by test), ingredients, microbial test results, and overrun. Management must establish a maximum storage time during which the product can be held without deteriorating to an unacceptable level of quality. This time will vary with the product—for example, nonfat ice creams have an inherently shorter shelf life than full fat products. Also affecting this time will be conditions of storage and the expected conditions of distribution, sales, and handling at the final destination. Personnel of the firm must be able to detect defects of each type of product and interpret the cause(s). Furthermore, it is important to have personnel capable of predicting the proper storage time for each product.

Distribution Systems

Once ice cream leaves the storage freezer in the manufacturing plant, it typically goes through a shipping and handling system designed to deliver the product to the consumer with the highest possible quality. Packaged ice cream for consumer sale undergoes a series of transportation and storage steps that lead to the consumer's home freezer, with the particular system being dependent on manufacturer, the distance for distribution, and the equipment and facilities available. The ice cream may go through a centralized warehouse for redistribution to the retail outlet, or it may be shipped directly from the manufacturing plant to the retail outlet. A more detailed breakdown of typical times and temperatures at each stage of the storage and distribution system is provided in Chap. 12.

There are numerous potential problems that can arise during shipping and handling, any one of which can seriously detract from product quality. The most important of these potential problems is thermal abuse and its effect on ice crystals. Temperature fluctuations during shipping and handling of ice cream may be associated with (1) changes in temperature of storage as the product moves from point to point in the chain, (2) heat shocks, where product is left at ambient (room) temperatures for extended periods of time, (3) normal cycling inherent in mechanical refrigeration cycles, and (4) opening and closing of doors in freezers and storage cabinets. Each time the temperature changes, the amount of ice changes according to the equilibrium freezing point relationship (Chap. 5). Assuming that temperature fluctuations are relatively slow compared to the rate of heat transfer into the ice cream, an increase in temperature results in a decrease in the amount of ice in the product according to the freezing point depression curve. When the temperature goes back down again, the amount of ice increases accordingly. A detailed discussion of the changes that take place in ice cream structure and quality is provided in Chap. 12.

Monitoring of temperatures during processing, freezing, and storage is highly important. Even the temperatures of stored ingredients must be monitored. Control within a plant is accomplished more readily than in the distribution system. To

monitor temperatures on trucks and in facilities that do not have built-in temperature recorders, use of data loggers, or temperature monitors that preserve a record on a computer chip, is recommended. It is important to place monitors in locations where the optimal temperature is most likely to be compromised. Shippers often place recorders at the front, center, and rear of trucks. Vehicles must be designed, constructed, and maintained to avoid heat shock to products.

The temperature of frozen desserts in the distribution system should never get above the desired temperature in the retail cabinet. Therefore, truck bodies must have been well insulated, cooled prior to loading, and kept cold by mechanical refrigeration. The refrigeration system must be operated optimally during distribution. Exposure of frozen product to warm temperature during off-loading into store freezers must be limited to a few minutes to avoid heat shock and development of large ice crystals.

Although the temperature in the storage and distribution environments is important, the most critical element is that the temperature of the product remains low so that the maximum amount of shelf life remains when the consumer purchases the product. One approach to monitoring product temperature and quality is use of a time-temperature indicator/integrator (TTI) (Taoukis and Labuza 2003). TTIs are designed to attach directly to the product and indicate thermal abuse. The simplest versions simply indicate when the product experiences a temperature greater than some critical threshold value. More sophisticated integrators, through a controlled reaction (enzyme, diffusion, etc.) that causes a change in color or some other physical attribute, indicate the sum history of thermal exposure of a frozen product. By carefully matching the kinetics of change of the TTI with those of the product, remaining shelf life can be determined. Detailed discussion of use of TTI for shelf life of frozen foods, including ice cream, can be found in Labuza and Fu (1997).

Shipping with Dry Ice

On special occasions it may be necessary to ship frozen desserts under conditions that require dry ice (carbon dioxide) as refrigerant. This lightweight refrigerant has a high cooling capacity and leaves no residue as it vaporizes. Heat removed from the materials around it causes the vaporization. The recommended practice is to saw the ice into appropriately sized pieces and to wrap them in paper to slow vaporization.

Some disadvantages to use of dry ice include the relatively high cost; the very low temperature (−109 °F, –78°C), which may freeze the product so firmly that it takes a long time to soften enough to be consumed; and its potential for burning to handler. The extremely low subliming point of dry ice makes it easy to freeze fingers without feeling the cold sensation until damage has been done. Dry ice should always be handled with insulated gloves.

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Chapter 11
Ice Cream Structure

Introduction

Ice cream is arguably one of the most complex food products, with multiple phases that can influence product quality and attributes. The mix ingredients supply water, fat, milk solids-not-fat (casein micelles, whey proteins, lactose, and milk salts), sugars (sucrose and partially hydrolyzed starch, including glucose, maltose, and higher saccharides), stabilizers, and emulsifiers. Air is subsequently added prior to dynamic freezing. All of these contribute to the structural elements in ice cream (Fig. 11.1). Fat either remains as partially crystalline globular, emulsified droplets, or is converted to partially coalesced fat globule clusters, a process known as fat destabilization that is enhanced by the action of the emulsifiers at the fat globule interface. Water is converted to ice crystals. Air is whipped into small bubbles. The sugars and stabilizers become freeze-concentrated in the unfrozen serum phase. The functionality of proteins contributes to the fat and air structures by adsorbing to interfaces and to the unfrozen phase by providing bulk and water-holding properties, both of which add viscosity.

The structures/components found in ice cream include:

1. *Serum*. Even at the coldest storage temperatures, not all of the water is frozen in ice cream. This water contains dissolved sugars and salts as well as any aqueous phase proteins and stabilizers. It is this serum phase that forms the lamella between the other structures (ice, air, fat globules and clusters, micelles, etc.). When cooled below its glass transition temperature (T_g), the serum phase becomes glassy in nature. T_g of a typical ice cream is below −32°C, meaning that the serum phase is not in the glassy state under normal storage conditions.
2. *Ice crystals*. As a frozen dessert, ice crystals are an integral component of ice cream. The ice crystals should be sufficiently small to provide a smooth mouthfeel and melt readily in the mouth. Ice crystals generally range in size from a few microns to over 100 μm, with an average size somewhere between 35 and 45 μm for hardened ice creams. After dynamic freezing, approximately half of the water

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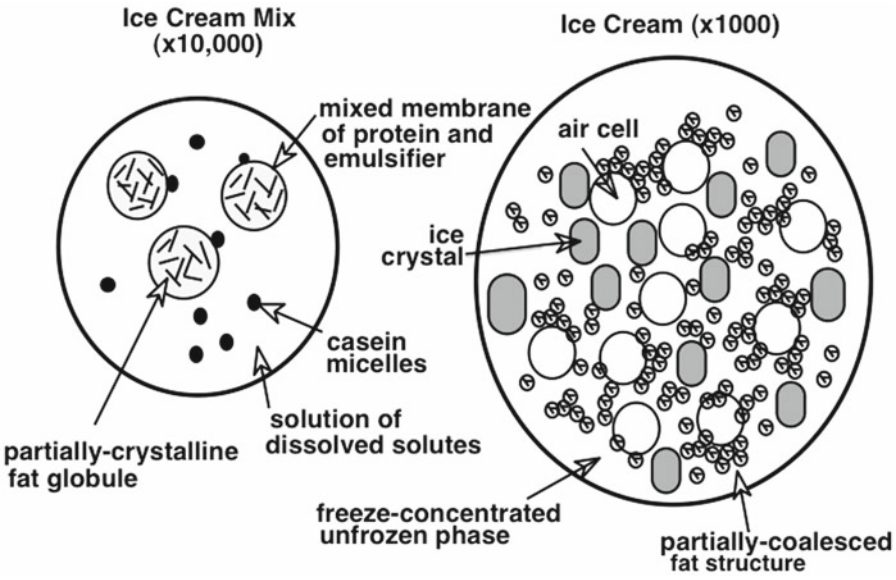

Fig. 11.1 Illustration of the structure of ice cream mix and ice cream. Ice cream mix contains the partially crystalline fat globules and casein micelles as discrete particles in a solution of sugars, salts, dispersed whey protein, stabilizers, etc. The surface of the fat globule demonstrates the competitive adsorption of casein micelles, globular, partially denatured whey proteins, β-casein, and added emulsifiers. Ice cream contains the ice crystals, air cells and partially coalesced fat globules as discrete phases within an unfrozen serum containing the dissolved material. The partially coalesced fat agglomerates adsorb to the surface of the air cells, which are also surrounded by protein and emulsifier, and link the bubbles through the lamellae between them. Highly schematic

has been frozen, depending on the freezing point of the mix. After hardening, about 75–80% is frozen, depending on storage temperature. The amount and size of ice crystals affects numerous attributes of the finished product, from scoopability and hardness to the cooling effect and meltdown rates.

3. *Air cells*. Up to or more than half the volume of ice cream is air, with overrun values (the increase in volume from air incorporation as a % of mix volume) that can range all the way from as low as 25% to as high as 150%. This air phase is found as finely dispersed cells with a size range between a few microns to over 100 μm. Mean air cell size is often found between 20 and 25 μm. Air cells provide a light texture to frozen desserts.
4. *Fat globules and clusters*. In ice cream mix, individual emulsion droplets are typically between about 0.5 and 2 or 3 μm with an average size about 0.8 μm. After freezing, fat globule clusters are formed as a result of partial coalescence of the individual globules. Clusters vary in size between 5 and 10 μm up to 70–80 μm, with some clusters reaching upwards of 100 μm. This partial coalescence of the fat globules is often characterized by a percentage of fat destabilization, given as

the ratio of clusters above some size to the initial emulsion droplets. Fat globule clusters are one of the important parameters that determine shape retention properties and meltdown rates.

5. *Protein/stabilizer structure*. Ice cream mix contains both caseins and whey proteins in a ratio depending on the dairy sources used in the formulation. Caseins are found in micellar form with mean size about 0.3–0.4 μm, whereas whey proteins are dissolved in the aqueous phase/serum. The various stabilizers (proteins and gums) used in ice cream take on structure and orientation depending on the nature of the molecule and its interactions with the other components of ice cream. Some may form a weak gel while others remain dissolved in the aqueous phase. Interactions between stabilizers and dairy proteins can also greatly affect ice cream characteristics, particularly when they undergo thermodynamic phase separation.

A summary of the components in ice cream along with some important attributes is provided in Table 11.1. Conversion of ice cream mix into a frozen dessert involves processing under conditions that simultaneously induces formation of these structures. Homogenization during mix manufacture establishes the fat globule size distribution and allows for adsorption of protein to the newly formed fat interface to stabilize it. Aging allows for the fat to crystallize and also provides time for rearrangement of the adsorbed surface layer due to the action of emulsifiers at displacing proteins from the interface. The liquid mix entering the freezing barrel contains suspended fat globules and colloidal proteins as well as dissolved carbohydrates, salts, and proteins. This liquid mix is transformed into a viscous, multiphase product containing dispersed ice crystals and air cells, partially coalesced fat globules and colloidal proteins held together by a high-viscosity solution with dissolved sugars, stabilizers, proteins, and salts (Goff 2002). Figure 11.1 provides a schematic diagram of both mix and finished ice cream.

In dynamic freezing, the most important changes are the formation of ice crystals, incorporation of air (overrun), formation of small air cells, and destabilization (or partial coalescence) of the fat emulsion. Each of these steps is critical to production of a high quality ice cream with the desired physical characteristics and must occur whether freezing is done in batch or continuous processes. However, differences in formation of these structural elements may occur based on the type of freezer used to make the ice cream and the type (and amount) of ingredients used in the mix. The product of dynamic freezing is soft frozen and flowable, but the degree of stiffness varies with formula, process, freezer design, overrun, and temperature. Destabilization of the fat and formation of minute air cells result in a dry appearing and relatively stiff product as it exits the freezer. Transport and packaging of the product are affected by each of these variables.

Each of the structures and phases noted above affect the physical and sensory attributes of ice cream. As well, interactions among these structures and phases during storage generally cause product deterioration and end of shelf life (see Chap. 12).

Table 11.1 Particle size and states of dispersion of the constituents of ice cream

1 nm (1/100 μm)	10 nm	100 nm	1 μm	10 μm	100 μm	1 mm (1,000 μm)
Particle characteristics						
Transmission electron microscope		Scanning electron microscope	Light microscope		Visible	
Passes filters and membranes	Passes filters but not membranes		Pass neither filters nor membranes			
Molecular movement	Brownian movement			Gravitational movement		
No sedimentation or creaming		Sedimentation and creaming				
High osmotic	Low osmotic	No osmotic pressure				
Milk constituents						
Lactose and soluble salts	Whey proteins	Casein micelles		Fat globules		
Ice cream constituents						
Sugars and soluble salts	Whey proteins, stabilizers	Casein micelles	Fat globules	Fat aggregates	Ice crystals, air bubbles	Flavoring particles

Microstructural Elements

Serum Phase

As the continuous phase that interacts with each of the other phases/states present in ice cream, the unfrozen serum is what holds the entire structure together. It is comprised of whatever water is unfrozen at the product temperature and all the dissolved components, including sugars, salts, some proteins, and some stabilizers. The properties of the serum phase are dependent on mix composition and temperature (see Chap. 3).

As temperature of ice cream decreases, more and more water is turned into ice and the remaining fluid phase becomes increasingly concentrated since ice freezes in essentially pure form (other molecules are excluded from ice as crystals form). Consequently, the freezing point of the unfrozen phase of the mix decreases as ice crystallizes due to this freeze concentration. Assuming that there is phase volume equilibrium (meaning the ice cream contains the maximum amount of ice permitted by the phase diagram at that temperature), the relationship between temperature and percentage water frozen is given by the freezing point depression curve of the mix (as calculated in Chap. 6). Depending on the drawing temperature (as the ice cream is removed from the freezer) and composition of the ice cream, anywhere between 33 and 67% of the initial water in the mix is crystallized in the dynamic freezing stage, and the hardening process then may account for freezing of an additional 23–57%. This relationship between temperature, freezing point, and percentage ice frozen can be seen schematically in Fig. 11.2.

These freezing curves become invaluable for processors in controlling the amount of water frozen, hence hardness, at any given temperature, such as within a cabinet freezer (refer back to Fig. 5.13). Especially for bulk ice cream that is to be scooped, it is essential that the freezing curves for multiple products and flavors be matched to ensure that similar levels of hardness are achieved. Freezing point depression is a function of the molar concentration of solutes present in solution (Raoult's law); hence mono- and disaccharide sugars (sucrose, lactose) and milk salts are the greatest contributors to freezing point depression. Detailed calculations for determining freezing curves are provided in Chap. 6.

The increase in serum phase concentration with decreasing temperature also leads to an increase in serum phase viscosity as more and more ice freezes. If the concentration of dissolved substances were to increase to a point where only about 18–20% of the original water remained unfrozen, the freezing point would reach a temperature at which no more ice could be formed due to molecular mobility limitations (that is, no more ice freezes because water molecules are not sufficiently mobile to move to and incorporate into the ice crystal lattice). This point is often called the glass transition temperature at maximal freeze concentration, T_g' . A state diagram for sucrose, shown in Fig. 11.3, is often used to describe the approximate phase/state behavior of ice cream. As seen, there are two transition temperatures, T_g' at ~−40°C and T_m' at ~−32°C (Sahagian and Goff 1995; Goff and Sahagian

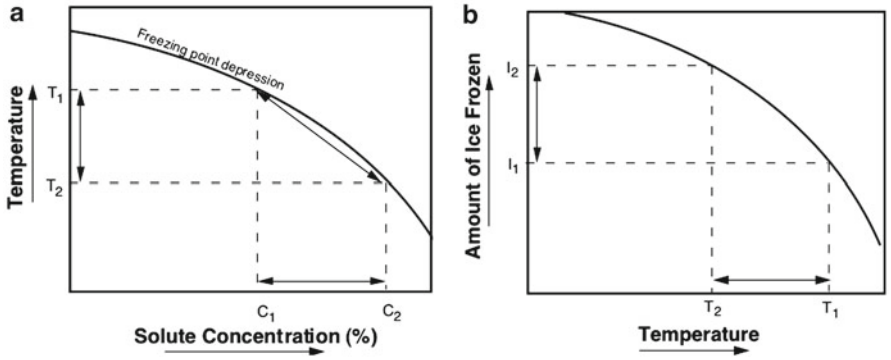

Fig. 11.2 (**a**) Slow freezing of ice cream along the freezing point depression curve. (**b**) Corresponding amount of ice formed at each temperature (adapted from Hartel 2001)

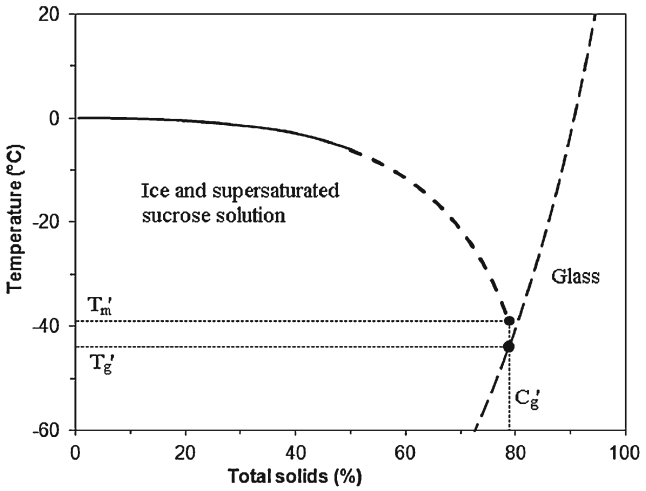

Fig. 11.3 Sample state diagram for ice cream mix containing 10% milk solids nonfat, 16% sucrose, and 38% total solids; T'_g is the glass transition temperature at maximal freeze concentration, T'_m is the end of the freezing point curve, and C'_g is the maximal freeze concentration (Hartel 1996; Schawe 2006). The *dashed lines* indicate that there is a degree of uncertainty when predicting the glass transition curve and the freezing curve for ice cream mix with high solids (Cook and Hartel 2010, with permission)

1996; Goff et al. 2003; Roos 2010). Below T'_g, the serum phase of ice cream becomes a sugar glass with ice crystals, air cells, fat globules and clusters, and any other structures embedded within that glass. The T'_m is the mechanical glass transition temperature, the temperature at which molecular mobility has increased sufficiently to allow flow of the molecules to occur. Hence, while T'_g is the temperature at which the glass state is actually achieved, T'_m is more practical for food manufacturers, since it becomes the critical storage temperature, below which

product will be infinitely stable but above which shelf-life becomes reduced as a result of diffusion of molecules and growth of ice crystals (Roos 2010). At normal manufacturing and storage temperatures, well above −32°C, a significant portion of the water remains in the liquid state, a factor that influences the stability of ice cream (see Chap. 12).

Is ice cream at phase equilibrium under normal conditions? Yes, under most normal commercial operating conditions, ice cream contains the equilibrium ice phase volume. Even though ice cream freezes within a minute or two in a continuous freezer (see Chap. 7), ice freezing is so rapid, particularly under conditions found in an ice cream freezer, that approximate phase volume equilibrium is attained. When the temperature of the ice cream during freezing in a continuous freezer has been measured, it has been found to decrease quickly in the early stages of the freezer barrel and more slowly thereafter until reaching draw temperature (Hartel 1996; Russell et al. 1999). In order for water to freeze, a driving force for crystallization is needed, meaning the mix temperature needs to be slightly below the freezing point at that point in the barrel. So rather than following the exact freezing point curve, the temperature must be slightly below the line to ensure that freezing continues, as shown schematically in Fig. 11.2a. This leads to ice cream that is slightly colder than the freezing point depression point as it exits the freezer—it is slightly supercooled[1] (a nonequilibrium phenomenon). In fact, if a thermometer is placed in an insulated container of ice cream just after it exits the draw of the continuous freezer, the temperature usually increases by about 0.5°C (Hartel 1996; Russell et al. 1999). The reason for this temperature increase is the slight supercooling of the ice cream exiting the freezer. Since it is supercooled, there is still a driving force for additional freezing to occur, which releases sufficient latent heat to cause that slight increase in temperature. So, under normal conditions, ice cream reaches approximate phase equilibrium through the freezing/hardening process while in the package.

When freezing is extremely rapid, as in liquid N_2 immersion, phase equilibrium is not maintained during the freezing process. When temperature decreases that rapidly, the concentration of the serum phase does not follow the freezing point depression curve; there is significantly less ice formed than would be expected at phase equilibrium. Once temperature decreases below T_g', no further freezing occurs since the serum phase has turned into a glass and further cooling below T_g' simply causes the semi-frozen mix to get colder with no further change of state. During rapid freezing in liquid N_2, for example the manufacture of pelleted droplets of mix, a small amount of ice forms in the shape of dendritic crystals (Hindmarsh et al. 2007) with the remainder of the drop a glassy sugar matrix. However, when that droplet warms back up above T_g', freezing can then continue, releasing latent heat that can potentially melt the droplet. It is for this reason that drops of ice cream

[1] The oft-used term "supercooled" to represent a temperature below the freezing point is often argued. Many prefer the terms "undercooled" or "subcooled" to signify that temperature is below freezing point. However, in the context that supercooled means "beyond" cooled, the term "supercooled" can be justified.

mix frozen in liquid N_2 need to be stored at exceedingly low temperatures to maintain integrity and quality.

Lactose is relatively insoluble and crystallizes in two main forms, an alpha monohydrate and beta anhydride, depending on conditions. The alpha monohydrate crystals, which take on a characteristic tomahawk shape, lead to the defect known as sandiness when they are allowed to grow sufficiently large (about 15 μm). Lactose content of ice cream mix is about 6% if no whey powder has been used in the formulation. Levels of lactose in ice cream mix in excess of this lead to reduced freezing point (causing a soft ice cream and increasing the potential for development of iciness) and a greater potential for lactose crystallization or sandiness. The lactose solubility in water at room temperature (25°C) is about 16.6%. During freezing, this concentration is exceeded as a result of freeze concentration (water removal in the form of ice). When 75% of the water is frozen in a mix consisting originally of 11% MSNF (6% lactose), the lactose content in the unfrozen water corresponds to ~40%. Probably much of the lactose in ice cream exists in a supersaturated, amorphous (non-crystalline) state, however, due to extreme viscosity. Stabilizers help to hold lactose in a supersaturated state due to enhancement of viscosity. Lactose crystallization and sandiness is discussed in detail in Chap. 12.

The role of milk proteins in the unfrozen aqueous phase is recognized but is less well studied than their role at the fat interface. Milk proteins interact with water, and their hydration is responsible for a variety of functional properties, including rheological behavior. Thus, freeze concentration of proteins in ice cream greatly increases the viscosity of the unfrozen phase, and this has a great effect on ice crystallization, ice crystal stability, and solute mobility (Flores and Goff 1999). Jonkman et al. (1999) studied the effect of ice cream manufacture on the structure of casein micelles and found that the micelles per se were not affected by the process. Although the stability of the micelle was expected to be affected by low temperature, this was offset by an increasing concentration of milk salts in solution during freeze concentration, such that the micelle remained intact and in a state similar to that found in the mix.

Ice Crystals

Ice crystals are formed only in the dynamic freezing step of ice cream production. This is where unfrozen mix contacts a cold surface or refrigerant and freezing is initiated. In hardening, the ice crystal phase volume increases as temperature decreases, with the process generally following the freezing point depression curve. Due to this increase in ice phase volume, ice crystals increase in size during hardening, although if hardening is slow, ripening processes cause some crystals to melt away as the others grow. Proper hardening is necessary to minimize these negative changes in ice crystals. The cold extrusion process addresses these changes in ice crystal size during hardening by cooling rapidly and uniformly, thereby increasing ice cream quality by retaining smaller ice crystal sizes (among other things);

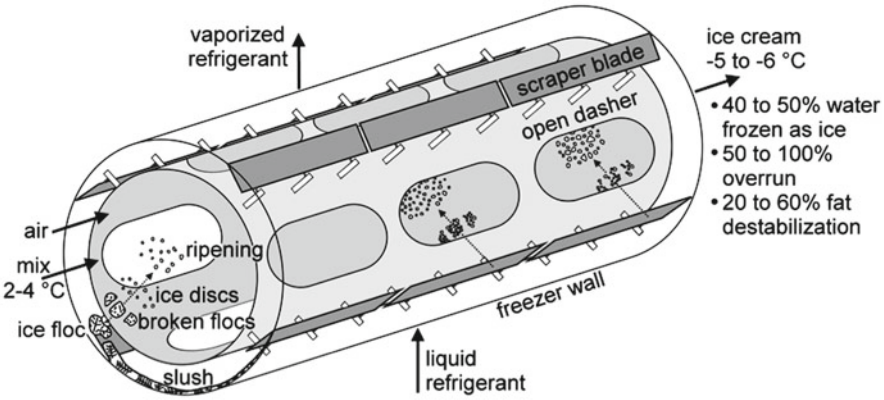

Fig. 11.4 Three-dimensional schematic diagram of ice crystallization and fluid flows through a scraped-surface heat exchanger for ice cream manufacture. The scraper blade removes a slush of ice crystals and concentrated ice cream mix from the barrel wall in flocs, the dasher breaks apart these ice flocs, and the warm bulk liquid melts the flocs apart into disc-shaped crystals. Near the inlet, the warm bulk temperatures melt the majority of the ice. As freezing continues more ice crystals survive in the bulk. Close to the exit, the bulk crystals are larger; the wide size range causes many small new crystals to melt (Cook and Hartel 2010, with permission)

see Chap. 10 for further details of this process. During storage and distribution, temperature fluctuations result in melting and regrowth (with ice phase volume going up and down accordingly), leading to recrystallization of ice crystals. This is evidenced by an increase in size over time during storage (see Chap. 12).

In dynamic freezing, the mix enters the freezing chamber at about 0–4°C, so the refrigerant must first remove heat to bring the mix temperature below its freezing point. Typically, the mix cools quickly at the barrel wall, where the temperatures are at the lowest point in the freezer. Once freezing begins, the ice forms preferentially at the barrel wall, in part because of the low temperature there, but also in part because of the natural affinity of ice to form on a surface (rather than in the bulk of the fluid). Numerous mechanisms have been proposed to describe the formation of ice in the type of scraped-surface freezer commonly employed in ice cream manufacture. Still, our understanding of the exact process of freezing in such a freezer is incomplete, primarily because of the difficulty of actually determining the processes that take place in the enclosed barrel of the dynamic freezer. Recently, Cook and Hartel (2010) summarized the complex processes of ice formation in a scraped-surface freezer, shown schematically in Fig. 11.4. In brief, an ice layer of sorts forms at the barrel wall, is scraped off by the dasher, and dispersed into the interior of the freezer where some of the ice crystals melt while others grow, with product crystals ripening into the disc-shaped blocks seen at the draw of the freezer. Further details, as currently understood, are provided below.

Mix above its freezing point temperature enters the barrel of the scraped-surface freezer, where it is quickly cooled by the refrigerant, especially near the barrel wall. Because of the low temperatures and the rapid freezing process at the cylinder wall,

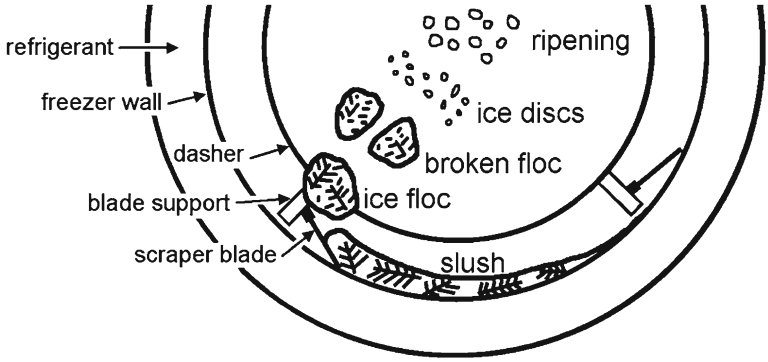

Fig. 11.5 Two-dimensional view looking down the length of the dasher showing a larger view of ice crystallization near the freezer exit. At this stage, the ice crystals ripening in the bulk are mostly larger than the ice discs formed from the material scraped off the freezer wall, likely resulting in the large crystals growing at the expense of the smaller crystals. For clarity, the size of the crystals inside the slush and ice flocs has been exaggerated (Cook and Hartel 2010, with permission)

the ice layer that forms there is probably not fully crystallized, but forms as a slushy layer (Fig. 11.5). This slush contains abundant small ice crystals (mostly dendritic in nature) in addition to a concentrated solute (sugars, salts, etc.) with slightly higher density than the original mix. The scraper blade removes this cold slush layer from the barrel wall and mixes it with the warmer mix remaining in the center of the barrel. The dasher design and rotational speed determine the mixing behavior as the slush combines with warmer mix (Cook and Hartel 2011). The cold slush melts as it cools the warmer mix. In a continuous freezer, this process occurs near the entry point of mix into the freezer barrel as freezing begins. Once the bulk of the mix is cooled sufficiently, some of the ice crystals from the slush layer begin to survive. These ice crystals grow, or ripen, into rounded disc-shaped crystals based on the conditions (heat transfer and mixing) in the barrel. As ice content increases during the freezing process (or along the length of the freezer in a continuous process), the new ice layer scraped from the wall primarily contributes to growth of the ice crystals formed earlier in the process, although some nuclei from the slush layer survive and grow, ending up in the product. Further details of this process can be found in Cook and Hartel (2010).

Formation of the correct amount of ice during freezing is not sufficient to guarantee a high quality ice cream. The average size and distribution of sizes of ice crystals has a significant impact on smoothness and eating quality of ice cream. The freezing operation must be designed to produce mostly small crystals to yield a smooth ice cream. Typical size distributions of ice crystals in ice cream are shown in Fig. 11.6. Ice crystals range in size from a few to over 100 μm, with a mean size somewhere between 15 and 30 μm for product exiting the scraped-surface freezer to between 35 and 45 μm for hardened ice cream. The number of ice crystals, if assumed to be in the form of 40 μm cubes, would be approximately 7.8×10^6 per gram, and the total surface area of these ice crystals about 0.08 m^2 (Berger 1997).

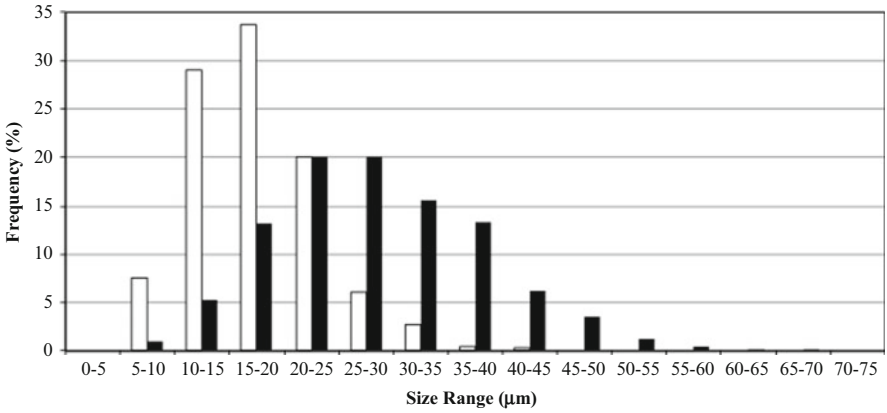

Fig. 11.6 Typical ice crystal size distribution in ice cream (**a**) as it exits the scraped-surface freezer and (**b**) after hardening to −18°C

Although many factors influence the eating quality of ice cream, it is generally accepted that smooth ice cream requires the majority of ice crystals to be smaller than about 50 µm in size. If many crystals are larger than this, or if there are extremely large ice crystals (over 100 µm), the ice cream will be perceived as being coarse (icy). Russell et al. (1999) demonstrated a good correlation between mean ice crystal sizes in 8% fat ice creams that were heat-shocked to varying extents, resulting in mean sizes from 30 to 50 µm, with sensory perception of smoothness and ice crystal detectability assessed by a panel of experts.

To develop ice crystals with the proper dispersion (number, size, and shape), it is necessary to control the freezing process. One way to think about this is in terms of the relative rates of nucleation vs. growth of crystals. To generate numerous small crystals, the freezing conditions must promote nuclei formation and minimize ice crystal growth (Hartel 2001). Promoting ice nucleation requires very low temperatures at the appropriate point in the process. Primary refrigerants (i.e., liquid ammonia or freon) are used to provide temperatures as low as −30°C to promote rapid nucleation at the wall of the freezer. Once nuclei have formed, conditions that minimize their growth are needed to keep the crystals as small as possible. As noted above, our understanding of exactly what happens to the ice in the barrel of a freezer is still somewhat limited, although control of these processes is mandatory to maintain the many small crystals desirable. Both Russell et al. (1999) and Drewett and Hartel (2007) clearly demonstrated the inverse relationship between residence time in the freezer and ice crystal size. To obtain the smallest ice crystals it is necessary to have the shortest residence time possible so as to minimize the amount of ripening that occurs within the freezer barrel itself. One option to minimize residence time in the freezer and produce the smallest ice crystals is to use solid dashers with high-throughput rates. However, the choice of freezer and dasher type and of operating conditions is based on many quality factors other than size of ice crystals.

Ice does not conduct heat as fast as steel. Therefore, if ice is permitted to form a layer inside the cylinder, it acts as an insulator slowing release of heat from the mix to the refrigerant. Besides ice layer build-up, the rate of heat transfer is a function of the difference in temperature between the mix and the refrigerant, the thermal conductivity of the heat transfer surface, and the rate of renewal of surface films (ice on the ice cream side and an oil film on the refrigerant side). During ice cream manufacture, the rate of heat transfer should be as high as possible to promote formation of numerous small ice crystals since this leads to the smoothest ice cream with the greatest stability during distribution and storage.

The types and amounts of ingredients in the ice cream mix affect the characteristics of the ice crystals. Mix ingredients can influence ice crystal formation and growth by two main mechanisms: (1) effect on freezing point depression and (2) specific effects on ice crystallization mechanisms (nucleation, growth, and ripening). As discussed in Chaps. 5 and 6, freezing point depression is influenced primarily by the amount of low-molecular-weight components in the mix. Higher concentrations of simple sugars and salts lead to lower freezing points and less ice being formed at a given temperature. A mix with low freezing point produces soft ice creams due to the low amount of ice crystals. Certain individual components in ice cream also can directly affect the mechanisms of ice crystallization. Sugars and many stabilizers have been shown to reduce the rate of either ice nucleation and/or crystal growth. Recently, there has been interest in using ice-structuring proteins (from either arctic fish or winter wheat) to inhibit ice crystal growth and maintain uniformly small ice crystals in ice cream (see Chap. 12). These proteins adsorb firmly onto the ice crystal surface and prevent further growth, thereby preventing formation of larger ice crystals (Regand and Goff 2006). It also appears the propylene glycol monostearate (PGMS) also can adsorb directly to the surface of ice crystals, blocking their growth (Aleong et al. 2008; see Chaps. 3 and 12 for more details of PGMS as an ice cream ingredient). ISPs can also alter the ice crystal morphology for the development of block-like crystals that can stack or align, perhaps providing an opportunity for new and innovative products (Crilly et al. 2008). Mix components like stabilizers are often used to inhibit recrystallization, or the gradual increase in ice crystal size, during storage of ice cream (see Chap. 12). Although the specific effects of these components are widely recognized, our understanding of how these ingredients affect ice crystallization is still incomplete.

Because of the importance of small ice crystals and the energy-intensive process in dynamic freezing, alternative methods of freezing ice cream and frozen desserts to reduce ice crystal size (and perhaps minimize refrigeration/energy use) are always being sought. One notable recent effort involves high pressure-low temperature treatment (Volkert et al. 2011). Here, pressure shift technology was utilized to freeze an aerated, sugar-rich, dairy-based emulsion. By control of pressure and temperature to control the type of ice formed, it was possible to produce ice crystals with a mean size of 34 μm compared to 40 μm for the same system traditionally frozen. The feasibility of this technology to produce commercial frozen products remains to be seen.

Destabilization of the Fat Emulsion

The whipping and freezing processes convert some of the fat in the mix into a three-dimensional aggregated fat structure that provides structural integrity, a process known as fat destabilization. This is especially important if such integrity is needed when the structural contribution from ice is relatively weak (i.e., before hardening or during melting). Fat aggregates contribute dryness at extrusion for fancy molding, slowness of melting, some degree of shape retention during melting, and smoothness during consumption. Therefore, more fat destabilization is needed in situations where more structural integrity is needed, for example in extruded novelty items or cakes, but less may be required for packaged ice cream. In other words, the process needs to be optimized depending on the end product—not enough destabilization leads to poor shape retention and rapid melting whereas too much destabilization may lead to formation of visible fat granules in the ice cream and ice cream that does not "melt" (or collapse structurally, although the ice melts) within a reasonable time at ambient temperature.

The aggregation process itself is one of partial coalescence, in which the individual fat droplets stick together during collisions caused by the shear forces in the dynamic freezing step, but the fact that the droplets are partially crystalline (partially solid) means that the spherical integrity of the droplets is maintained, which limits the extent of true coalescence of the fat into progressively larger droplets (Goff 1997, 2002; Pawar et al. 2012). These aggregates adsorb to air interfaces and develop interconnectivity throughout the unfrozen serum phase. This process is very similar to the one responsible for structure formation during the whipping of dairy cream. Several parameters are involved, and need to be controlled to achieve the optimal level of partial coalescence: the total amount of fat (low fat products exhibit less structure formation whereas high fat products are more prone to churning of the fat to visible fat granules); the size distribution of the fat droplets (number of droplets and surface area, which are controlled by homogenization conditions); the solid fat content at the whipping/freezing temperature (a function of fat type, i.e., saturated fat content, and aging time depending on the kinetics of crystallization); the type of protein present at the fat interface (caseins, whey proteins, or whey protein aggregates); the quantity and type of emulsifier used (since emulsifiers modify the fat droplet surfaces and reduce the quantity of adsorbed proteins); and the shear forces generated in the dynamic freezer, or whipping time in the batch freezer. Hence mix ingredients including fat, protein, and emulsifier, and processing steps, including homogenization, aging, whipping, and dynamic freezing, are all involved. Once the fat network is created during whipping and dynamic freezing, very little further change occurs as a result of hardening or storage of the ice cream. The following discussion elaborates on these parameters.

The process of fat structure formation really begins at the homogenizer, which is responsible for creating fat droplets in the mix that are stable in the mix state without creaming and that are of appropriate size for fat structure formation in the ice cream. If the goal is emulsion stability, there is sufficient protein in the

mix to stabilize the fat droplets. Unless there has been a problem with homogenization, the fat globules in ice cream mix remain suspended indefinitely (or at least as long as needed). It is generally recommended to reduce the homogenizer pressure with higher fat mixes and to increase the homogenizer pressure with lower fat mixes, to control the size distribution sufficiently to achieve optimal fat destabilization.

Fat globules in ice cream mix are in a partially solidified state based on the broad range of triacylglycerol molecules that make up milk fat or other saturated fats that are used for ice cream manufacture such as coconut oil or palm kernel oil. That is, the fat triacylglycerols with high melting points are crystalline in ice cream mix while those with low melting points are in liquid form. It is during cooling after pasteurization and then aging of the mix that most of the fat crystallization takes place. Typically, about 2/3 of milk fat will crystallize at 4°C and this has fully crystallized after 4–5 h of aging (Adleman and Hartel 2001). Thus, as a general rule, fractionated milk fats or nondairy fats are usually selected that provide about 50–70% solid fat at 4°C (Persson 2009). Too much solid fat leads to insufficient partial coalescence, as the liquid oil component is thought to hold globules together when they collide, but too much liquid oil will result in coalescence rather than partial coalescence, which will not build up the desired aggregated structure (Goh et al. 2006; Crilly et al. 2008; Sung and Goff 2010). Fractionated milk fats with higher solid fat content (more crystalline fat) caused less fat destabilization than those lower in solid fat (Adleman and Hartel 2001). On the other hand, fractionated milk fat with higher unsaturated fat content has been shown to lead to smaller air bubbles and better foam stability in whipped emulsions (Bazmi et al. 2007). The kinetics of the crystallization process is also important. If a nondairy fat is slow at nucleation and developing internal crystalline structure with the fat droplet, then more time will be required for aging, and this is undesirable from a manufacturing point of view. Polymorphic stability of the fat also affects fat destabilization and physical properties of ice cream (Persson 2009), although little work has been published on the effect of lipid polymorphism on fat destabilization.

In the aging step, the proteins that stabilize the fat globules are partially replaced by emulsifiers present in the mix (Goff et al. 1987; Goff and Jordan 1989; Barfod et al. 1991). Depending on the type of proteins and the type of emulsifiers, the surface adsorption is approximately 10–12 mg protein per m^2 of fat in the absence of emulsifier and 3–6 mg protein per m^2 of fat in the presence of emulsifier (Bolliger et al. 2000a). This exchange at the surface of the fat globule is initiated because of the ability of the emulsifiers to lower the interfacial tension but the net result is reduction of the steric stabilization layer, which decreases the stability of the globules rendering them prone to destabilization during shearing in the scraped-surface freezer. Proteins are large, bulky macromolecules that exist mostly on the aqueous side of the fat interface compared to the very small monoglycerides, which exist mostly on the fat side of the interface. Thus the thickness of the membrane and hence the stability of the globule to shear is greatly reduced from the action of the emulsifiers. This competitive displacement of proteins by small molecule surfactants at the fat interface in emulsions has been thoroughly studied in model systems

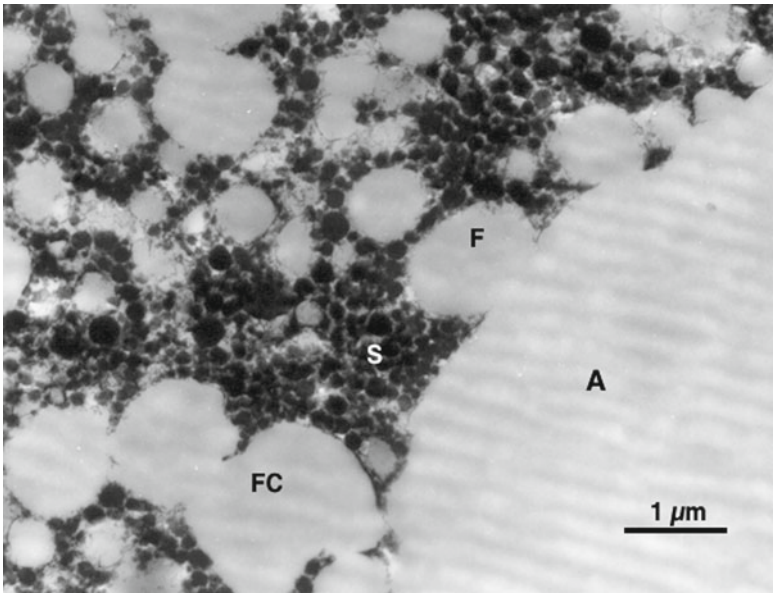

Fig. 11.7 Transmission electron micrograph of ice cream showing air interface (A) with adsorbed fat globules (F) and partially coalesced fat clusters (FC) extending into the serum phase (S) containing the casein micelles

(e.g., Courthaudon et al. 1991; Chen and Dickinson 1993; Dalgleish et al. 1995; Euston et al. 1995, 1996) and in ice cream (Goff et al. 1987; Goff and Jordan 1989; Gelin et al. 1994, 1996a, b). Bolliger et al. (2000a) showed that the quantity of protein adsorbed to the fat droplets in ice cream mix correlated with major characteristic analyses describing the fat structure in ice cream (fat agglomerate size, fat agglomeration index, solvent extractable fat).

The decreased adsorbed protein layer at the surface of the globules from the action of the emulsifier and the shearing action during freezing result in destabilization of the emulsion and formation of clusters or aggregates of fat globules. Because the globules are partially crystalline (and are continuing to crystallize as the temperature is lowered during freezing), they can only partially coalesce, forming clusters of fat globules as shown schematically in Fig. 11.1 and by transmission electron microscopy in Figs. 11.7 and 11.8. These partially coalesced fat globules migrate towards the air cell interface and provide structure to the unfrozen phase of the mix as they help to stabilize the air cells being incorporated into the ice cream. Air cells are primarily stabilized by the fat phase, including the partially coalesced fat globules, which preferentially migrate to the air cell interface. This behavior is clearly shown in cryo-SEM micrographs of air cells in ice cream (Fig. 11.9). Goff et al. (1999a) have shown by cryo-scanning electron microscopy and freeze-substitution transmission electron microscopy that the air bubble surfaces in dairy fat ice cream are stabilized by a continuous protein layer with adsorbed fat globules and partially coalesced fat globule aggregates.

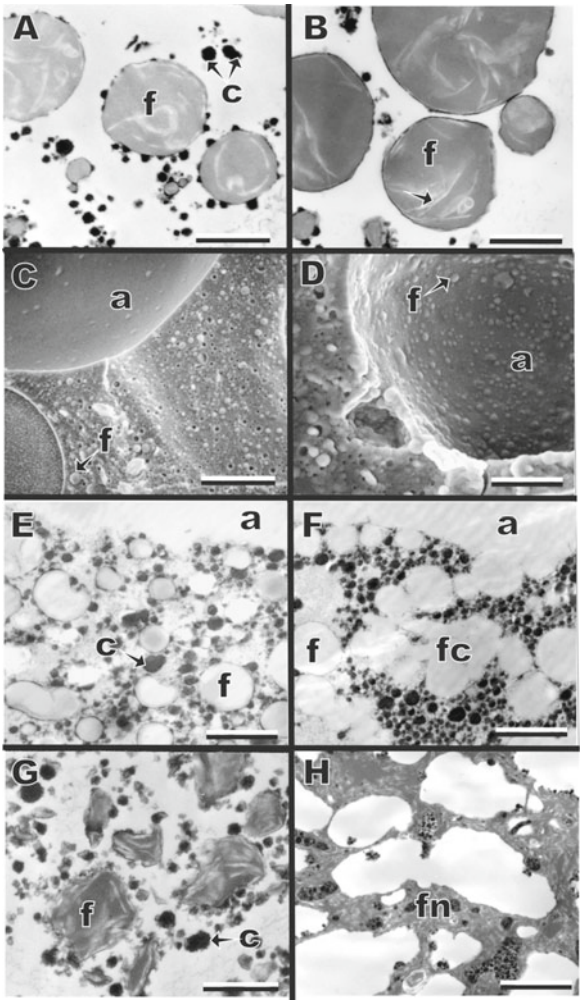

Fig. 11.8 The colloidal structure of ice cream mix, ice cream, and melted ice cream, as viewed by electron microscopy, focusing specifically on the effect of added emulsifiers on fat structure formation. (**a**, **b**) Ice cream mix with no surfactant and with added surfactant, respectively, as viewed by thin section transmission electron microscopy. f = fat globule, c = casein micelle, arrow = crystalline fat, bar = 0.5 μm. See Goff et al. (1987) for methodology. (**c**, **d**) Ice cream with no surfactant and with added surfactant, respectively, as viewed by low temperature scanning electron microscopy. a = air bubble, f = fat globule, bar = 4 μm. See Caldwell et al. (1992) for methodology. (**e**, **f**) Ice cream with no surfactant and with added surfactant, respectively, as viewed by thin section transmission electron microscopy with freeze substitution and low temperature embedding. a = air bubble, f = fat globule, c = casein micelle, fc = fat cluster, bar = 1 μm. See Goff et al. (1999a) for methodology. (**g**, **h**) melted ice cream with no surfactant and with added surfactant, respectively, as viewed by thin section transmission electron microscopy. f = fat globule, c = casein micelle, fn = fat network, bar = 1 μm in (**g**) and 5 μm in (**h**). See Goff et al. (1987) for methodology

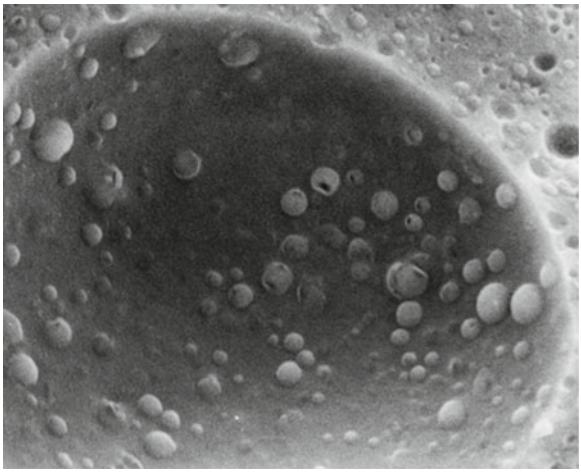

Fig. 11.9 Cryo-scanning electron micrograph of interior of an air cell in frozen ice cream. The projections are fat globules. Picture width = 10 μm

The total quantity of adsorbed protein is not the only determinant factor of partial coalescence when it comes to proteins, however. The traditional ratio of proteins in milk solids is about 80% casein micelles and 20% whey proteins. However, when these ratios are modified by the use of whey protein ingredients in the mix, the integrity of the droplet membrane can be affected. Casein micelles are in the range of 50–300 nm in diameter. When they adsorb to fat droplets, the hydrophobic interior spreads at the fat interface but the micelle remains as a bulky protrusion into the aqueous phase (Fig. 11.8). The emulsifier can easily penetrate into the area around the micelle to initiate displacement (Goff et al. 1987). Generally, whey proteins provide thinner membranes than casein micelles but the membrane is more cohesive and coverage of the surface area more complete compared to casein micelles, which makes displacement of whey proteins by emulsifiers more difficult, and whey protein stabilized droplets less prone to fat destabilization (Segall and Goff 1999). Relkin et al. (2006) showed that heat aggregation of whey proteins prior to emulsification improved the extent of fat destabilization by making them easier to displace by surfactants.

Homogenization of ice cream mix influences the initial fat globule size distribution, which can potentially alter the nature of fat globule aggregation during freezing. Double-stage homogenization of ice cream mix at 15 MPa (first stage) and 3 MPa (second stage) resulted in fat globules with mean size of about 0.8–1 μm, depending on the fat content of the mix (Koxholt et al. 2001; Hayes et al. 2003). An increase in homogenization pressure up to 30 MPa caused a decrease in fat globule sizes in both mix and melted ice cream made with 10% fat, although these changes only caused a change (faster) in meltdown rate at the highest pressure (Koxholt et al. 2001). In 15% fat ice cream, an increase in homogenization pressure up to 15 MPa (single stage) caused a decrease in mean fat globule size of both mix and melted ice cream (Tosaki et al. 2009). Further increase in homogenization pressure up to 25 MPa resulted in an increase in mean fat globule size in the mix but a continued decrease in fat globule size in the melted ice cream. The 15% fat ice creams

were seen to meltdown more slowly with increased homogenization pressure (Tosaki et al. 2009), in contrast with the results on 10% ice cream (Koxholt et al. 2001). The effects of high-pressure (100 and 200 MPa) homogenization on fat globules were also dependent on fat content of the ice cream mix (Hayes et al. 2003). Studies of the effect of fat globule size and homogenization pressure on fat partial coalescence and meltdown rates are complicated by the fact that, on the one hand, more droplets provide more surface area, which should stabilize more air surface area and should create more fat aggregates, but on the other hand, smaller droplets are more stable (greater protein adsorption per surface area) and thus require more emulsifiers to enhance fat destabilization. This explains why melt rates would increase with higher pressures when they are expected to decrease.

The distribution of fat globules also has a significant impact on physical properties of the finished product. Improperly homogenized mix leads to ice cream that might appear either wet or dry at extrusion, depending on the size distribution of globules created and the extent of flocculation of the droplets (typical of homogenization with only one stage) and has a weak body. The rate of meltdown (as measured by the drip-through test) during holding at temperatures above the freezing point generally decreases as the extent of fat destabilization increases. However, since there are numerous structural factors that influence the rate of meltdown, a direct correlation between fat destabilization and meltdown rate has not always been observed (Warren and Hartel, unpublished data).

The use of polysorbate 80 as an emulsifier leads to greater fat destabilization than does the use of mono- and diglycerides due to the greater effect of polysorbate 80 on lowering interfacial tension and hence displacing more protein (Goff et al. 1987; Adleman and Hartel 2001). The degree of saturation of the fatty acids present in mono- and diglycerides also influences the level of fat destabilization with unsaturated fatty acids giving greater destabilization (Barfod et al. 1991; Zhang and Goff 2005). High levels of unsaturated monoglycerides have also been shown to form clusters of plate-like fat crystals in ice creams made with palm kernel oil (Mendez-Velasco and Goff 2011, 2012a), which was responsible for producing a high level of dryness and shape retention. It was postulated in this work that the high mobility of the unsaturated emulsifier is responsible for unique interactions with the specific crystal morphologies of the palm kernel oil, a response that was not seen to the same extent with milk fat.

A unique approach to controlling fat phase structure in ice cream to maintain desired structure (fat destabilization) with lower saturated fat content was developed by Mendez-Velasco and Goff (2011). Recognizing the need for some solid fat to provide structuring, they blended separate emulsions of a partially crystalline fat with an unsaturated liquid oil to produce an ice cream mix with more desirable lipid profile. The liquid oil was stabilized with protein to prevent coalescence under the shear conditions in the freezer, whereas the solid fat droplets contained emulsifier to promote formation of the structures desired for high quality ice cream. They demonstrated that such an approach could work to utilize more of an unsaturated fat source, either for health purposes or to utilize domestic oil sources rather than reliance on imported tropical fats. The textural properties were improved as a result of

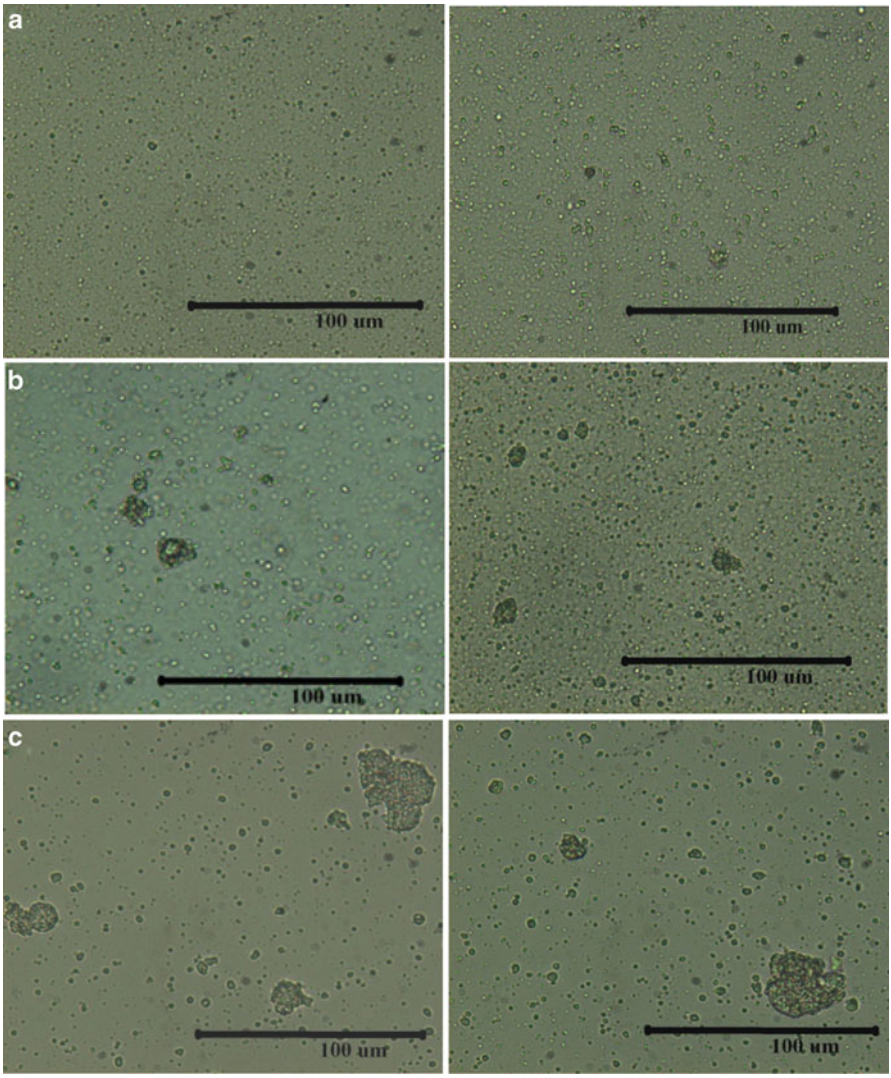

Fig. 11.10 Photomicrographs of fat globule clusters observed in melted ice cream. (**a**) Low level, (**b**) moderate level, and (**c**) high level of fat destabilization

this two-stream blending. This work also confirmed our understanding of emulsion droplet stability and its role in structure formation.

The exact nature of the clusters found in melted ice cream has been the subject of recent study. Figure 11.10 shows light microscope images of fat globule structures observed in ice creams with low, medium, and high fat destabilization. Fat destabilization in ice cream is thought to occur due to partial coalescence, where the shear forces of the dasher within the freezer bring partially crystalline fat globules

together and the low steric stabilization of the droplets from a reduction in adsorbed protein allows sharing of liquid fat between globules. The crystalline fat network within the droplets maintains some droplet integrity but prevents complete coalescence, leaving aggregated clusters of fat globules. However, others (Koxholt et al. 2001; Goh et al. 2006) have speculated that fat globule clusters in ice cream are held together by proteins at the surface rather than by the physical connection due to partial coalescence. To help clarify this question, Mendez-Velasco and Goff (2012b) used a combination of light scattering techniques employing SDS or EDTA to reduce various interactions. They confirmed that partial coalescence is the main mechanism for fat destabilization in ice cream and that flocculation through protein interactions does not contribute to formation of fat globule clusters.

Typically, greater fat destabilization occurs in continuous freezers than in batch freezers due to the higher shearing action of the scraper blades in the former. Dasher design and rotational speed both influence the shearing processes in the freezer and affect fat destabilization. The shear forces applied in low temperature extrusion of ice cream following initial freezing induce greater fat destabilization (Bolliger et al. 2000b; Eisner et al. 2005). Under certain conditions in an ice cream freezer (i.e., high fat content, low solid fat content, high shearing, etc.), excessive fat destabilization leads to churning of the fat. In this case, the fat globules come together in a sufficiently large mass (>30 μm; Wildmoser and Windhab 2001) such that butter granules appear as distinct entities. These butter granules detract from the appearance of the finished product (dry product), influence the physical properties (increased stiffness), and affect the sensory aspects of the ice cream, imparting a buttery texture to the product.

Several methods have been used to measure the extent of fat destabilization. One of the earliest methods involved measuring the difference in absorption of light (by spectroscopy) in diluted mix compared to diluted ice cream (Goff and Jordan 1989). Dilution of the mix leaves a dispersion of fat globules that absorbs a certain amount of light based on the size and number of fat globules. After freezing, there are fewer individual fat globules and more clusters or aggregates. Dilution of ice cream leaves a dispersion of fat aggregates that absorbs light to a different extent than does the initial mix. The difference in absorbance between mix and the melted ice cream can, therefore, be used as a measure of fat destabilization. Extent of destabilization has also been measured as the amount of easily extracted fat since the partially coalesced aggregates are more susceptible to organic solvent extraction than are the individual globules (Barfod et al. 1991). More recently, light scattering techniques have been used to quantify the differences in the fat globule size distribution between mix and finished product and to document the increase in size due to aggregation (Bolliger et al. 2000a). The light scattering method clearly distinguishes the initial mix emulsion droplets (0.8–1.0 μm) and the clusters of fat droplets that form due to partial coalescence, as seen in Fig. 11.11. Quantification of the extent of fat destabilization is generally done by comparing the volume percent of fat globule clusters above a certain size, depending on the size of the emulsion droplets in the mix. See Chap. 14 for more details of the method. In some cases, the casein micelles (0.2 μm) can be identified separately (Fig. 11.11) and in some cases they cannot (Fig. 14.2),

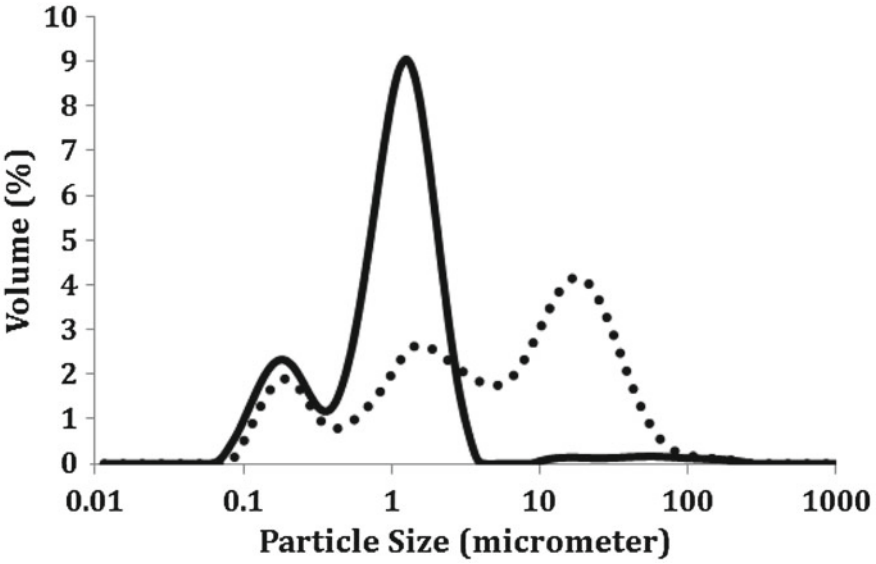

Fig. 11.11 Light scattering curves of mix (*solid line*) and melted ice cream (*dashed line*) showing casein micelles (peak around 0.15–0.25 μm), fat globules of the initial emulsion (peak around 0.8–2.0 μm), and fat globule clusters formed due to partial coalescence (peak at >10 μm)

depending on the sizes of the fat globules, since a population of small fat globules can obscure the end of the micelle peak from the beginning of the fat globule peak.

Air Cells

The air content of ice cream is measured by its overrun. This air is in the form of microscopic bubbles, or cells, and these air bubbles need to be properly formed and stabilized during manufacturing. Controlling air incorporation into ice cream is critical for product quality and stability (Xinyi et al. 2010). In most dynamic freezing operations, air is incorporated and air cells are formed simultaneously with freezing. In fact, whipping air into ice cream and reducing air bubble size generally requires the shear stresses built up as the ice freezes. In some sense, however, the dynamic freezing step must account for competing phenomena (Koxholt et al. 2000). Shorter freezing times are needed to produce small ice crystals, but longer freezing times enhance air bubble comminution to give smaller air cells. For this reason, pre-aeration may be a good choice to better control ice cream structures. Pre-aeration equipment is discussed in detail in Chap. 7.

Although the specifics of the breakdown of air cells depend on the type of freezer being used, the principles of air incorporation during freezing are generally the same regardless of the type of freezer. Air cells start out as large entities, with size depending on the type of freezer and air incorporation technique, but the air bubbles

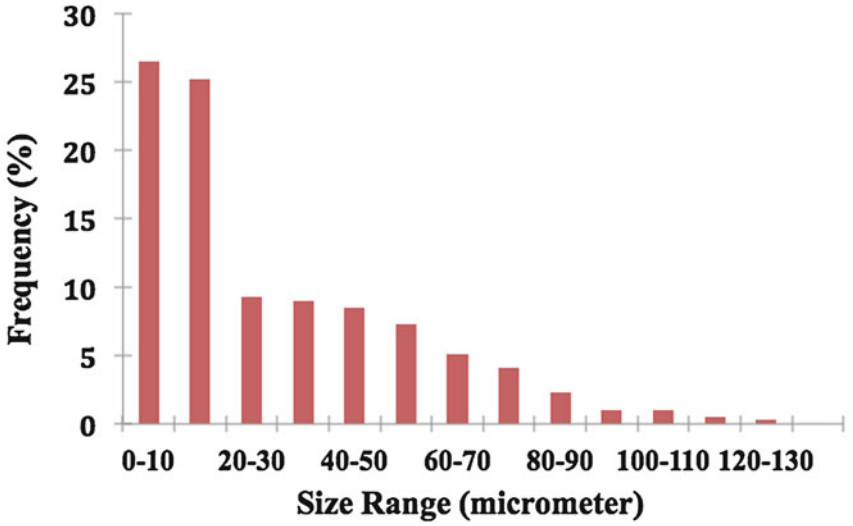

Fig. 11.12 Air cell size distribution in a commercial ice cream

are continually being reduced in size and the air more evenly dispersed by the shearing action during freezing. In continuous ice cream freezers, air is injected in the form of small bubbles under pressure, whereas in batch freezers, air is incorporated through the folding and mixing of the liquid. In both cases, air cells are reduced in size as freezing progresses, dependent on the shearing conditions in the freezer. Air can be incorporated prior to freezing in a pre-aeration step (under high shear conditions) to provide improved control of air cell size distribution.

The air cells that form in the dynamic freezing step may differ significantly in size depending on whether the product is being made in a batch- or continuous-type freezer. The batch-type freezer operates at atmospheric pressure, so air that is incorporated exists at the same pressure both inside and outside the freezer. However, the freezing cylinder of the continuous freezer is held under pressures up to about 690 kPa (100 psi). Pressures of about 520 kPa (75 psi) produce about 100% overrun with the normal mix, and the air cells in the freezer make up 15–20% of the volume of the mix. Due to expansion, the same air cells constitute about 50% of the product volume when the pressures equilibrate to atmospheric pressure (1 atm is 101.4 kPa or 14.7 psi absolute) outside the freezer.

In finished ice cream, the air cells are found in a range of sizes, from a few μm to over 100 μm. Figure 11.12 shows the air cell size distribution in a typical commercial ice cream. Assuming that ice cream contains 100% overrun in the form of 60 μm diameter air cells, the number of air cells per gram is approximately 8.3×10^6, and the total surface area is approximately 0.1 m^2 (Berger 1997). However, the research literature shows wide variation in mean size of air cells found in ice cream. Berger and White (1979), based on optical micrographs of ice cream, estimated a mean size of about 60 μm. Chang and Hartel (2002a) compared an optical

microscope method with a cryo-SEM method for measuring air cell size distribution and found a mean air cell diameter of about 20 μm. Improvements in processing equipment would certainly account for some of this variation, as would different mix composition. A recent survey of a wide range of commercial ice creams showed that mean air cell sizes, as measured with the method of Chang and Hartel (2002a), varied from as low as 19.9 μm to as large as 38.2 μm for regular ice creams although two frozen dessert products were identified with mean air cell sizes of 45.3 and 74.9 μm (Warren and Hartel, unpublished).

Studies of air incorporation and air cell size reduction during manufacture of ice cream have clearly shown that formation of ice is necessary for air incorporation under the conditions found in typical ice cream freezers. That is, whipping of ice cream mix in ice cream freezers at temperatures above the freezing point of the mix results in limited overrun development and relatively large air cell size (Chang and Hartel 2002b). The capacity to reduce air cell sizes depends on the increased viscosity that comes from freezing. During freezing, a slurry of ice crystals is being formed in an increasingly viscous continuous (unfrozen) phase. This combination of the dispersed (ice crystals) and the freeze-concentrated continuous phases causes the viscosity of the ice cream to increase dramatically during freezing. This increased viscosity enhances stabilization of air cells and allows air cells to be reduced to smaller and smaller sizes. Chang and Hartel (2002b) found that the decrease in air cell size during batch freezing correlated with the increase in shear forces due to ice formation, in accordance with the critical Weber number concept. Factors that did not affect viscosity during freezing (fat content, emulsifier type and content) did not have an effect on air cell distribution. Stabilizer content was observed to affect air cell size in the early stages of batch freezing where mix viscosity played a role in the applied shear forces. After 6 min of batch freezing, stabilizer content had no further effect on air cell size since shear forces were dominated by ice crystals formation. Caillet et al. (2003), characterizing ice cream structure with a direct optical microscopy method, also showed that decreasing draw temperature (increased ice crystal content) led to smaller air cells during continuous freezing.

Changes in air cell size distribution also occur during the hardening step (Chang and Hartel 2002c; Sofjan and Hartel 2004). Air bubbles undergo changes through four potential mechanisms: disproportionation (Ostwald ripening), coalescence (fusion of neighboring bubbles), drainage (leading to an uneven distribution of air as bubbles rise, especially at warmer temperatures when ice cream is still soft), and distortion of air bubbles by growing ice crystals during hardening, leading to rupture of air bubble interfaces if the membrane is not sufficiently stabilized by adsorbed protein and fat globules or partially coalesced fat. The rate of each mechanism depends on the conditions, primarily influenced by formulation and temperature. During hardening, ice cream temperature decreases from draw temperature (about −6°C) to hardening freezer temperature (−18°C) at a rate depending on the hardening freezer conditions (temperature, air velocity) and the size of the carton. Hardening can take several hours for larger sized cartons, meaning that ice cream at the center of the carton remains at elevated temperatures for sufficient time that air bubbles can undergo dramatic changes. Reducing temperature as quickly as possible during

hardening ensures the minimum change in air cell sizes, although formulation factors were seen to influence air cell changes as well. Increasing serum viscosity through addition of stabilizers decreased rates of drainage and slowed air cell growth. Addition of emulsifiers also reduced air cell changes during hardening, most likely by increasing the extent of fat destabilization. Low temperature extrusion of ice cream also limited the changes in air cells during hardening by decreasing temperature quickly (Eisner et al. 2005). Further, lower extruder outlet temperature led to smaller air cells, whether using a single screw or twin-screw extruder.

Milk proteins are well known for their ability to form foams. Foaming is important during the manufacture of ice cream, because air is incorporated to about 50% of the phase volume. Thus, it should not be surprising that milk proteins contribute to stabilizing the air interface in ice cream. This air interface is important for overall structure and structural stability (Turan et al. 1999). During freezing, proteins at the air bubble surface interact with both the added emulsifying agents (which are also surface active) and partially coalescing fat at the air interface (Pelan et al. 1997). Incorporation of air into ice cream is rapid, within seconds, and at the same time, viscosity of the surrounding matrix is increasing exponentially due to freezing, such that air bubbles, after formation, become physically entrapped into a semisolid matrix, making their collapse quite difficult. Loss of air can lead to a defect known as shrinkage, the occurrence of which is fairly common and responsible for the loss of quality and acceptability of the product (Dubey and White 1997). This will be discussed further in Chap. 12.

Recent efforts to control air bubble size distribution in ice cream have focused on the use of hydrophobins, proteins produced by filamentous fungi (Linder 2009). Due to the high surface activity at air-water interfaces, it appears to have potential to inhibit changes in air cell size during ice cream hardening and storage (Crilly et al. 2008). The potential use of hydrophobins to create "air-filled emulsions" to reduce fat content in emulsion-based foods has also been proposed (Le Reverend et al. 2010).

Hydrocolloid Phase Behavior

Proteins are an important part of the MSNF component, and as described above, they adsorb at the fat interface and contribute to emulsion stability and they adsorb at the air interface and contribute to air bubble stability. Those proteins that are not adsorbed become freeze-concentrated in the unfrozen serum phase where they contribute to viscosity and water-holding properties. Polysaccharides are also added to ice cream mix to increase solution viscosity and to modify properties of the unfrozen phase, notably to control ice recrystallization, which will be discussed in detail in Chap. 12. They also become freeze-concentrated in the unfrozen serum phase. The polysaccharides that are used in ice cream manufacture (locust bean gum [LBG], guar, carboxymethyl cellulose [CMC]) are all incompatible in solution with

milk proteins (especially casein micelles and to a lesser extent the whey proteins) leading to a microscopic or macroscopic (visual) phase separation. Because both types of molecules are large polymeric hydrocolloids, their behavior in the unfrozen phase is mostly governed by their interactions, so given this context both will be discussed together here.

Milk protein-polysaccharide phase separation has been extensively studied in model systems (Syrbe et al. 1998; Bourriot et al. 1999a; Schorsch et al. 1999, 2000; Thaiudom and Goff 2003). In a series of papers, Goff and coworkers have examined the interaction between milk proteins and various polysaccharides, including LBG, guar gum, and CMC in frozen systems using fluorescently labeled polysaccharides and fluorescence microscopy (Goff et al. 1999b; Flores and Goff 1999; Regand and Goff 2002, 2003; Patmore et al. 2003). They demonstrated a clear phase separation in the unfrozen phase between proteins and all polysaccharides. LBG was seen to produce a structured gel-like network around the ice crystals, which became more distinct with repeated temperature cycling. Such a network was not evident with guar gum or CMC. However, in the presence of the proteins, all polysaccharides led to the development of discernable aggregated protein networks created by freezing. These structures were related to control of ice recrystallization, as will be discussed in Chap. 12. It thus appears that the microscopic phase separation of the milk protein induced by polysaccharides, and "aggregation" of casein into a weak gel-like network, promoted also by freeze concentration, is at least partly responsible for ice crystal stability and thus for improvement of texture during consumption.

Huppertz et al. (2011) also demonstrated the importance of protein structure in the unfrozen phase by the use of high-pressure hydrostatic processing of mix to rearrange the casein proteins into a micellar network of sorts, which resulted in a very smooth ice cream of high viscosity with a higher melting resistance. This technology could be adapted to prepare MSNF ingredients for ice cream with enhanced functionality (Lim et al. 2008). Zhang and Goff (2004) were also able to show the importance of protein functionality in the unfrozen phase by partially disrupting the casein micelle structure with EDTA, which improved air bubble stability and enhanced mix viscosity, but also led to the development of more stable emulsion droplets, all of which suggested the partially disrupted casein micelles led to higher soluble casein proteins, which enhanced their functional contributions. This again indicates that modifications of MSNF ingredients for ice cream manufacture can enhance functional properties.

Although protein-polysaccharide phase separation may lead to distinct polymeric networks that contribute structure to the unfrozen phase and help to deliver functionality from reduction in ice recrystallization, such phase separation may also be undesirable, especially in two instances. Phase separation may lead to the leaking of a clear watery serum layer or small "curd" particles (aggregated proteins) during melting of ice cream, which has an undesirable appearance. Phase separation is also particularly apparent and problematic in soft-serve ice cream mixes during quiescent storage of up to 3 weeks at 5°C. In the latter, phase separation leads to the generation of two discernible and immiscible liquid phases, one of them being opaque and containing most of the colloidal protein and fat components of the

original emulsion and the other being transparent or translucent and containing dissolved solutes but depleted in protein and fat. Whether the transparent phase sediments (thus appears at the bottom), creams (thus appears at the top) or flocculates and appears mottled will depend on phase densities and overall mix formulation.

The typical preventive action for this serum separation is the inclusion of a second stabilizer in the formulation, κ-carrageenan. The means by which κ-carrageenan achieves stabilization in dairy systems containing polysaccharides has been extensively studied (Schorsch et al. 1999, 2000; Thaiudom and Goff 2003). Supportive data exist for the electrostatic interaction between κ-casein and κ-carrageenan, which would lead to complex formation (Snoeren et al. 1975, 1976; Dalgleish and Morris 1988), and also for the formation of a weak κ-carrageenan gel, which may entrap casein micelles thus holding them in suspension (Bourriot et al. 1999b).

A series of papers by Goff and coworkers has studied the effect of κ-carrageenan, casein-whey protein ratios, and caseinate vs. micellar casein in the presence of several polysaccharide stabilizers on the stability of soft-serve ice cream mixes to phase separation during quiescent storage (Thaiudom and Goff 2003; Vega et al. 2004, 2005; Vega and Goff 2005; Spagnuolo et al. 2005). The minimum amount of κ-carrageenan to stabilize the mix against serum separation fluctuated between 0.015 and 0.02% regardless of polysaccharide concentration in the range of 0.06–0.2%. Reduction of casein-whey protein ratio at constant protein concentration increased mix stability, as did inclusion of sodium caseinate, indicating that casein micelles are the principal driving force. Mix viscosity was not found to be predictive of mix stability since unstable and stable mixes showed similar apparent viscosities. Addition of κ-carrageenan did not inhibit microscopic phase separation between protein and polysaccharide. A higher degree of "emulsification" of the protein-enriched phase into the continuous serum phase was observed as the κ-carrageenan concentration increased, which correlated with inhibition of macroscopic (visual) serum separation in the mix. Before macroscopic phase separation occurred, microscopy demonstrated that casein micelles and LBG in these systems were incompatible, leading to protein-enriched and protein-depleted domains in a water-in-water emulsion or bicontinuous network structure (Fig. 11.13). Increasing concentrations of κ-carrageenan led to smaller protein-enriched domains, suggesting a form of emulsification induced by the κ-carrageenan. However, the systems with the highest concentration of κ-carrageenan were still phase-separated. After macroscopic phase separation, the serum phase was completely devoid of casein micelles whereas the opaque phase was nearly devoid of polysaccharide but contained most of the κ-carrageenan. Whey proteins were slightly concentrated in the opaque phase. Thus, while κ-carrageenan did not inhibit phase separation at the microscopic scale, it appeared that the protein-enriched domains were inhibited from coalescence and separation by the κ-carrageenan. Thus, κ-carrageenan functionality in preventing or inhibiting macroscopic phase separation between casein and stabilizers in soft-serve ice cream mix resulted from direct interaction with casein micelles, thereby forming protein domains that cannot as easily separate from the serum phase.

The work of Spagnuolo et al. (2005) suggested that both κ-carrageenan adsorption to casein micelle surfaces and κ-carrageenan helix aggregation are required

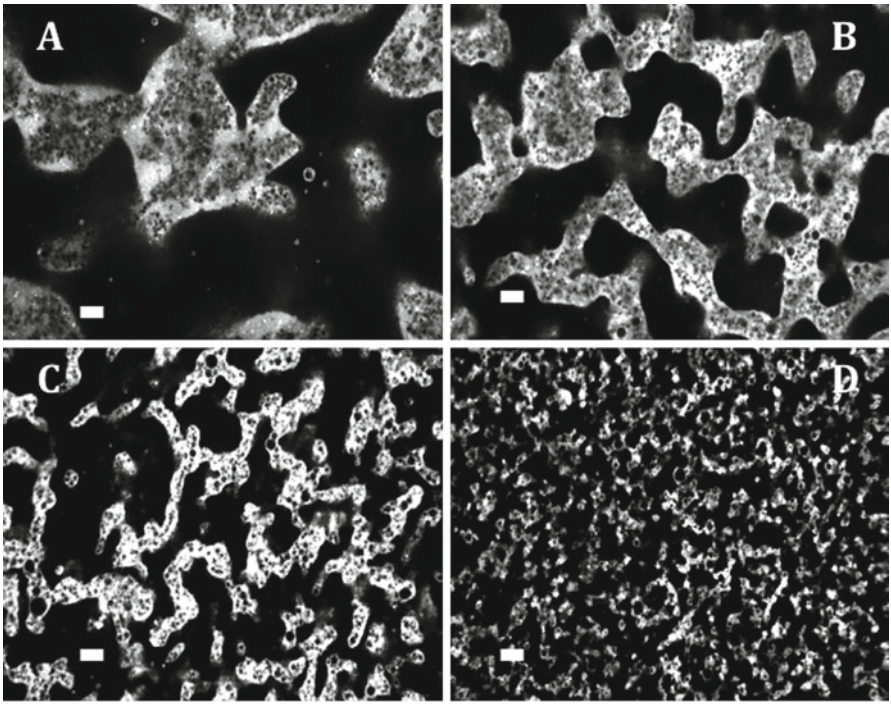

Fig. 11.13 Soft-serve ice cream mixes after preparation containing 0 (**a**); 0.0125 (**b**); 0.015 (**c**); or 0.02% (**d**) κ-carrageenan, as viewed by confocal scanning laser microscopy. *White areas* are the protein-enriched domains; *dark areas* are protein-depleted. Bar = 40 μm

for it to be effective at preventing casein micelle macroscopic phase separation from polysaccharides. κ-carrageenan in the helix form interacts with the surface of the casein micelle, perhaps because of its degree of sulfation and increase in charge density when in the helical form. They suggested that κ-carrageenan functions at the periphery of microscopically phase-separated discrete domains of casein micelles, stabilizing the micro-domains and preventing them from coalescing and forming visual protein-enriched and protein-depleted phases (Fig. 11.14).

Effects of Structure on Physical Properties

Figure 11.1 shows the structural aspects of ice cream and the above discussion relates how both formulation and process conditions influence those structures. It is these structures that influence consumer perception of ice cream. From appearance to cooling effect during consumption, the microstructural elements including ice crystal, air cells, fat globules, and serum phase all govern consumer perception.

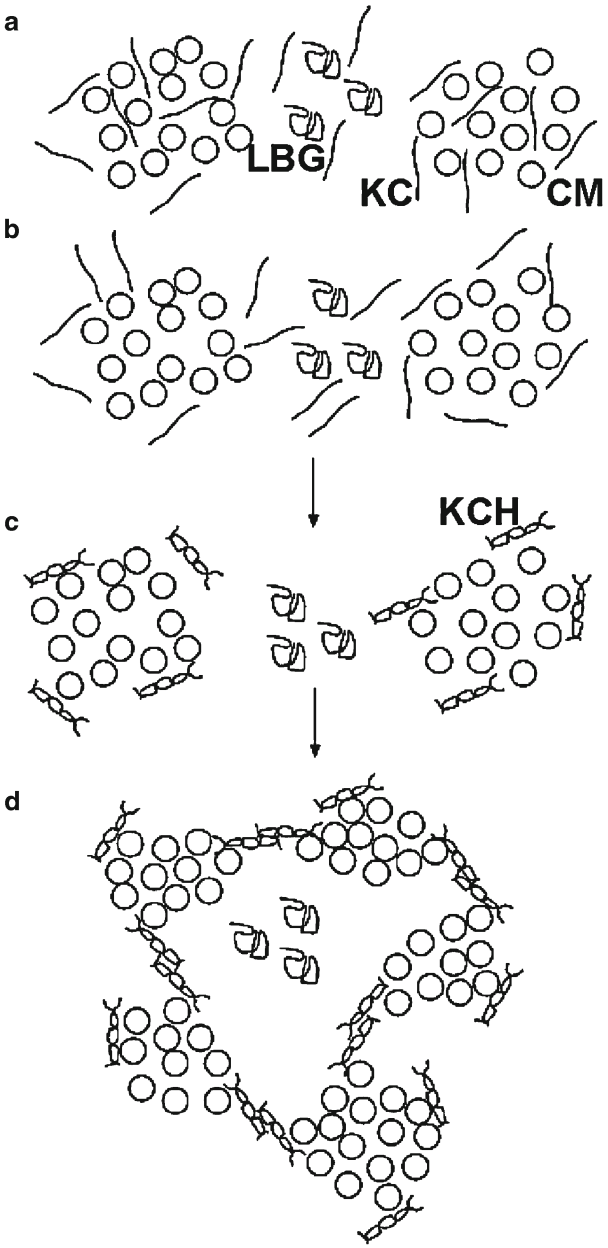

Fig. 11.14 Schematic diagram outlining the mechanism of stability of κ-carrageenan against phase separation between casein micelles (CM) and locust bean gum (LBG) (modified from Spagnuolo et al. 2005). (**a**) At high temperatures (i.e., during pasteurization) κ-carrageenan (KC) is in the random coil conformation and is found distributed within solution. Casein micelles have been concentrated via incompatibility with LBG. κ-Carrageenan may be trapped within these domains. (**b**) When the ratio of casein micelles:κ-carrageenan coils within the domains becomes

The discussion here will focus on the physical attributes of ice cream, whereas the sensory attributes of ice cream are discussed in Chap. 14.

Hardened ice cream is stored at cold temperatures (ideally below −20°C) to minimize changes to the microstructure, since these changes generally cause quality deterioration (as discussed in Chap. 12). For consumption, however, ice cream needs to be warmed up and as temperature goes up, the ice phase volume decreases according to the freezing point depression curve. Thus, the effects of increasing temperature on physical properties associated with melting (thermal diffusivity) are important, as are the melting properties, both in air and in the mouth.

Thermal Diffusivity

When the temperature of ice cream is changed, several changes occur that influence the microstructure. First, a change in temperature causes a change in specific heat of the serum phase, in part due to the change in temperature (gives a slight change in specific heat), but also because of a change in ice phase volume, which changes in order to retain phase volume equilibrium. Assuming the temperature changes are relatively slow (relative to heat transfer into the ice cream), ice phase volume changes according to the freeing point depression curve. Melting and refreezing cause changes in serum concentration, which changes specific heat of the serum phase. Further, when temperature goes up, ice melting removes energy (latent heat) from the environment, offsetting to some extent the increase in temperature, at least locally. In a sense, this change in ice content provides an insulation effect when ice cream is exposed to warm temperatures. When temperature is reduced, ice crystals refreeze in order to maintain phase volume equilibrium. Freezing releases latent heat, causing a local increase in temperature and again offsetting the lower temperature.

These changes in both serum phase and latent heat mean that the energy associated with changes in temperature of ice cream must be accounted for in an energy balance. Typically, this phenomenon is handled through a thermal property called thermal diffusivity, which accounts for both thermal conductivity and specific heat. Thermal diffusivity is defined as

$$\alpha = \frac{k}{\rho C_{\mathrm{p}}} \tag{11.1}$$

Fig. 11.14 (continued) unfavorable, there is an exclusion of κ-carrageenan via depletion flocculation and/or segregative interactions. (**c**) Once the temperature is lowered κ-carrageenan, now at the periphery of the domains, changes conformation to the helical form (KCH). (**d**) Interaction between κ-carrageenan helices and casein micelles at the periphery of the microdomains occurs and subsequent interaction between neighboring helices on adjacent domains stabilizes the domains against flocculation and coalescence and eventual separation

where k is the thermal conductivity (W m^{-1} K^{-1}), ρ is the density (kg m^{-3}), and C_p is the specific heat (J kg^{-1} K^{-1}).

Thermal diffusivity of ice cream during both heating and cooling was measured by Ben-Yoseph and Hartel (1999) in order to be able to model changes in ice crystal size distribution during storage. Their equations are given here as (11.2) for warming and (11.3) for cooling.

$$\alpha = -0.00003072 * T^3 - 0.0013486 * T^2 - 0.019787 * T - 0.064228 \tag{11.2}$$

$$\alpha = -0.00004243 * T^3 - 0.0016521 * T^2 - 0.024518 * T - 0.072711 \tag{11.3}$$

In both (11.2) and (11.3), T is temperature given in °C giving thermal diffusivity, α in cm^2 min^{-1}. Thermal diffusivity is lower during cooling due to the release of latent heat when ice refreezes.

It is unclear how widely variable thermal diffusivity is for different ice creams since this has not been studied (or published). Factors that would be expected to affect thermal diffusivity include overrun, air cell size distribution, amount of ice phase, and ice crystal size. Increasing both the amount and dispersion of air cells as well as the amount and dispersion of ice crystals would be expected to reduce thermal diffusivity, resulting in slower melting.

Meltdown Properties

Ice cream melting is important in two ways—melting in the mouth during consumption and meltdown related to storage at warm temperatures. Little work has been done to characterize melting of ice cream or frozen desserts on the sensory attributes during consumption, although some recent efforts along those lines will be discussed in the next section. More work has been done on standardized meltdown tests (see Chap. 14 for a description of the meltdown, or drip-through, test). The discussion here will focus on the effects of the various microstructural elements on those meltdown characteristics. Namely, each of the structures/phases discussed in the previous section influences how ice cream melts when left at elevated (e.g., room) temperature.

As heat penetrates into the ice cream and ice melts (removing latent heat), the water from melted ice must diffuse and mix with the more concentrated serum phase. This diluted, and less viscous, serum phase then drains through the remaining structures and through a screen on which the meltdown (drip-through) test is typically conducted. Some ice creams melt and flow completely through the screen, leaving only residue remaining (Fig. 11.15a), whereas other ice creams collapse

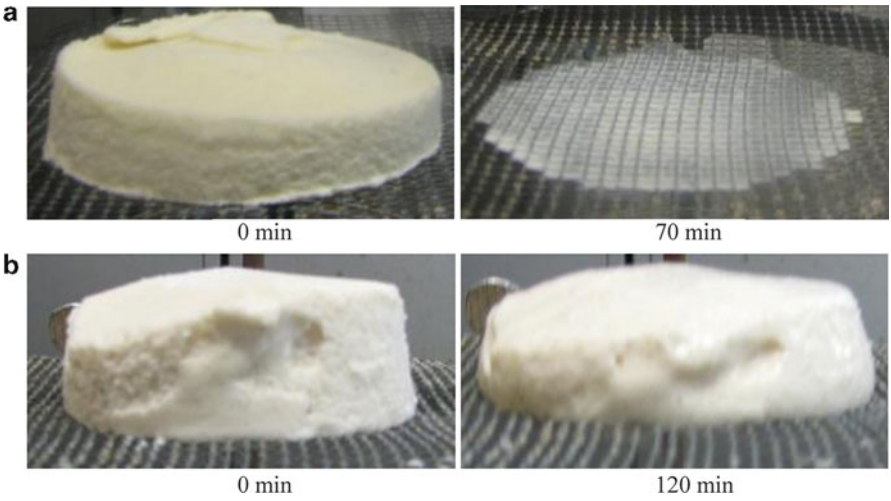

Fig. 11.15 Ice cream meltdown test. (**a**) Ice cream that completely melts through (70 min 22°C); (**b**) ice cream that remains standing even after complete meltdown (120 min at 22°C)

only slightly, leaving a nearly intact structure remaining on the screen (Fig. 11.15b). The amount of each structural element, their size and/or internal structure, and their level of interconnectedness in the melting ice cream influence the ability of the diluted serum to drain.

What is clear is that ice cream meltdown rates and characteristics are influenced by numerous factors (Hartel et al. 2003). For one, the ability of heat to penetrate into the ice cream (thermal diffusivity) affects the rate of meltdown (see section above). Higher overrun would be expected to decrease thermal diffusivity, providing an insulation effect, and thus, retard meltdown rates, as found by Sofjan and Hartel (2004). However, higher overrun also means there are more cells per unit volume of ice cream and as the mass collapses, these air cells will fall upon one another. Depending on how well these air cells are stabilized determines whether the mass collapses or retains its shape even after the ice has melted. Although one would expect that air cell size distribution would influence meltdown, no evidence of that has been published in the literature. Ice cream with larger air cells, given a constant overrun, might be expected to melt more quickly since the lamellar gap between bubbles would be on average larger than for the same ice cream with more smaller air cells.

It is thought that fat clusters are important structural components that impede drainage of melting serum phase. As expected, a higher extent of fat destabilization (generally characterized by more and larger clusters) has been seen to reduce meltdown rate (Muse and Hartel 2004), although exceptions to this behavior have been noted. Koxholt et al. (2001) studied the effect of fat globule size, created by varying homogenization pressure, on meltdown rates in ice cream. They also concluded that

meltdown rate is highly dependent on fat agglomerates in the unfrozen serum phase, but they also showed that slow meltdown is not necessarily correlated with high values of fat destabilization. They suggest that air bubbles are stabilized by individual fat droplets (or fat agglomerates), proteins, and emulsifiers at the interface, while the fat agglomerates required to effect meltdown rates act to link the structures together. They found a critical average fat globule/cluster size in ice cream above which meltdown was significantly retarded. Interestingly, in the ice creams studied, they found a critical average median size of only 0.85 μm, which was only slightly higher than the median size of fat droplets in the mix, 0.65 μm. Only the ice cream homogenized at the highest pressure (30/5 MPa) had mean droplet size smaller than 0.85 μm and thus, exhibited faster meltdown. Increasingly larger mean sizes had only slightly further effect of slowing meltdown rates. They concluded that homogenization pressures of at least 10 MPa are required to induce sufficient fat agglomeration for satisfactory meltdown, which is lower than the typical pressures of 15–20 MPa that are commonly used.

Numerous other factors also influence meltdown, which is probably why only approximate correlations with fat globule clusters have been observed. For one, the nature of the ice phase affects meltdown through both heat transfer and the process of melting and dispersing melted water into the serum phase. Larger ice crystals increase meltdown rate (Muse and Hartel 2004), possibly because larger ice crystals take longer to melt than smaller ones. Increasing ice phase volume generally increases the number and surface area of ice crystals; this might be expected to reduce the rate of meltdown.

Viscosity of the serum phase is another factor that significantly slows meltdown rate (Muse and Hartel 2004). More viscous serum phase, especially after being diluted by melted ice, will drain more slowly through the lamellar spaces between air cells, although it is possible that other rheological properties, including yield stress, will also influence drip-through. El-Nagar et al. (2002) found that increased inulin content caused an increase in serum viscosity and subsequent decrease in meltdown rate. The effects of high-pressure treatment on the rheology of ice cream mix and the resulting meltdown rates of ice creams produced from these mixes was studied by Huppertz et al. (2011). High-pressure treatment caused protein denaturation/disruption and formation of network of casein micelle fragments. This led to increased viscosity of the mix and reduced meltdown of the finished ice cream.

Although numerous studies have been conducted on melting ice cream, detailed knowledge of the specific steps that occur as ice melts and structures collapse is still quite limited. Methods to better characterize ice cream as it melts are needed. One such potential method, laser speckle technology, was used to follow the transient behavior as ice cream melted (Da Silva et al. 2010). Differences in the melting of ice crystals and subsequent dispersal of air bubbles between ice creams containing either glucose or fructose solids were evaluated and related to differences in freezing point (and thus, ice phase volume). Such techniques may allow ice cream scientists to better understand the complex forces applied as ice cream melts.

Rheological/Mechanical Properties

Hardness of ice cream is an important property since it directly affects scoopability. As any consumer who has tried to scoop ice cream out of a container directly taken from a very cold freezer knows, hardness is directly proportional to the temperature of the ice cream. The cold temperature indicates a high ice phase volume, which inhibits penetration of a spoon into the product. The consumer's solution is to warm the product, either by leaving the container out at room temperature for a brief time or by heating slightly in the microwave. Once the ice cream reaches a warmer temperature, sufficient ice has melted so that hardness has decreased to allow easier scooping. This example demonstrates both the influence of temperature, as influenced by ice phase volume, and the standard measurement method for hardness of ice cream—the penetration test. More formally, a penetrometer probe is pressed into the hardened ice cream and the amount of force required to penetrate a specified distance is typically used as a measure of hardness. Alternatively, the penetration distance for a given applied force may be used to characterize ice cream hardness. More recently, ice cream researchers have used mechanical measurements (small angle oscillatory shear) to quantify ice cream properties to correlate with sensory attributes.

Penetrometer Testing

Numerous factors have been found to influence hardness of ice cream, as measured by penetration tests (Hartel et al. 2003). As noted above, ice phase volume directly affects hardness, as found by Muse and Hartel (2004). Wilbey et al. (1998) found an exponential increase in hardness with calculated ice content, as controlled by the freezing point of the ice cream mix. Increased size of ice crystals has also been found to lead to harder ice cream (Sakurai et al. 1996; Muse and Hartel 2004). This effect is likely caused by accretion of ice crystals and the establishment of an ice crystal network as the ice crystals become larger (Goff et al. 1995).

Air content also affects hardness by providing an additional resistance to deformation. Numerous studies have found that increased overrun decreases the hardness of ice cream, as measured by force required to penetrate a specified distance (Goff et al. 1995; Wilbey et al. 1998; Muse and Hartel 2004). Wilbey et al. (1998) found hardness to decrease exponentially with increasing overrun. The presence of a gas filler within the continuous ice cream matrix allows easier penetration; thus, ice cream with higher overrun is more scoopable. Although one would also expect hardness to be affected by air cell size, Muse and Hartel (2004) did not find such a relationship, perhaps because of the small differences in air cell size in the study.

The nature of the fat phase also influences hardness of ice cream, although to a lesser extent than ice and air phases. Muse and Hartel (2004) found that hardness

increased with an increased extent of fat destabilization (larger fat clusters). Tharp et al. (1998) found a similar effect when polysorbate-80 was added to the mix since this emulsifier is widely known to enhance fat destabilization.

Another factor that affects hardness of ice cream is the nature of the serum phase, with higher viscosity leading to harder ice cream (Muse and Hartel 2004). Goff et al. (1995) found a similar relationship, with addition of stabilizer to ice cream mix increasing both apparent viscosity of the mix and hardness of the finished ice cream. In part, this effect was due to a slight increase in T_g of the serum phase, bringing it closer to the glassy state (harder) at storage temperature. High-pressure treatment of ice cream mix also led to increased apparent viscosity of the mix, mostly due to aggregation of proteins, which led to increased hardness of the finished ice cream (Lim et al. 2008).

Small Angle Oscillatory Measurements

In recent years, ice cream scientists have applied small-angle oscillatory shear technology to characterize the mechanical properties of ice cream. A sample of ice cream is exposed to a small-angle sinusoidal input (either shear or strain) and the response of the ice cream (either strain or shear, respectively) is recorded. The very low levels of shear or strain applied, within the linear viscoelastic region of the ice cream, mean the structures are not disrupted (as in the penetration test). Typically, storage (G') and loss (G'') moduli are used to characterize the elastic and viscous characteristics of the material, respectively. The ratio of loss modulus to storage module, or tan (δ), provides an index of liquid-to-solid like characteristics, with values of tan (δ) varying from close to zero for an elastic solid to above one for fluids.

The change in storage and loss moduli as the temperature of ice cream is increased is shown in Fig. 11.16 (Goff et al. 1995; Wildmoser et al. 2004; Granger et al. 2005). At low temperatures (<−10°C), G' is significantly greater than G'', indicating the solid-like nature of frozen ice cream. Harder ice creams have higher G' values at freezer storage temperatures. Higher G' values at these temperatures can result from the numerous factors affecting hardness, as discussed above. This includes increased ice phase volume, increased overrun, and the addition of stabilizer in the formulation (Goff et al. 1995). In this temperature range (below about −10°C), the physical attributes of ice cream are dominated by the ice phase (Wildmoser et al. 2004). The continued increase in G' as temperature decreases below −10°C is attributed to the slowly increasing ice phase volume, although each of the structural elements discussed above can influence hardness. Both processing and formulation influence the magnitudes and ratio of G' and G'' in this temperature range. For example, the low-temperature extrusion process for manufacturing ice cream resulted in lower G' and G'' values (by 10×) compared to traditional ice cream made by freezing and hardening (Wildmoser et al. 2004). This was attributed to the smaller ice crystals with reduced connectivity produced by the cold-extrusion process. Wildmoser et al. (2004) also found that increasing overrun caused G'' to decrease slightly in the temperature range below

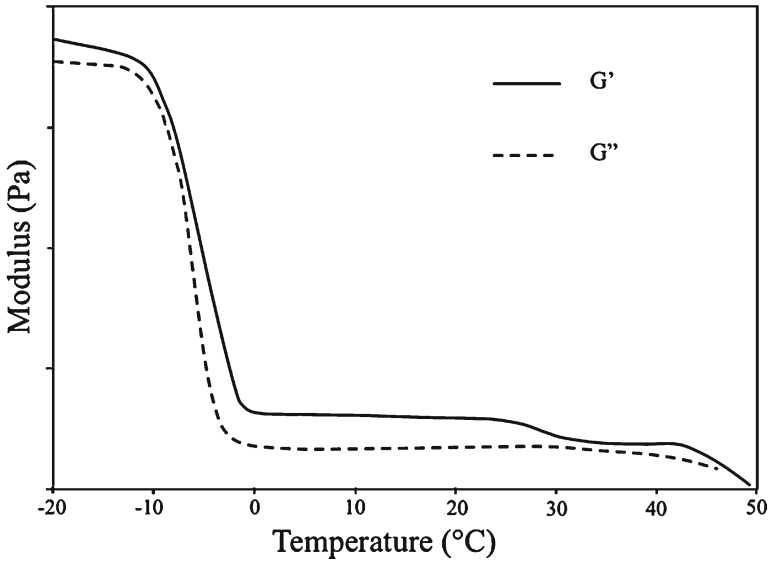

Fig. 11.16 Storage (G') and loss (G'') moduli of ice cream during thawing (highly schematic)

−10°C. This was attributed to the loss of connectivity between ice crystals due to the presence of air cells and resulted in improved scoopability of the ice cream.

In the temperature range between −10 and 0°C, both G' and G'' decrease precipitously as the ice crystals melt. The sharpness of this decrease has been correlated to the sensory characteristic of coldness of ice cream during consumption (Wildmoser et al. 2004; Eisner et al. 2005). A sharper decrease in G' suggests a colder ice cream. Interestingly, values of G'' are nearly the same order of magnitude as G' values in this temperature range, indicating a significant extent of ice crystal connectivity during melting (Wildmoser et al. 2004). This gives a peak in tan (δ) between −10 and 0°C as the ice melts, indicating an increase in the fluid-like characteristics during melting (Granger et al. 2005). Process and formulation factors also affect G' and G'' in this temperature range. The low-temperature extrusion process resulted in less steep decreases in both G' and G'' over this temperature range due to the smaller ice crystals and air cells compared to the traditional freezing and hardening process (Wildmoser et al. 2004). Overrun was also seen to affect the slope of G'' with temperature due to the effects of air on meltdown rates. Decreased overrun led to a sharper melting profile (Wildmoser et al. 2004) since air reduces the thermal diffusivity of the ice cream, slowing meltdown.

Once the ice has melted completely, the physical attributes of melted ice cream are dependent on the foam structure, fat globules, and proteins. Even in the temperature range above 0°C, ice cream behaves more like a solid than a liquid, with G' greater G'' due to the network formed by air cells and partially coalesced fat (Wildmoser et al. 2004). Higher G'' values in this region have been correlated with enhanced sensory scores for creaminess (Wildmoser et al. 2004). Increased G'' was

associated with increased overrun and the low-temperature extrusion process. G' is relatively flat between −2 and 15°C (Granger et al. 2005), but shows two distinct stages at higher temperatures where G' decreases. Between 15 and 30°C, there is a decrease in G' associated with melting of the fat. Between 35 and 50°C, a second decrease in G' is observed where dispersed air and the structures contained in the serum phase (proteins, stabilizers, etc.) govern melt rheology.

The nature of the fat phase also influences the changes in rheological properties of melted ice cream. Solid fat content and emulsifier type, for example, affect the extent of fat destabilization and nature of fat globule clustering (Granger et al. 2005; Mendez-Velasco and Goff 2011, 2012a). Interestingly, a strong correlation between G' of melted ice cream at 20°C and melting rate of ice cream has been found (Granger et al. 2005). Higher values of G' at 20°C correlated well with delayed meltdown. That is, ice creams that had higher G' values at 20°C took longer to melt, suggesting that the same structures that influence the solid-like characteristics of melted ice cream are also responsible for ice cream meltdown.

Conclusion

From a practical perspective, structure has its greatest effect on texture and stability. Since these are two of the greatest concerns of manufacturers and consumers alike, it is critically important to understand the structure of ice cream and the role of the various ingredients in creating and maintaining it. As examples, without an understanding of the formation of the unfrozen phase, the effects of changing sugar composition on hardness would not be comprehended. Without an understanding of the fat destabilization phenomenon, a change in emulsifier type on dryness during manufacture and meltdown stability would not be comprehended. Without an understanding of ice crystallization (and recrystallization, which will be discussed in Chap. 12), the effect of slow freezing or slow hardening on ice cream smoothness would not be comprehended. Thus it is critically important for manufacturers, ingredient suppliers, and equipment suppliers all to understand the principles of structure formation in ice cream.

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Chapter 12
Shelf Life

Ice Cream Storage and Distribution

Once ice cream leaves the storage freezer in the manufacturing plant, it typically goes through a shipping and handling system designed to deliver the product to the consumer with the highest possible quality. Packaged ice cream for consumer sale undergoes a series of transportation and storage events that lead to the consumer's home freezer, with the particular system being dependent on manufacturer, the distance for distribution, and the equipment and facilities available. The ice cream may go through a centralized warehouse for redistribution to the retail outlet, or it may be shipped directly from the manufacturing plant to the retail outlet.

Although more than two decades old, a study by Keeney (1992) is the most recent survey of US ice cream manufacturers to give typical time scales for storage at the different points during shipping and handling. Typically, the ice cream spent about 2 weeks in the warehouse freezer in the manufacturing plant (36% of respondents), although the times varied from 1 to over 4 weeks. The ice cream was then shipped to a distribution center where it spent over 4 weeks (64% of respondents) before being shipped to the retail outlet. Ice cream was typically purchased within 2 weeks (68% of respondents) of arrival at the retail outlet and used within 2 weeks by the consumer. Some (21%) of the respondents indicated that the ice cream spent over 4 weeks at the retail outlet prior to consumption. At each point in shipping and handling, temperatures are slightly different and temperature fluctuations may occur. Approximate times and storage temperatures during shipping and handling of ice cream are shown in Table 12.1.

Arguably the most important problem during storage is thermal abuse and its effect on ice crystals, air cells, and the other structural elements. Ice recrystallization, or the general increase in ice crystal size (Figs. 12.1, 12.2, and 12.3), is the leading cause of end of shelf life since consumers prefer ice cream with a smooth texture (although one ice cream manufacturer recommends salvaging ice cream that has become too coarse by making milk shakes out of it). The mechanisms by which ice crystals and air cells change, and the rate at which these changes occur, has been

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Table 12.1 Approximate distribution sequence for ice cream[a]

Step in storage and distribution system	Temperature (°C)	Duration
Storage freezer in manufacturing plant	−22°C	2 weeks
Vehicle from plant to central warehouse	−19°C	6 h
Storage freezer in central warehouse	−24°C	4 weeks
Vehicle from warehouse to retail outlet	−19°C	3 h
Storage in retail outlet (freezer and retail cabinet)	−15.6°C	1 week
Consumer vehicle from retail outlet to home	21.0°C	0.5 h
Consumer home freezer	−12.0°C	1 week

[a]Adapted from Keeney (1992) and Ben-Yoseph and Hartel (1998)

a topic of intense research for many years. Although much has been learned about these processes in recent years, the exact steps by which ice crystals and air cells change in size are still not clearly understood.

Mechanisms for End of Shelf Life

Shelf life of foods involves numerous considerations regarding changes in the microbial content, chemical nature (e.g., flavor), and physical attributes of the product. In many foods (i.e., milk, bread, cheese, etc.), microbial growth during storage is an important factor in determining shelf life. In frozen foods like ice cream, microbial growth does not occur to any significant extent (although microbial content is certainly a concern, as discussed in Chap. 13) so that physicochemical changes are generally considered most important for end of shelf life. However, if certain microorganisms are present in mix during freezing, they can survive the cold chain and cause problems during consumption. Some cold-adapted strains of microorganisms have recently been uncovered that increase the likelihood of their survival in ice cream during storage (Mastronicolis et al. 2011), making excellent sanitary practices even more important (see Chap. 13).

Numerous physicochemical changes can occur during shipping and handling, any one of which can seriously detract from product quality. Ice crystals and air cells change in size due to the changes in temperature, leading to coarse ice cream. Changes in ice cream volume can occur when ambient pressure changes, leading to shrinkage. Lactose crystallization can occur during storage, leading to a sandy texture. Product may also dry out during storage, particularly if opened, partially used, and returned to the freezer, leading to problems of gumminess and other textural defects. Further, flavors may change during storage, for example, oxidation of unsaturated fats due to the high oxygen content present in the foam phase or light-induced oxidation that might occur with clear packaging.

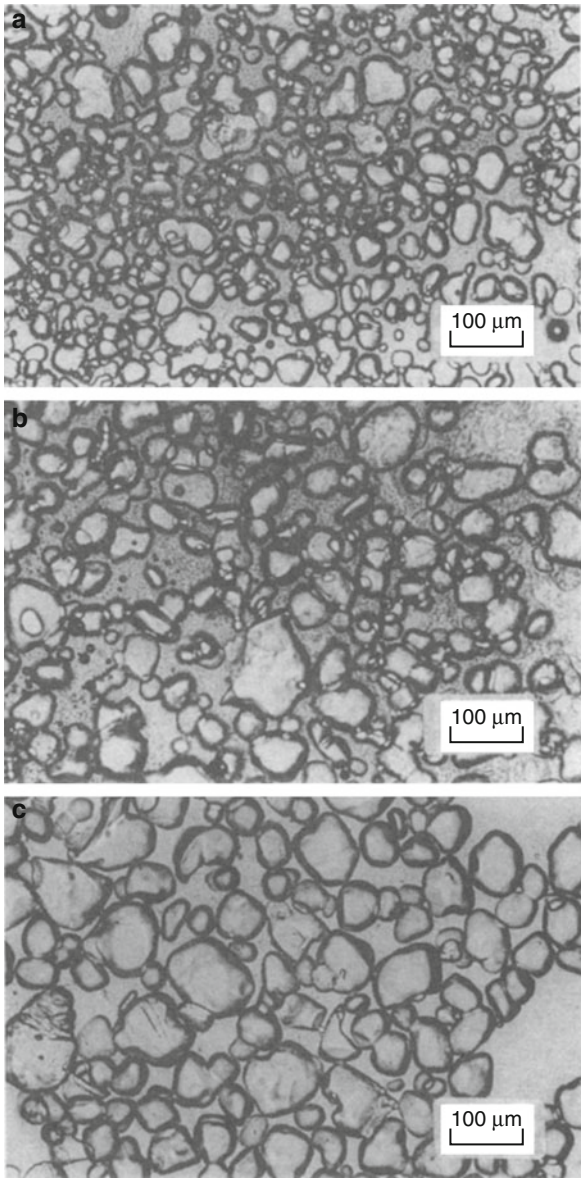

Fig. 12.1 Photomicrographs of ice crystals in ice cream held at −15°C. Mean ice crystal sizes, calculated as the equivalent circular diameter derived from the projected area of each crystal, were 35.8, 52.9, and 64.6 µm, respectively, on days 1 (**a**), 22 (**b**), and 200 (**c**). The ice cream formula was typical of high-quality product, viz., 12% milk fat, 11% MSNF, 16.5% sweetener, 0.2% stabilizer, and 0.1% emulsifier for a total solids content of 39.8%. Hardening was at −40°C for 24 h

Ice Recrystallization

During initial freezing and hardening, numerous small ice crystals are formed with size distribution depending on the conditions during processing and the mix composition, as discussed in Chap. 11. The aim is to make as many small crystals as possible to enhance smooth texture, but this also helps protect against changes in ice

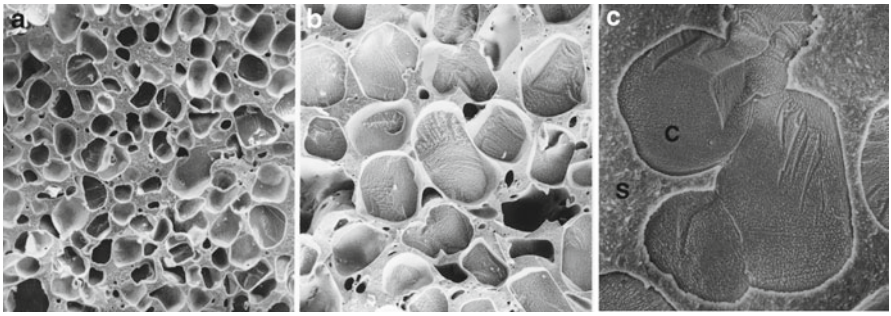

Fig. 12.2 Ice crystal structure in ice cream as viewed by cryo-scanning electron microscopy. (**a**) Ice cream after hardening, bar (in **c**) = 100 μm. (**b**) Ice cream as in **a** after heat shock, bar (in **c**) = 100 μm. (**c**) Ice crystals as in **b** showing accretion, bar = 25 μm. See Caldwell et al. (1992) for methodology

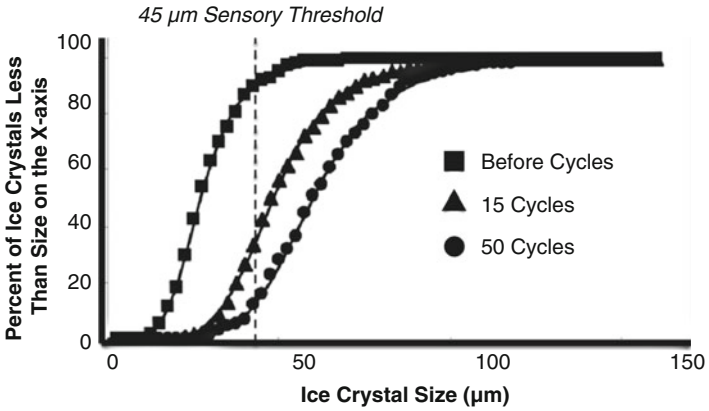

Fig. 12.3 Cumulative distribution of ice crystal sizes in fresh ice cream (before cycles) and after 15 and 50 temperature cycles (−10°C to −20°C, 12-h ramp, 12-h hold, for a total of a 48-h cycle). The sensory threshold of 45-μm average size is indicated, showing that whereas 80% of the distribution was smaller than this size in the uncycled ice cream, only 30 and 5% were smaller than this after 15 and 50 cycles, respectively

crystal size distribution during shelf life since a smaller starting point ensures a longer time to coarse texture. Unfortunately, all ice creams eventually become coarse as ice crystals grow during storage, especially at normal freezer temperatures. This grainy or icy feeling is accompanied by unusual coldness when the defect is pronounced. Factors that increase the probability that coarseness will develop include low solids, low freezing point, high drawing temperature, dull scraper blades, inadequate stabilizer, insufficient aging with some stabilizers, slow hardening, long storage time, and high and variable storage temperature. At common dipping cabinet temperature of −15°C (5°F), ice crystals increase significantly in size in just 35 days (Fig. 12.1). From a sensory standpoint, Wittinger and Smith (1986) showed that ice creams stored in a "supermarket-type frost/defrost freezer" with

temperature cycles between −9.4 and −15°C became detectably icy in 1–4 weeks and objectionably icy in 3–10 weeks, depending on the stabilizer and sweeteners used. Labuza and Fu (1998) show shelf life data for ice cream based on sensory iciness perception. In their data, ice cream stored at −10°C had a shelf life of about 1 week, whereas storage at −15.5°C (0°F) gave a shelf life of about 5 weeks. As storage temperature decreased to about −30°C, shelf life increased logarithmically (i.e., ln(shelf life) was inversely proportional to temperature).

Recrystallization may be defined as "any change in the number, size, shape, orientation, or perfection of crystals following completion of initial solidification" (Fennema et al. 1973). There are several types of recrystallization, or ripening, depending on conditions, but all of them lead to an overall increase in mean ice crystal size during storage. Over the course of storage, the increase in ice crystal size eventually reaches the point where the consumer realizes a coarse texture in the ice cream. At some threshold size, the ice cream is considered too coarse, and the product has surpassed its shelf life. No exact value for this critical threshold detection size has been put forth, although many people consider a mean size of about 50 μm to be an average limit. Not surprisingly, detection of ice crystals at 50 μm depends on numerous factors beyond the sensing abilities of the taster, including the presence of particulate inclusions, viscosity of the serum phase, fat content, and most likely, the extent of partial coalescence. Due to the complex nature of ice cream, an exhaustive sensory study of ice cream coarseness has not been done. Regardless, the primary aim of the storage and distribution system should be to minimize the extent of recrystallization to increase shelf life.

Mechanisms of Recrystallization

Several types of recrystallization occur that can lead to changes in ice crystal size over time. The thermodynamic driving force for recrystallization is either completion of phase equilibration (if not accomplished in initial freezing) or, more commonly, the slightly different melting points of very small and large crystals. The fine dispersion of small ice crystals in freshly made ice cream moves towards a lower energy state where surface free energy is minimized through melting of small crystals and growth of large ones.

One form of recrystallization, called irruptive recrystallization, occurs when the initial solidification does not result in the equilibrium ice phase volume. For example, when ice cream mix is dropped into liquid nitrogen, it cools and freezes so fast that only a portion of the maximal ice formation occurs before the limited molecular mobility of the glassy state prevents additional freezing. Said another way, the quench-cooled matrix has less ice than it would if thermal and phase equilibrium were attained. When that quenched product is warmed again above the glass transition temperature, T_g, molecular mobility increases enough that ice formation can then continue, releasing latent heat as additional ice forms. This additional change in ice crystal status after initial solidification is an example of irruptive recrystallization. Pelleted ice cream novelty products ("dots," formed by quenching drops of

mix in liquid nitrogen) need to be handled carefully because of this phenomenon. In fact, if a bead of quench-cooled ice cream is immediately placed into a home freezer, it will soon turn into a puddle of frozen ice cream. As the bead warms up to freezer temperature, the increased molecular mobility allows ice to form, which releases latent heat. At the relatively warmer temperatures of the home freezer, this heat of crystallization is sufficient to actually melt the bead, momentarily allowing it to flow (to form a puddle). Once irruptive crystallization is complete, however, the now liquid mass refreezes, leaving a puddle of frozen mix (K. Cook, unpublished). It is recommended that pelleted ice cream be maintained at temperatures as low as −35 to −40°C to maintain integrity of the individual pieces.

Recrystallization can and does occur in commercial ice cream at normal storage temperatures even when the equilibrium ice phase volume has been attained during initial solidification (which is generally the case in commercial ice cream manufacture). Although fluctuating temperatures help promote recrystallization, it occurs even when temperature is constant. The rate of recrystallization depends greatly on temperature and the extent of temperature fluctuations.

The fundamental driving force for the ripening of ice crystals is the slightly different equilibrium that exists for small (<10 μm) and large crystals. Thermodynamically, the Kelvin or Gibbs–Thomson equation defines the effect of curvature on equilibrium temperature (Hartel 1998, 2001).

$$\Delta T = T_{\infty} - T(r) = \frac{2\sigma T_{\infty}}{\rho(\Delta H_{\mathrm{f}})r}. \tag{12.1}$$

In (12.1) ΔT is the difference in melting temperature for a crystal of infinite size with a flat surface, T_{Δ}, and crystal of size r, $T(r)$, σ is the interfacial tension at the crystal surface, ρ is crystal density, and ΔH_{f} is the latent heat of fusion. Small crystals with a lower radius of curvature (sharply curved surface) have a slightly lower melting point than larger crystals with higher radius of curvature (flat surfaces).[1]

Thus, even at constant temperature, small crystals can melt while large crystals grow with rates that depend on radius of curvature and storage temperature. In effect, a dispersion of small ice crystals with a large total surface area is driven to reduce surface energy by minimizing surface area. This results in small crystals melting away and large crystals growing larger. The number of crystals and the total surface decrease accordingly.

The increase in average crystal size, $\overline{r}$, over time, t, during recrystallization is generally given as

$$\overline{r}^{n} = \overline{r}_{\mathrm{o}}^{n} + \frac{t}{\tau}, \tag{12.2}$$

[1] Radius of curvature is defined as the radius of a circle that fits within the surface curvature, meaning that a surface that is highly curved has a low radius of curvature.

where $\overline{r}_o$ is the initial size, n is the order of recrystallization, and τ is a time constant for recrystallization that depends on the rate. The parameter, n, depends on the mechanisms that apply to recrystallization (Lifshitz and Slyozov 1961; Hartel 1998, 2001). At long times, (12.2) can be transformed to give

$$\overline{r} = \overline{r}_o + Rt^{1/n}, \tag{12.3}$$

where R is a recrystallization rate (in units of size/time$^{1/n}$). Conditions that give higher R values have faster rate of coarsening. Since recrystallization at constant temperature means constant ice crystal phase volume, this increase in mean size leads to a corresponding decrease in the crystal number. The rate at which recrystallization occurs depends on the mechanisms involved. Several potential mechanisms can be pertinent during storage of ice cream. Phenomena that occur at constant temperature include Ostwald ripening, isomass rounding, and accretion. Fluctuating temperatures enhance these phenomena but also introduce another phenomenon called the melt–refreeze mechanism of recrystallization.

The process of a small ice crystal melting away as a large neighboring crystal grows according to (12.1) is called Ostwald ripening. As crystal size, r, decreases, the driving force, ΔT, for Ostwald ripening increases. For a crystal of 5-μm radius, ΔT is about 0.0095°C compared to a very large ice crystal (Hartel 2001). This is a small driving force, but over the time scales of ice cream storage can lead to significant changes in ice crystal size distribution. An example of a small crystal disappearing due to its proximity to a larger ice crystal can be seen in Fig. 12.4. Although the instability due to Ostwald ripening is the basis for recrystallization, other mechanisms of recrystallization are generally faster and have more effect on ice crystal size in ice cream during storage.

Many ice crystals in ice cream are irregular-block shaped, as seen in Figs. 12.1 and 12.2, meaning that some regions of the same crystal have different radii of curvature. The more pointed aspects, with lower radius of curvature, have a slightly lower melting point according to (12.1) than the flatter elements (higher radius of curvature) of that crystal. If that crystal was isolated in a constant temperature environment, eventually the regions with greater curvature would melt away and the flatter regions would grow accordingly. If constant ice phase volume were maintained at phase equilibrium, the crystal would undergo isomass rounding, which occurs rapidly at warm storage temperatures (Donhowe and Hartel 1996). Figure 12.5 documents the change in shape of an ice crystal undergoing rounding. The end result in a distribution of ice crystals in ice cream would be that the average crystal size increased at the same time as the circularity of the population increased.

In ice cream, ice crystals are extremely close together, most likely separated by <10 μm. If ice crystals average 30–40 μm and are separated by <10 μm, clearly neighboring crystals can influence each other. Specifically, the region between two ice crystals becomes a region of instability, leading to formation of a bridge or neck between the two crystals. Once a neck has formed between two crystals, this is a region of low radius of curvature (highly curved surface) and, according to (12.1),

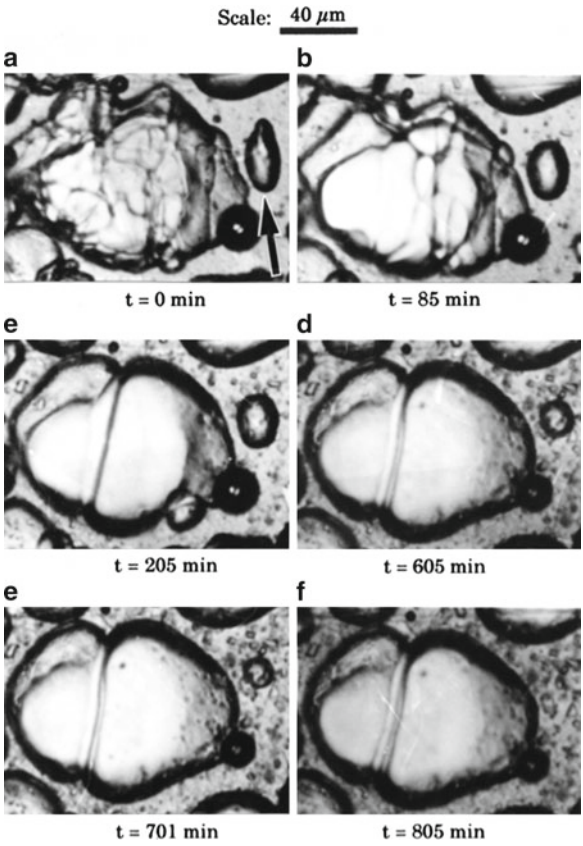

Fig. 12.4 Ostwald ripening of a small crystal (*arrow*) in proximity to a larger ice crystal during hold at −10 ± 0.01°C on a microscope stage (from Donhowe 1993; with permission from Hartel 1998)

is prone to recrystallization. This phenomenon is similar to that of sintering or coarsening of a distribution of crystals in air (as in snow packing) (Hobbs 1974). Accretion leads to joining of two smaller crystals to form a larger crystal, which over time is likely to undergo isomass rounding (Figs. 12.2 and 12.6). The process of accretion between two ice crystals is significantly faster than Ostwald ripening.

The changes in ice crystals due to these thermodynamic ripening phenomena occur at constant temperature, but are significantly enhanced by temperature fluctuations. Small crystals, with a slightly lower melting point, are more sensitive to temperature fluctuations than larger crystals. Once a small crystal disappears, it does not reappear (nucleation does not occur) and the remaining crystals all grow a little larger to incorporate the amount of ice needed to maintain the phase equilibrium. The disappearance of a small crystal due to melt–refreeze is shown in Fig. 12.7.

Temperature fluctuations during shipping and handling of ice cream may be associated with (1) changes in temperature of storage as the product moves from point to point in the chain, (2) heat shocks, where product is left at ambient (room) temperatures for extended periods of time, (3) normal cycling inherent in mechanical

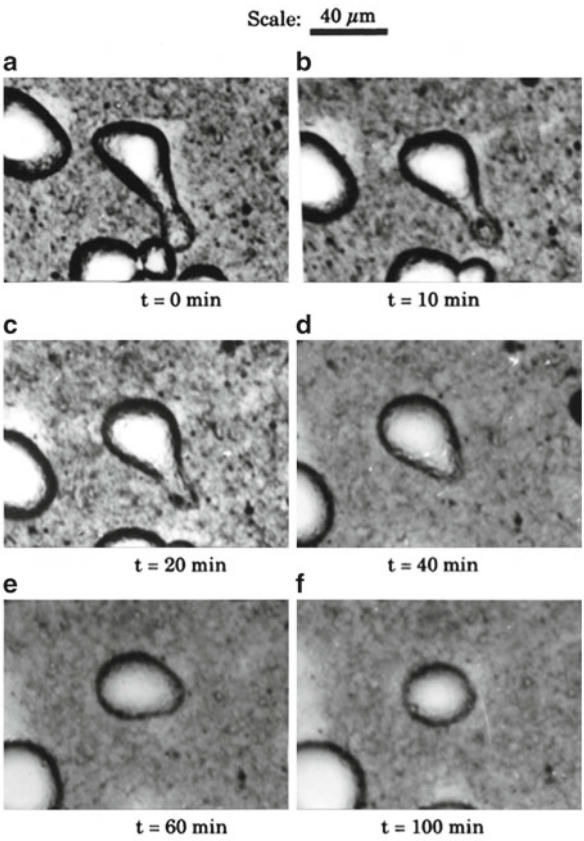

Fig. 12.5 Isomass rounding of ice crystals in ice cream held at −5 ± 0.01°C on a microscope slide (with permission from Donhowe and Hartel 1996)

refrigeration cycles, (4) temperature fluctuations due to automated defrost cycles, and (5) opening and closing of doors in freezers and storage cabinets. Each time the temperature changes, the amount of ice changes as the system tries to maintain the equilibrium freezing point relationship (see Chaps. 5, Mix Properties, and 6, Freezing Curve Calculations). Assuming that temperature fluctuations are relatively slow compared to the rate of heat transfer into the ice cream, an increase in temperature results in a decrease in the amount of ice in the product according to the freezing point depression curve. When the temperature goes back down again, the amount of ice increases accordingly (see Fig. 5.13 for the relationship between ice content and temperature). Even if cycling temperatures are faster than the time required to maintain thermal and phase equilibrium throughout an ice cream package, the increase and decrease in ice phase volume associated with temperature cycles causes melt–refreeze, especially near the surface of the container. Since ice cream distribution and storage involve thermal variations, it is no surprise that melt–refreeze is the main cause of coarsening of ice crystals in ice cream (Donhowe and Hartel 1996). However, recrystallization studies have traditionally been done on two-dimensional samples (or images of samples), either by photomicroscopy or by scanning electron

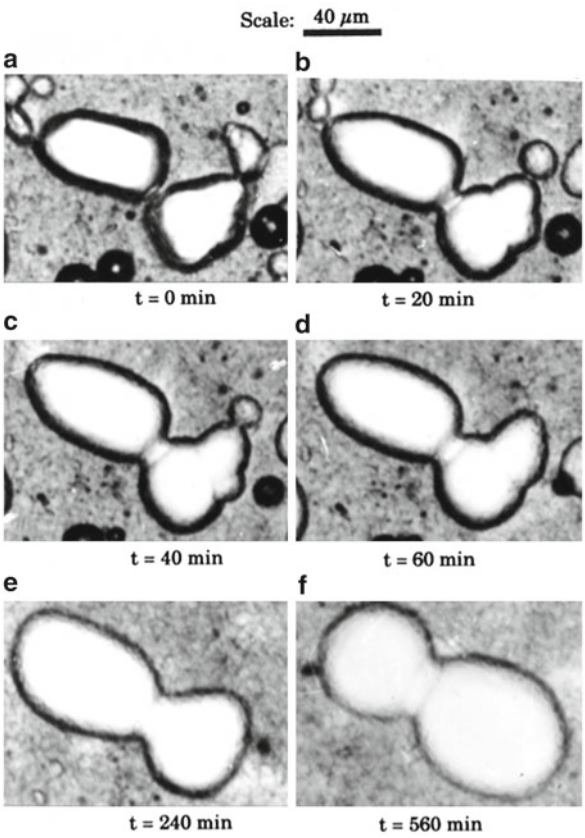

Fig. 12.6 Accretion of two ice crystals in ice cream while held at −5 ± 0.01°C on a microscope stage (with permission from Donhowe and Hartel 1996)

microscopy, rather than in situ in three dimensions. Recently, a study of ice crystal evolution during storage of ice cream used three-dimensional characterization of intact ice cream with X-ray tomography to confirm that the primary mechanism of ice recrystallization is indeed melt–refreeze (Pinzer et al. 2012). Interestingly, a similar phenomenon is thought to play a role in texture development in igneous rocks, as studied through a magma analog system (Mills et al. 2011).

Process and Storage Factors that Influence Ice Recrystallization

Numerous factors influence the rate of recrystallization, including the freezing and hardening processes, storage conditions, and ice cream composition (Hartel 1998). Since the average size and distribution of sizes influence recrystallization, the initial freezing and hardening steps can have considerable effect on shelf life due to recrystallization. Smaller initial starting size and narrower initial ice crystal distribution generally lead to longer shelf life, all else being constant, since the ice crystals must grow to a larger extent. Even though recrystallization is also dependent on initial ice

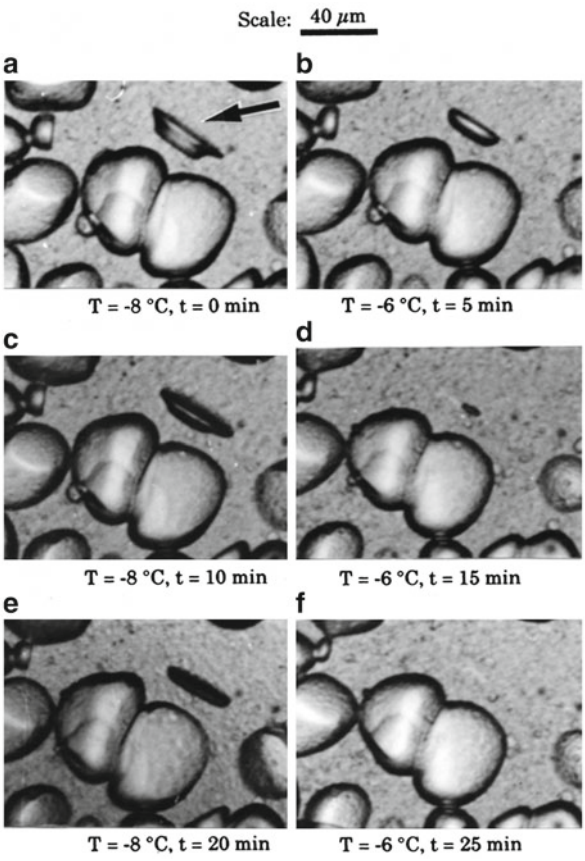

Fig. 12.7 Disappearance of a small ice crystal (*arrow*) in ice cream due to melt–refreeze while being held at −7±1°C on a microscope stage (with permission from Donhowe and Hartel 1996)

crystal size (Sutton et al. 1996), with smaller crystals exhibiting a faster recrystallization rate, there is an advantage to having small starting size (Fig. 12.8).

Recrystallization is also dependent on storage conditions, namely temperature and temperature fluctuations (Donhowe and Hartel 1996). The ideal storage temperature to reduce recrystallization would be below the glass transition temperature, T_g', as shown in Fig. 11.3 (Goff and Sahagian 1996; Roos 2010). Below T_g', the ice cream matrix (unfrozen phase) is in the glassy state, and the limited molecular mobility means that most reactions and processes, including recrystallization, occur very slowly. Since T_g' is below about −32°C for many commercial ice creams, storage at such low temperatures is not feasible. Normal storage temperatures (Table 12.1) are well above T_g', meaning that recrystallization can occur readily, especially at warmer temperatures. In fact, storage below about −25°C gives a sufficiently slow recrystallization rate to give extended shelf life. Even fluctuating temperatures do not increase recrystallization rate substantially at average temperatures below about −20°C, primarily because of the minimal amount of phase volume change associated with these low temperatures (as seen schematically in Fig. 11.2) (Donhowe and Hartel 1996). As storage temperature increases above

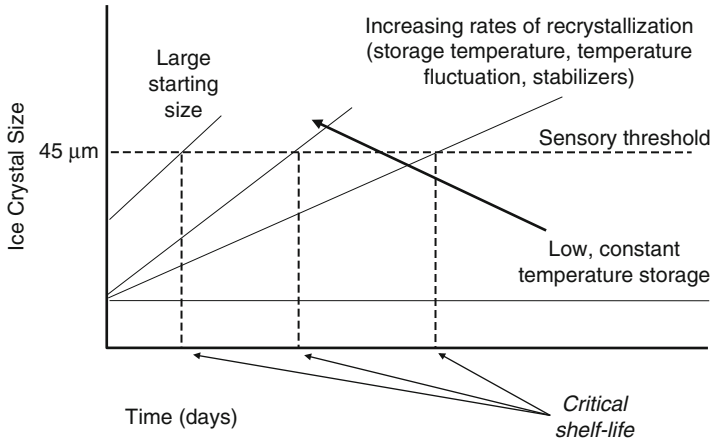

Fig. 12.8 The effect of rate of recrystallization on shelf life as determined by exceeding a threshold maximum average size for ice crystals for optimum smooth texture

about −15°C, the rate of recrystallization increases dramatically, especially with wide temperature fluctuations (Ben-Yoseph and Hartel 1998).

Clearly, colder storage temperatures are better for extended shelf life of frozen desserts, yet that goes against current trends for reducing costs and greenhouse gas emissions, both of which go up substantially as freezer temperatures go down. In fact, many frozen food manufacturers are investigating alternatives that decrease energy consumption and enhance sustainability, many of which are not in the best interests of high-quality ice cream. For example, manufacturers could potentially raise the temperature in their storage freezers slightly to reduce costs. According to Buyck et al. (2011), warehouse freezer temperatures could be raised from −29 to −26°C to save energy without sacrificing quality, but this is only aspect of the cold chain. Another option to conserve energy is to turn the refrigeration off during off-hours to reduce costs, despite the potential negative effects on ice cream quality. The slow rise in temperature when the refrigeration system is off is likely to cause considerable ice recrystallization and reduce shelf life of ice cream considerably, depending on the extent of warming. One approach being studied recently to offset the negative effects of refrigeration system interruptions (planned or otherwise) involves the use of phase-change materials within freezers (Oro et al. 2012). Panels filled with a phase-change material with appropriate temperature range (i.e., ammonium chloride, sodium nitrate) are placed either along the walls of the freezer or in tubes that fit over the evaporator tubes. When temperature goes above the melting point of the phase-change material (−15 to −18°C), whether due to door opening or power outage, the material begins to melt and provides a refrigeration effect to maintain cold temperatures. Results clearly show that freezer temperatures remain lower for longer times in the presence of these phase-change materials (Oro et al. 2012). Ice crystal size in ice cream stored in a freezer with these panels remained smaller when the power was shut off compared to the control (power off with no panels) (Gin and Farid 2010).

Compositional Factors that Influence Ice Recrystallization

Besides freezing and storage conditions, the manufacturer can control ice recrystallization through control of the composition of the ice cream. Among the formulation factors that provide control of recrystallization include fat content, the protein content, the sweetener system, and the stabilizer blend. Recently, other additives that have been found to reduce recrystallization rate include ice-structuring proteins (ISP) and propylene glycol monostearate (PGMS).

Milk fat content has been shown to influence development, or at least sensory perception, of coarseness during storage (Prindiville et al. 1999). The tendency for ice crystals to grow decreases in the following order: nonfat, low-fat, light, reduced fat, regular, premium, and superpremium ice creams. Fat globules are thought to mechanically obstruct growth of ice crystals in the ice cream matrix, slowing the rate of recrystallization. More importantly, perhaps, is that fat globules and partially coalesced clusters help lubricate the mouth. That is, higher fat content moderates consumer perception of coarseness due to larger ice crystals. Milk proteins also play a role in reducing rates of ice recrystallization, possibly through their water holding capacity but also in conjunction with polysaccharide stabilizers due to localized, microscopic phase separation (Regand and Goff 2002, 2003).

Sweeteners exhibit some control over recrystallization, either through their effect on freezing point temperature or on T_g' (Hartel 1998). Sweeteners that decreased T_g' (high-fructose corn syrup, etc.) increased recrystallization rate when studied at a set temperature, whereas sweeteners that increased T_g' decreased crystallization rate (Livney and Hartel 1997). This may not always be the case since Whelan et al. (2008) did not find a significant reduction in recrystallization rate when sucrose was replaced with trehalose to raise T_g'. They claimed that perhaps their storage temperature and heat shock conditions were far enough removed from T_g' that the effect of limiting molecular mobility was no longer important. Additives that change T_g' may also cause changes in freezing point depression and the equilibrium ice phase volume, which could potentially affect recrystallization rate (Hagiwara and Hartel 1996). In fact, ice phase volume was a reasonably good predictor of recrystallization rate in unstabilized ice creams, as seen in Fig. 12.9 (Hagiwara and Hartel 1996). In this study, ice crystal phase volume of unstabilized ice creams was changed either by changing the storage temperature or changing the freezing point (sweetener composition). As seen in Fig. 12.9 for unstabilized ice creams, there is an excellent correlation, with slower recrystallization rate at higher ice phase volume. Although T_g' also changed slightly with the difference in formulations, ice phase volume had the larger effect, related to the decrease in the amount and the mobility of liquid water molecules at high ice phase volume (Hagiwara and Hartel 1996). However, the presence of stabilizers confounded that relationship, suggesting that stabilizers exert a different, more specific, effect on recrystallization rate (Hartel 1998).

Stabilizers are added to ice cream specifically to control ice recrystallization (Bahramparvar and Tehrani 2011); however, our understanding of exactly how and when these hydrocolloids affect the ice crystals during storage is still the topic of considerable research. Numerous studies in the past few decades have shown that

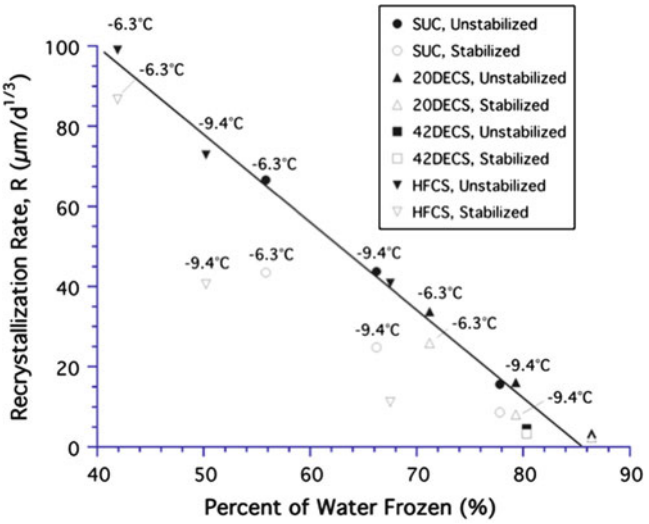

Fig. 12.9 Effect of calculated amount of water frozen on recrystallization rate of unstabilized and stabilized ice cream. The numbers above each symbol represent storage temperature of each sample. No number indicates storage at −15.2°C. Sweeteners are sucrose (SUC), 20 dextrose equivalent (DE) corn syrup (20DECS), 42DE CS, and high-fructose corn syrup (HFCS) (with permission from Hagiwara and Hartel 1996)

different stabilizers affect recrystallization rate to different extent and the effect may also depend on ice cream type and storage conditions (Hagiwara and Hartel 1996; Livney and Hartel 1997; Sutton and Wilcox 1998; Regand and Goff 2003; Soukoulis et al. 2008). Several of these earlier studies have suggested that it is either the water-binding properties or the effects on microviscosity of the stabilizer that leads to the recrystallization effect. Recent developments in nuclear magnetic resonance (NMR) techniques have enabled measurement of effective water diffusivity coefficients under conditions pertinent in the unfrozen phase of ice cream (Martin et al. 1999; Hagiwara et al. 2006; Herrera et al. 2007). For recrystallization to occur (refer to the mechanisms described above), water molecules have to move from regions of greater instability to regions of greater stability based on the Gibbs–Thomson equation (12.1). Thus, the rate of diffusion of water molecules should play an important role in determining recrystallization rate. In fact, this is seen in the temperature dependence of recrystallization, where temperatures below T_g', where molecular mobility is severely limited, effectively halt any changes in ice crystal distribution. Hagiwara et al. (2006) found that recrystallization rate in frozen sugar solutions correlated well with the self-diffusion coefficient of water in the unfrozen phase. Hagiwara et al. (2009) further showed that estimates of diffusion coefficients by molecular modeling gave values that matched well with the experimental data and correlated nicely with recrystallization rates. However, Herrera et al. (2007) suggested that the effects of stabilizers on ice recrystallization may be only partially explained by diffusion coefficients measured by NMR, leaving the possibility that some other mechanism(s) may still be important. Phase separation between hydrocolloid

and milk protein or gel formation may be other potential mechanisms of stabilizer activity (Regand and Goff 2002, 2003).

A relatively new ingredient that can be found in some frozen dessert products are ice-structuring proteins (ISP) (formerly, yet sometimes still, called antifreeze proteins) (Yu et al. 2010; Hassas-Roudsari and Goff 2012). Found primarily in cold-weather-adapted fish, insects, and plants, these proteins are thought to attach tightly to the ice crystal surface and thereby inhibit subsequent interchange of water molecules from crystal to crystal. The result is a severe reduction in ice recrystallization. For example, Regand and Goff (2006) studied ice recrystallization in ice cream with up to 0.00375% of ISP from winter wheat and found a reduction in recrystallization of up to 46%. Sensory analysis confirmed that reducing recrystallization rate during storage by addition of ISP maintained smoother ice cream. The possibilities of using ISP to advantage in frozen desserts go beyond preventing ice recrystallization in ice cream. One commercial product available in the United States utilizes ISP to provide a slower melting profile for quiescently frozen popsicles, due to ice crystal morphology changes and the formation of block-shaped crystals that can "stack" to form ice crystal networks (Crilly et al. 2008). The potential for ISP is high enough that researchers are "bioprospecting" for proteins with ice-structuring capabilities (Christner 2010). Others are creating synthetic antifreeze glycoprotein analogs with potential for tailoring specific properties (Budke et al. 2009).

New and novel ice-structuring peptides have recently been produced that can provide protection against ice recrystallization in ice cream. Peptides produced by enzymatic hydrolysis of gelatin have been found to inhibit ice recrystallization in ice cream (Damodaran 2007; Wang and Damodaran 2009). Mechanistically, they are thought to work in much the same way as natural ISP, through binding of a protein segment to the ice crystal interface, a hypothesis that was verified by molecular dynamics modeling (Kim et al. 2009). Future work in this area may lead to natural protein hydrolysates that can retard ice recrystallization.

Propylene glycol monostearate (PGMS), an emulsifier used in cake mixes and aerated toppings, has also been identified as an inhibitor of ice recrystallization at levels up to 0.5% (Barfod et al. 2005). The addition of 0.3% PGMS was found to decrease ice crystal size in ice cream both before and after heat shock (Aleong et al. 2008). PGMS caused a significant reduction in ice crystal size when it was added to ice cream mix that was frozen in a traditional scraped surface freezer, but the same effect was not seen in quiescently frozen systems. Since substantial ripening occurs within the barrel of the freezer (see Chap. 11), it is no surprise that PGMS significantly reduces ice crystal size exiting the freezer. Mixing and shearing must be necessary to distribute the PGMS across the ice crystal surfaces, influencing crystal growth and changing crystal shape. Then, after heat shocking the ice cream, the PGMS sample had significantly less ice recrystallization than the control without PGMS, again documenting the significant effect of PGMS on ice crystals.

Excellent ice cream can be made, and considerable amounts are made, without the use of added stabilizer. Because the proteins in milk and milk products can act as natural stabilizing materials, mixes containing specialty dairy ingredients, which may also be given a selected heat or other processing treatment, produce ice cream

of excellent quality. These ingredients are discussed in Chap. 3. High heat treatment of the ice cream mix also denatures whey proteins and allows them to interact with casein micelles to form aggregates, thereby increasing mix viscosity and reducing the need for stabilizers.

In summary, much effort and research has gone into finding methods to minimize ice recrystallization during storage of ice cream. These efforts have led to increased stability of ice cream during storage and distribution although further advances are most certain to extend shelf life even beyond current norms.

Air Coarsening

Air incorporation into ice cream frozen in a continuous freezer occurs either through a pre-whipping device or by injection of air under pressure directly into the freezing barrel (see Chap. 11). In a batch freezer, air is incorporated through the continual folding and mixing operation. During aeration, progressively smaller air bubbles are created by the shearing forces, particularly from the increasing ice phase volume during freezing (Chang and Hartel 2002a). Since these small, newly formed air bubbles are not stable, they are prone to collapse through a variety of mechanisms, including drainage, coalescence, and disproportionation (the equivalent of Ostwald ripening of ice crystals). These phenomena already begin to occur during hardening (Chang and Hartel 2002b), especially if the process is slow and temperatures remain elevated for an extended period of time (Chap. 11). The use of low-temperature extrusion (see Chap. 7) directly following the initial freezing and aeration step helps to prevent air bubbles from coming together in order to retain the smallest size distribution (Eisner et al. 2005).

Once the ice cream has been hardened, changes in air bubble size are greatly reduced due to the viscous matrix that surrounds the air bubbles (reduced drainage and contacts leading to coalescence) and the decreased molecular mobility of all components in the frozen product (decreased disproportionation). However, even in frozen ice cream during storage, there is still a driving force for air bubble coarsening. For air bubbles, the numbers decrease as their average size increase, similar to ice crystals in recrystallization. Again, if ice cream is held below its T_g', the rate of change in air bubble size should decrease virtually to zero (Roos 2010).

The driving force for changes in air bubble size is a difference in the Laplace pressure between two bubbles of different size. Laplace pressure of an air bubble, ΔP, is governed by interfacial tension, σ, and droplet size, r, according to (12.4).

$$\Delta P = \frac{2\sigma}{r}. \tag{12.4}$$

Smaller bubbles have higher Laplace pressure and thus, there is a driving force to reduce energy by increasing the size of bubbles through one of the mechanisms noted above.

Changes in air cell size in ice cream over time have not been studied nearly as extensively as the changes in ice crystal size, so much less is known about specific mechanisms. However, several studies have investigated changes in air bubble size in ice cream as a function of storage temperature. Similar to ice crystals, mean air bubble size tends to increase over time in storage, with a larger rate of growth at warmer temperatures. Recently, Pinzer et al. (2012), using X-ray tomography to nondestructively characterize air bubbles in ice cream, found that mean air bubble size increased rapidly at −5°C and much more slowly at −15°C. These results verified those of Chang and Hartel (2002b) and Sofjan and Hartel (2004), who used microscopy to assess changes in air bubble distributions.

Chang and Hartel (2002b) studied changes in air cell size using an optical microscopy method, backed by cryo-SEM images. Mean air bubble size increased with time to the one-third power during 4 months of storage at −15°C, similar to the time dependence of ice recrystallization (Donhowe and Hartel 1996). This similar time dependence suggests that the mechanisms that govern changes in air bubble size are the same as those that influence ice recrystallization, namely coalescence and disproportionation (Ostwald ripening). By holding samples on the microscope at different temperatures, the relative effects of the different mechanisms could be distinguished. When ice cream was held at −6°C, all three mechanisms (drainage, coalescence, and disproportionation) were observed to happen relatively quickly, causing significant changes in air bubble size distributions. However, at −15°C, drainage was eliminated due to the increase in serum viscosity and although both coalescence and disproportionation could still be observed, their rates were significantly reduced compared to −6°C. Further, at −15°C, some air bubbles did not completely coalesce into spheres but rather remained as partially coalesced, irregularly shaped air cells. The ice cream structure, namely ice crystals and viscous serum phase, at this storage temperature was sufficient to arrest complete coalescence of air bubbles.

Sofjan and Hartel (2004) investigated the effects of overrun on changes in air cell distribution during storage and found slightly different results from those of Chang and Hartel (2002b). At all overruns (80, 100 and 120%), mean air bubble size increased from draw to hardening, with the ice cream with lowest overrun showing the largest increase in mean air bubble size. Upon placing the samples into a cabinet at −10°C with normal refrigeration cycles, all ice creams showed a slight decrease in mean air bubble size for the first week or two, followed by a gradual increase through 9 weeks of storage. Under these warmer and abusive storage conditions, apparently disproportionation was more important than coalescence, at least initially, since the air bubble size distributions indicated an increasing population of both smaller and larger air bubbles during short-term storage.

Over time, arrested coalescence of air bubbles leads to a complete change in air cell distribution, which contributes to a change in texture and quality of ice cream during storage. Fresh ice cream is properly considered a foam, with discrete air

bubbles easily distinguished from each other. During storage, arrested coalescence of these discrete air bubbles leads to channel formation so that stored ice cream becomes more like a sponge, with interconnected air cells (Fig. 12.10). These changes cause significant changes in meltdown and eating characteristics of aged ice cream, lead to enhanced crumbliness in body, especially during scooping where friability is increased due to cracking of the texture through the channels, and may also promote shrinkage, as will be discussed in the next section.

Recent efforts to control air bubble size distribution in ice cream have focused on the use of hydrophobins, proteins produced by filamentous fungi (Linder 2009). Due to the high surface activity at air–water interfaces, hydrophobin appears to have potential to inhibit changes in air cell size during ice cream hardening and storage (Crilly et al. 2008). The potential use of hydrophobins to create "air-filled emulsions" to reduce fat content in emulsion-based foods has also been proposed (Le Reverend et al. 2010).

Shrinkage

Another potential problem that occurs during storage of ice cream is shrinkage. This appears as the ice cream pulling away from the walls of the container (Fig. 12.11). The exact mechanisms of this problem have not been completely understood, although the defect occurs most often when ice cream is transported between regions of different pressure (as when ice cream is transported over mountains). The change in pressure associated with changes in elevation causes expansion and contraction of the air cells, which can lead to shrinkage.

Shrinkage results from a loss of discrete air bubbles as they coalesce and begin to form continuous channels, eventually leading to collapse of the product itself into the channels (Turan et al. 1999). Weakness of the air cell lamellae and large changes in pressure on the air cells are responsible for this defect. Contributing factors can be high overrun, low solids, low protein (or insufficient foamability in the protein that is present), and changes in external pressure (Dubey and White 1997). Shrinkage tends to occur most often after the ice cream experiences a significant decrease in pressure, as when ice cream is shipped across mountains or transported by plane, which first causes a volume expansion. Fluctuations of temperature accentuate the defect by allowing supporting structure of ice to melt and refreeze, causing pressures on air cells to change. The physical effect of freezing to unusually low temperature, especially hardening with dry ice, can cause shrinkage.

The extent of air channeling, and hence a measure of ice cream susceptibility to collapse and shrinkage, can be measured by determining the response in volume of the ice cream to pressure changes. The volume of discrete bubbles correlates directly to pressure changes whereas the volume of air channels will not (Turan and Bee 1999).

According to the ideal gas law, the size (volume) of an air bubble is related to the external temperature and pressure, assuming the volume is free to change.

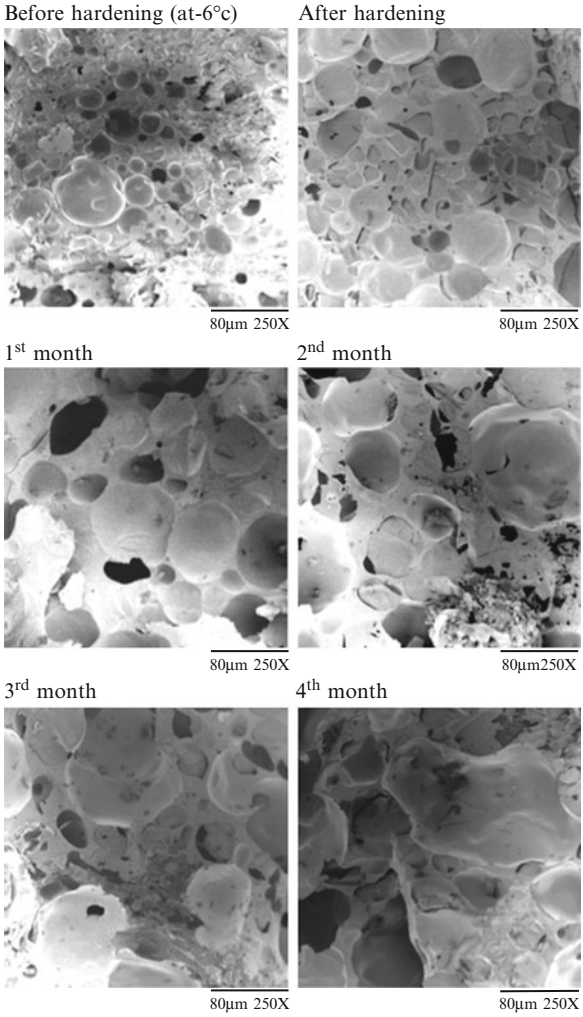

Fig. 12.10 Change in ice cream structure, as measured by SEM, during 4 months of storage at −15°C (with permission from Chang and Hartel 2002b)

As temperature is decreased, at constant pressure, the volume of an air bubble will decrease. As pressure is increased, at constant temperature, the air bubble should also contract. For example, when ice cream exits the draw of a continuous freezer, pressure is reduced (pressure within the freezer is higher than atmospheric pressure) and all of the air bubbles should expand slightly. At this point, though, the viscosity of the ice cream is sufficiently low that this expansion can easily be accommodated by the surrounding matrix, and the air bubbles approach an equilibrium at atmospheric pressure. Cartons of ice cream are filled to their volume, and consequently final weight, at this point and any changes in volume during later storage and distribution may lead to undesirable changes in the appearance of the ice cream. During hardening, the volume reduction in the air phase is offset by the volume expansion of the ice phase. After hardening, when

Fig. 12.11 Shrinkage in ice cream

the surrounding matrix has stiffened considerably, changes in pressure (or temperature) can lead to changes in the forces between the air cells and the surrounding matrix. Expansion or shrinkage, depending on the conditions, may be the result.

Goff et al. (1995) reported on the effects of vacuum storage on expansion and shrinkage of ice cream. Containers of ice cream at −16°C were exposed to reduced pressure (200 mm Hg) for 3 h and then stored at atmospheric pressure for 6 days at −16°C. Volume changes were measured 3 h after release of vacuum and again at the end of 6 days of storage. Expansion of the ice cream was observed after the vacuum storage, in accordance with the ideal gas law. However, after 6 days of normal storage those same ice creams exhibited shrinkage. In all cases, ice creams made with higher overrun had the greatest expansion and subsequent contraction. At −16°C, the unfrozen matrix must still be sufficiently pliable that a change in atmospheric pressure can cause a change in volume of the ice cream. Interestingly, although the period of vacuum exposure caused expansion, the ultimate result when pressure was brought back to atmospheric was shrinkage of the ice cream. This suggests that membranes of the air bubbles expanded initially, and the expansion must have been sufficient to rupture some of the bubbles and allow release of air from the structure when the pressure was returned to normal. Goff et al. (1995) related this to the nature of the interface between the air bubble and the unfrozen serum. They suggested that components like proteins, stabilizers, and emulsifiers play an important role in determining the viscoelasticity of this interface and subsequent changes in ice cream volume during storage under variable pressures.

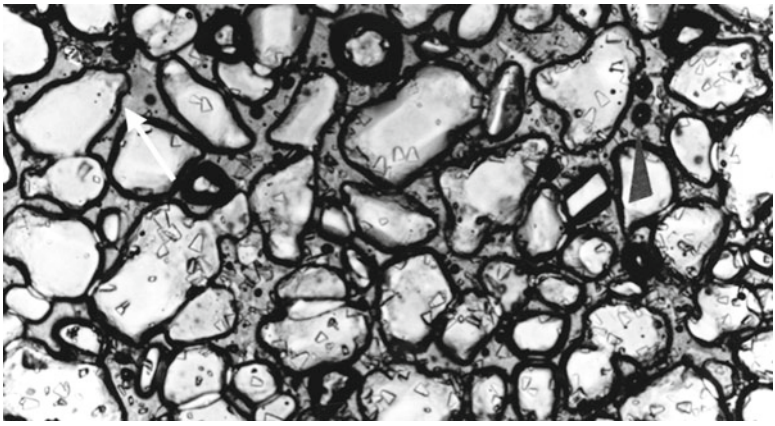

Fig. 12.12 Lactose crystals visible by light microscopy in ice cream stored at −10°C (with permission from Livney et al. 1995)

Lactose Crystallization and Sandiness

Sandy texture is one of the most objectionable defects in a frozen dessert. The gritty mouthfeel results from crystallization of lactose from the concentrated syrup within the frozen foam. Lactose crystals (Figs. 12.12 and 12.13) can be differentiated from ice crystals in the mouth by their comparatively slow rate of dissolution. Because of this slow dissolution, when lactose crystals exceed about 15 μm in size, they can be detected in the mouth (as compared to 50 μm for ice crystals). Nickerson (1956) reported on the range of factors that influence lactose crystallization in ice cream.

At the low temperatures of storage of ice cream, the lactose dissolved in the unfrozen water is in the supersaturated state yet far enough from T_g' that it is prone to crystallize (Fig. 12.14). Lactose crystallization occurs most readily when ice cream contains milk solids-not-fat levels over about 16% and is stored at temperatures from −10 to −15°C (Livney et al. 1995). This temperature range represents an intermediate state between two factors that affect lactose crystallization. At higher temperatures, the supersaturation of lactose is decreased (greater solubility at higher temperatures), and at lower temperatures, molecular mobility limits lactose crystallization as the system approaches T_g'. Hand packing is also known to promote lactose crystallization since agitation tends to promote nuclei formation. Addition of certain dry ingredients, such as fruits and nuts, may also promote sandiness.

Prevention of sandiness involves controlling (reducing if necessary) the lactose content of the mix, dividing the air cells into very small units, and minimizing storage time and fluctuations of temperature. Stabilizers also help to inhibit lactose crystallization. Low temperature further concentrates the lactose but at the same time promotes high viscosity in the unfrozen phase (as do stabilizers), which inhibits the nucleation/crystallization processes.

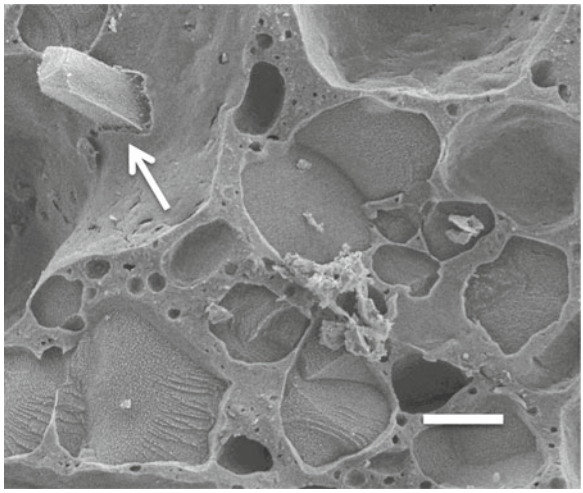

Fig. 12.13 Lactose crystal (*arrow*) protruding an air bubble, as seen in sandy ice cream by cryo-scanning electron microscopy. Bar = 50 μm

Gumminess

Over time, some ice cream can develop a gummy texture, being sticky or even stringy when scooped. Gumminess is unattractive in appearance and texture. The primary causes of gumminess in ice cream after hardening include the use of high levels of corn syrup and use of too much or poor quality stabilizer, while the principal cause of gumminess development during storage is loss of moisture in the storage freezer. Soukoulis et al. (2008) found that sensory perception of gumminess in ice cream made with different hydrocolloids was predominantly found in those products made with guar gum, regardless of time of storage. The perception of gumminess was also moderated by increased overrun.

During storage, gumminess is often found in ice cream cartons at home that have been opened, partially eaten, and returned to the freezer for too long, or in scooping shops where a large surface area of partially scooped ice cream is exposed to the storage freezer environment. In these cases, moisture loss from the surface is due to sublimation of ice to vapor, which then leaves a gummy layer of ice cream, particularly at the edges of the ice cream against the container where moisture loss is more prominent. This defect can be mitigated by maintaining the surface of the ice cream covered to as great an extent as possible. In scooping operations, a plastic lid that can be dropped down onto the surface of the ice cream in the tub at night can help reduce surface sublimation. At home, a layer of plastic wrap on the surface could also help, although often gumminess appears when the product has simply been kept too long.

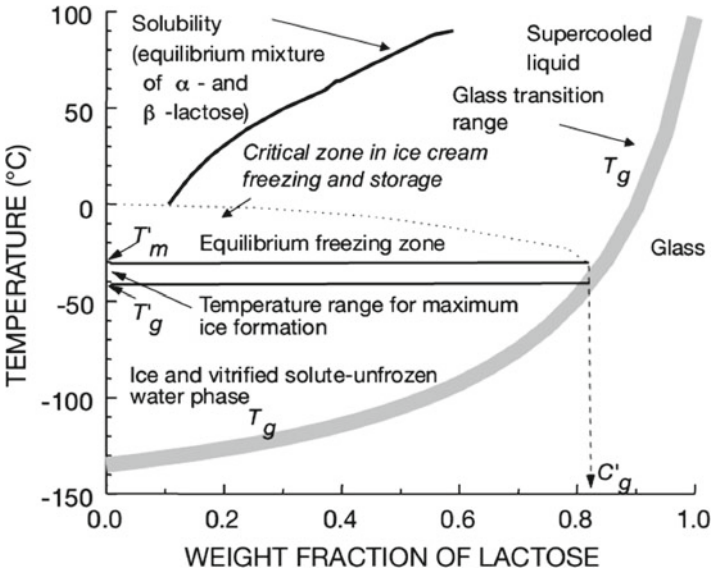

Fig. 12.14 State diagram for lactose (Roos 2010; reprinted, with permission, from the Annual Review of Food Science and Technology, Volume 1 © 2010, by Annual Reviews www.annualreviews.org)

Flavor

Flavor changes can occur during storage of ice cream although flavor loss is rare and typically not the first indicator for end of shelf life. An example might be the development of an oxidized flavor due to lipid oxidation in products that have consumer windows and are stored under fluorescent lights.

Conclusion

From the discussion present in this chapter, it should be obvious that shelf life is totally dependent on temperature, and the limitations of shelf life are mostly related to ice recrystallization or other structural rearrangements that lead to structural or textural defects. Microorganisms do not grow at freezer temperatures, enzymatic reactions occur only very slowly, and flavor changes are rare; therefore in the case of ice cream, the "end" of shelf life is usually a textural consideration. It is common practice in many manufactured foods to put "best before" dates on packaged products; these are often very accurate. In the case of ice cream, the shelf life can range from many months at −30°C to a few days at −14°C before changes would begin to become noticeable.

Therefore "best before" dates in the case of ice cream are quite arbitrary and mostly meaningless. What is critically important is for the manufacturers to build into their products some resilience to the rigors of heat shock and temperature abuse, so that shelf life remains sufficiently long to get product through the distribution network and when product is warmed to eating temperatures, as in scooping cabinets. This implies attention to freezing point depression and the use of good stabilizing agents in the formulation, rapid freezing and rapid hardening in well-designed and maintained equipment, and a very reliable cold chain from point of manufacture to point of consumption. Retailers and consumers should also understand that ice cream is unlike most other frozen foods—it is eaten frozen and therefore ice crystal size is critical for smooth texture, and to maintain small ice crystal size, temperature control is vital.

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Chapter 13
Cleaning and Sanitizing for Microbiological Quality and Safety

Introduction

Consumer confidence in the microbiological quality and safety of frozen desserts is one of the greatest assets of an ice cream-producing firm and of the food industry in general. Flavor and textural quality of ice cream are extremely important to the consumer and are often the factors affecting purchasing decisions (e.g., superpremium purchases). These quality attributes are influenced by composition, ingredients, processing, and handling. Flavor quality can be compromised due to the selection of inferior ingredients. Composition, chiefly fat and air content, affects the perceived richness and textural quality in the product. Textural quality can deteriorate, chiefly as a result of ice crystal growth, due to improper storage and handling of the frozen products. While all of these detract from the pleasure of consumption of the product, a compromise of microbiological quality can result in illness, and this has to be avoided at all cost. Flavor and textural quality can vary widely, but there cannot be any compromise in microbiological quality. Ice cream is very unique compared to other dairy products due to the considerable amount of processing and ingredient addition that is done after pasteurization. Thus the ice cream industry needs to be especially concerned about product safety due to the susceptibility to contamination from post-pasteurization handling. The only control of bacterial contamination post-pasteurization is through quality flavoring ingredients and sanitation and hygiene.

Factors that contribute to the microbiological quality and safety of frozen desserts include (1) ingredients of unquestionably high microbiological quality, especially those that are added post-pasteurization (flavors, colors and inclusions); (2) proper mix pasteurization methods, as pasteurization is our most critical biological control point in the control of organisms that might arise from raw ingredients; (3) complete physical separation of raw and processed products to eliminate sources of cross contamination; (4) maintenance of low temperature of mixes post-pasteurization to prevent growth of bacteria; (5) immaculate cleanliness and effective sanitization procedures to prevent post-pasteurization contamination, especially in light of

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the amount of post-pasteurization processing that occurs; (6) excellent equipment that is able to be properly cleaned; (7) clean, healthy employees who are well trained and have a conscientious attitude; and (8) a sanitary processing environment conducive to the production of safe food products.

The ice cream industry very effectively uses two measures of microbial quality in finished products, as does most of the dairy industry, viz., the standard plate count (SPC) (or aerobic plate count (APC)), and the coliform count (or *Enterobacteriaceae* count), for both products and the processing equipment and environment through surface contact (e.g., swab) tests. These are both very good indicators of microbial hygiene, as will be discussed below. Test methods are described in Chap. 14. Although the frozen storage, distribution, and consumption of ice cream and related products relieve the manufacturer of worry about microbial growth or spoilage of the finished product during its shelf life, it does not eliminate the risk of transmission of pathogenic microorganisms or toxins via frozen desserts. Several small and one very large outbreaks of foodborne illness have been associated with ice cream and related products, and many millions of dollars have been spent on recalls of product due to pathogenic contaminations. No pathogens survive pasteurization. The vast majority of pathogenic-contaminant issues are associated either with cross contaminations with raw ingredients or environmental contaminations from unsanitary conditions. It is not possible to provide high-quality frozen desserts for consumers unless it is possible to remove soil and microorganisms from the surfaces that touch the ingredients and the products that ultimately go into the consumer package. Therefore, it is important that cleaning and sanitizing in the context of microbiological quality and safety of frozen desserts be discussed. Readers are referred to Marth and Steele (2001), *Applied Dairy Microbiology*, or books such as Jay et al. (2005), *Modern Food Microbiology*, for general knowledge on foodborne microorganisms, their growth, and control.

Planning for Product Safety

No frozen desserts manufacturer should be without a plan to manage product quality and safety. The recommended elements of such a plan are embodied in a system known in the food industry as Total Quality Management (TQM):

1. Top management is committed to the TQM goals, objectives, and action plans.
2. The recorded management structure shows clear lines of authority and responsibility.
3. Specifications are written for ingredients, packaging materials, supplies, and equipment with procedures for receiving, inspecting, accepting, and rejecting each. Certificates of approval or compliance may be required of suppliers, and, if so, a system of checking should exist.
4. Current good manufacturing practices are applied (Source: US Code of Federal Regulations, Title 21, Part 110).

5. Manufacturing procedures and quality standards exist for each product.
6. Analytical methods for each product are selected and recorded.
7. Standards exist for performance of equipment and for maintenance schedules.
8. There is a hazard analysis critical control points (HAACP) plan for each product type and processing system.
9. Procedures are written for sanitation and pest control within and outside the plant.
10. There is a product traceability, recall, and consumer response plan.
11. Plans exist for audits by the firm and by outside professionals.
12. Training is supplied for employees.

The hazard analysis critical control points (HACCP) program to ensure the safety of finished processed foods has been adopted by dairy and food manufacturers globally and has become the minimum operational standard for many regulators or even retail-chain purchasers of ice cream. HACCP represents an approach for the management of biological, chemical, and physical hazards that could affect food safety. It shifts the focus away from costly, and many times inconclusive, end-product testing to more rigorous and scientific management of food processing activities. The procedure calls for the processing steps of every product to be completely documented in flow diagrams. Potential hazards are identified; for example, points are examined at which the lethal pasteurization process could fail or microorganisms could enter the product after the lethal process is completed (biological hazards), sanitizer might inadvertently get into product (chemical hazard), or a bolt from a piece of equipment could get into product (physical hazard). Once all hazards are identified, critical control points in production of a food product, those steps where hazards can be eliminated, are identified and monitored. The method of documentation that these controls have been exercised on each lot of product is then described. Follow-up to assure continued use of the HACCP plan is vital. HACCP systems are unique for each establishment and specific food product within that establishment. HACCP systems for dairy products are thoroughly described in Jooste and Anelich (2008) and Fernandes (2009).

The seven principles of HACCP are as follows: (1) conduct a hazard analysis, (2) identify critical control points, (3) establish control limits for each control point, (4) establish monitoring procedures, (5) establish corrective actions, (6) establish record keeping procedures, and (7) establish record verification procedures. Prerequisite programs for effective HACCP operation include premises; transportation, receiving, and storage; equipment; personnel; sanitation and pest control; and recall.

The International Dairy Foods Association (IDFA), Washington, has developed training programs and computer software that outlines basic sanitation, good manufacturing practices, and preventative management of product safety under HACCP. The software generates flow diagrams based on inputs of information on materials and operations for each product. It then assists in identifying critical control points in each model program (details available from their website). The Ice Cream Alliance in the UK likewise has available much information pertaining to the implementation of HACCP programs in ice cream operations.

Additionally, IDFA makes available planning guidelines and related information for inspections by the Food and Drug Administration (FDA), the Environmental Protection Agency (EPA), and the Occupational Safety and Health Administration (OSHA).

The following are several ways that managers can demonstrate commitment to HACCP programs: (1) allocate time and money for program development and utilization, (2) require and use regular reports on progress of the program, (3) reinforce the importance of HACCP by personally opening meetings and training sessions, (4) always adhere to the recommended practices when appearing in the plant, and (5) define and enforce consequences of not adhering to the policies and practices of HACCP.

Despite the importance of HACCP in shifting analyses away from end-product testing, a certain amount of testing is still required. The data from end-product tests serve to protect the firm against claims for variance from the expected and required qualities if those data show the product to be within specifications. They can serve as references to guide in planning future production operations. Some firms err greatly by spending money for tests then not using the data for planning to improve efficiency, quality, safety, economy, and, ultimately, profit.

The chance that food might be used as a vehicle of terrorist activity against a state or nation was recognized in the United States in the form of the Public Health Security and Bioterrorism Act of 2002. Suppliers in foreign countries must register with the Secretary of Health and Human Services and must give prior notice of when shipments of food will arrive at US ports. Furthermore, a chain of distribution records must be maintained throughout the food industry that reveals from whom the food was directly received and to whom it was directly delivered. The IDFA in Washington has prepared a guidance document to help dairy processors deal with issues of biosecurity in dealing with a deliberate act of tampering. Considerations include (1) Incoming materials: (a) milk tankers, (b) other ingredients, and (c) security in the receiving bay; (2) General plant security: (a) plant perimeter and interior (b) processing areas; (3) Personnel: (a) employee access and (b) visitors and vendors/general surveillance; (4) Distribution: (a) final product distribution; (5) Crisis planning: (a) authorities (Vasavada 2004).

In addition to quality, the whole area of risk management can be viewed holistically and scientifically. Operational Risk Management (ORM) is a program to minimize and manage risk. ORM programs systematically identify operational risks and determine the best courses of action; they are preemptive rather than reactive. ORM is based on four principles: accept no unnecessary risk (that which carries no return in terms of benefits or opportunities, recognizing that everything carries some risk), or, as a corollary “accept necessary risk”; make risk decisions at the appropriate level, with those who can effectively allocate resources to minimize the risk; accept risk when benefits outweigh the cost; and integrate ORM into planning at all levels—identifying hazards, assessing risk, analyzing risk control measures, making control decisions, implementing risk controls, and supervising and reviewing the effectiveness of control measures at reducing risk (Vasavada 2004).

Microbiological Quality and Safety

Microbiological Standards

Microbiological standards continue to change and evolve, so it is best to ensure that updated legislation from the appropriate legal jurisdictions is always available. In the USA, standards for the coliform count are almost uniformly ten colony-forming units (CFU)/g of pasteurized ingredients, such as concentrated milk, and of finished product, although some state governments allow for up to 20 CFU/g for bulky-flavored ice creams. There are no US federal standards for the SPC, although most governments at the state level specify either 40,000 or 50,000 CFU/g, to as low as 20,000 CFU/g. The USA maintains a zero-tolerance policy for *Salmonella*, *Campylobacter coli*, *Campylobacter jejuni*, *Escherichia coli* O157:H7, *Listeria monocytogenes*, and *Yersinia enterocolitica* (Wehr and Frank 2004).

Although the EU had adopted standards for *L. monocytogenes* (absent in 1 g), *Salmonella* spp. (absent in 25 g), and *Staphylococcus aureus* (<10/g, although 2 out of 5 samples can reach 100/g) specific to ice cream and related products, this has been changed in the latest directive European Commission Regulation No. 1441/2007 on microbiological criteria for foodstuffs. They adopted the principle that foodstuffs should not contain microorganisms or their toxins or metabolites in quantities that present an unacceptable risk for human health. They followed the recommendation of the Scientific Committee on Veterinary Measures relating to Public Health (SCVPH), which issued an opinion on 23 September 1999 on the evaluation of microbiological criteria for food products of animal origin for human consumption. It highlighted the relevance of basing microbiological criteria on formal risk assessment and internationally approved principles. The opinion recommended that microbiological criteria should be relevant and effective in relation to consumer health protection. The SCVPH issued at the same time a separate opinion on *L. monocytogenes*. That opinion recommended that it be an objective to keep the concentration of *L. monocytogenes* in food below 100 CFU/g.

European Commission Regulation No. 1441/2007 states that for ice creams containing dairy ingredients and frozen dairy desserts, the maximum limit for the microorganism *Enterobacteriaceae* at the end of the manufacturing process is 10 CFU/g, although 2 of 5 samples can reach as high as 100 CFU/g, according to analytical reference method ISO 21528-2. The specified action in the case of unsatisfactory results is improvements in production hygiene. The Euroglaces (European Ice Cream Association) Code for Edible Ices, 2006, follows this directive for microbiological standards, as follows:

Food safety criteria: *L. monocytogenes* (according to analysis method EN/ISO 11290-2), <100 CFU/g in five samples of finished products during the shelf life of the product; *Salmonella* (according to analysis method EN/ISO 6579), absent in 25 g from five samples of finished products during the shelf life of the product.

Process hygiene criteria: the maximum limit for the microorganism *Enterobacteriaceae* at the end of the manufacturing process is 10 CFU/g, although 2 of 5 samples can reach as high as 100 CFU/g, according to analysis method ISO 21528-2.

Euroglaces Code for Edible Ices further states that edible ices must be manufactured to conform to good hygienic practice, complying with the general rules of hygiene for foodstuffs, as laid down in Regulation (EC) No. 852/2004, based on HACCP principles. However, processed products of animal origin used to prepare edible ices shall be obtained and handled in accordance with the requirements of Regulation (EC) No. 853/2004, and when unprocessed products of animal origin, for example, raw milk, are used, Regulation (EC) No. 853/2004 applies entirely.

In Canada, the microbiological standards for all frozen dairy products specify mesophilic aerobic bacteria (at 32°C) and coliform count. The maximum limit for mesophilic aerobic bacteria is 10,000 CFU/mL, although 2 of 5 samples can reach as high as 50,000 CFU/mL. The maximum limit for coliforms is 10 CFU/mL, although 2 of 5 samples can reach as high as 100 CFU/mL.

The Ice Cream Alliance in the UK have suggested guidelines for microbiological criteria for surfaces in contact with food products, as follows: aerobic plate count <10 CFU/g (although 2 of 5 samples could reach 100 CFU/g), coliforms 0 CFU/g (although 2 of 5 samples could reach 10), and 0 CFU/g for *E. coli*, *S. aureus*, and *L. monocytogenes* (Papademas and Bintsis 2002). Further discussion of swabbing techniques is available in Chap. 14.

Incidents of Pathogenic Contaminations in Ice Cream

Except for a large outbreak of salmonellosis (which was associated with cross contamination with raw product, as described below), few cases of foodborne illness have been traced to commercially manufactured ice cream. Although ice cream is not a sterile product, it contains no pathogenic microorganisms after pasteurization, since pasteurization time–temperature combinations are designed to eliminate all pathogens, and provided no post-pasteurization contamination has occurred. Furthermore frozen storage of the product prevents growth of all microorganisms, which keeps their numbers low, although many species have been shown to survive frozen storage conditions very well. Dean and Zottola (1996) showed that the viable count of *L. monocytogenes* in ice cream, after inoculation at various levels, remained constant during freezing and three months storage at −18°C, due to the cryoprotective effect of the solutes creating an unfrozen phase which holds and protects the cells. Interestingly, though, freezing using batch freezers results in significant destruction of bacterial cells, probably through mechanical damage caused by ice crystals, whereas in continuous systems, which freeze more rapidly, the destructive effect is much less marked (Alexander and Rothwell 1970; Papademas and Bintsis 2002).

The pathogens of most concern from the ice cream industry are those associated with raw ingredients, as discussed further below, notably *Salmonella* spp., *L. monocytogenes*

and verotoxin-producing *E. coli*. *L. monocytogenes* has received considerable attention, and several outbreaks of listeriosis have been associated with dairy products. They are widely distributed in the environment, including plants and animals, and are capable of living in moist, cool places. Unlike most pathogenic bacteria, *L. monocytogenes* grows at temperatures as low as 3°C. These factors raise the probability of contamination of frozen desserts from the environment by *L. monocytogenes* compared with other foodborne pathogens. It shows fairly high-heat resistance, although it is adequately killed by pasteurization (Fernandes 2009). Listeriosis can be a severe human illness that can cause deaths among susceptible persons, especially infants, pregnant women, the elderly, and immune-compromised individuals. Ice cream mix needs to be pasteurized at higher time–temperature combinations than milk, since the fats, sugars, and elevated viscosity offer some protection to microorganisms from heat destruction. Holsinger et al. (1992) showed that *D*-values at 54.4°C for *L. monocytogenes* in ice cream mix (the time for one log cycle reduction of this microorganism at this temperature) were approximately 4–6 times those obtained in milk. The normal pasteurization standards for ice cream mix result in more destruction of all microorganisms so that after pasteurization, SPC should be 500 CFU/g or less (Fernandes 2009).

The most serious foodborne illness associated with ice cream globally occurred in Minnesota, USA in 1994. Transportation of pasteurized ice cream mix occurred in tank trucks in which liquid raw eggs had previously been hauled. The tanks that were used had been inadequately cleaned and sanitized prior to receiving the ice cream mix. The mix was not re-pasteurized prior to freezing at the plant to which it was delivered. As a result, the ice cream was contaminated with *Salmonella* spp. and 224,000 people across the USA were infected (Hennessy et al. 1996; Vought and Tatini 1998).

Bren (2004) reported that in the United States between 1996 and 2000, there were 17 Salmonella outbreaks in homemade ice cream, leading to 500 illnesses, from uncooked or improperly cooked mixes with raw eggs. Salmonella cells are easily killed by pasteurization, but their frequent presence in raw milk and eggs means that all frozen dessert mixes containing these ingredients should be treated to destroy the organism.

During the U.S. Food and Drug Administration Dairy Initiative Microbiological Surveillance Program (1986–1987), *L. monocytogenes* was isolated from 3% of packaged ice cream and 8% of ice cream novelty products sampled. There was more than 30 recalls of ice cream products in the United States from 1986 to 2000 due to *L. monocytogenes* contaminations, leading to destruction of many thousands of liters of products (Ryser 2007). Since then, processors have implemented a myriad of programs, including HACCP, to alleviate the incidents of contamination, so that the numbers of recalls from 2000 to 2010 are considerably below those of the earlier period. A 1989 survey of 530 samples of ice cream mix (85), ice cream (394), and ice cream novelties (51) by Health and Welfare Canada revealed only two samples that contained detectable *L. monocytogenes*. The working group of the World Health Organization found that the incidence of *L. monocytogenes* in frozen desserts varied from 0 to 5.5% and that the number of colony-forming units was usually <15/g of

sample (Marshall 2001). Fortunately, there have been no disease outbreaks associated with *L. monocytogenes* contaminations, but the incidence of contaminations means that constant vigilance is warranted.

A relatively small outbreak of verotoxin-producing *E. coli* (VTEC) occurred in farm-produced ice cream in Belgium in 2007 (De Schrijver et al. 2008). VTEC has a very low infective dose and a general ability to survive in unfavorable environments.

In the UK, 1,200 samples of soft ice creams surveyed in 1997 showed 26% of samples, mainly from mobile vendors, failing to meet microbiological standards. *Salmonella* spp. was not found in any of the samples but *L. monocytogenes* was detected in ten samples. Despite the fact that no foodborne disease outbreaks were associated with these samples, the number of unacceptable samples illustrates the need for a high level of diligence about food safety across all sectors of the manufacturing and retailing of frozen dairy products (Papademas and Bintsis 2002). The same types of warnings were issued in 2010 in Canada when a sampling of mobile soft ice cream vendors in Toronto found several vendors with extraordinarily high counts of coliform organisms.

Raw Ingredients

Ice cream can be made with a variety of ingredients, some of which carry much more inherent risk than others. On the one hand, recombined products that use dried milk powders, butter oil or nondairy fats, sweeteners, and other dry ingredients have very little risk of pathogen contamination associated with incoming ingredients. Pasteurization following recombination blending ensures that the risk of contaminated mix is low. On the other hand, mixes involving raw (unpasteurized) cream and/or milk and/or raw eggs provide inherent sources of pathogens within the incoming ingredients. Effective pasteurization, prevention of cross contamination of raw and processed product, and elimination of post-pasteurization contamination from unsanitary practices become much more critical to prevent pathogenic contaminations when it is recognized that pathogens will be present in the plant. Given the incidence of raw milk and raw egg contaminations with pathogens, this assumption—that pathogens will be present in the raw ingredients and hence in the plant—has to be made.

Jayarao et al. (2006) examined bulk tank milk in the USA from the 248 participating dairy farms for foodborne pathogens. *C. jejuni* (2%), Shiga toxin-producing *E. coli* (2.4%), *L. monocytogenes* (2.8%), *Salmonella* (6%), and *Y. enterocolitica* (1.2%) were detected in the milk samples. *Salmonella* isolates were identified as *S. enterica* serotype Typhimurium ($n=10$) and *S. enterica* serotype Newport ($n=5$). Of the 248 bulk tank milk samples, 32 (13%) contained ≥1 species of bacterial pathogens. Van Kessel et al. (2004) reported results on the prevalence of foodborne pathogens in bulk tank milk as part of the USDA's National Animal Health Monitoring System Dairy 2002 Survey. They observed an isolation rate for *L. monocytogenes* of 6.5% and *Salmonella* spp. of 2.6% in bulk tank milk.

Oliver et al. (2005) reported the following isolation rates for foodborne pathogens from raw milk from various international sources: *C. jejuni* 0.4–12.3%, Shiga toxin-producing *E. coli* 0.8–3.8%, *L. monocytogenes* 1.3–12.6%, and *Salmonella* spp. 1.5–6.1%. They suggested that manure, bedding, feeds, water, equipment, vermin, and farm pets were the main sources of entry.

Oliver et al. (2009) reviewed food safety hazards associated with raw milk. Proper milking practices, udder hygiene, and good mastitis prevention and control practices should allow dairy producers to routinely produce milk with a low SPC (<5,000 CFU/mL). They reported that most farms can produce milk with counts of <10,000 CFU/mL. High bacterial counts (>10,000 CFU/mL) suggest that bacteria are entering milk from a variety of possible sources. The most frequent cause of high SPC is poor cleaning of milking systems. Cows with mastitis (streptococcal and coliform), soiled cows, unclean milking practices, and failure to cool milk rapidly to <4°C can also contribute to high SPCs in raw milk. High-quality milk should also be free of foodborne pathogens. They reported several surveys that have detected foodborne pathogens in bulk tank milk, including *C. jejuni*, Shiga toxin-producing *E. coli* (STEC), *L. monocytogenes*, *Salmonella* spp., enterotoxigenic *S. aureus*, *Y. enterocolitica*, *Mycobacterium bovis*, *Brucella* spp., *Coxiella burnetti*, and others. Some of these foodborne pathogens have habitats in food-producing animals, such as skin and gastrointestinal tracts, and in the farm environment.

D'Amico et al. (2008) studied 11 farmstead cheese operations manufacturing raw milk cheese. Overall, 96.8% of samples had SPCs of <100,000 CFU/mL, 42.7% of which were <1,000 CFU/mL. 61% of samples tested had <10 coliforms/mL. Of the 11 farms, 8 (73%) produced samples that were positive for *S. aureus*, which was detected in 34.6% (46 of 133) of milk samples. *L. monocytogenes* was isolated from three milk samples (2.3%). Their findings of this study suggest that most raw milk intended for farmstead cheesemaking is of high microbiological quality, but nevertheless a low incidence of pathogens was detected.

The incidents associated with *Salmonella* infected ice cream from raw eggs, as discussed above, attests to the widespread presence of this microorganism and the inherent hazards associated with raw eggs as mix ingredients. Although the risk of microbial contaminations from other ingredients is low, they should be routinely tested as well, especially those added post-pasteurization (flavoring and coloring materials, fruits, nuts, cakes, pastries and confections). In addition to SPC and coliform counts, yeast and mold count, psychrotrophic count, and thermoduric count can be useful tests. Sampling and test methods for various ice cream ingredients are described in "Standard Methods for the Examination of Dairy Products" (Wehr and Frank 2004).

Processing and Environmental Considerations

There is strong reason to demand that the processing operation produce frozen desserts that are pathogen-free and with no detectable coliform bacteria in 1 g samples. This group of nonspore-forming bacteria is readily killed by pasteurization, and, if

cleaning and sanitizing are done as well as is currently possible, numbers of coliform bacteria introduced after pasteurization should be practically nil. Numbers of total aerobic bacteria in today's fresh raw milk and cream are generally well below 100,000/mL (in Canada, the maximum allowable number is 50,000 CFU/mL). Furthermore, only a few hundred per milliliter of these bacteria normally exist in the spore form, and it is mostly the spore-forming bacteria that are able to survive pasteurization. This means that aerobic bacteria counts (SPC) of ice cream should be <500/g and that coliform counts should be <1/g. Any time that a viable coliform bacterium is found in ice cream, the chance exists that pathogenic bacteria have entered with the coliform. Although the risk of disease transmission is extremely low when very small numbers of microorganisms enter the product after pasteurization, it is important that the processor realize that the risk does exist.

In general, the order of survival of microorganisms in frozen desserts, from highest to lowest survivability, are (a) bacterial spores, (b) spores of molds and yeasts, (c) Gram-positive bacteria, (d) vegetative cells of molds and yeasts, and (e) Gram-negative bacteria (Marshall 2001). Positive coliform counts and significant SPC are indicative of either contaminated flavoring ingredients added after pasteurization or a failure in the cleaning and sanitizing process, usually some area where product is accumulating that is not being accessed by the cleaning regime. It is not unusual to find *Listeria* in plant environments; however, hygienic practices have been successful in keeping them out of products (Marshall 2001).

The test for *Enterobacteriaceae* instead of coliforms is a more sensitive test for post-pasteurization contamination, because the test detects all of the heat-sensitive, nonspore-forming Gram-negative rods and provides good evidence that contamination has occurred (*Enterobacteriaceae* are all killed by pasteurization, Marshall 2001). In this case, the media used for the coliform test must contain glucose instead of lactose (e.g., Violet Red Bile Glucose Agar, VRBGA). For coliform counts, the direct plating of an ice cream sample on media like Violet Red Bile Agar (VRBA) may cause some false-positive results, because non-lactose-fermenting bacteria may ferment sugars contained in the undiluted sample. It should be remembered that contamination with *Enterobacteriaceae* shows that serious pathogens may have contaminated the product as well (Papademas and Bintsis 2002). Specific test methods, including those for monitoring microbiological quality of surfaces, are described in Chap. 14.

Holm et al. (2002) investigated the length of time between washing on ice cream microbial quality during the manufacturing of ice cream. Various product and product contact surfaces were sampled progressively throughout the time period between cleaning cycles and analyzed for microbial growth. The coliform and SPCs of these samples did not vary significantly over time after 0, 24, 48, or 62 h from cleaning-in-place (CIP). However product contact surfaces showed the effects of cleaning frequency on SPC as the numbers increased significantly. Some of the variables in production practices had a significant influence on microbial loads. An increase in the number of flavors manufactured caused a decrease in SPC within the first 24 h, but by the 48 h interval the SPC increased. More washouts within the first 24 h

interval were favorable, as indicated by decreased SPC. The more frequently the liquifier was sanitized within the 62 h interval, the lower the SPC.

A biofilm is defined as a community of microorganisms attached to a surface, producing exocellular polymeric substances, which act to anchor cells, and interacting with each other (Mostert and Buys 2008). Areas in which biofilms could develop are those that are the most difficult to rinse, clean, and sanitize, including dead ends, gaskets, joints, pumps, grooves, surface roughness due to surface defects (e.g., welds), bypass valves, abraded equipment parts, sampling cocks, and overflow siphons in filters (Mostert and Buys 2008). Gunduz and Tuncel (2006) investigated the sites of biofilm formation in an ice cream plant by sampling both the production line and the environment. Most of the biofilm formations were seen on the conveyor belt of a packaging machine 8 h after the beginning of the production. Most of the Gram-negative bacteria identified belong to Enterobacteriaceae family such as *Proteus*, *Enterobacter*, *Citrobacter*, *Shigella*, *Escherichia*, *Edwardsiella*. The other Gram-negative microflora included *Aeromonas*, *Plesiomonas*, *Moraxella*, *Pseudomonas*, or *Alcaligenes* spp. were also isolated. Gram-positive microflora of the ice cream plant included *Staphylococcus*, *Bacillus*, *Listeria*, and lactic acid bacteria such as *Streptococcus*, *Leuconostoc*, or *Pediococcus* spp. The results from this study highlighted the problems of spread of pathogens like *Listeria* and *Shigella* and spoilage bacteria. They concluded that in the development of cleaning and disinfection procedures in ice cream plants, an awareness of these biofilm-forming bacteria is essential.

Kokkinakis et al. (2008) studied the microbiological quality of the final product and the safety of the production procedures in an ice cream factory after implementation of a HACCP system. They analyzed 30 vanilla, 30 strawberry and 30 chocolate samples of ice cream, 30 samples of water, 90 personnel hand swabs, 150 plastic ice cream container swabs and 50 sanitized equipment-surface swabs. After HACCP introduction, *S. aureus* was not detectable in ice cream, while the spoilage markers in ice cream and the environment were reduced by 20–35%. Coliforms in ice cream samples were reduced from 2.3–2.6 mean log CFU/g to 1.6–1.8, SPC from 4.6–5.1 log CFU/g to 3.5–3.8.

Gougouli et al. (2008) studied the growth of *L. monocytogenes* in ice cream in both chilling and freezing conditions. Under chilling conditions, *L. monocytogenes* grew well at all temperatures tested. Under freezing conditions, no significant changes in the population of the pathogen were observed throughout a 90-day storage period for either of the inoculum levels tested (10^3 or 10^6 CFU/g). The pathogen was able to initiate growth within a very short time after a temperature increase from freezing to chilling temperatures. This indicates that the freezing conditions did not cause a severe stress in *L. monocytogenes* cells. Therefore there would be no significant "additional" lag phase during the subsequent growth of the pathogen at chilling conditions.

Recalls

Having in place a plan for retrieving product from the market is a necessary component of safety systems, including a prerequisite program of HACCP systems.

Hopefully, it never has to be induced, but processors must be prepared in the event that such has to occur. The importance of product coding for traceability cannot be overemphasized. The effects of a product recall can be minimized through ingredient tracking and product coding. All incoming ingredients should be coded and recorded by number, date, lot size, etc. This is a necessary part of inventory control and stock rotation as well. The ingredients used for each batch lot of ice cream made should then be recorded. This is the "what goes where" aspect of the program. Finished product should be coded with records available as to exactly what went into each batch. Finally, some monitoring of delivery of coded product must get done. This is the "who gets what" aspect. With this kind of ingredient-tracking program, if a supplier were to call and advise that he had shipped a bad batch of ingredient, some knowledge as to where that ingredient was would be available. Conversely, returned product with some defect would be identifiable so that others of the same batch could be retrieved (Jooste and Anelich 2008).

Cleaning Procedures

Cleaning and sanitizing are the frontline defense against microbial contaminations. As such, they have to be regular, thorough, and effective. Regardless of the magnitude of the cleaning operation, from hand washing to large clean-in-place installations, the rule of 5 + 4 applies. For effective cleaning, you need the following five steps with appropriate attention to the four main factors of cleaning, viz. (1) preparation; (2) prerinse; (3) wash (alkaline or acid or dual phase—alkaline followed by an intermediate rinse followed by acid); (4) post-rinse, to remove cleaning compound residues; and (5) sanitize, with attention in the washing steps to (a) time, (b) temperature, (c) chemical action, and (d) physical action. The procedures and compounds for thorough and effective cleaning will now be discussed in further detail.

Water quality is an important factor in the cleaning of equipment. The salts of calcium and magnesium that dissolve into water as it trickles through the soil are carried to the ice cream plant in the form of water hardness. Hardness in water is expressed as the amount of calcium carbonate (which includes both calcium and magnesium salts) present in milligrams per liter (the same as parts per million—ppm). Soft water contains <60 mg/L, medium hard water 60–120 mg/L, hard water 120–180 mg/L, and very hard water >180 mg/L. *Temporary hardness* (the bicarbonate fraction) is precipitated by most alkaline materials and heat. *Permanent hardness* (mostly the chlorides and sulfates) is not precipitated by heat (Cords et al. 2001). As hardness salts precipitate they clog boilers and leave deposits on equipment, especially where heat is applied. The films they leave on product contact surfaces can adsorb milk proteins, fat, and minerals forming *milkstone*. The harder the water, the higher the concentration of cleaner needed to be effective. Water softening to provide the large volumes of water required for equipment and pipeline circuit cleaning is formidable, however, so if hard water is an issue with film

formation, then higher level of sequestrants in the cleaning compounds or more frequent acid washes may be required.

Organic soils that need to be removed in ice cream plants include lipids, proteins, carbohydrates, and mineral salts. Heated surfaces are much more difficult to clean than non-heated surfaces, the former usually requiring acid washes, as will be discussed below. Lipids can be removed at temperatures >55°C with alkalis that contain emulsifying and suspending properties. Proteins can be removed with a combination of alkalis and chlorine, but proteins become insoluble when heated and form films, requiring acids for effective removal. Carbohydrates are very soluble and easily removed by alkali cleaners although caramelization of carbohydrates on hot surfaces requires oxidizers in the alkali cleaners for effective removal. Soluble salts are removed by alkaline cleaners containing chelating or sequestering agents, but mineral salts can form milkstone, which requires acid washing for complete removal (Cords et al. 2001).

Practices that minimize soil deposition and maximize ease of removal of surface films include the following: (1) using minimum time and temperature of heating, (2) cooling of product-heating surfaces before and during the emptying of processing vats, (3) rinsing of films from equipment before they dry, (4) keeping organic soil moist until cleaning is begun, and (5) rinsing with warm—not hot—water. The ease or difficulty of removal of soil is determined by the nature of the surface on which it exists. Stainless steel surfaces of processing equipment should be designed for effective cleaning (see 3-a below), but pores in rubber parts, crevices in insufficiently polished surfaces, and holes in corroded surfaces protect soil and microorganisms from the actions of detergents and sanitizers.

Functions of Detergents in the Dairy

Cleaning compounds are comprised of the following main ingredients: surfactants (wetting agents), builders (alkaline or acid), water conditioners (phosphates or alternatives and chelating agents), and oxidizers. The following are the major functions performed by formulated cleaners:

1. *Emulsifying*: causing fats and oils to be suspended in the cleaning medium.
2. *Dispersing*: breaking clumps of soil into small individual particles.
3. *Dissolving*: making both organic and inorganic soil constituents soluble.
4. *Peptizing*: hydrolyzing proteins, thus increasing their solubility.
5. *Rinsing*: assisting rinse water to remove the solution and its suspended components from the surface.
6. *Saponifying*: combining the alkaline cleaner with residual fat to form a removable soap.
7. *Sequestering or chelating*: removing or inactivating hard water components by forming a soluble complex.
8. *Wetting*: lowering of the surface tension of a cleaning solution to increase its penetrating power.

A good detergent causes the solution to penetrate the soil to be removed by strong surface action; displaces soils from the surfaces by saponifying fats, peptizing proteins, and dissolving minerals; disperses soil components by deflocculation and/or emulsification; and prevents redeposition of the dispersed soil by providing good rinsing properties.

Major Detergent Components and Their Functions

Surfactants. The surface active agents, or wetting agents, provide good penetrating, emulsifying, solubilizing, and dispersing action, to keep organic soils suspended for removal. Some of the best emulsifying agents are the nonionic wetting agents, as they are effective over a wide pH range and are not affected by water hardness. Since they do not ionize, they work well combined with either anionic or cationic wetting agents. Alkyl aryl sulfonates are the anionic wetting agents commonly used in dairy cleaners.

Alkalis. The strongest of the alkaline detergent ingredients is sodium hydroxide (NaOH). It saponifies fat excellently but performs few other cleaner functions. Solutions of NaOH are often used to clean heavy deposits of protein and fat from surfaces of heat exchangers. A moderately strong alkaline detergent that inhibits corrosion is sodium metasilicate (Na_2SiO_3 $5H_2O$). It emulsifies and deflocculates well. When used with water softening chemicals, sodium carbonate (Na_2CO_3) is a good alkaline detergent ingredient for washing equipment by hand. When used in combination, baking soda ($NaHCO_3$) and sodium carbonate form sodium sesquicarbonate, an effective alkaline detergent. The effectiveness of alkaline detergents against proteinaceous films is improved as much as 40% by the addition of hypochlorite.

Acids. Acid cleaners are primarily employed as a secondary cleaner, following application of alkali cleaners, and are used for effective milkstone (protein and mineral film) removal, particularly from heated surfaces, and also film removal associated with water hardness. The most commonly used acids for cleaning dairy equipment are nitric acid or nitric acid/phosphoric acid blends. These are milder than hydrochloric acid, which tends to be very corrosive. Nitric acid is less corrosive than hydrochloric acid because it produces protective oxide films on stainless steel.

Acid washing should be performed with every cleaning circuit of heated equipment (pasteurizers, homogenizers, and associated piping) but may be used less frequently (e.g., weekly) with non-heated equipment. The best practice is to prevent the buildup of significant amounts of mineral deposits by using soft water and detergents that suspend minerals in the alkaline cleaner. To further decrease the possibility of needing a strong and corrosive acid detergent, acidified water for the final rinse of equipment may be used, which also helps to neutralize alkaline residues, provided that chlorinated compounds are not present in the alkaline cleaner to ensure no formation of chlorine gas.

Phosphates. The general utility cleaner that softens water by precipitating hardness ions is trisodium phosphate (Na_3PO_4 $12H_2O$). The polyphosphates, on the other hand, soften water without precipitating hardness components. These detergent ingredients include tetrasodium pyrophosphate ($Na_4P_2O_7$), sodium tripolyphosphate ($Na_5P_3O_{10}$), sodium hexametaphosphate $(NaPO_3)_6$, and sodium tetraphosphate ($Na_6P_4O_3$). Having the appearance of glass in the dry state, the latter two are called glassy phosphates. They rinse freely from surfaces, emulsify, peptize, deflocculate, and suspend. Sodium tetraphosphate is the most effective of the polyphosphates. Since polyphosphates may be undesirable in effluent and may need special treatment for disposal, other alternative water conditioning agents are also available.

Chelating agents. Salts of organic acids, such as sodium citrate, and ethylenediaminetetraacetic acid (EDTA) are effective chelators or sequestrants of metal ions in detergent solutions. They improve wetting of soils and penetration of water into the soil. They tend to adhere to particles of soil, suspending or emulsifying them. They are effective in preventing scale and lime deposits, removing water hardness and other metal ions by forming soluble complexes.

Oxidizing agents. Sodium or potassium hypochlorite or hydrogen peroxide can be added to cleaning compounds to assist in protein removal by oxidizing them. Corrosion to metals is a disadvantage of using chlorinated compounds at high temperatures over a prolonged time. Hydrogen peroxide is not as corrosive as chlorine, although it is not as effective as chlorine. Combinations of hypochlorites and acids can release chlorine gas, so care must be taken to ensure these compounds are not inadvertently mixed.

Cleaning Methods

Cleaning methods include (1) hand or manual cleaning of dismantled equipment, parts, and utensils with a brush and detergent solution using appropriate gloves and eye protection depending on the cleaner; (2) spray cleaning with high-pressure, low-volume solutions; (3) foam or gel thin-film cleaning with appropriate cleaning compounds that adhere to surfaces for long contact times; and (4) cleaning-out-of-place (COP) tanks in which disassembled parts are placed into recirculating water with appropriate pump action to develop sufficient physical force, or cleaning-in-place (CIP) systems in which physical force is generated by sufficient high-pressure, high-volume pumps that circulate specially formulated cleaning compounds (Cords et al. 2001). Equipment has to be appropriately designed to be suitable for CIP. In the ice cream industry, many of the large pieces of equipment, including continuous freezers, are now CIPable, although several components such as ingredient feeders or variegating pumps may have to be disassembled for adequate cleaning. CIP systems often can be designed to reclaim and reuse various solutions or rinses.

Regardless of cleaning method, the first principle to remember in regard to cleaning is that it is not possible to kill residual microorganisms with chemical sanitizers

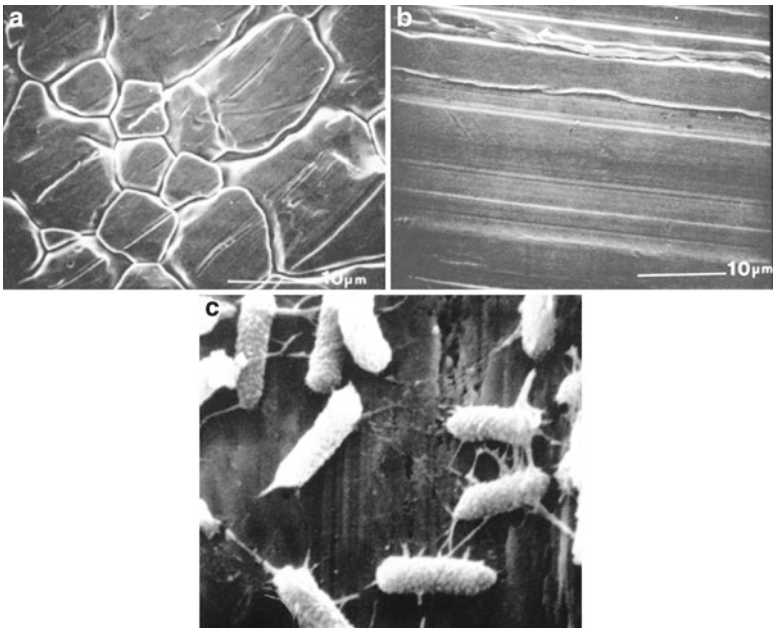

Fig. 13.1 Surfaces of polished stainless steel with a number 2b finish (**a**), with a number 4 finish (**b**), and with *Pseudomonas* bacteria resting within crevices of an inadequately cleaned surface of 304 stainless steel with a number 4 finish (**c**) (Image (**c**) courtesy E.A. Zottola, University of Minnesota)

if the microorganisms are protected in films. Planktonic (suspended) bacteria are much more easily inactivated by dairy sanitizers than are sessile (adsorbed) ones. Even more protected are bacteria residing in cracks and crevices. This is why stainless steel, product contact surfaces of dairy equipment are polished to a fine number 4 finish, compared to the non-product contact surfaces with a number 2b finish (Fig. 13.1a, b). Even the number 4 finish provides plenty of space for soil and bacteria (Fig. 13.1c) to find protection from the lethal effects of sanitizers if they are not dislodged and carried away or at least suspended by the detergent solution.

The 3-A Sanitary Standards (www.3-A.org) have been developed to provide guidance to equipment fabricators regarding issues of hygiene. 3-A Sanitary Standards Inc. is a collective organization of equipment fabricators, equipment users, and sanitarians that is concerned with the design, construction, and finish of dairy processing equipment as it affects cleaning, sanitizing, operation, and maintenance. There are two stages involved—the first is the preparation of standards for a piece of equipment, and the second is allowing fabricators to use the 3-A designation on equipment meeting those standards.

No single procedure or set of conditions will work equally well in cleaning all of the equipment in a frozen desserts operation. Already it has been stressed that water quality, soil type, and type of detergent (*chemical action*) are important variables. It is now important to show that *temperature*, *physical action*, and *time* also affect

cleaning markedly. If a cleaner is suited to the soil and the water, and if it is of sufficient concentration, then these three physical factors become relevant variables. Decreasing the magnitude of any one of them requires that at least one of the others be increased in magnitude. Higher temperatures promote faster rates of reaction and decrease solution viscosities. Decreasing viscosity increases turbulence, a very important force. Within the temperature range of 32–85°C (90–185°F), an increase of 10°C (18 °F) will produce approximately double the cleaning rate. Milk fat is partially solid at temperatures below 33°C; therefore, cleaning solutions should be at least this warm.

Physical force is necessary to dislodge firmly adsorbed films. Brushing does this well. In circulation cleaning or CIP systems, turbulence of circulating solutions substitutes for the brushing. Turbulence is affected by the rate of flow and the nature of surfaces and is expressed as the *Reynolds number*. The higher the Reynolds number, the greater the turbulence. In pipeline systems a desirable value for circulation cleaning is >10,000, even though turbulent flow begins at about 3,000 (Mostert and Buys 2008). Falling films of cleaning solutions on walls of storage tanks are turbulent when the Reynolds number is 200 or above. The International Dairy Federation has sanctioned the empirical rule that cleaning solutions need to flow at a rate of at least 1.5 m/s (5 ft/s) to adequately clean in a CIP system (Jooste and Anelich 2008).

Rinsing removes over 90% of soil on most ice cream equipment. Furthermore, most of the remaining soil is removed within the first 3 min of circulation cleaning if cleaner and temperature are appropriate and the soil layer is not unusually heavy. However, the rate of removal of soil decreases logarithmically with time, making it necessary to continue circulation for 15–30 min to assure that tenacious soil is removed.

Cleaning-in-place of large surfaces such as walls, ceilings, and floors of tanks is done with spraying devices located strategically inside the tanks or placed in them after they have been emptied of their ingredients or products. However, in cleaning vessels and tanks there must be a balanced flow rate at the proper pressure and rate of removal of the cleaning solution. Flooding of the bottom of a vessel may impede cleaning because of low turbulence. Flow control in both lines and tanks is now done with precision because meters and adjustable rate pumps can be tied to programmable logic controllers. Concentrations of detergents can be monitored with conductivity probes and the data used to activate feed pumps when concentrations need to be strengthened.

Cleaning-in-place permits use of strong cleaners and high temperatures. It virtually eliminates human error in the cleaning operations, especially if systems are used that automatically prepare the cleaning solutions and control their concentration, temperature, and time of application. This releases workers for other important work. Importantly, the processes can be monitored effectively and records kept electronically. Computer-based CIP monitoring systems can track on a time basis the critical variables of return temperature, conductivity of the returned solution, the flow rate, and more.

Surfaces should be drained dry after cleaning. Microorganisms that may have escaped removal or death during cleaning cannot grow in the absence of moisture even if organic matter remains on the surface to provide nutrients for growth.

Biofilms should not accumulate with thorough and effective cleaning and sanitizing; however, if they do, they can be more difficult to clean than normal planktonic cells, due to the protective effect of the layering of cells with exopolymeric substances that anchor them in place (Mostert and Buys 2008). Enhanced mechanical force is the best approach to the removal of biofilms once formed.

In summary, the five steps that should be taken after use of dairy equipment are (1) preparation of the equipment for cleaning (including disassembly, if required, or attachment of CIP lines); (2) rinse with warm water; (3) wash with a detergent of proven effectiveness, dissolving it in appropriately conditioned water at a temperature commensurate with the soil, equipment, and method of washing (by hand, CIP, or COP); (4) rinse with warm or hot water to promote drying (depending on equipment considerations); and (5) sanitize immediately after final wash. Frequent turnover of air in processing rooms is important to promote drying of surfaces. If equipment requires reassembly or will not be used again for more than 4 h after washing, it should be resanitized immediately before use (see below).

Sanitizing Procedures

Sanitization is the process of treating equipment surfaces with chemical or physical agents that will destroy all of the pathogenic microorganisms and most of the spoilage bacteria. Sterilization destroys all microorganisms. Sterilization is seldom necessary in frozen dessert operations, because microbial growth is not possible in the frozen products. However, bacteria may not all be removed during cleaning, postrinse solutions can carry microorganisms to equipment, and some surfaces may be subject to contamination during periods of disuse. Therefore, it is imperative that all product contact surfaces be treated with sanitizer immediately after washing or, if reassembly is required or equipment has been exposed to the environment for more than 4 h after sanitizing, just prior to use. The commonly used chemical sanitizers include the chlorine-bearing compounds, iodophors, acids, and quaternary ammonium compounds.

Sodium hypochlorite is an effective and inexpensive sanitizing agent. It is readily soluble, unaffected by hard water, and highly efficacious, killing bacterial spores readily. Guidelines for applying sodium hypochlorite found in the Grade A Pasteurized Milk Ordinance call for exposure to at least 50 mg/L (ppm) of the sanitizer for at least 1 min at 24°C (75 °F). Chlorine sanitizers are corrosive to stainless steel at high temperatures.

Iodine has excellent antimicrobial properties but is sparingly soluble in water, tends to stain, and is volatile at moderate temperatures. Iodophors (“iodine carriers”) have been developed to overcome most of these deficiencies. An iodophor contains iodine, nonionic wetting agent, and buffered phosphoric acid. The wetting agent stabilizes the iodine and increases its ability to permeate microbial cells. The acid provides the low pH necessary for quick bactericidal action of the iodine. The color

of dilute solutions of iodophor is proportional to the concentration, and solutions with a straw color are effective in most applications. However, although this is an indication, the proper concentration must be measured rather than simply visualized by eye. Use concentrations range from 12.5 to 100 mg/L. The activity of iodophors increases with concentration, temperature, and acidity, but instability and corrosiveness also increase. Temperature and pH should be kept below 49°C (120 °F) and 5.0, respectively, to ensure that iodine is available to kill microorganisms and that sublimation of iodine does not occur. Organic matter reduces the activity of iodophors but not as much as it affects hypochlorites. Iodophors work well in hard water.

Mixtures of organic acids such as sulfonic acid with anionic or nonionic wetting agents and phosphoric acid provide detergency, solubilization of minerals, and bactericidal action. The lethal effect on microorganisms is provided by the pH of about 2 and the activity of the wetting agent at this low pH.

Quaternary ammonium compounds ("quats") are cationic wetting agents that destroy microorganisms slowly and are not as effective on Gram-negative bacteria. However, they are noncorrosive, nonirritating, stable to heat, relatively stable in the presence of organic matter, relatively stable up to about 500 ppm of water hardness, and active over a wide range of pH. For the latter reasons there are applications in which quats may be the preferred sanitizer, particularly in environmental sanitization rather than product contact surfaces. In such cases they should be used at concentrations of at least 200 mg/L at pH 5 or above and for exposure times of at least 30 s.

The acid-anionic sanitizers are excellent sanitizers that were designed to combine sanitizing and acid treatments in one step. They are typically used in CIP systems.

Sanitization with heat, a common practice in the fluid milk industry, is seldom used in frozen dessert plants. A major reason is that large changes in temperature can damage freezers and other equipment operated at below freezing temperatures. In systems containing large numbers of valves, pumps, and gasketed lines, heat from hot water penetrates well into minute areas protected from chemical sanitizers. Where such systems exist in ice cream plants, it may well be desirable to use hot water for sanitization. Exposure to hot water should be for at least 5 min at an outlet temperature of 77°C (170 °F). Small pieces of equipment may be sanitized in cabinets with steam or hot air. Exposure to steam at 77°C for 15 min or at 93°C for 5 min is minimal.

Controlling and Monitoring Plant Sanitation

Effective control of cleaning and sanitizing operations cannot be expected unless employees are informed and trained to perform the tasks needed. As with processing operations, cleaning and sanitizing practices should be described in a manual in which the following minimal information should appear:

- Name and source(s) of cleaners and sanitizers.
- Description of cleaning and sanitizing procedures.
- Use concentrations of chemicals and how to obtain them.

- Time and temperature of application of cleaners and sanitizers.
- Procedures for handling, storing, and disposal of chemicals.
- Procedures for cost control.
- Procedures for auditing of the sanitation program.

Validation of the effectiveness of cleaning and sanitizing procedures is ultimately done by monitoring SPC and enterobacteria levels in products, as discussed above. Surfaces can be monitored for microbiological quality using surface swabbing, rinse solution methods, or contact plates. Specific test methods are described in Chap. 14.

Sanitary Environment

Sanitary surroundings and clean personnel are a must if equipment is to be kept in hygienic condition without fail. All rooms, especially toilets and locker rooms, must be kept as clean and sanitary as the area immediately surrounding packaging equipment. The factors essential in hygienic construction are similar for utensils, equipment, work rooms, buildings, and surroundings:

1. Surfaces, especially those that contact products, must be smooth and free from scratches and grooves. Floors are the only exception. They should be slightly rough to prevent slipping.
2. Surfaces should be sloped to drain and free from depressions.
3. Corners should be rounded with a radius large enough to permit scrubbing with a brush.
4. All surfaces not cleaned in place must be easily accessible or easily disassembled for cleaning. Equipment should have enough clearance above the floor to permit cleaning daily or should be completely sealed to the floor.
5. Materials used in construction must be impervious to moisture and free from odors.
6. Lighting must be adequate for the operation that takes place in the specific area. Locations where the highest amounts of light are required include those where data must be taken or recorded.
7. Ventilation with fresh clean air is essential.
8. Rodents and insects must be kept out of the facility and places for them to be harbored must be eliminated. For example, all dry storage areas should have the shelving set away from the walls adequately for observation and cleaning to take place.
9. Operations must be segregated to minimize chances of pathogenic microorganisms being carried from raw materials to finished products. Persons handling raw milk or cream must not be allowed access to rooms where pasteurized products are exposed unless those persons have first changed their clothes completely and have disinfected themselves.
10. Processing room air pressures should be maintained higher than ambient, so air flow leaves the processing areas on opening of doors. Packaging areas

should be at the highest pressures, so the flow of air will be away from the most critical contaminant area. Specialists in engineering of ventilating equipment may need to periodically check the air flow and balance in the system.

11. The supply of hot and cold water must be unrestricted, and facilities for disposal of both liquid and solid wastes must be adequate.

Hygienic Personnel

Hygienic and conscientious personnel are an absolute must for the frozen dessert manufacturer, since they have many opportunities to affect microbiological quality of product, from direct contamination to inappropriate exercise of responsibilities (Papademas and Bintsis 2002). No worker should be allowed to perform tasks in the plant without having been adequately taught the necessities of personal hygiene and approved practices within the plant. The importance of these factors can be conveyed best to all employees when top managers regularly demonstrate their endorsement of the firm's adopted practices.

Freedom from chronic contagious diseases should be confirmed yearly by medical examinations. Hygienic practices that should be practiced in the plant include the following:

1. All workers must be clean, including fingernails. Hands must be washed before commencing work and whenever there is a chance that they have been contaminated.
2. Hair restraints must be worn, including coverings for beards.
3. Clean clothes and shoes must be worn, and the shoes should be disinfected in a sanitizer foam spray or foot bath any time a person enters the processing or packaging area. Clothing should be laundered by the processor.
4. Jewelry should not be worn in the processing or packaging environment, and all pens, pencils, and other objects that might fall into a vat or other container of ingredients or products should be placed at or below waist level and in a secure holder.
5. No one should be allowed to enter the processing or packaging environment without knowledge of the required sanitary procedures and without having dressed appropriately and performed the required steps in personal hygiene.

In addition to processing personnel, those serving the products in retail environments are likewise responsible for their personal hygiene and for dispensing products (scoops for cones, desserts, etc.) in a sanitary manner (Papademas and Bintsis 2002). Soft-serve freezers are discussed specifically in Chap. 8.

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Chapter 14
Analyzing Frozen Desserts

Introduction

Testing of product attributes and quality occurs for a number of reasons: routine quality control, in which chemical composition and microbiological quality are perhaps the most relevant tests; formulation modifications or new product development, in which sensory and other non-microbiological quality attributes such as meltdown rate become important; or research, in which the effects of novel ingredients on functionality, for example, become important, attributes like fat destabilization, ice crystal size, air bubble size, or other structural measures. For quality control purposes, it is important that no product be shipped that has not met the specifications of the manufacturer. These specifications should be established when the product line is developed. The tests usually are dictated by regulations, either chemical compositional or microbiological, quality considerations and economic considerations. Specifications are set based on achievable and detrimental levels of important attributes or potential deficiencies in a product. Fat and total solids content should vary from the target by no more than 0.2% and 0.5%, respectively. In addition to compositional specifications, products must be stable during the shelf life of the product and meet consumer expectations or there will be no return purchase, thus the importance of measuring structural and physical quality attributes. Therefore, producers of ice cream and suppliers of ingredients use and depend upon specific procedures for analysis and evaluation of finished products. This chapter describes the major chemical, microbiological, physical, and sensory characteristics of ice cream and selected methods of analysis of them.

A major source of detailed methods of microbiological and chemical analysis for dairy products is "Standard Methods for the Examination of Dairy Products" published by the American Public Health Association (Wehr and Frank 2004). The International Dairy Federation (IDF) has published methods of analysis of milk and milk products (IDF Standards, various dates, summarized by Bintsis et al. 2008). The Codex Alimentarius Commission provides standards to be used in international trade of milk and milk products (see http://www.codexalimentarius.net). Sections

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include food hygiene, food labeling, and import and export inspection and certification systems. Handbook 44 of the US National Conference on Weights and Measures provides specifications, tolerances, and other technical requirements for weighing and measuring devices (see http://ts.nist.gov/WeightsAndMeasures/h44-07.cfm).

Chemical Analyses

Compositional analyses usually involve testing for fat, protein, mineral (ash) content, moisture or total solids and, by difference, carbohydrate content, with fat and total solids being the principal two tests that are performed routinely. Methods involve either chemical analysis or instrumental analysis. Acidity is also frequently monitored. It is also possible to test for defects in fat, such as oxidation or rancidity, for specific carbohydrates and for minor intended or unintended chemical constituents, although such tests tend to be when problems are suspected rather than on a routine basis.

Fat

There are several test methods available to measure the fat content in ice cream mix or frozen dairy products by chemical means, including the Pennsylvania modification of the Babcock test for frozen dessert mixes, the Gerber method and the Mojonnier ether extraction method (the official method of which now replaces the older Roese-Gottlieb method). The Mojonnier method has been shown to be more precise than the Babcock method and has been accepted by the dairy industry, as well as IDF and AOAC, as a more accurate reference. However, a great deal of effort has gone into refining the Babcock method to make it more precise and closer to the Mojonnier method, so if it is practiced then the specifications of the official test method must be adhered to (Wehr and Frank 2004). Instrumental tests for fat, protein, and other components will be discussed below.

The principle of the Babcock method for fat analysis is that the dairy product and concentrated sulfuric acid are mixed to produce an exothermic reaction that disintegrates the emulsion structure to release free fat. The solution is centrifuged (46–51°C) and the free fat is collected in the graduated portion of the neck of the Babcock bottle, which is calibrated to express the fat content of the product on a percent fat by mass basis with a fixed sample size. Specific Babcock bottles, pipettes, and Babcock centrifuge are required to conduct the test. The Pennsylvania modification is appropriate for samples containing sugar, since added sugar makes it more difficult to centrifuge out all of the fat. Thus ammonium hydroxide (2 mL) and normal butyl alcohol (3 mL) are used to help free the fat and a diluted sulfuric acid is also used (sp. Gr. 1.73 ± 0.01 at 20°C). Bottles are available specific for frozen dessert mixes with

20% fat graduation for 9 g samples and 17.5 mL diluted sulfuric acid that include a stoppered side opening for ease of addition of sample into the bottle (Paley bottles). Ice cream and frozen desserts are melted to room temperature and mixed thoroughly. A sufficiently large sample should be melted and mixed to get a representative portion of fat, given that the fat distribution in frozen product may no longer be homogeneous due to fat destabilization during freezing. Sampling should be done by weight rather than volume, due to the presence of entrained air in the melted foam. If particulates are present, the sample can be passed through a blender first.

The Gerber method for fat analysis similarly uses the exothermic reaction between water in the product and concentrated sulfuric acid in combination with isoamyl alcohol to disintegrate the emulsion structure and release the fat. The fat is collected in the graduated portion of the neck of the Gerber bottle.

The Mojonnier method for fat analysis is a solvent-extraction method. In this test, ammonium hydroxide, ethyl alcohol, ethyl ether, and petroleum ether are added sequentially to extract the fat from the sample in three separate extraction steps using specific Mojonnier test bottles. After centrifugation the fat-containing solvent is decanted from the aqueous phase, the solvent is evaporated and the fat is determined gravimetrically. Although collaborative studies have verified its precision and accuracy across labs for milk and cream, the same has not occurred for frozen dessert mixes and products. Nevertheless specific test procedures and sample and solvent quantities are available for frozen dessert products (Wehr and Frank 2004).

Tests for free fatty acids might be done if a milk fat-based product is suspected of being rancid (hydrolytic rancidity). This is referred to as the acid degree value test. The principle is that fatty acids are released from triglycerides when milk fat undergoes hydrolysis (the specific flavor defect associated with rancidity comes especially from free butyric acid) and these fatty acids can easily be separated and titrated (Wehr and Frank 2004). Non-dairy fats can also hydrolyze to free fatty acids, but if they do not contain volatile fatty acids, such as butyric, then the defect is not noticeable from a sensory perspective.

For issues of oxidative rancidity, the peroxide value (POV) can be used. This method measures peroxides and other products of fat oxidation (Wehr and Frank 2004). Additionally, thiobarbituric acid is used in the TBARS test (thiobarbituric acid reactive substances) to measure aldehydes, which are end products of lipid oxidation that form from peroxides. Both POV and TBARS provide indicators of the progression of lipid oxidation—with POV more sensitive at the early stages and TBARS being more sensitive at the latter stages.

Protein

Protein is measured by the Kjeldahl test that involves digestion of the sample with a mixture of concentrated sulfuric acid and potassium sulfate, a catalyst (copper II sulfate) and heat, then distilling and measuring the nitrogen in the sample. Organic nitrogen is thus converted to ammonium sulfate, which is liberated and

titrated with hydrochloric acid. Nitrogen content is calculated from the amount of ammonia produced and then multiplied by a factor of 6.38 to calculate the protein value. Specific Kjeldahl glassware, digestion apparatus, and distillation apparatus are required to conduct the test. This test measures all of the nitrogen in the sample and direct calculation assumes all of that to be protein nitrogen. However, there can be other sources of nitrogen (urea, for example) so if true protein is required, a non-protein nitrogen test can be made, also using Kjeldahl equipment, to subtract from total nitrogen. As well, both whey protein nitrogen and casein protein nitrogen can be determined separately, if required.

Moisture and Total Solids

To analyze for total solids (100-moisture), about 3 g of melted ice cream are weighed into a dried and weighed pan. Moisture is evaporated on a steam bath and then in a forced draft or vacuum oven at 100 ± 2°C for 3.5 h. On cooling, the pan with its dry contents is weighed and the percentage of total solids is calculated (Wehr and Frank 2004). The IDF method varies from the one described above by calling for the weighed sample to be diluted with an equal volume of water and mixed with dried sand in the pan. The sample is pre-dried on a steam bath and then subjected to 102°C for 2 h before cooling and weighing.

In the USA, the total milk solids, the sum of the milk fat and the milk solids-not-fat (MSNF), contained in an ice cream formulation is regulated (see Chap. 2). If the protein component of the MSNF is 36%, as it is in skim milk-based ingredients such as condensed skim or skim powder, then fat and protein measurements can be used to calculate the total milk solids. However, when whey products of varying protein content are used as MSNF sources, then lactose and ash would have to be measured as well as fat and protein, the sum of which would generate the total milk solids. Thus tests for total milk solids are not performed by regulatory agencies because of the complexity of ice cream formulae and the difficulty of testing specifically for lactose in a mix that also contains sucrose and perhaps maltose and other mono-, di-, and trisaccharides. Rather, control agencies have the option to check records of production and of dairy ingredient utilization to ascertain whether, on a general basis, a firm has met the ice cream standard.

Lactose and Minerals

Lactose can be analyzed by either chemical or instrumental methods. In milk and milk products to be used in ice cream the concentration of lactose can be determined by removing the fat and protein by precipitation and filtration followed by measuring the degree of rotation of polarized light, which is proportional to the concentration of lactose. This polarimetric method cannot be used for testing the lactose content

of ice cream because of the presence of significant amounts of other sugars in it. The 9.610 nm wavelength of infrared light is highly absorbed by the hydrogen bonds that are abundant in lactose, and this provides the principle of a widely used instrumental method of analyzing for lactose in milk. For ice cream itself, high-pressure liquid chromatography (HPLC) is the method of choice for determining the concentration of lactose and other sugars.

Ash is defined as the residue, primarily minerals, remaining after ignition at 550°C to constant weight (5 h), which eliminates all organic matter. A weighed sample of 10 g is first evaporated in a forced draft oven at 100°C or steam bath for 1 h. The sample is then carbonized over flame for 30 min and then dried at 550°C in a muffle furnace until a light gray or white ash remains. The sample is then moistened to form a paste, crushed with a stirring rod, re-evaporated at 100°C and returned to the muffle furnace for about 1 h, to ensure all organic material has been eliminated. Ash is determined as wt. of residue/wt. of sample (Wehr and Frank 2004).

Multicomponent Instrumental Methods

Fat, protein, and lactose in milk and dairy products can be measured instrumentally by infrared (IR) or near infrared (NIR) light spectroscopy, based on absorption of IR energy at specific wavelengths by carbonyl groups in ester linkages of fat molecules, by peptide linkages between amino acids of protein molecules and by hydroxyl groups in lactose molecules (Wehr and Frank 2004; Bintsis et al. 2008). There are many instruments available for this rapid and routine testing (e.g., Foss, CEM). Fat, protein, and total solids can easily be measured with several instruments commercially available. Proper calibration and maintenance is essential for reliable results. Total solids can also be measured rapidly using commercially available instruments based on microwave drying technology (e.g., CEM).

Acidity

If fresh milk components of excellent quality are used, the mix can be expected to have a normal acidity. The apparent or natural acidity of ice cream mix is caused by the milk proteins, mineral salts (mostly phosphates and citrates), and dissolved CO_2. The normal titratable acidity of mixes varies with the percentage of MSNF contained and may be calculated by multiplying the percentage of MSNF by the factor 0.017. Thus, a mix containing 11% MSNF would have a normal titratable acidity of 0.187%. The normal pH of ice cream mix is about 6.3[1]. The acidity and pH are related to the composition of the mix—an increase in MSNF raises acidity and lowers the pH.

[1] A neutral substance (i.e., neither acidic nor alkaline) would have a value of 7.0, with decreasing values indicating increasing acidity and increasing values indicating alkalinity.

Table 14.1 Approximate titratable acidity[a] and pH values for ice cream mixes containing 7–13% milk solids-not-fat (MSNF)

MSNF (%)	Approximate acidity (%)	Approximate pH
7	0.119	6.40
8	0.136	6.35
9	0.153	6.33
10	0.170	6.32
11	0.187	6.31
12	0.204	6.30
13	0.221	6.28

[a]As lactic acid

The percent titratable acidity and pH values for mixes of various MSNF content are given in Table 14.1.

Developed acidity is caused by the production of lactic acid by bacterial fermentation of the lactose in dairy products. When the acidity of the mix or ice cream is above normal, developed acidity was probably present in the dairy products used in the mix. A high acidity is undesirable as it contributes to excess mix viscosity, decreased whipping rate, inferior flavor, and a less stable mix. The latter may contribute to "cook on" during processing and pasteurization, because heat and acidity accelerate the denaturation of proteins.

To test for acidity, a standardized solution of 0.1 N sodium hydroxide (NaOH) is added to a specified volume of sample (9 or 18 g) with added phenolphthalein indicator (0.5 mL) and titrated until the indicator turns to a permanent (30 s) light pink color. The sample is usually diluted 2:1 with distilled water before titrating. If color indication is difficult due to a darkly colored sample, the solution can also be titrated to pH 8.3. Frozen dairy products should be warmed to room temperature or to 37 ± 10°C (be consistent with test method) and mixed thoroughly by shaking or stirring. Acidity is expressed as percentage of lactic acid (1 mL of 0.1 N NaOH = 0.009 g lactic acid) (Wehr and Frank 2004).

Other Tests for Chemical Components

Tests to quantify certain nutrients might be done for purposes of nutritional labeling if a reliable database is not available for the selected ingredient(s). Specific vitamins and minerals would require analysis by specialized testing laboratories. Minerals are quantified using flame photometry or atomic adsorption spectroscopy. Biometric or spectrophotometric assays are used for the several vitamins. Energy content is assayed by burning a sample in a bomb calorimeter to determine how much heat is produced per unit sample. However, caloric content is usually determined by calculation (see Chap. 2). Tests for antibiotics or drug residues that may be present in raw milk are outlined by Wehr and Frank (2004). Alkaline phosphatase (AP) is a natural milk enzyme that is destroyed at just-below pasteurization standards, so is used as

a measure of adequate pasteurization. There should be no issues with AP presence in ice cream mix, due to its higher time-temperature combination for pasteurization than milk, but AP tests may be useful on milk ingredients if they are suspected of improper pasteurization. Test methods for AP are outlined by Wehr and Frank (2004).

Microbiological Analyses

Microbiological analyses routinely done with frozen dairy desserts are the standard plate count (SPC), also called the aerobic plate count (APC) or the mesophilic APC (typically incubated at 32–25°C), and the coliform count or the enterobacteria count. Standards are commonly set at 20,000/g for the SPC and 10/g for coliforms or enterobacteria. Whereas the SPC method reveals numbers of most of the bacteria capable of growing in an atmosphere of air and at moderate temperatures, the coliform count method selects for pasteurization-sensitive Gram-negative, facultatively anaerobic bacteria capable of fermenting lactose and of growing in the presence of certain dyes and bile. Since both coliforms and enterobacteria are killed by pasteurization, the count in ice cream should be <1/mL unless contamination has occurred after pasteurization of the mix. A false positive coliform test can occur when other bile-resistant but lactose non-fermenting bacteria ferment other sugars present in ice cream. Therefore, confirmation of typical colonies is important. The enterobacteria include the coliform bacteria plus other similar Gram-negative bacteria that are able to ferment glucose. See Chap. 13 for a discussion of microbiology and safety of ice cream products.

Sampling for Microbiological Tests

Microbiological tests should be performed when there is need to reach a decision about an ingredient, a product or a process. When testing is to be done, a procedure for sampling should be followed that will maximize the probability that a correct decision will be made based on the results of testing. Samples must be representative and adequate in number to provide a low risk of error in the decision-making process. When test results are meant to provide a basis for acceptance or rejection or for classification as defective or not defective, "attribute sampling," e.g., of an ingredient or a product, is applied. Bacteria count is a frequently measured attribute. A second type of sampling, called "variables sampling," is usually applied to instrumental measurements of weights, temperatures pressures, etc. In cases in which the target analyte may not be distributed randomly, knowledge of the potential source of the analyte and of the overall process are vital to selection of sample numbers and sites to be sampled. For example, parts of filling equipment may be targets for sampling based on difficulty of cleaning and sanitizing. Frequencies and locations

for taking environmental samples for *Listeria* spp. and other important bacteria should be based on the probability of existence of the bacteria at the location as well as the probability of the bacteria being transported to the finished product.

All statistical sampling plans should be based on an acceptable quality level (AQL). An AQL of 0.1% reveals that the sampling plan and the method of detection provide no more than 1 chance in 1,000 that a product will be accepted when it does not meet the specification of the AQL. At this level of probability the "producer's risk" is quite low that a product will be rejected when it meets the AQL and, conversely, that the user's risk of receiving an unacceptable product is low. Sample size within a given lot determines the probability of accepting a defective lot. For example, the probability of accepting a lot having 5% defective units is 0.61 when 10 samples are negative but only 0.01 when 100 samples are found negative. When numbers of analytes are low, the probability of confirming on retest the presence of the defective analyte increases as the square of the incidence of the defect. For example, if 1 of 2 samples of a lot tests positive, a retest of a single unit has only a 1-in-4 chance of being positive. Similarly, if the defect is found in only 1 of 5 samples, 25 samples would need to be examined to obtain the same probability of finding a positive sample on retest.

Attribute sampling requires that the incidence of defects within a lot of product be randomly distributed. When the distribution is skewed or nonhomogeneous, "stratified sampling" can be done. Nonrandom distributions of bacteria sometimes occur in frozen desserts when, for example, filling equipment is contaminated so that product in the first packages of a lot contain many more bacteria than product packaged later in the lot. It is not within the scope of this book to provide details of sampling plans. Therefore, readers are referred to "Standard Methods for the Examination of Dairy Products" (Wehr and Frank 2004) for further details.

Microbiological Test Methods

Standard Plate Count. The SPC enumerates the microbial population of primarily mesophilic aerobic and facultatively anaerobic bacteria. The principle is that measured aliquots of product are introduced directly or diluted into or onto Standard Methods Agar using specific techniques. Plates are incubated aerobically at 32 ± 1°C for 48 ± 3 h. Determination of the number of microorganisms per mL or g of a sample is obtained by selecting plates containing 25–250 CFU/mL or g or selecting plates with counts closest to this range. For ice cream and related products, frozen samples are thawed up to 40°C for no more than 15 min and stirred to make homogeneous before weighing. For initial dilutions, aseptically transfer an 11 g portion into 99 mL of dilution buffer and make appropriate serial dilutions (Wehr and Frank 2004). Sampling and test methods for various ice cream ingredients are also described in "Standard Methods for the Examination of Dairy Products" (Wehr and Frank 2004). The Petrifilm methods for SPC are sample-ready plating procedures

with premade film plates that use a dehydrated cold water-soluble gelling agent, selective nutrients, and an indicator that facilitates colony enumeration.

Many rapid microbiological tests have been developed recently to avoid prolonged incubation methods, including antibody and nucleic acid-based methods, miniaturized biochemical kits, modified conventional methods, selective membranes, and ATP bioluminescence methods (Seo et al. 2006; Grossi et al. 2008; Bintsis et al. 2008).

Coliform count. The coliform count enumerates all aerobic and facultatively anaerobic, Gram-negative, non-spore-forming rods that are able to ferment lactose with the production of acid and gas at 32° or 35°C within 48 h. These include the genera *Escherichia*, *Enterobacter*, and *Klebsiella*. Coliforms isolated from pasteurized products suggest improper pasteurization and/or post-pasteurization contamination, indicating the presence of defective equipment or a need for improved plant sanitation. In this test, the sample is applied directly or decimally diluted and plated with violet red bile agar (VRBA). Plates are incubated for 24 ± 2 h at 32 ± 1°C. Confirmation of atypical colonies from VRBA plates should be made by transferring each of five colonies to 2% brilliant green bile (BGB) broth and incubating at 32°C or 35°C. BGB broth tubes showing gas after 48 ± 3 h of incubation represent confirmed colonies (Wehr and Frank 2004). Petrifilm coliform count plates are also available.

Some dairy products may contain injured cells (for example, as a result of recent heat treatment or freezing and thawing) that will not grow on VRBA with the specified procedures. To obtain more accurate results, the coliform test may be modified by using a resuscitation step in which the sample is first plated with Tryptic Soy Agar (Wehr and Frank 2004).

In those plants that experience very low counts of coliform bacteria, it may be desirable to use a more sensitive test for post-pasteurization contamination. By the addition of 1% glucose to violet red bile lactose agar all of the *Enterobacteriaceae* are able to grow in this medium and ferment a carbohydrate. This increases the sensitivity of the coliform type test to include all of the non-spore forming, facultatively anaerobic, Gram-negative rods that are killed by pasteurization. Excellent sanitary conditions are indicated when a very high percentage of samples tested at a 1:1 dilution show no colonies on plates of this medium. This is good evidence that pathogens, such as *Listeria monocytogenes* and *Salmonella*, have not entered the product. Use of this test for enterobacteria may be justified for another reason as well. False coliform tests can appear when sufficient glucose or sucrose are plated with the sample for non-lactose fermenters to produce enough acid to form deep red colonies in the agar. This sometimes happens with mixes high in these sugars when large amounts of sample are plated (Marshall 2001).

Other bacterial species and groups. "Standard Methods for the Examination of Dairy Products" (Wehr and Frank 2004) describes procedures for the enumeration of psychrotrophic bacteria, Gram-negative bacteria, thermophilic bacteria, aerobic bacterial spores, anaerobic sporeformers, yeasts and molds, and pathogens, including *Salmonella* spp., *L. monocytogenes*, and *Staphylococcus aureus*, amongst others. In some instances, it may be desirable to enumerate these nonpathogenic

organisms, especially if trying to identify the cause of high SPC or coliform counts. Pathogenic organisms should only be enumerated in certified, off-site laboratories. Standard Methods also describes methods for antibiotic and drug residues.

Counts of psychrotrophic bacteria may be useful in evaluating the quality of fresh milk and cream, especially if storage time has reached 3 days. However, the information obtained is not useful for the specific lot of raw material since it most certainly should be used before the results of analysis become available.

Counts can be made of culture bacteria in frozen yogurt by using a medium that is both selective for the target bacteria and able to differentiate the growing colonies. On plates of modified Elliker's lactic agar incubated at 37°C in an atmosphere of CO_2, colonies of *Streptococcus thermophilus* appear small and red whereas those of *Lactobacillus delbrueckii* subsp. *bulgaricus* appear large and white.

Surfaces. Tests for enumeration of the sanitary quality of equipment and containers are available (Wehr and Frank 2004). For equipment, the rinse solution method repeatedly flushes a measured volume of sterile, buffered sanitizer-neutralizing solution or nutrient broth over the product contact surface and then determines the bacterial population of the rinse solution by plating or membrane filter techniques. Large equipment assemblies can be checked by circulating water that has either been chlorinated and neutralized or sterilized by membrane filtration over or through the equipment. The increase in the bacterial population is determined by membrane filter techniques. Sanitation of assemblies can also be checked by sampling of product at successive points of access along the processing lines, to identify specific sites where contamination is being picked up.

Surface contact methods involve the replicate organism direct agar contact (RODAC) procedure, the Petrifilm aerobic count plate procedure, and the swab procedure, together with traditional plating or the ATP bioluminescence procedure (see details in Wehr and Frank 2004). Swab techniques should be used for surfaces with cracks, corners, or crevices. The RODAC and Petrifilm procedures are better used for flat surfaces such as walls, floors, ceilings, and some equipment surfaces. In the RODAC method, microorganisms on the test surface are transferred to a Standard Methods Agar plate by bringing the plate into direct contact with the surface and then incubating the plate for 24–48 h at 32°C and enumerating the resulting colonies. The swab technique consists of taking a sterile swab attached to a 12–15 cm long stick moistened in an appropriate solution and brushing it over a measured surface area. The swab is then rinsed thoroughly in a measured amount of sterile solution and the liquid is plated. This technique allows for the enumeration of colonies that can be isolated from areas that may be difficult to clean (due to these areas being irregular, rough-seamed, ridged, small, rounded with small radii or less conventionally reached). Food processing equipment and other environmental surfaces can also be sampled using the cellulose sponge swab technique, to swab larger areas than the stick applicator swabs (e.g., 1 m^2). The ATP bioluminescence procedure is a rapid, sensitive, and simple enumeration method that allows environmental sampling to become proactive, since results of interventions can be determined almost immediately. Various commercial systems are available.

Physical Analyses

Fat Globule Size Distributions in Mix

Fat globule size distributions are measured either as an indication of homogenizer performance or as a benchmark for changes in the emulsion as a result of freezing (fat destabilization, see below). The critical mean fat globule diameter in mix should be slightly less than 1 μm and the distribution should be fairly normal with a maximum size of the distribution at 2–3 μm. Any bimodal distribution with sizes larger than 2–3 μm are indicative of improper homogenization. When fat globules in the mix are very large, excess churning of the fat may occur during freezing. Single stage homogenization at a pressure of 10 MPa (1,450 psi) is sufficient to produce a favorable size distribution with cream as a fat source but higher pressures (15–17 MPa, 2,000–2,500 psi) may be required when using solid fat sources such as butter, butter oil, or vegetable fats. The second stage of a homogenizer functions to reduce the amount of clustering of the fat globules induced by the first stage. Fat globule sizes can be determined by light microscopy with an oil immersion lens (1,000×) plus eyepiece and stage micrometers for sizing. Dilution with glycerol may be necessary to inhibit Brownian motion.

Laser light scattering techniques (Bolliger et al. 2000a) may also be used, if such equipment as a Malvern MasterSizer is available (Fig. 14.1). Mix at refrigerated or ambient temperature is diluted approximately 1:1000 with pure water and size is measured directly by the instrument. These instruments report several different types of weighted mean size distributions. The $d_{4,3}$, a volume-weighted mean, and the $d_{3,2}$, a surface-weighted mean, put more emphasis on the larger particles, thus producing higher averages than a number-weighted mean. The relevance of these weighted means is that often a population of very small particles will skew a distribution to a small value although it is the quantity of larger particles that may be of more interest structurally. In some cases, weighted medians (e.g., $d_{50,3}$ for a volume-weighted median or $d_{50,2}$ for a surface-weighted median) are reported rather than weighted means. When observing fat globule size distributions of ice cream mix with laser light scattering equipment such as the Mastersizer, a separate peak for casein micelles at 100–300 nm may or may not be discernible, depending on the sizes of particles within each category, the relative volume fraction of each category, and the configuration of the equipment (for example, see Fig. 11.11, which shows the casein micelle peak, compared to Fig. 14.1, which does not). The casein micelles also affect the absolute values of weighted means from laser light scattering distributions, whether or not the peaks have been separated. Mendez-Velasco and Goff (2012) utilized a Malvern Mastersizer 2000 (http://www.malvern.com) with refractive index of 1.46 and 1.33 for the fat and water, respectively, absorbance of 0.001 and obscuration value in the range of 12–14% and found the casein micelle peak, which may have been expected at 100–300 nm, to be obscured by the high content of fat globules at 300–1,500 nm.

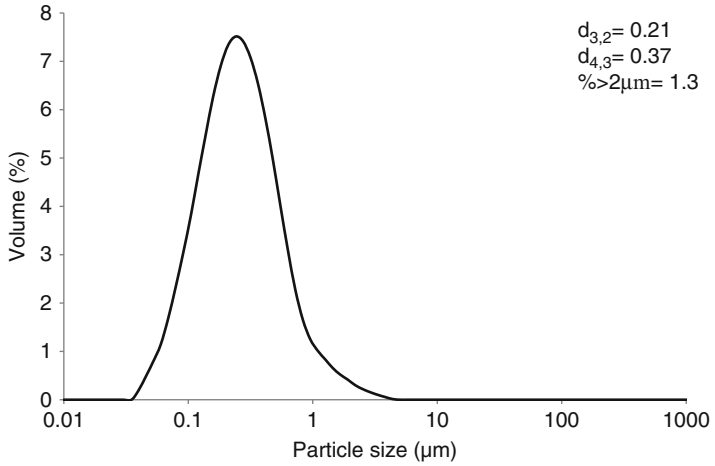

Fig. 14.1 The distribution of sizes of fat globules in an ice cream mix as determined by a laser light scattering technique (Malvern MasterSizer in this case). Volume- and surface-weighted means are shown for comparison. The maximum size of the normal distribution from proper homogenization is normally 2.0 μm

Freezing Point of Mix

The initial freezing temperature of ice cream mix provides an indication of the quantity of solutes present (mostly sugars) and the freezing characteristics to be expected from the mix. It is also used to further calculate the freezing curve (see Chaps. 7 and 11 for further discussion of freezing curves). Freezing point can be determined in the laboratory with a cryoscope (used to test freezing point of milk, although dilution may be necessary to bring it into the proper operating range), a vapor pressure osmometer, or a differential scanning calorimeter. Measurement of freezing curves can also be performed with a differential scanning calorimeter (Livney et al. 2003; Whelan et al. 2008). Freezing point depression and freezing curves can also be calculated with considerable accuracy (see Chap. 6, Mix Calculations).

Viscosity of Mixes

Viscosity, the resistance of a liquid to flow, is defined as the shear stress (σ, the imposed force per area, N/m^2 or Pa) divided by the rate of shear ($\dot{\gamma}$), the velocity gradient resulting in the liquid as a result of the applied shear stress, in m/s/m, or s^{-1}). The standard unit of viscosity is thus the Pascal-second, Pa·s (or frequently the mPa·s). The viscosity of water at 20°C (68°F) is 1.005 mPa·s (or 1.005 centi-Poise, cP, an older, non-SI unit). If the shear stress shear rate relationship is linear, i.e., if viscosity is constant regardless of applied stress, the liquid is said to be

Newtonian and the viscosity can be reported. An example of a Newtonian liquid is water. Ice cream mix, however, is usually pseudoplastic as a result of the protein and polysaccharide macromolecules that are dispersed in solution. As the shear rate increases, the viscosity decreases. Thus, to characterize the viscous behavior of an ice cream mix, both the underlying viscosity and the shear rate dependence are necessary. The Power Law is frequently used to characterize non-Newtonian liquids, which is given by

$$\sigma = K\dot{\gamma}^{n}$$

where K, a consistency index (equal to viscosity when $n = 1$), and n, a dimensionless number (Power Law Index) that indicates the closeness to Newtonian flow. For a Newtonian liquid n is 1; for a dilatant fluid n is greater than 1, and for pseudoplastic fluid n is less than 1. The term "apparent viscosity" is often used to describe the viscosity of a pseudoplastic material at one shear rate, e.g., 25 mPa·s at 100 s^{-1}. Also, ice cream mix exhibits thixotropy, which means that its apparent viscosity also decreases with time of applied shear stress. A defined pre-shearing time is thus required before the underlying viscosity can be measured.

The viscosity of a mix is affected by:

Composition—viscosity increases with increasing concentration of stabilizer, protein, corn syrup solids, fat and total solids, with the contribution of each decreasing in that order (i.e., stabilizer has more influence on mix viscosity than does fat). Also, heat and salts (such as calcium, sodium, citrates, phosphates) can affect the viscosity due to their effect on casein and whey proteins.

Processing and handling of the mix—elevated pasteurization temperatures, increasing homogenization pressures, and aging for up to about 4 h will each increase mix viscosity.

Temperature—as with all fluids, viscosity is temperature dependent, so decreasing storage temperature will result in increased mix viscosity.

There is no ideal mix viscosity, although viscosity values that are too low or too high will be indicative of problems. For fast freezing (rapid whipping) in modern equipment a lower viscosity seems desirable. In general, as the viscosity increases, the resistance to melting and the smoothness of texture increases, but the overrun decreases, especially in batch freezers or continuous freezers without good air flow. The mix should be properly balanced (in regard to composition, concentration, and quality of ingredients) and then properly processed to produce the desired whipping ability, body, and texture. Under these conditions, a desirable viscosity is assured. Viscosity values of ice cream mix are useful as indicators of whether there are any factors that may be influencing the mix unduly.

Mix viscosity can be measured quite simply by the time required to flow under a fixed pressure through a pipet or specially constructed tube (for example, gravitational flow from a 100 mL pipet held vertically), although it must be recognized that this would only measure apparent viscosity at the shear rate generated by the pipet orifice, which would be unknown, and would only generate a "flow time" value in

s, rather than a viscosity value in mPa·s. Viscosity is more appropriately measured as a function of varying shear rate or shear stress within a rheometer (there are several commercially available instruments). Power Law modeling would then generate K and n parameters. Probe geometries could include parallel plates or a small-angle cone and flat plate or concentric cylinders between which the mix is placed. Some viscometer instruments rotate a spindle or bob in a beaker of mix at varying rotation rates. In these types of instruments, the exact shear rate is unknown, so viscosity can be calculated as a function of speed to determine its pseudoplasticity. Temperature control is also essential in all of these instruments, since viscosity is strongly affected by temperature.

Density of Mixes

The density or specific gravity (density relative to water) of ice cream mix varies with composition. Measurements of specific gravity may be made with a hydrometer and of density by weighing a known and very exact volume of mix at a known temperature on a gravimetric balance. Density can also be calculated based on composition as shown in Chap. 6. The density of a mix may vary from 1.05 to 1.12 g/mL, with an average for a 10% fat mix of approximately 1.1 g/mL.

Adsorbed Protein to Fat Globules in Mix

Fat globules readily adsorb protein during homogenization to create a fat globule membrane and enhance stability. Emulsifiers are used to reduce this adsorbed protein level to induce appropriate levels of fat destabilization (see Chap. 11). The quantity of adsorbed protein to fat droplets can be quantified by first separating fat droplets from mixes by centrifugation (optimum conditions are 40°C, 10,000 g, 40 min; Segall and Goff 1999). The supernatant layer containing the protein-coated droplets is removed from the centrifuge tube with a spatula and spread on a filter paper to dry. The protein content in the adsorbed layer can be measured with nitrogen analysis (see above). Adsorbed protein is calculated by dividing the protein content of the supernatant layer (mg protein/g fat) by the specific surface area (m^2/g fat, determined by light scattering).

Phase Separation in Mix

Casein micelles will naturally migrate away from polysaccharides in solution, leading to the problem of phase separation in mixes (see Chap. 11). Carrageenan addition to stabilizer blends will often alleviate this problem. It can occur quickly and

can be evident in aged mix as a watery layer or it can appear more slowly, which is problematic for the packaging and distribution of mix for soft-serve operations. Mix instability can be monitored by storing samples in standard 500 mL glass jars at 5°C for several days and measuring the serum phase height present at the bottom of the mix. Serum separation can be calculated as the volume fraction of the mix (serum height/total height). The higher the serum phase quantity, the more unstable the mix. It should be noted that serum separation is slower in graduated cylinders than in wide-mouth beakers, perhaps due to wall effects, so jars or beakers are preferred as standard devices.

Overrun and Volume in Ice Cream

The weight per unit volume of product is an important physical characteristic affecting quality, and its minimum may also be a regulatory requirement. This is affected by the overrun developed in the product. When enough air is whipped into a mix during freezing to cause doubling of the volume, 100% overrun has been obtained. Thus, a mix weighing 1.1 kg/L would produce 2 L of ice cream weighing 0.55 kg each. Ice creams are classified by industry as super premium, premium, regular or trade brand, and economy. The overrun of super premium ice creams may be as low as 25%, whereas that of economy ice creams may be as high as 110% or more, or at the maximum limit if regulated (see Chap. 2). Overrun is calculated based on weight of a specific volume or volume of ice cream generated from a specific volume of mix (see Chap. 6 for details and examples). Weight control should be within +/−30 g for 2 L packages (1 oz/0.5 gal) and within +/−0.8% for 10 L or 3 gal containers. One percent overfill of ice cream at 100% overrun amounts to approximately 0.65 g, 5 g, and 10 g per package of 4 oz., 1 L, and ½ gal capacities, respectively. Variations in overrun, volume filled, and particulate content can account for differences in weight of filled containers. A statistics-based weight control program should be followed, including check tests of scales at least daily (see Chap. 10, Packaging).

Determining the volume of frozen novelties is often difficult. Tests usually involve immersion of the frozen novelty into a cooled liquid, such as glycol, and determining the amount of liquid displaced (Dubey and White 1997.) Handbook 133 of the National Bureau of Standards (1981).

Hardness of Ice Cream

Hardness of the product at typical serving temperatures is an important consideration, especially for retail dipping operations. Hardness is affected by several factors: principally initial freezing point (sugar content), total solids, overrun and amount and type of stabilizer. However, choice of the amount and type of stabilizer depends on factors other than hardness, and especially on the need to modify the

properties of ice and the aqueous phase to increase shelf life. When an ice cream store keeps several containers of product in a single cabinet from which each is to be dipped or scooped, only one temperature setting is available. Therefore, it is desirable to have the freezing curves and overruns of all flavors of ice cream nearly the same. This is not easy to accomplish because formulae involve several variables that affect the concentration of dissolved solutes and, therefore, the freezing curve.

Hardness can be determined with a penetrometer or a puncture probe placed on a texture analyzer to record force and deformation data. The resistance to penetration of the probe is measured repeatedly in ice cream that is adjusted to a precise temperature (Goff et al. 1995a). Comparisons to a reference curve enable decisions to be made regarding needs for changes in formulation.

Fat Destabilization in Ice Cream

The state of dispersion of the fat after freezing is another important structural characteristic. Fat undergoes partial coalescence during freezing and the extent of aggregation dictates properties such as shape retention after extrusion and melting rate of the frozen product (see Chap. 11). At least four different techniques can be used to evaluate destabilization (partial coalescence) of fat. The first is by dilution of both mix and ice cream (1:500 with water) and measurement of turbidity (absorbance) in a spectrophotometer with visible light at 540 nm (Goff and Jordan 1989). Dilution of the mix leaves a dispersion of fat globules that absorbs a certain amount of light based on the size and number of fat globules. After freezing, there are fewer individual fat globules and more, larger aggregates. Dilution of ice cream leaves a dispersion of fat aggregates that absorbs light to a different extent than does the initial mix. Amount of fat destabilized is taken as the percent of change in turbidity.

The second technique is by extraction of agglomerated fat with a mild solvent (Barfod et al. 1991; Bolliger et al. 2000a). This technique is based on the principle that as fat becomes less emulsified, it becomes more available to be dissolved in a mild solvent, whereas well-emulsified fat has sufficient protein membrane that it is not dissolved in the solvent.

A third and more sophisticated, but more useful, technique involves determination of sizes of agglomerates using laser light scattering, similar to determining fat globule sizes in a mix as discussed above (under the section “Fat Globule Size Distributions in Mix”). Ice cream is held at 4°C for a few hours to soften the samples, stirred manually and gently and added dropwise to the light scattering instrument (e.g., Malvern Masterizer), which dilutes the sample approximately 1:1,000 with pure water (Bolliger et al. 2000a). Degassing is not necessary under these conditions, as air bubbles are easily dispersed by the dilution effect of water. Partial agglomeration of fat results in a bimodal distribution of particle sizes: those remaining from the original emulsion and those formed by agglomeration (Figs. 14.2 and 11.11, which also shows the casein micelle peak). The percentage of the distribution greater than a cutoff size (e.g., 2 μm, which is typically the end

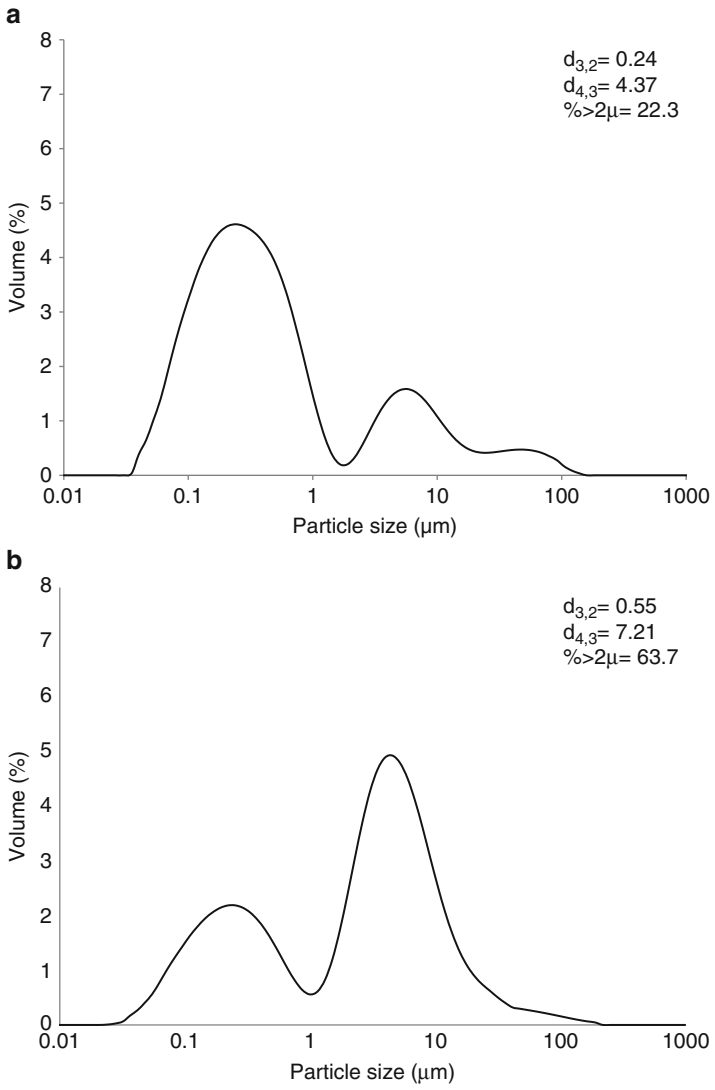

Fig. 14.2 Representative size distributions of fat globules and aggregates in ice cream determined by a laser light scattering technique (Malvern MasterSizer). Volume- and surface-weighted means are shown for comparison, although the distribution is bimodal. The percent of the distribution less than 2 μm allows for measuring the increase in fat aggregate size as a result of fat destabilization. (**a**) Low level of fat destabilization. (**b**) High level of fat destabilization

of the normal distribution of fat globules in a well-homogenized mix, see Figs. 14.1 or 11.11) correlates well with other methods of measurement of destabilization of fat. It should be noted that mean values of the distribution, such as $d_{3,2}$ or $d_{4,3}$, as defined above under the section "Fat Globule Size Distributions in Mix," do not adequately characterize bimodal distributions, although they can be used as

indices for approximate characterization of changes to the distribution caused by whipping and freezing. It should also be noted that aggregates are treated as spherical during measurement by the instrument, which is also only an approximation of the real shape. Light scattering has recently been used by Mendez-Velasco and Goff (2012) to discern different types of fat aggregates in complex ice cream formulations (non-dairy fats with saturated or unsaturated emulsifiers) by utilizing different dissociating solvents (SDS and EDTA). They recommend not using SDS or EDTA for routine size distributions in ice cream. SDS may sever the fat structure into separate particles while EDTA, depending on the droplet crystalline content, may yield artificially larger particles, causing inaccuracy or misinterpretation of results in both cases.

Finally, a simple technique is measurement of the percentage of fat in the ice cream that drips during a meltdown test (see next section) and comparing that to the original fat content in the ice cream as a whole (Bolliger et al. 2000a; Goff and Spagnuolo 2001). The premise here is that agglomerated fat will be held into a 3-dimensional fat network as ice cream melts and will not drip as readily through a mesh screen.

Meltdown of Ice Cream

Melting rate has the greatest significance to the consumer when the product is being eaten from a cone or stick. If the product melts too fast, a messy situation often ensues. A fast-melting product is undesirable also because it tends to become heat shocked readily. Low freezing point is the primary cause of rapid melting, environmental conditions being about equal. However, adjusting the formula to produce slow melt can cause slow release of delicate flavors. Products containing a high amount of air (high overrun) or fat tend to melt slowly. Air cells act as an insulator. Fat stabilizes foam structure. Treatments that destabilize proteins cause the curdy and free whey appearance of melted ice cream.

The meltdown of ice cream (Fig. 14.3) can be quantified by determining the mass that drips from the product through a mesh screen as a function of time when the product is allowed to melt while being held at a selected temperature (Bolliger et al. 2000a). The product must be of a uniform, standardized size for all comparisons. The test should be conducted in space that is free from any varying air currents that might affect heat transfer. Meltdown curves, plots of melted product versus time, can then be generated. In addition to drip loss, shape retention, which correlates well to fat destabilization, can also be assessed semiquantitatively or with photography. Commercial equipment is also available to conduct meltdown tests in this manner (http://www.certa-fides.com). The effects on meltdown due to changes in formula can be made by comparisons to melting properties of a "standard" formula. Since the rate of heat transfer should be constant for all tests, the rate of meltdown is largely affected by the freezing curve of the mix and the extent of agglomeration of fat within

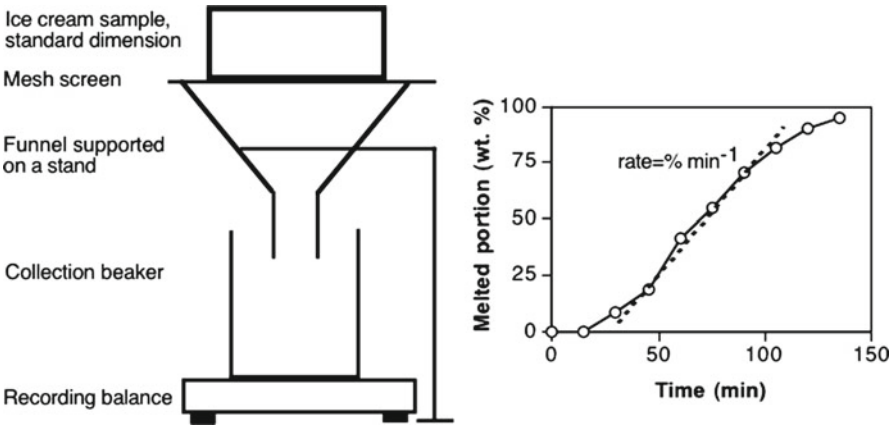

Fig. 14.3 Meltdown apparatus and typical melting curve for standard ice cream

the sample (except in products with low fat content). Therefore measurement of the percentage of fat in the dripped portion is a reliable indicator of the extent of destabilization, provided that the freezing curves are similar (Goff and Spagnuolo 2001).

Meltdown can also be assessed qualitatively by observing melting ice cream when scooped into a flat-bottom dish such as a petri plate. Clear dishes allow for product characteristics to show up well when the dish is lifted to allow light to shine through from below. The environment for testing melting quality should be clean, well-lighted, and about 20°C (70 °F). Ice cream with desirable melting quality begins to show definite melting within 15–20 min of having been dipped and placed at room temperature. Melting product flows readily and forms a homogeneous fluid with the appearance of the unfrozen mix and with little foam. *Curdy* melt means that irregularly shaped curd particles are seen floating in the melt. Causes include protein destabilization by acids, imbalance of salts (high proportion of calcium and magnesium versus phosphates and citrates), and over-stabilization, especially with certain gums that cause phase separation of proteins. *Does not melt* means the ice cream retains shape after 15–20 min in a glass petri dish. The common causes are excess fat destabilization and high overrun (see Chap. 11). *Foamy* means that large air bubbles retain their shape and presence in the melting product. Highly surface-active substances (emulsifiers and egg yolk) are responsible for the high stability of the foam. *Wheying off* means that watery fluid appears, and in it is often seen curd particles. The usual cause is protein destabilization or phase separation between proteins and polysaccharides as with curdiness. The addition of κ-carrageenan as part of the stabilizer usually prevents phase separation (see Chap. 11). *Low viscosity* means the melted ice cream is thin in appearance like milk. The cause is most often low solids in the mix. Appearance, causes, and remedies of melting quality defects are shown in Table 14.2.

Table 14.2 Major melting quality defects associated with ice cream, as characterized by the ADSA scoring system (adapted from Alvarez 2009)

Defects	Appearance	Causes	Remedies
Does not melt	Shape retention for long periods of time	Excessive fat destabilization or excessive stabilizer	Reduce freezer backpressure or freezing time, reduce emulsifier or stabilizer level
Foamy	Bubbles are clearly evident in melt	High overrun together with improper formulation of protein or emulsifier	Modify formulation
Curdy	Distinct particles evident in melt	Excessive fat churning or protein separation	Reduce fat destabilization; improve protein stability (check pH)
Wheying off	Clear serum separates during melting	Protein: polysaccharide incompatibility	Add κ-carrageenan

Ice Crystal and Air Bubble Size Distributions in Ice Cream

The structure of ice cream is characterized mostly by examining the state of dispersion of the fat and the sizes of ice crystals and air bubbles. Tests are performed immediately after freezing, after hardening, and after storage under predetermined conditions that usually include cycling of temperature for accelerated shelf life testing. Sizes of ice crystals (Donhowe et al. 1991) and air cells (Chang and Hartel 2002) in frozen ice cream can be measured with a light microscope. A sample is usually prepared as a smear diluted with a cooled solvent (Donhowe et al. 1991) or by cutting a thin section (Regand and Goff 2002). The microscope must be maintained in a temperature-controlled room (Bolliger et al. 2000b) or a refrigerated glove box (Donhowe et al. 1991), or be equipped with a cold stage (Regand and Goff 2003). Images obtained by microscopy can be transferred to a microcomputer for analysis. Application of image analysis enables large data sets to be analyzed, thus increasing accuracy in determinations of sizes of dispersed components.

Other more sophisticated microscopic methods can be used to gather structural information, particularly about the spatial distribution of the dispersed components. Both cryoscanning (Caldwell et al. 1992) and transmission (Goff et al. 1999) types of electron microscopy are applied. However, equipment for electron microscopy is expensive, and methods are costly and time-consuming.

Cryoscanning electron microscopy allows for visualization of surface features of a sample. Samples are frozen in liquid nitrogen and then fractured to produce new surfaces. Samples are then partially sublimated (freeze-dried) to remove a layer of ice from the ice crystals, thus accentuating structural features, coated with a thin layer of platinum or gold to prevent further sublimation, and viewed in the frozen state while under a high vacuum.

Transmission electron microscopy of ice cream requires either low temperature fixation followed by cutting thin sections at ambient temperature for viewing with a conventional transmission electron microscope, or cutting of thin sections at subzero temperatures followed by viewing on a cold stage (cryo) transmission electron microscope.

Confocal laser scanning microscopy on a cold stage has the advantage of permitting examination of the ice cream in the native state. The instrument scans thin parallel layers of a sample and can develop a three dimensional image from the data. This might allow for more spatial information on structural elements than cannot be gained from electron microscopy but as of yet has not been used much to produce published images of ice cream structure. Confocal laser scanning microscopy has been used to examine protein and polysaccharide phase separations in ice cream mix, see, for example, the methods and 2-dimensional images in Vega and Goff 2005.

Sensory Analyses

Most people enjoy ice cream due to its sensory attributes, which include a rich sweet flavor, a smooth, creamy, and viscoelastic texture, and a cold sensation that contrasts to the warmth of most other foods. The chemical and physical properties

imparted by the ingredients and the processes used in manufacture and handling largely determine the sensory properties, and these all have to be optimized to achieve perfection. This, in turn, requires proper evaluation of the sensory attributes of a product. Defects result from faults in flavor, body, texture, melting characteristics, color, package, microbial content, and/or composition.

The human senses most used in evaluating ice cream are taste, smell, touch (feel), and sight. Our perception of flavor is a unique combination of taste, as perceived by the taste receptors on the tongue, and aroma or smell, as detected when volatiles leave the food matrix in the mouth and are detected in the nasal cavity. While we can only detect four or five basic taste sensations, including sweet, salty, sour, and bitter, we can detect thousands of different aroma compounds. Thus, the best eating sensations come when food is allowed to warm in the mouth and held long enough to release the volatile aromas.

The analyses of sensory properties can be conducted for various reasons and each will require different testing methods and numbers of opinions. When looking for defined flavor or texture defects or to determine whether products meet specifications, only a few expert graders may be required. In formulation or flavor development or modification testing, the consensus opinion of several trained panelists may be necessary to choose the best options. Consumers are the ultimate judge but they may not have the training or the sensitivity to make informed evaluations. Nevertheless consumer panels ensure that the opinion of expert or trained panelists matches consumer's wishes. Since sensory detection abilities vary among individuals, as do preferences for various attributes, for consumer panels the number of opinions required is much higher than it is for trained and experienced panelists.

The ideal product possesses a typical, natural, fresh, clean, pleasant, and delicate flavor with a creamy and rich aftertaste. High quality unflavored ice cream tastes sweet, heated (cooked), nutty, and creamy or buttery. Flavor, sweetener, and dairy ingredients are in balance. Depending on the type and amount of flavoring added, all of these flavors except sweet may become imperceptible to all but the expert evaluator. Mild flavors like vanilla tend to mask little of the background flavor, whereas, chocolate masks other flavors well. The ideal body is sufficiently firm to give the sensation of abundant solid matter in the product, yet not so firm as to restrict easy dipping at the usual temperature. The product does not stick to the dipper or break apart when dipped. Texture of the ideal ice cream is velvety smooth and creamy. Neither ice crystals nor air cells are large enough to be detected by the tongue. The mouth is not coated with fat or any other substance on expectoration of the sample. The mouth remains comfortable with the low temperature when the product is eaten at a leisurely pace. The ice cream melts slowly into a liquid with the appearance of the original mix; has a natural color; any particulates, ripples or other inclusions are evenly and liberally distributed; and the bacterial count is low. Additionally, the product must meet the compositional specifications implied by its name plus the requirements imposed by the ingredient and nutritional labels.

The task of the ice cream formulator is to describe a mix that will provide the balance of ingredients to give consumers a product with the most desirable flavor, texture, color, appearance, and keeping quality at a price that is acceptable. The engineer must provide a process that enhances, or at least does not damage, these properties. The manufacturer must ensure that the ingredients are of high quality and that the process is performed correctly. Unfortunately, there are many factors that can affect the sensory properties adversely.

The sensory evaluation of ice creams, sherbets, ices, and other frozen desserts presents a difficulty not encountered with most other dairy products, in fact most other food products, namely temperature control. Body and texture are extremely dependent on temperature and the low temperatures required mean that proper handling is required to provide panelists with samples that are all at exactly the same temperature and the appropriate temperature for the formulation. If temperature control is not held consistent, the evaluations will be variable and potential defects in body, such as coarse/icy, will be missed.

Defects in flavor associated with mix ingredients have been discussed in Chap. 5 (Mix Properties) and associated with flavoring ingredients in Chap. 4. Some of the main flavor defects and their causes and remedies are summarized in Table 14.3. Defects in body and texture have been described in Chaps. 11 and 12. Some of the main body and texture defects and their causes and remedies are summarized in Table 14.4. Methods for various sensory evaluations will be discussed next.

Considerations for Effective Sensory Evaluation of Frozen Desserts

The evaluation of frozen desserts is no easy task. The analyst must be experienced, mentally alert, and have senses that are physically unimpaired. The environment must be clean, free of odors, well lighted, comfortable of temperature, convenient, and well equipped. A table or computer should be conveniently placed so results can be easily recorded.

Samples must be tempered at least overnight to a temperature of −15° to −13°C (5° to 8 °F). The tempering cabinet should have a uniform temperature throughout and should be monitored for such. This is most easily assured by placing all samples at the same height in the freezer. If samples are too cold, they are difficult to dip or spoon, and the cold tends to numb the mouth and tongue of the analyst. Samples that are too warm cannot be properly evaluated for body and texture attributes.

Samples within a formulation type should be examined in random order and presented so analysts do not know the identity. Products with a mild flavor and low fat content should be examined ahead of those with strong flavors and/or high fat content.

For calibration of the scales used by trained panelists, at least one negative and one positive sample should be presented to the analysts who should discuss

Table 14.3 Major flavor defects associated with ice cream, as characterized by the ADSA scoring system (adapted from Alvarez 2009)

Defects	Flavor note	Causes	Remedies
Unnatural	Wrong flavor note present	Poor-quality flavoring materials; errors in flavor addition	Use only high-quality flavoring ingredients
Cooked	Heated or burned milk	High pasteurization temperatures; high-heat milk powders	Maintain time-temperature control, especially batch pasteurization; use low-heat milk powders
Syrup flavor	Cotton-candy, caramel-like; unnatural sweetness with non-sucrose-like sweet profile	Excessive corn syrup solids, esp. unrefined CSS; other sweeteners	Modify formulation, obtain higher quality sweeteners
Acid	Sourness	Developed acidity in raw dairy ingredients from lactic acid bacteria	Maintain strict temperature control on farm and in raw milk storage
Salty	Salty	High content of whey powder; improper use of salted butter; too high salt addition	Maintain limits on whey powder use; use appropriate ingredients; do not add salt
Oxidized	Cardboardy, metallic	Dairy fat from cows with spontaneous oxidation; dairy or non-dairy fat exposed to metal ion catalysts	Monitor fat-containing ingredients for oxidation
Rancid (lipolyzed)	Blue-cheese	Damaged fat globules in raw milk; foaming of raw milk or cream; lipase activity; growth of psychrotrophic bacteria	Ensure that pumps do not excessively agitate or foam raw milk or cream; heat sufficiently before homogenization

Table 14.4 Major body and texture defects associated with ice cream, as characterized by the ADSA scoring system (adapted from Alvarez 2009)

Defects	Texture note	Causes	Remedies
Coarse/icy	Roughness in the mouth, but melts	Ice crystals of large size; low total solids, low or inappropriate stabilizer; inappropriate freezing processes; temperature fluctuation during storage	Modify formulation; modify process; maintain strict temperature control
Greasy	Mouthcoating or fatty sensation on the lips	Excessive fat content or fat destabilization; overchurning; excessive emulsifier	Reduce backpressure or freezing time; reduce emulsifier
Crumbly	Breaks apart easily during scooping	High overrun; low total solids; inappropriate stabilizer	Increase stabilizer; modify formulation
Fluffy	Light, airy, marshmallow	High overrun, inappropriate stabilizer	Reduce overrun; modify formulation
Gummy	Too chewy, heavy or sticky	High solids, low overrun; high or inappropriate stabilizer	Reduce stabilizer; modify formulation
Sandy	Chalkiness or roughness in the mouth, does not melt	Lactose crystallization; high lactose content; low or inappropriate stabilizer; temperature fluctuation during storage	Modify formulation; maintain strict temperature control
Weak	Melts rapidly in the mouth to watery texture	Low total solids, low or inappropriate stabilizer	Increase total solids or stabilizer level

them prior to assessment. These samples should be available during the assessment session, but there should be no intercommunication among analysts during this time.

In taking samples it is usually wise to remove the surface to a depth of about 1 cm unless the surface needs to be examined for a special purpose. Product at the surface may contain absorbed flavors and is subjected to the greatest chances of heat shock. Individual foam type plates are suitable for taking samples for tasting. Metal or plastic spoons are favored over wooden because they do not impart flavors. About 60 mL (2 fl oz) of sample is proper for each analyst to examine. Dippers are the best sampling instruments, and they always should be removed from the product. The analyst should never remove a sample with the personal spoon.

Appearance is evaluated by observing the cut surface of the frozen sample. Texture and body are determined by feel while cutting the sample with a spoon then chewing it and letting it melt in the mouth. Flavor and odor are observed as the sample melts in the mouth. Melting quality is assessed by observing samples of equal size and temperature as they melt in flat dishes at 22 +/−2°C. The detailed accepted sequence of examining samples is as follows (Alvarez 2009):

1. Examine the container for fill, shape, printing flaws, soil, and seal or closure.
2. Check the color intensity, hue, and distribution. Cut through samples containing inclusions to determine the quantity, quality, and distribution.
3. "Feel" the resistance of the product as it is scooped to determine the extent of gumminess, heaviness, fluffiness, or weakness of body. Place a scoop of sample in a glass or plastic petri dish to observe later for melt down characteristics. Set a timer to indicate when 15 min have elapsed to examine samples for melting qualities. The clear dish allows for easy observation of the homogeneity and quality of the melt.
4. Examine the body and texture of a small portion (about 1/2 teaspoon) taken into the mouth. The sample should be sufficiently firm that the analyst can bite into the product or manipulate it across the palate, tongue, and lips, to get a tactile feel of the texture (being careful not to induce pain from the coldness of the sample, which will dull the senses for further evaluations). Melting of the sample means that the sensations in the mouth are constantly changing and that the analyst must practice introspection (concentrate on the sample, shutting out all outside distractions).
5. Turn attention to the flavor. Usually this requires that a second sample be tasted. Again, the sensory characteristics change rapidly as the sample melts, so the analyst must keep mental notes of these characteristics and integrate them into thoughts that lead to a description in the end. Since flavor mostly comprises aroma, the sample must be manipulated and warmed in the mouth to release volatiles. The analyst must remember that cold dulls the senses and that it is important to allow the mouth to warm between samples as well as to allow each sample to melt completely during tasting. Sweetness suppresses other taste sensations and is fatiguing to the analyst. Fat can coat the taste receptors lessening flavor perception. Each of these factors argues for rinsing the mouth between

samples and taking time for the taste receptors to become refreshed between samples.
6. Check the meltdown dish(es) for melting qualities.
7. Record accurately and clearly the results of the analyses.

Manufacturers should find it valuable to conduct regular ice cream sensory evaluation clinics to compare their products with those of the competition and to give the employees responsible for the products valuable insights into the quality of the job they are doing. The following steps can be taken to organize an evaluation clinic:

1. Select a competent taste panel to evaluate and criticize (constructively) the products.
2. Choose a regular time, preferably at least once per month, to conduct the clinic.
3. Have an employee, preferably one who is not involved in the clinic, to collect samples of both the firm's and competitor's products from retail outlets. For some clinics choose the oldest samples in the display cases. Ensure that you are not comparing fresh samples from your storage facility to competitor's products from the market, since distribution can affect quality.
4. Transfer samples in refrigerated cases to the clinic site and temper them to −15 to −13°C (5–10 °F).
5. Place samples in randomly numbered paper bags or otherwise disguise them to avoid prejudicing the participants, by wrapping them in aluminum foil, for example.
6. Place samples in random order.

The steps in examination of the samples follow:

1. Dip into a petri dish a 50 mL (about 2 oz) sample for melt down tests.
2. Instruct each participant to use two spoons: one for dipping, one for tasting. Alternatively, provide a dipper for each sample and place it beside the container on a large plate.
3. Numerical scoring may not be necessary; score by quality class as excellent, superior, good, fair, or poor.
4. Provide for criticisms to be collected to provide insight into how to correct observed deficiencies. Tabulate and summarize the data, making results available to persons responsible for the products.
5. Follow up on the defective products to ascertain whether improvements have been made.

Sensory Methods

Three basic approaches are used to evaluate frozen desserts for sensory quality. These are (1) by experts working alone or in small numbers, (2) by trained panelists using formal sensory evaluation methods, or (3) by untrained consumers in large numbers. Experts who evaluate samples on an informal basis commonly refer to defect recognition score cards and scoring guides such as those developed by the

Committee on Dairy Products Evaluation of the American Dairy Science Association (ADSA) (see section "ADSA Scoring System and Quality Defect Recognition"). However, for formal sensory analyses, either trained or consumer panels are used. The IDF has established standards for evaluation of dairy products, including ice cream (IDF Standard 99C). This standard defines an expert assessor as a person "with a high degree of sensory sensitivity and experience of sensory methodology, who is able to make consistent and repeated sensory assessments of various products." A panel consists of "a group of expert assessors."

The standard gives instruction on the sampling and preparation of samples; the test room; recruitment, selection, training and monitoring of assessors; requirements for a panel; supervision; documents and equipment; and assessment. Furthermore, a scale is recommended that rates each chosen attribute in relation to the preestablished sensory specification as follows: 5—conforms, 4—deviates minimally, 3—deviates noticeably, 2—deviates considerably, 1—deviates very considerably, and 0—unfit for human consumption. Descriptions of the deviations should be given for samples scoring 1, 2, or 3. Furthermore, when scores of individual assessors fail to agree within one point, rescoring of the attribute is required. The mean value of the final score is then recorded. Terms used to describe sensory attributes should be listed in the order of most to least significance for the quality of the product.

An evaluation of the effects of various formulation or process variables on specific sensory properties of ice creams usually requires use of trained panelists who employ techniques such as difference testing or descriptive analysis and free choice profiling (Lawless and Heymann 1996; Drake 2009). Development of new products commonly involves screening of several formulations by a few experts followed by tests of a small number of prospective products by large numbers of consumers. A small panel of experts usually monitors the quality of finished products.

Difference testing compares a modified product to a standard to determine if the difference is notable. For example, triangle testing in which two products the same and one different are presented to a panelist who is asked to pick out the different one, is a common difference test. Appropriate statistical analyses can determine if the different sample was correctly identified by the panel. Descriptive analysis involves selection of qualified panelists, training these panelists and using them to describe the product attributes. Training consists of several sessions during which panelists, through examination of the type of product to be evaluated and related samples, produce a list of applicable descriptive terms on which they have come to agreement by discussion and consensus. Reference samples are developed for each descriptor. Similarly, free-choice profiling involves development of descriptors, but each judge develops a personal list of terms. Panelists then rate on a point scale the intensity of each of the terms selected with 1 = low and 9 = high intensity. Results of these types of analysis are tested statistically by analysis of variance and multivariate analysis of variance. Maps of the attributes,

as they relate to treatments and to each other, can be drawn by canonical variate analysis for descriptive analysis or by general Procrustes analysis for free-choice profiling (Drake 2009).

A useful technique for testing the time and intensity of flavor release in a food is called time-intensity evaluation. The technique can be applied in evaluating the effect of ingredients on the release of volatile flavors such as vanilla and chocolate. For example, it has been shown in ice cream that the higher the amount of milk fat, the slower the release of vanilla flavor.

Consumer panelists are chosen to represent the target market. Because they are untrained, numbers of panelists should be more than 50 and preferably closer to 100. Panelists may be asked to indicate preferences by ranking a few samples, or they may indicate their degree of liking on a numerical scale (called hedonic evaluation). A typical scale consists of nine points where 1 = dislike extremely, 2 = dislike very much, 3 = dislike moderately, 4 = dislike slightly, 5 = neither like nor dislike, 6 = like slightly, 7 = like moderately, 8 = like very much, and 9 = like extremely. Line scales can be used rather than numerical scales, although the latter tend to be preferred. For children, a smiley-face scale can be used that can easily be converted to a numerical scale. If desired, it is also possible at the same time to collect demographic (age, gender, income, education, etc.) or other personal attributes (e.g., shopping frequency or frequency of consumption of product categories), which can be correlated to sensory scores. Hedonic tests can be analyzed statistically when sufficient panelists are used (Lawless and Heymann 1996; Drake 2009). Focus groups can also be used to collect subjective information about the desires and preferences of consumers for various product attributes.

The ADSA Scoring System and Quality Defect Recognition

The ADSA has developed over many years scorecards for various dairy products, including frozen desserts, that can be used for grading (Clark et al. 2009). The system is based on evaluation for the presence of defined defects. If no defects are present, a perfect score is obtained. If any defects are present, depending on the severity of the defect and its intensity (slight, definite, pronounced) a reduced numerical score is given. The advantages of this system are that it describes the collection of defects for products that have been recognized, developed, discussed, and debated by experts for many years. Also, once effectively trained, a few expert opinions can easily detect product quality problems and find appropriate remedies for them (see Tables 14.2, 14.3 and 14.4). Reliability of scores placed on ice cream depends heavily on the judge's concept of the ideal product as well as an ability to recognize slight deviations from the ideal. The latter is accomplished by considerable practice with other knowledgeable analysts and by tasting products with known types and intensities of defects.

Although this system is used for competitions, as described below, for manufacturers as a quality tool, defect recognition is the most critical aspect, thus the score itself is perhaps less important. This evaluation system also has some other drawbacks. It should not be used in a sensory evaluation panel. The "score" assigned is not linear, since it could come from a variety of defect combinations each with their own "markdown" so cannot be evaluated with statistical analysis. It does not give any indications of intensity, preference, or liking of positive attributes and thus is not a replacement for trained or consumer panels or consumer focus groups. Rather, the sensory methods described above should be considered among the more sensory evaluation tools (Drake 2009).

This ADSA grading system is used regularly in the Collegiate Dairy Products evaluation contests sponsored by the ADSA, the International Association of Food Industry Suppliers (IAFIS), and the International Dairy Foods Association. Teams from many universities across North America have competed in various competitions that have spanned several decades. Ice cream companies contribute product, time, facilities, and money to support these contests. Once trained, the abilities of competitors to identify defects and to place a score on them is usually far superior to the abilities of consumers. This makes these trained persons valuable to manufacturers who should desire to have defects detected and corrected before they become objectionable to consumers.

The scorecard in Fig. 14.4 is a modification of the ADSA scorecard for ice cream. It lists the various identified defects in flavor, body and texture, color, appearance and package, and meltdown. Flavor defects and their causes and remedies are shown in Table 14.3, likewise body and texture defects and their remedies and causes in Table 14.4, and meltdown defects and their causes and remedies in Table 14.2. Samples are evaluated for the presence of the defect and its intensity, which are noted on the scorecard. A defect is considered "slight" when recognized by the experienced judge or the "connoisseur" but not by most consumers. It is "definite" when detectable by many consumers and "pronounced" when detectable by most consumers. Professionals in the Dairy Foods Division of the ADSA have developed the scoring guide for vanilla ice cream (Table 14.5). According to the severity of the defect and its intensity recommended scores are provided. A slight cooked flavor, for example, is not nearly as severe as a slightly rancid sample, so the allotted score reflects that. Likewise, the defect *too high flavor* gets small point deductions as it is only a minor defect and could be easily corrected. On the scorecard (Fig. 14.4), flavor is rated on a scale of one to ten. Body and texture scores range from 1 to 5 as does the category containing color, appearance, and package. Melting quality is given three points and bacteria content two points (although perfect scores are given automatically for this attribute). This makes a total of 25 points. As mentioned above, grading itself is far more important for manufacturers than scoring and the recognition of defects (Table 14.5), their severity and their causes and remedies (Tables 14.2, 14.3 and 14.4) provides the manufacturer with a great deal of information to assist in the production of product of excellent quality.

ICE CREAM SCORE CARD

PRODUCT: _____ **DATE:** _____

FLAVOR: _____

Sample Number	1	2	3	4	5	6	7	8	9	10
Flavor, No Criticism=10 Score =										
Flavoring System										
Lacks fine flavor										
Low flavoring										
High flavor										
Unnatural flavor										
Sweeteners										
Low sweetness										
High sweetness										
Syrup Flavor										
Processing										
Cooked										
Dairy Ingredients										
Acid										
Salty										
Lacks freshness										
Old ingredient										
Oxidized										
Rancid										
Whey										
Other										
Storage										
Body and Texture, Score = No Criticism=5										
Coarse/icy										
Greasy										
Crumbly										
Fluffy										
Gummy										
Sandy										
Soggy										
Weak										
Color, appearance/ Score = Package, No Criticism= 5										
Dull color										
Nonuniform color										
High color										
Pale color										
Unnatural color										
Soiled container										
Product on container										
Underfill/overfill										
Damaged container										
Defective seal										
Melting Quality, Score = No Criticism= 3										
Does not melt										
Flaky										
Foamy										
Curdy										
Wheying off										
Watery										
Bacterial count, No criticism = 2										
Total, No criticism=25										

Fig. 14.4 A modified version of the ADSA ice cream score card (adapted from Alvarez 2009)

Table 14.5 ADSA scoring guide for sensory defects in vanilla ice cream (adapted from Alvarez 2009)

	Slight	Definite	Pronounced
Flavor, no criticism = 10			
Flavoring system			
Lacks fine flavor	9	8	7
Low flavoring	8	6	4
High flavor	9	8	7
Unnatural flavor	8	6	4
Sweeteners			
Low sweetness	9	8	6
High sweetness	9	8	7
Syrup flavor	9	7	5
Processing			
Cooked	9	7	5
Dairy ingredients			
Acid	4	2	0
Salty	8	7	5
Lacks freshness	8	7	6
Old ingredient	6	4	2
Oxidized	6	4	1
Rancid	4	2	0
Whey	7	6	4
Other			
Storage	7	6	4
Body and texture, no criticism = 5			
Coarse/icy	4	2	1
Greasy	4	2	1
Crumbly	4	3	2
Fluffy	3	2	1
Gummy	4	2	1
Sandy	2	1	–
Soggy	4	3	2
Weak	4	2	1
Color, appearance, package, no criticism = 5			
Dull color	4	2	0
Nonuniform color	4	2	0
High color	4	2	0
Pale color	4	2	0
Unnatural color	4	2	0
Soiled container	3	1	0
Product on container	4	2	0
Underfill/overfill	4	2	0
Damaged container	3	1	0
Defective seal	2	0	0
Melting quality, no criticism = 3			
Does not melt	3	2	1
Flaky	3	2	1

(continued)

Table 14.5 (continued)

	Slight	Definite	Pronounced
Foamy	3	2	1
Curdy	3	2	1
Wheying off	3	2	1
Watery	3	2	1

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Chapter 15
Formulations for Specialty Products

Introduction

Ice cream formulations were discussed in Chap. 2, mix ingredients in Chap. 3 and mix calculations, to turn formulations into recipes based on ingredients, were demonstrated in Chap. 6. Ice cream, as defined in Chap. 2, makes up the vast majority of the frozen dairy desserts market; however, there are a number of other frozen dairy desserts and non-dairy frozen desserts that can be manufactured to offer further choice to consumers. This chapter will review formulations for light, low-fat and nonfat products, no-sugar-added and sugar-free formulations, reduced and lactose-free formulations, gelato, frozen yogurt, sherbet, water ices and sorbet, and vegetable protein-based desserts. Most of these formulations make use of the ingredients already discussed in Chap. 3 and mix calculations shown in Chap. 6 are still required, in most cases, to balance mixes based on ingredients used. Many manufacturers offer a range of products, including many of those discussed here, to augment their mainstay ice cream formulations.

Light, Low-Fat, and Nonfat Formulations

As fat is removed from ice cream formulations, other ingredients must be added to keep the water content within reasonable limits for two reasons: (1) too much water means too much ice in the frozen product resulting in a very hard and very cold and icy product with weak body and poor keeping quality, and (2) regulations may stipulate a minimum concentration of food solids or dry matter. It is possible to formulate reduced-fat or "light" ice creams, down to about 4–5% fat, with traditional ingredients (Table 15.1). Total solids is reduced slightly but some of the displaced solids is made up with slightly enhanced levels of sugar (to maintain similar freezing curve to regular ice cream in the presence of more water), and slightly enhanced levels of corn syrup solids and stabilizer, to enhance viscosity and body. A new development in the arena of commercial light products has been the application of the low-temperature extrusion process, which takes ice cream from −5 to −12°C

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Table 15.1 Suggested mixes for low-fat ice cream or ice milk products (4–5% fat) and light ice cream products (6–8% fat)

	Percent (%)			
Milk fat	4.0	5.0	6.0	8.0
Milk solids-not-fat	12.5	12.5	12.0	11.5
Sucrose	12.0	12.0	12.0	12.0
Corn syrup solids	6.0	5.5	5.0	5.0
Stabilizer[a]	0.35	0.35	0.35	0.35
Emulsifier[a]	0.10	0.10	0.15	0.15
Total solids	34.95	35.45	35.5	37.0

[a]Highly variable depending on type; manufacturers recommendations are usually followed

under defined shear conditions in a screw extruder, to enable reduced-fat products with similar textures to their full-fat counterparts due to reduced ice crystal and air bubble size distributions. See Chaps. 7 and 11, for more details regarding low-temperature extrusion.

However, with low-fat products, less than 4% fat, there exists a greater product development challenge and the need to utilize fat replacers. Traditionally, fat replacers have been classified in relation to the materials that comprise them: carbohydrate, protein, or fat-based. Water-soluble carbohydrate polymers typically used in low-fat formulations include cellulose products, starches, dextrins, maltodextrins, and polydextrose. Carbohydrate-type fat replacers contribute bulk and increase viscosity while helping to limit growth of ice crystals. The common sources of protein-type fat replacers are cheese whey and egg white. These proteins are processed into colloidal particles that vary in diameter from 0.1 to 3.0 mm, a size range that permits them to be sensed on the tongue as creamy. Monoacylglycerols and diacylglycerols are useful in low concentrations (<1.0%) as fat-based fat mimetics. Fat replacers are discussed in detail in Chap. 3.

Fat-free formulations typically contain 12–13% milk solids-not-fat along with a combination of sugars (sucrose and corn syrup solids), either high molecular weight carbohydrates or protein-based fat replacers, and appropriate stabilizers. Suggestions for sweetener and fat mimetic combinations include:

- Sucrose 12%, maltitol 10%, corn syrup solids 4%.
- Sucrose 8%, 36 DE corn syrup solids 9%, whey or egg protein-based fat replacer 5%.
- Sucrose 15%, 5 DE maltodextrin 3%.
- Sucrose 14%, 10 DE maltodextrin 7%, 5 DE maltodextrin 2%.
- Sucrose 11%, 36DE corn syrup solids 8.5%, 5 DE maltodextrin 2%, polydextrose 2%.
- Sucrose 10%, 36DE corn syrup solids 9%, 10 DE maltodextrin 2%, whey or egg protein-based fat replacer 1.5%.

A suggestion for a sweetener and fat mimetic combination in a fat-free, sugar-free formulation includes:

- 8% polydextrose, 5% sorbitol, 5% 10 DE maltodextrin, 1% microcrystalline cellulose, 0.023% acesulfame K, 0.023% aspartame.

Flavoring Low-fat and Nonfat Frozen Desserts

Decreasing the fat content of ice cream decreases the creamy sensation and increases the intensities of flavors of skim milk powder and of corn syrup. It also impacts on added flavors, since there are many flavor components that are fat soluble, which are released to the olfactory senses as fat melts. If there is insufficient fat to carry these flavors, they are perceived quickly and tend to disappear relatively quickly from the flavor profile. Panelists found the peak intensity of flavor occurred significantly earlier during tasting of ice creams containing pure bourbon vanilla and 0–1% fat than with ice creams containing the same vanilla and 2, 4, 6, 8, or 10% fat. No significant difference was observed among the 2–10% fat group (Li et al. 1997). Free vanillin concentration, determined by HPLC, was 10% lower in ice cream containing 10% fat and 39.5% total solids that in ice cream containing no fat and 34% total solids. Hyvonen et al. (2003) showed similar results with strawberry ice cream, a more intense flavor and a faster flavor release in the absence of fat compared to 5% fat or higher. No differences in flavor profiles were seen between 5 and 18% fat. Likewise, Frøst et al. (2005) showed faster increases and subsequent decreases in dynamic flavor perception with lower fat levels in 3% fat ice cream compared to 6% or 12%.

Fat replacers used in nonfat and low-fat ice creams usually consist of modified whey proteins or starch hydroylsates. Both tend to bind and to mask delicate flavors. Whey proteins, for example, even in concentrations as low as 0.5%, are prone to bind aldehydes through hydrophobic interactions. As little as 1% milk fat can reduce the vapor pressure of flavorful substances, which impacts their volatility and hence their release and detection in the mouth. Hence the balance of volatile components needs to be varied considerably in developing flavors for nonfat frozen desserts, depending on the ingredients.

Ohmes and Marshall (1998) showed that vanillin intensities did not vary among three whey-based fat replacers added at a concentration of 4.8% to nonfat ice cream, the control low-fat ice cream that contained 4.8% milk fat, and a second control that contained 4.8% additional nonfat milk solids. However, the control that contained milk fat had lower "syrup, whey, and cooked milk" flavors than the other four samples. Samples containing a whey protein-based fat replacer (Simplesse) did not differ from either control in texture, while those containing a carbohydrate-based fat replacer were smoother and more gummy than the controls. Similarly, Liou and Grün (2007) showed that the flavor and flavor release profile of 4% fat strawberry ice creams were more similar to the 10% fat control if the fat mimetic used was protein-based rather than polydextrose-based.

Regular fat (9%) and reduced fat (6%) chocolate ice creams were more smooth and creamy in texture, had a less intense cocoa flavor, and melted more slowly compared with low-fat (4%) and nonfat (<0.5%) ice creams when all samples were adjusted to the same total solids (41.6%) with equal portions of Simplesse and polydextrose (Prindiville et al. 1999). Furthermore, fat protected against damage from heat shock. Some flavors are compatible with fat replacers. In tests by the same researchers (Prindiville et al. 2000) low-fat (2.5%) chocolate ice cream had a less

intense cocoa flavor and was more resistant to textural changes over 3 months of storage than samples containing 2.5% of either cocoa butter, Simplesse, or Dairy Lo (see Chap. 3, Fat Replacers). Each of the latter is a whey protein-based fat replacer. Examinations by gas chromatography–mass spectrometry of the headspace volatiles of the samples of chocolate ice creams described above revealed that concentrations of most of the selected volatiles were negatively correlated with concentration of fat and were higher in the presence of fat replacers instead of an equal amount of milk fat (Welty et al. 2001).

Flavors that tend to be complementary to fat replacers are butterscotch, butter pecan, and cheesecake. These "heavier" flavors tend to cover flavors contributed by the fat replacers while providing flavor notes that blend well with those of the typical nonfat product.

No-Sugar-Added and Sugar-Free Formulations

The global rise in prevalence of Type II diabetes mirrors the global epidemic in obesity. Diabetic people have an impaired capacity to decrease blood glucose levels after consumption of high sugar-containing products. For these people, the large amount of sucrose and glucose normally used in ice cream needs to be replaced with an acceptable sweetener, to lower the glycemic index of the product. The sugar alcohols, or polyols, have been the sweeteners of choice, since they are absorbed much more slowly than glucose. When substituting sweeteners in ice cream formulations, the factors to be considered include sweetness, freezing point depression, and contribution to total solids. Sorbitol (a monosaccharide) has been used for many years but the intake of sorbitol must be restricted because of its laxative nature. Other polyol sweeteners include xylitol or mannitol (both monosaccharides) or maltitol or lactitol (both disaccharides). These sweeteners allow matching of the freezing curves to conventional formulations due to their freezing point depression characteristics. If necessary, sweetness levels can be boosted with a nonnutritive high potency sweetener such as aspartame or sucralose, but these by themselves do not contribute to total solids or freezing point depression. Likewise, total solids or viscosity (bulk) can be enhanced with a product like polydextrose, but this by itself does not contribute either sweetness or freezing point depression. Thus careful blending of alternative sweeteners is required to provide all of the necessary functional properties when producing no-sugar-added products. Sugar-free products have the added complication of needing to eliminate lactose from the milk solids not-fat component of the mix, which can be done through either lactose hydrolysis or with the use of milk protein-derived ingredients as sources of MSNF.

Several recent published papers have shown the potential for maltitol as a polyol sweetener for ice cream. Ozdemir et al. (2003) produced diabetic ice cream using maltitol, sorbitol, and high fructose corn syrup as the sweetening agents and compared them to a sucrose-sweetened control. Sensory analysis showed that maltitiol-based ice cream was more preferred than ice cream containing sorbitol. Bordi et al. (2004)

compared a regular 12% fat vanilla ice cream and a maltitol-sweetened ice cream using a large taste panel and showed an overall consumer preference for the maltitol-sweetened ice cream. Whelan et al. (2008) examined a number of polyol sweeteners in low glycemic index formulations. Once the freezing curves were matched, other physicochemical properties also were found to match. Sweetness and sweet taste then could be adjusted for sensory optimization with a combination of these sugars and supplementation with sucralose to boost the sweetness as necessary. Their results showed that an acceptable low-GI ice cream cannot be produced without satisfying the need for dairy and vanilla flavor as well as desired sweetness. A strong correlation was found between perceived dairy flavor, sweetness liking and vanilla flavor. From the formulations studied, a combination of tagatose (6%), polydextrose (6%) and maltitol (3%), or maltitol (15%) and trehalose (2.5%), made with milk, cream, and MPC, showed to be potential formulations that could satisfy both physicochemical and sensory requirements. Several products are currently on the market that are sweetened with maltitol and sucralose, the maltitol provides the physicochemical characteristics while the sucralose boosts the sweetness level.

Suppliers continue to make available increasing numbers and varieties of sugar-free fruits and chocolate products, including blueberry chunks, raspberry, and strawberry revels and purees, chocolate flakes and chunks, chocolate revel, and chocolate-coated peanuts and almonds.

Reduced-Lactose and Lactose-Free Ice Cream

A significant number of consumers suffer from some degree of inability to completely digest lactose. These lactose malabsorbers sometimes experience discomfort in the lower bowel when lactose that escapes being absorbed in the small intestine is fermented into acid and gas in the colon of the individual. This can cause gas pains, and, in severe cases, diarrhea. Four approaches can be used to reduce the possibility of an individual experiencing lactose malabsorption from frozen dessert products. First, the consumer may select ice creams high in fat. The higher the fat content of the ice cream, the lower the MSNF content and, consequently, the lower the lactose content. High fat ice creams tend to be the super-premium types, and the source of MSNF in such ice creams is usually limited to skim milk solids. Skim milk solids contain about 50% less lactose than do whey solids. The latter may replace up to one-fourth of the MSNF in ice cream, and whey solids, being low in cost, are often used to the extent permitted to replace skim milk solids in economy ice creams. A second approach is to consume ice cream at the end of a meal. This ensures relatively slow flow of lactose through the digestive system and reduces the load on the enzyme that is present. It also presents a more dilute solution of lactose to the colonic bacteria. The third approach is to consume frozen yogurt. This product, properly prepared, carries living yogurt bacteria that have already fermented part of the lactose in the skim milk solids used to make the yogurt. To the extent

these bacteria remain alive to the time of eating they supply lactase to the human intestine.

The fourth approach to alleviating lactose malabsorption is to reduce or eliminate lactose from the frozen dessert. This can be done by hydrolyzing the lactose with purified β-D-galactosidase before the product is frozen. The enzyme is relatively expensive and several hours are needed for the process. Furthermore, since two molecules are produced for each lactose molecule split, freezing point of the mix may be lowered excessively. Another approach is to remove lactose from skim milk by ultrafiltration and diafiltration. In diafiltration after about one-half of the volume is removed by ultrafiltration, water is added to the retentate and ultrafiltration is continued until the volume is again reduced to about 50% of the initial volume, thereby continually washing out low molecular weight soluble compounds, including lactose, into the permeate. The removal of lactose by ultrafiltration reduces the concentration of dissolved solids in the product and raises the freezing point. On the contrary, hydrolysis of the lactose produces two molecules for every lactose molecule hydrolyzed and therefore, lowers the freezing point. Removal of 50% of the lactose by ultrafiltration/diafiltration followed by enzymatic hydrolysis of the remainder provides concentrated skim milk solids with about same freezing point as concentrated skim milk of the same solids content.

Gelato

Italian-style ice cream is referred to as gelato, which is the Italian word for ice cream. However, there are significant differences between traditional gelato and North American-style ice cream. Gelato is lower in fat and total solids than regular ice cream but typically higher in sugar content, to give it a soft, scoopable texture. A typical formula might contain 8.0% milk fat, 7.5% MSNF, 16.0% sugar, and optionally up to 4.0% egg yolk solids. Usually fresh dairy ingredients, cream, milk, and cocnetrated skim, are used to supply the milk fat and MSNF. Note that no stabilizer or emulsifier is recommended in this formula. It carries abundant rich flavor and has very low overrun (20–40%). It is often flavored with liqueurs and various combinations of fruit and is available in a large number of flavors usually based on fresh ingredients. The low overrun and high solids provide the distinctive body and texture and desirable release of flavor. While it is not extruded directly for consumption as is soft serve, gelato typically is frozen in a batch freezer and not hardened as such, but rather drawn into shallow tubs from which it can be scooped with a characteristic gelato paddle-shaped scoop. It is kept at appropriate temperatures at which the frozen product is pliable and sticky, which gives gelato a more warm-eating experience. Gelato is typically produced fresh daily in relatively small quantities.

Batch freezers for gelato production vary slightly from traditional batch freezers for ice cream production. The freezer has to be designed for low overrun, so typically dasher speed is low. The low overrun places more demand on the motor load due to its heavier density so the torque has to be sufficient to obtain the desired low

draw temperature. Hence companies like Carpigiani, Technogel, and Taylor all produce batch freezers designed specifically for gelato production.

Frozen Yogurt

Yogurt is a well-established dairy product, and is generally characterized by live microorganisms and developed acidity (lactic acid) from fermentation of lactose by the bacterial culture. The acidity destabilizes the casein micelles in the milk, and they, in turn, establish the typical acid gel. Frozen yogurt, therefore, should be much like the unfrozen version, and be characterized also by live microorgansims and developed acidity from fermentation. Although there are no regulatory standards for frozen yogurt in most countries, these characteristics help to maintain consumer confidence and respect the meaning of yogurt. The example formulation provided below is typical of a more traditional frozen yogurt. However, a wide range of products exists in the marketplace, including those in which the acidity is not developed by bacterial culture but has been added in the form of citric acid and in which yogurt flavors or yogurt powders are used to provide yogurt-like flavor characteristics.

The frozen yogurt market in the United States has been quite cyclical. Of the 1,600 million US gallons of frozen dairy desserts produced in 2010, less than 5% or 74 million gallons was frozen yogurt. Approximately 2/3 of the frozen yogurt is soft-frozen, the remainder is hard frozen (USDA, National Agricultural Statistics Service, as reported by the International Dairy Foods Association in Dairy Facts). However, from 1993 to 1995, it averaged 150 million US gallons per year and at its peak represented 10% of the US market of frozen dairy desserts. From 1997 to 2000 it averaged 92 million US gallons per year and from 2003 to 2009, it averaged 70 million US gallons per year.

Like most frozen dairy desserts, frozen yogurt contains milk fat, milk solids-not-fat, sweetener, stabilizer, emulsifier, and water. It is low in fat, typically 2–4%. It may contain any of numerous flavoring agents, but it is most often flavored with fruits. Most often, plain, unsweetened yogurt is added to a sweet, pasteurized mix. The yogurt ingredient is cultured with a mixture of *Lactobacillus delbrueckii* sbsp. *bulgaricus* (commonly *Lactobacillus bulgaricus)* and *Streptococcus salivarius* sbsp. *thermophilus* (commonly *Streptococcus thermophilus)* bacteria after the milk has been pasteurized. Usually a very high heat treatment, e.g., 85°C (185°F) for 15 min, is given to the milk before it is inoculated with the yogurt culture, to ensure no residual bacterial species will grow during the incubation step. The minimal acidity of 0.30% that is required by some regulatory authorities is used to set a theoretical minimum amount of yogurt to be added to the mix. The amount added by most manufacturers ranges from 10 to 20% of the total weight of the mix.

In general manufacturers attempt to limit the amount of the acetaldehyde flavor in the frozen yogurt, believing that most customers do not prefer that flavor which characterizes plain yogurt. Yogurt definitely has a somewhat acidic flavor as compared with low-fat ice cream containing the same amount of fat. The apparent

reason that frozen yogurt has been preferred over a similarly comprised and prepared low fat ice cream product is that the yogurt bacteria are thought by many people to assist in digestion of lactose and to have other health-promoting properties (probiotic effects). Probiotic cultures colonize in the colon, produce various short chain fatty acids, lower the colonic pH, and modify the growth rates of other colonic species. The yogurt culture organisms are not probiotic *per* se, although several species of lactic acid bacteria have been shown to have probiotic properties, including *Lactobacillus acidophilus*, *Bifidobacterium*, and *Lactobacillus casei*. Hence several frozen yogurt products in the market contain one or more of these species along with the yogurt-fermenting strains. Attempts to provide high numbers of probiotic bacteria in frozen yogurts are hampered by the susceptibility of the organisms to low pH and destruction during freezing. Addition of prebiotic components to frozen yogurt provides preferred nutrients to the probiotic bacteria that survive in the human intestinal tract, thus improving chances that the culture will colonize the small intestine of the host. Examples of prebiotics include fructooligosaccharides or inulin from sources like Jerusalem artichoke or chicory root.

A typical frozen yogurt formulation and processing instructions are as follows. A mix containing 2.5% fat, 14.4% MSNF, 18.75% sugar, and 0.44% stabilizer is pasteurized, homogenized, cooled, and aged (typical for ice cream processing). This can be prepared with traditional fat and MSNF ingredients like cream, milk, skim milk powder or condensed skim milk, or with alternative ingredients such as milk protein concentrates. This mix is combined at 80% with 20% plain, unsweetened yogurt and blended to make the frozen yogurt mix, which is then flavored and frozen as for ice cream, either for hard-pack or soft frozen. Soft serve products, including frozen yogurt, are discussed more fully in Chap. 8. The yogurt can either be purchased as plain, unsweetened yogurt or it can be prepared by blending skim milk and skim milk powder to 12.5% MSNF, pasteurizing this milk at a high temperature (e.g., 85°C (185°F) for 15 min), cooling to 40–43°C (104–110°F), inoculating with a yogurt culture (typical of yogurt processing), incubating for 4 h or until fermentation is complete (to the desired acidity), and cooling to 4°C. After blending at 80/20, the final composition will be 2% milk fat, 14% MSNF, 15% sugar, 0.35% stabilizer, and 31.35% total solids. This frozen yogurt would meet the characteristics of developed acidity and live microorganisms.

Cell viability during storage of frozen yogurts has been investigated. Recent studies have shown <1 log cycle reduction in lactic acid bacteria at −23°C for >60 weeks (Lopez et al. 1998) and <1 log cycle reduction of *L. acidophilus* and *Bifidobacterium* spp. after 90 days (Akalin and Erisir 2008) in frozen yogurt.

Sherbet

A sherbet is a frozen dairy product made from water, sweeteners, milk solids, stabilizer, and coloring. They are acidified with fruit acid and typically are fruit flavored. Sherbets contain up to 1–2% milk fat and at least 1% milk solids-not-fat,

with the total milk solids between 2 and 5% (U. S. Standards: 21 CFR 135.140). Standards in other countries may vary; for example, in Canada not more than 5% milk solids, including milk fat, are permitted. Sherbets have a minimal titratable acidity of 0.35% calculated as lactic acid. The final weight per gallon must be at least 6.0 lb (U.S.).

Compared with ice cream, sherbets have the following characteristics:

- Higher fruit acid content, and a tart flavor.
- Lower overrun, ranging from 25 to 50%.
- Higher sweetener content (25–35%), therefore a lower melting point, although the high acidity decreases the sweetness.
- Coarser or icier texture and more cooling feeling to the consumer.
- Less richness of taste because of the low milk solids content.

Ices or water ices, sometimes called Italian ices, have essentially the composition as sherbets except that they contain no milk solids and no egg ingredient other than egg white. They are frozen with from 0 (quiescently frozen bars) to 30% (dynamically frozen items) overrun. Sorbets are an upscale version of ices in that they contain fruit, fruit juices, and/or fruit extracts rather than imitation flavorings. Sherbets and water ices are defined foods (21 CFR 135.140 sherbets and 21 CFR 135.160 water ices), but sorbets are not a defined food in the United States. Sorbets and water ices will be further defined below.

Of the total frozen desserts produced in 2010 in the United States, about 1.6 billion gallons, sherbets and ices comprised about 3.5% (53 million US gallons) and 4.0% (60 million US gallons), respectively. This production has remained fairly steady over a 20-year period from 1990. Nevertheless, about half of ice cream processors also produced a sherbet product. Only 2.8 million US gallons of sherbet was soft-frozen, the rest was hard-frozen. In Canada, sherbet production in 2010 was 5,966 kL, only 2.8% of the total hard and soft ice cream production. Water ice production in 2010 was 21,126 kL, about 10% of the total hard and soft ice cream production. These products are in greatest demand in the summer months. Popular flavors of sherbet include orange (about 25% of sales), lemon, lime, pineapple, raspberry, and three-flavor rainbow sherbet.

The Composition of Sherbet

Two typical sherbet formulas are given in Table 15.2. Formula 1 contains less milk solids but more corn syrup solids and would give a more coarse, acidic, chewy product than formula 2, which would give a more smooth and creamy product. Sherbet generally requires at least some fat (~0.5%) to provide a slightly more pleasant mouthfeel compared to nonfat formulations.

Another approach to making the sherbet mix is to combine ice cream mix with sugar, corn syrup, stabilizer, and water. In this case the amounts of sweeteners and stabilizer in the ice cream mix must be considered in the calculations.Tables 15.3,

Table 15.2 Sherbet formulations based on composition of components

Component	Formula 1 (%)	Formula 2 (%)
Milk fat	0.5	1.5
Milk solids-not-fat	2.0	3.5
Sucrose	24.0	24.0
Corn syrup solids	9.0	6.0
Stabilizer/emulsifier	0.3	0.3
Citric acid (50% solution)	0.7	0.7
Water	63.5	64.0
Total	100.0	100.0

Table 15.3 Sherbet formulation that will develop a smooth texture and a chewy, heavy body[a]

Ingredients	Amount (Kg)	Fat (Kg)	MSNF (Kg)	Sugar (Kg)	TS (Kg)
Sugar	9.0	–	–	9.00	9.00
Corn syrup solids 42 DE, 96.5% TS	22.0	–	–	15.92	21.23
Ice cream mix (12% fat, 11% MSNF, 15% sugar)	17.5	2.1	1.92	2.62	6.65
Stabilizer	0.4	–	–	–	0.40
Fruit puree (5 + 1)	15.0	–	–	2.50	4.75
Water plus color	35.3	–	–	–	–
Citric acid	0.7	–	–	–	–
Total	100.0	2.1	1.92	30.04	42.03

[a]Acidity, 0.57%; freezing point −3.1°C (26.4°F)

15.4, and 15.5 show proof sheets in which ice cream mix is used in three mixes that provide a wide range of textural and flavor release characteristics.

In general the sugar content of sherbets, sorbets, and ices is about twice that of ice cream. It is important to have the correct sweetener content to obtain the desirable flavor, body, and texture. An excess of sweetener results in a soft and sticky product while a deficiency causes the product to be hard and crumbly. Sherbets should be of the same firmness at dipping cabinet temperature as is ice cream. If the overrun is kept at 30–35% and the sugar concentration at 28–32%, firmness should be suitable for dipping at the usual cabinet temperature of −13 to −16°C (3–8°F).

When sherbets are made with sucrose as the sole source of sweetener, they tend to develop a hard crust on the surface due to crystallization of the sugar. Replacement of 20–25% of the sugar with corn syrup solids lessens the chance for the defect. The maximum amount of corn syrup solids that can be substituted favorably for sucrose is about one-third. Partial replacement with invert sugar

Table 15.4 Sherbet fromulation that will develop a medium smooth texture with a medium firm body[a]

Ingredients	Amount (Kg)	Fat (Kg)	MSNF (Kg)	Sugar (Kg)	TS (Kg)
Sugar	11.0	–	–	11.00	11.00
Corn syrup solids 36 DE, 96.5% TS	10.0	–	–	6.30	9.65
Ice cream mix (12% F, 11% NMS. 15% sugar)	17.5	2.1	1.92	2.62	6.65
Stabilizer	0.4	–	–	–	0.40
Fruit puree (5 + 1)	15.0	–	–	2.50	4.75
Water plus color	45.4	–	–	–	–
Citric acid	0.7	–	–	–	–
Total	100.0	2.1	1.92	22.42	32.45

[a]Acidity, 0.55%; freezing point, −2°C (28.4°F)

Table 15.5 Sherbet formulation that will develop a coarse texture with a medium firm body[a]

Ingredients	Amount (Kg)	Fat (Kg)	MSNF (Kg)	Sugar (Kg)	TS (Kg)
Sugar	17.0	–	–	17.0	17.0
Dextrose	7.0	–	–	5.6	6.75
Ice cream mix (12% F, 11% NMS. 15% sugar)	17.5	2.1	1.92	2.62	6.65
Stabilizer	0.4	–	–	–	0.40
Fruit puree (5 + 1)	15.0	–	–	2.50	4.25
Water plus color	42.4	–	–	–	–
Citric acid	0.7	–	–	–	–
Total	100.0	2.1	1.92	27.72	35.05

[a]Acidity, 0.55%; freezing point, −3.1°C (26.4°F)

may also result in less sugar crysatllization. Amounts of sugar added to these products with fruits or with ice cream mix need to be factored into the formula.

Sherbet mixes are then flavored with fruit juices, flavoring, coloring, and citric acid solution, as appropriate. Citric acid is the most commonly used acid in sherbets and ices and is usually added as a 50% solution. The amount of acid needed depends on the fruit used, the sugar content, and consumer preferences. A general rule is that the titratable acidity should be 0.36% at 25–30% sugar and should be

increased about 0.01% for each 1% increase in sugar above 30%. This level of acidity modifies the perception of sweetness that would otherwise be created by the high level of sugars. Acid should not be added to ice and sherbet mixes until just before freezing. Heating of some stabilizers in the presence of acid will reduce their effectiveness. Adding acid to a sherbet mix in which the milk solids have been included may cause aggregation/precipitation of the protein. Minimum amounts of fruit or fruit juice (including weight of the water used to reconstitute dried or concentrated products to their original moisture content) required by type of sherbet are: citrus—2%, berry—6%, and other—10% in relation to the weight of the finished sherbet. Because citric acid may cause precipitation of proteins, it is added to the mix just before freezing. Sherbets are frozen with overrun in the range of 25–50%.

Walker et al. (2010) examined a novel, sugar-free sherbet containing soy protein from 6.0 to 7.9 g/serving. The products were sweetened with sucralose (0.10%), asesulfame-K (0.02%), and erythritol (0.10%) and contained from 14.3 to 15.4% maltodextrin. Acceptability decreased as soy protein levels increased; however, the combination of sweeteners and bulking agents was considered acceptable to a panel of 140 consumers with fairly high interest shown by consumers in these products.

Lacto is made from sherbet mix that is composed from cultured sour milk, buttermilk, or other fermented milk product.

Defects

Common flavor defects in sherbets are unnatural or atypical; excessive or insufficient flavoring; acid (sour); improperly sweetened (too little, too much, or unnatural); and metallic or oxidized. Terpenes of citrus fruit tend to cause bitterness. To avoid these defects requires selection of high quality ingredients, especially fruits, juices and flavorings, and protection of the ingredients and finished products from prolonged storage and exposure to odorous substances. Selection of desirable artificial flavors should be given special attention during product development.

As with ice cream, the most frequently observed textural defect in sherbets and ices is coarseness or iciness. Some consumers prefer the type of sherbet that freezes initially with a slightly coarse texture because it can be especially light and refreshing. Others prefer velvety smooth texture. Nevertheless, either of the types can become offensively coarse and icy. The following steps are recommended to reduce this defect: (1) set the sugar content at 28–32% with about one-fourth of this amount, by weight, being corn syrup solids or corn sugar; (2) carefully select a stabilizer and use it at the concentration proven by test in the formula; (3) draw the product from the freezer in a firm condition and harden it quickly; (4) protect the frozen product from temperature fluctuations; and (5) market the product promptly.

A crumbly body indicates an insufficient amount of or improper stabilizer. When the body is too firm, the overrun may be too low or there may be insufficient sugar in the mix. A weak or snowy body is indicative of having whipped too much air into

the product. Stickiness suggests too much sugar or stabilizer in the formulation. Surface encrustation sometimes appears because some of the sucrose crystallizes. The liberated water may evaporate or may freeze into large ice crystals. The usual solution to the problem is to increase the concentration of stabilizer and/or to lower the freezing point by adding more sugar.

"Bleeding" or settling of syrup to the bottom of the container is more of a problem with sherbets and sorbets than ice cream. The internal structure of the foam of ice cream is stabilized to a much higher degree by abundant proteins and partially churned fat than is the structure of sherbets and sorbets. To prevent bleeding, one should avoid excessive overrun, provide sufficient stabilizer, hold the sugar content to less than 32%, and keep the temperature cold, i.e., below −20°C (−4°F) until tempering it to be served. Temperature abuse is the most important cause of body and texture defects in frozen desserts.

Water Ice

Water ices can be quiescently frozen in molds to make popsicle-type products or can be frozen while agitating in the same way ice cream is frozen. However, the rate of wear on the scraper blades is high because of the lack of fat to lubricate the metal surfaces that contact each other. Therefore, scraper blades must be sharpened frequently to maintain the capability to produce small ice crystals.

Formulas for ices are usually calculated for lots of 100 U of desired quantity by weight, 80 U being the "base mix" and 20 U being the flavoring, coloring, acid, and additional water. A desirable base or stock mix contains 21–25 U of sucrose, 7–9 U of corn syrup solids, and 0.4 U of stabilizer. Water makes up the remainder of the 80 U of this base mix. In other words, the base mix comprises 26.25–31.25% sucrose, 8.75–11.25% corn syrup, 0.5% stabilizer, and the balance in water, to which is added a flavor preparation at 25% by weight. Ices have a low TS content compared to ice cream; this means they have a greater tendency for sugar solids to separate and for the body to become crumbly than does ice cream. For this reason ices need more stabilizers than do ice creams.

This base is prepared by slowly adding the dry ingredients to at least part of the water, taking care to avoid creating lumps. Heating is necessary to facilitate solution of the stabilizer and to eliminate potential yeast and mold contamination. Homogenization is not required. The base is cooled before other ingredients are added. Aging for 4–12 h is necessary only if the stabilizer needs time for full activation.

This base mix is then ready for the flavoring and coloring materials. The flavor and color mixture is made from the following ingredients:

1. *Fruit and fruit juices.* The amount varies between 15 and 20% of the finished ice, depending on the intensity of the flavor. Variety of fruit and method of preparation affect the amount of these ingredients needed. Fruit seeds should be avoided.

2. *Flavoring*. Although fruit extracts and artificial flavors may not provide as desirable flavor as fruit juices, they are often needed to fortify the flavor and to produce a consistently uniform product.
3. *Coloring*. Approved food coloring should be selected to provide as near the natural color as possible while meeting the expectations of consumers as may be determined with a sensory panel.
4. *Acid solution*. To obtain the desired tart flavor, the fruit acids, citric or tartaric, should be used. Less desirable substitute acids are saccharic, phosphoric, or lactic. It is common practice to use 50% solutions of citric or tartaric acids made from equal weights of acid crystals and water. The amount of this concentrate to use varies from 250 to 600 mL/100 kg (4–10 oz per 100 lb of mix). The amount depends on the acidity of the fruit juice and the amount of sugar in the final mix. The final titratable acidity should range from 0.35 to 0.50% expressed as lactic acid.

Non-fruit sherbets or ices differ from fruit sherbets and ices mainly in the flavor-characterizing ingredients. The optional characterizing ingredients include ground spices, infusion of coffee or tea, chocolate or cocoa, confectionery, distilled alcoholic beverages (in an amount not to exceed that required to provide the flavoring), or any other natural or artificial food flavoring (except any having a characteristic fruit or fruit-like flavor).

Quiescently frozen confections consist essentially of the same ingredients as are in water ice, but usually in different proportions. A typical formula would be as follows: sucrose 13.80%, corn syrup solids 3.70%, stabilizer 0.37%, citric acid (anhydrous) 0.26%, water 80.62%, and flavor 1.25%. The ingredients are weighed and dissolved with necessary agitation. Heat is not essential in preparation but it is beneficial in the destruction of molds and yeasts should it be desired to store the mix. No overrun is involved with this type of product so the mix is dispensed into molds allowing sufficient under fill to permit expansion on freezing.

A relatively new item in the category of ices is the juice bar. It is a quiescently frozen upscale adaptation of water ice in which the major characterizing ingredient is fruit juice instead of fruit flavoring or extract in water. There is no federal standard for this product. Some manufacturers are adding nutrients to juice bars with the objective of gaining market share among health conscious consumers. For example, one such bar contains 11 g whey protein, while providing 130 cal and 100% of the RDA for vitamins A, C, and E in 100% fruit juice.

Sorbet

Sorbets are generally regarded as upscale versions of water ices that are frozen while whipping. The Italian name Sorbetto is also applied. In general, formulas for sorbets call for fruit and/or fruit juice (30–50% by weight) as the characterizing flavor rather than artificial flavorings. Fruit extracts provide enhanced flavor. Additionally, many formulas include egg white (2.6% solids), to aid in aeration, and

pectin or other stabilizing gums (0.4–0.5%). Sugar content varies from 28 to 32%, and the fructose, fruit sugar, content of the fruit should be considered as part of the sugar in the formulation. Percentages of fructose vary from 7% in kiwi fruit, raspberry, passion fruit, and blueberry to 16% in ripe banana, with most fruits containing 8–10%. Moisture content of fruits varies from 75% in banana to 89–90% in melon and kiwi fruit. Citric acid may be added to enhance flavor. The remainder is water. Exotic flavors are often used in sorbets. Overrun in sorbets is usually 20% or less, in part from the lack of protein in the formulation to provide any air cell stability.

Nutrition Facts labels of two nationally distributed brands of orange, raspberry, strawberry, and lemon sorbet revealed an average of 120 cal in a ½ cup serving weighing 106 g and containing 31 g of carbohydrate and 23–27 g of sugar. The products contained insufficient fat, protein, or calcium to be noted on the label.

Fruit and flavor supply houses provide what they call bases for sorbets. Bases contain the fruit, flavor, and stabilizer needed. The manufacturer adds sugar and water before freezing.

Italian ices and sorbets should be stored at temperatures of −30°C (−20°F) or lower and served at about −10°C (15°F) depending on the amount of sugar solids contained. This means the serving cabinet used for ice cream is not satisfactory for use with dipped sorbets and ices. These products are frequently produced in a soft serve freezer and dispensed directly to the consumer.

Non-dairy Frozen Desserts

Many consumers cannot or do not wish to consume any dairy ingredients. Hence, a number of frozen dessert products have come onto the market to cater to this demand, the most common of these being soy-based although there are other products that are nut-based or hemp-based, for example. The principles and procedures for these are very similar to ice cream, in that a mix is prepared by selection and blending of ingredients, pasteurization, homogenization, cooling, and aging, and then this mix is concomitantly whipped and frozen in batch or continuous freezers and the resulting frozen product is optionally flavored with inclusions, packaged and hardened. Often, the composition of the formulation is also similar in terms of fat, protein, sugar, stabilizer, and emulsifier; however, the source of these components varies.

In the case of soy-based frozen desserts, a soy milk is prepared by grinding of prepared and cooked beans with water to a fine particle size producing a smooth texture. Soy milk can vary from 8 to 12% total solids, of which on a dry basis approximately 27.5% is protein, 14.5% is fat, 5.5% is ash, and 52.5% is total carbohydrate including 33.5% sugars and 4% dietary fiber. In a typical soy-based formulation, soy milk would be blended with sources of non-dairy fat (typical of non-dairy fat ice cream: palm oil, palm kernel oil, or coconut oil, perhaps blended with an unsaturated oil such as corn or canola to give at least 70% solid fat at 4°C), sugars,

and stabilizers to produce a recipe that results in similar freezing curve, firmness, shelf-life, meltdown, and texture to ice cream. A full-fat product might be 6–8% fat. The functional properties provided by the milk solids-not-fat in ice cream have to be replaced by the functional properties of the soy protein and starch in the soy milk, perhaps supplemented with additional soy protein isolate. However, the stabilizers and emulsifiers also have to aid in water-binding, fat structuring, and aeration, perhaps more so than in ice cream since the interfacial properties of soy protein are not as good as those of milk protein. Since there is no lactose, additional sugar is needed to arrive at similar freezing properties to ice cream, perhaps up to 20% sugar (more if corn starch hydrolysates are used, less if monosaccharide sugars are used).

Ingredient listings from four vanilla soy-based products in the Canadian market in 2011 are as follows:

- Soy beverage (water, soybeans), sugar, coconut oil, guar, locust bean gum, soy lecithin, salt.
- Water, sugar, corn oil, high fructose corn syrup, soy proteins, tofu, cocoa butter, vanilla, guar, locust bean and cellulose gums, carrageenan, salt, vegetable mono- and diglycerides, caramel flavor, annatto color.
- Organic: Soy beverage (water, soybeans), brown rice syrup and/or tapioca syrup, dehydrated cane juice, soybean oil and/or safflower oil, chicory root extract, vanilla extract, carob bean gum, tapioca sugar, guar gum, carrageenan.
- Water, sugar, sunflower oil, soy protein, salts of phosphate and citrate, mono- and diglycerides, guar gum, sodium carboxymethyl cellulose, locust bean gum, carrageenan, natural and artificial flavor, natural color.

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