Impact of HFC Fire Extinguishing Clean Agents on Climate Change and Its System Design Requirements for Fire Hazards in India—A Brief Study

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Abstract This paper discusses the impact on climate change of hydrofluorocarbons (HFCs) in fire suppression applications. Alternatives and substitutes for HFCs, perfluorocarbons (PFCs), and ozone depleting substances (ODSs) have recently been extensively evaluated. NFPA 2001 defines a clean fire extinguishing agent as an electrically non-conducting, volatile, or gaseous fire suppressant that does not leave a residue upon evaporation. A clean agent must have no known effect on the ozone layer and also, no effect on any human survival within an enclosure protected by a clean agent, and in normally occupied areas must be used in a concentration that is less than "no observed adverse effect level (NOAEL)". NOAEL is a measure of clean agent toxicity to humans under test conditions. The HFCs that are projected for large volume use have global warming potentials (GWPs) lower than the replacing ODSs. GWPs of HFCs replacing ODSs ranges from 120 to 12,000 as per the year 2000 data of Intergovernmental Panel on Climate Change (IPCC). HFC-23 with a GWP of 12,000 is used as a replacement for ODSs to a very limited extent. However, there are relatively large emissions of HFC-23 from the HCFC-22 manufacturing process. However, the majority of HFCs have GWPs much lower than that of HFC-23. NFPA 2001 standard demonstrates the fact that the GWP value considered by itself does not provide an indication of the impact of fire extinguishing clean agent on climate change. Further, the paper briefly describes the clean agent fire extinguishing system design considerations to extinguish fires either by flame extinguishment or by inerting in accordance with the changing characteristics of fire hazard scenarios in building and industrial occupancies. An important finding of this brief study is that the value of 0.4858 kg/m^3 is a total flooding factor for HFC-227ea fire extinguishing agent representing the quantity of halocarbon clean agent required to achieve a selected design fire extinguishing concentration of 6% at a specified ambient temperature of 21 °C. It is further important to understand that the impact of a fire extinguishing clean agent on

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climate change is a function of both the GWP of the gas and the amount of gas emitted. For example, carbon dioxide has one of the lowest GWP values of all greenhouse gas emissions (GWP = 1), yet emissions of CO_2 account for approximately 85% of the impact of all greenhouse gas (GHG) emissions. The characteristics of fire hazard scenarios with respect to anticipated fires have been continuously changing in India due to emerging trends in the up gradation/modern furnishing and interior design considerations/requirements in almost all the urban, semi-urban, and rural occupancies. The data from IPCC and Asia Pacific Fire Magazine, October 25, 2011 showed that if nothing changes, the HFC emissions are likely to be equivalent to between 9 and 19% of global greenhouse gas emissions by 2050, which indicates that the impact of HFC fire extinguishing clean agents on climate change is minuscule. As a result, HFCs are expected to remain viable, sustainable, and environmentally acceptable replacements for Halon 1301, which was phased out due to ozone depletion potential problems under Montreal and other protocols.

Keywords Climate change · Hydro fluorocarbons (HFCs) · Fire extinguishing agents · Fire hazards · System design

Introduction

The results of a study of the effect of chlorofluorocarbons (CFCs) on the ozone layer won the Nobel Prize for two chemists (1–38) at the University of California Irvine, Frank Sherwood Rowland and Mario Mocina which resulted in a landmark international agreement, the Montreal Protocol, signed by the United States and 24 other countries in 1987, with significant amendments in 1990 and 1992. Alternatives and substitutes for HFCs, perfluorocarbons (PFCs), and ozone depleting substances (ODSs) have recently been extensively evaluated. The Montreal Protocol Technology and Economic Assessment Panel (TEAP) and its technical committees published a comprehensive assessment. Furthermore, reports were published within the framework of the joint IPCC/TEAP workshop and the second non-CO_2 greenhouse gases conference.

Kofi Annan, former Secretary General of the United Nations, said "perhaps the single most successful international agreement to date was the Montreal Protocol of 1987." The agreement was intended to sharply restrict the production of chemicals that had been identified as contributing to depletion of the stratospheric ozone layer. The ozone layer is a protective layer of our stratosphere that helps to filter the ultraviolet rays of the sun before they reach Earth. In the absence of the ozone layer, the incidence of skin cancer and melanoma increase. An ozone molecule consists of three oxygen atoms (O_3). Freon, released from air conditioners, and halogenated extinguishing agents rise to the stratosphere. Bromine and chlorine molecules from these agents break up the O_3 molecules and attach themselves to one of the free oxygen molecules. These gases, therefore, were included in the list of ozone depleting agents.

In advance of the Montreal Protocol, the Vienna Convention for the Protection of the Ozone Layer provided the framework for negotiations in 1985 (1–38). Immediately subsequent to the initial signing of the Montreal Protocol, evidence continued to mount that the ozone layer was continuing to shrink at a frightening rate. Numerous additional countries signed the Montreal Protocol, and the target date for ceasing production of halogenated hydrocarbons was advanced to January 1994. At present, 191 nations have signed the Montreal Protocol, making it one of the planet's most successful international agreements.

The cessation of halon production rapidly rendered existing halon systems (1–38) which are to be gradually phased out of the fire protection industry, has placed owners of halon systems and the companies that insure the hazards protected by halon systems, in an extremely uncomfortable position. Although the Montreal Protocol did not call for removing all existing halon systems, it prohibited the manufacture of new halon—making it impractical to legally purchase new halons. Owners and insurers of halon systems were faced with the prospect of a total loss of fire protection pursuant to an accidental or purposeful halon system discharge.

Figure 1 shows (1–9) (a) Arctic map from world atlas (b) Artic Ozone Hole, yellow area within red circle, could expose millions of people, wildlife and plants to

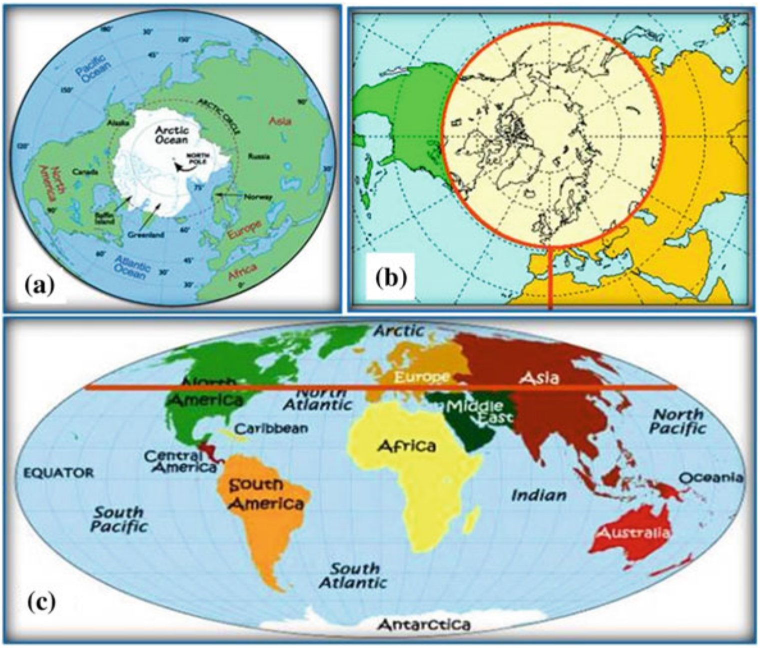

Fig. 1 It shows **a** arctic map from world atlas **b** artic ozone hole, *yellow area* within *red circle*, could expose millions of people, wildlife and plants to dangerous UV ray levels **c** the area that will be affected by formation of arctic ozone hole above the *redline*

dangerous UV ray levels; and (c) the area that will be affected by formation of Arctic Ozone Hole above the redline. To protect against this eventuality, many system owners opted to replace their halon systems with either a substitute gaseous system replacement or a water-based system replacement. Although introductory background of halon's replacements is covered in this paper, the primary focus is on clean agents and halon-alternative fire extinguishing agents.

Clean Fire Extinguishing Agents

NFPA 2001 (3–7) defines a clean agent as an electrically non-conducting, volatile, or gaseous fire extinguishant that does not leave a residue upon evaporation. For an agent to qualify as a clean agent, it must have no known effect on the ozone layer, it must have no effect on human survival within an enclosure protected by a clean agent, and in normally occupied areas must be used in a concentration that is less than the NOAEL—an abbreviation for "no observed adverse effect level." NOAEL is a measure of clean agent toxicity to humans, under test conditions. At present time, no drop-in agent is available that would allow Halon 1301 to be removed and an equivalent amount of replacement agent inserted. Systems with gaseous halon replacement agents require that more gas than halon be stored on a volumetric basis, with differing devices and appurtenances required. Clean agents have been found to be effective for electrical or electronic applications, telecommunication facilities, flammable liquids and gases, and high-value assets. They also may be considered for explosion suppression systems. NOAEL and LOAEL—lowest observable adverse effect level—% for halocarbon suppression agents as shown on Table 1.

Table 2 shows the Atmospheric properties [lifetime, global warming potential (GWP)] for the HFC chemicals.

Table 1 NOAEL and LOAEL percentages for halocarbon clean agents (NFPA 2004)

S. No.	Agent	NOAEL (%)	LOAEL (%)
1	FC-3-1-10	40	>40
2	FK-5-1-12	10.0	>10.0
3	HCFC Blend A	10.0	>10.0
4	HCFC-124	1.0	2.5
5	HFC-125	7.5	10.0
6	HFC-227ea	9.0	>10.5
7	HFC-23	30	>50
8	HFC-236fa	10	15

Source NFPA (2004)

Table 2 Atmospheric properties [lifetime, global warming potential (GWP)] for the HFC chemicals (1–38)

S. No.	Sub-sector	Chemical formula	Lifetime (year) (IPCC 1996)	GWP (100 year) (IPCC 1996)	Lifetime (year) (IPCC 2000)	GWP (100 year) (IPCC 2000)
1	HFC-23	CHF_3	264	11,700	260	12,000
2	HFC-32	CH_2F_2	5.6	650	5.0	550
3	HFC-125	CHF_2CF_3	32.6	2800	29	3400
4	HFC-134a	CH_2FCF_3	14.6	1300	13.8	1300
5	HFC-143a	CH_3CF_3	48.3	3800	52	4300
6	HFC-152a	–	1.5	140	1.4	120
7	HFC-227ea	CF_3CHFCF_3	36.5	2900	33	3500
8	HFC-245fa[a]	$CF_3CH_2CHF_2$	–	–	7.2	950
9	HFC-365mfc[a]	$CF_3CH_2CF_2CH_3$	–	–	9.9	890
10	HFC-4310mee	$CF_3CHFCHFCF_2CF_3$	17.1	1300	15	1500
11	R-404A					
	44%	HFC-125		3260		
	4%	HFC-134a				
	52%	HFC143a				
12	R-407C					
	23%	HFC-32		1525		
	25%	HFC-125				
	52%	HFC-134a				
13	R-410A					
	50%	HFC-32		1725		
	50%	HFC-125				
14	R-507					
	50%	HFC-125		3300		
	50%	HFC-143a				

[a] Atoms of middle Carbon-Cl_2

Clean Agent Classification

The two basic classifications of clean agents are halocarbon agents and inert gas agents. Agents addressed by NFPA 2001 are listed on Table 3 (1–38). Halocarbon agents consist of hydrofluorocarbons (HFCs), hydro-chlorofluorocarbons (HCFCs), and perfluorocarbons (PFCs) and are given numerical descriptions as shown in Table 3 in accordance with ANSI (American National Standards Institute) and ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) standards. Halocarbons are stored as a liquid and distributed to the hazard as a gas, and extinguish fires by chemical and physical mechanisms, as opposed to oxygen deprivation. The extinguishment mechanism is breaking the combustion chain. Inert gas agents contain one or more non-reactive gases, such as helium, neon, and argon, mixed with nitrogen or carbon dioxide. They extinguish

Table 3 Clean fire extinguishing agents (1–38)

1	FC-3-1-10	Perfluorobutane	C_4F_{10}
2	FK-5-1-12	Dodecafluoro-2-methylpentan-3-one	$CF_2CF_2C(O)CF(CF_3)_2$
3	HCFC blend A	Dichlorotrifluoroethane HCFC-123 (4.75%) Chlorodifluoromethane HCFC-22 (82%) Chlorotetrafluoroethane HCFC-124 (9.5%) Isopropenyl-1-methylcyclohexene (3.75%)	$CHCl_2CF_3$ $CHClF_2$ $CHClFCF_3$
4	HCFC-124	Chlorotetrafluoroethane	$CHClFCF_3$
5	HFC-125	Pentafluoroethane	CHF_2CF_3
6	HFC-227ea	Heptafluoropropane	CF_3CHFCF_3
7	HFC-23	Trifluoromethane	CHF_3
8	HFC-236fa	Hexafluoropropane	$CF_3CH_2CF_3$
9	FIC-1311	Trifluoroiodide	CF_3I
10	IG-01	Argon	Ar
11	IG-100	Nitrogen	N_2
12	IG-541	Nitrogen (52%)	N_2
		Argon (40%)	Ar
		Carbon dioxide (8%)	CO_2
13	IG-55	Nitrogen (50%)	N_2
		Argon (50%)	Ar

Notes Other agents could be added via the NFPA process in future editions or amendments of the standard. Composition of inert gas agents are given in vol.%. Composition of HCFC blend A is given in wt%. The full analogous ASHRAE nomenclature for FK-5-1-12 is FK-5-1-12 mmy2. *Source* NFPA 2001 (2004)

fires by lowering the oxygen concentration within a room from normal condition of 21% to a level below 15%—usually 12–13%, less than the level required to sustain combustion for most combustibles. Inert gas agents are approximately the same density as air and, therefore, mix better and display less settling to the floor than other gaseous agents such as carbon dioxide.

Discussion

In 1986, less than half of total ODS use was in insulating foams, fire protection, refrigeration, air conditioning, and heat pumps, with more than half as aerosol product propellants, non-insulating foam, solvent, and specialized applications (1–38). Alternatives and substitutes for HFCs, perfluorocarbons (PFCs), and ozone depleting substances (ODSs) have recently been extensively evaluated. The Montreal Protocol

Technology and Economic Assessment Panel (TEAP) and its technical committees published a comprehensive assessment (UNEP 1999b). Furthermore, reports were published within the framework of the joint IPCC/TEAP workshop and the second non-CO_2 greenhouse gases conference.

The HFCs that are projected for large volume use have global warming potentials (GWPs) which are generally lower than those of the ODSs they replace. The GWP of HFCs replacing ODSs range from 140 to 11,700. HFC-23 with a GWP of 11,700 is used as a replacement for ODSs to only a very minor extent. However, there are relatively large emissions of HFC-23 from the HCFC-22 manufacturing process. The majority of HFCs have GWPs much lower than that of HFC-23. PFCs have GWPs that are generally higher than those of the ODSs they replace, ranging from 7000 to 9200 as shown in Table 2 (1–38).

However, by 1997 (1–9), the global consumption of fluorocarbons (CFCs, HCFCs, and HFCs) had decreased by about 50% as solvent, aerosol product, and non-insulating foam applications switched to alternatives other than fluorocarbons. Refrigeration, air conditioning, and insulating foam accounted for about 85% of the remaining total fluorocarbon use. Eighty percent of projected chlorofluorocarbon demand was avoided by reducing emissions, redesign, and use of non-fluorocarbon technologies.

As CFCs, halons, and HCFCs are phased out globally, the quantities of fluorocarbons are expected to continue to decline in the short term, but are expected to grow in the longer term. Most HFCs are used for energy-consuming applications such as refrigeration, air conditioning and heat pumps, and building and appliance insulation. Life cycle climate performance (LCCP) analysis is being used to estimate the net contribution to climate change. The LCCP is a very system specific parameter that can be used to make relative rankings. However, LCCP analysis involves regional differences—including different fuel sources—and the related equipment operating conditions; the results can therefore not be generalized in order to make globally valid comparisons.

The energy efficiency of equipment and products can be expressed in at least three ways: theoretical maximum efficiency, maximum efficiency achievable with current technology, and actual efficiency for commercial scale production (often expressed as a range of values). Unlike anthropogenic greenhouse gases emitted as an immediate consequence of the burning of fossil fuels to generate energy, most HFCs and PFCs are contained within equipment or products for periods ranging from a few months (e.g., in aerosol propellants) to years (e.g., in refrigeration equipment) to decades (e.g., in insulating foams). Thus, emissions significantly lag consumption and, because HFC systems are relatively new, emissions will continue to grow after 2010. Systems optimized for a new refrigerant have been compared to sub-optimum systems with other refrigerants.

Furthermore, appliance sizes and features that influence energy performance vary between studies and test conditions, and methodologies are often significantly different. These factors have led to a wide range of energy efficiency claims in technical reports and commercial publications. Ultimately, the performance and cost effectiveness of specific products from commercial scale production must be directly compared. Furthermore, costs reported might not always be comparable because of differing estimation methods, including estimates based on both consumer and producer costs.

Future global HFC and PFC consumption and/or emissions as substitutes for ODSs have been estimated by IPCC (1995). Projected consumption data for 2000 and 2010 are primarily based on UNEP reports (1–9).

Considering that emissions lag consumption by many years, none of the scenarios have considered the implications of new uses of HFCs or PFCs other than as substitutes for ODSs (1–9).

With regard to the impact of HFCs in fire suppression on climate change, the International Fire Protection Magazine article "Climate Change and the HFC-Based Clean Extinguishing Agents" referenced in the original post for a factual discussion is worth reading (8–9). Based on US EPA data, the contribution of HFCs in fire suppression applications to climate change represents approximately 0.01% of the contribution of all greenhouse gases. With regard to regulations, HFCs in fire suppression applications are being treated differently than HFCs employed in other applications, and as a result it is important when encountered with an assertion of impending legislative or regulatory action related to HFCs in fire suppression applications to always request two items: (i) a copy of the legislation and (ii) the location of the text that is specifically related to HFCs in fire suppression applications (1–9).

FM-200 (HFC-227ea) and Novec 1230 are fire extinguishing agents characterized by zero ODP and whose use in fire suppression applications results in a negligible contribution to climate change (global warming). There are three major differences between Novec 1230 and all of the other clean agents, including FM-200. As regard to Chemical reactivity (8–9), unlike the HFC and inert gas clean agents, which are characterized by very low chemical reactivity, Novec 1230 is characterized by high chemical reactivity. The HFC and inert gas clean agents are all unreactive with water, alcohols, amines, and solvents. Novec 1230, on the other hand, is characterized by high chemical reactivity.

For example, Novec 1230 design manuals indicate (8–9) the following: (i) Contact of Novec 1230 with water or solvents either polar or hydrocarbon could render Novec 1230 fluid ineffective, (ii) the transfer of Novec 1230 requires the use of a drier because humid air may cause the agent to convert to acid. It is reported (8–9) that Novec 1230 is chemically reactive with nucleophiles such as alcohols. Novec 1230 is also chemically reactive with other fire extinguishing agents (8–9), e.g., it has been reported that Novec 1230 undergoes reaction with sodium bicarbonate. The reaction of Novec 1230 with water produces HFC-227ea and Perfluoropropionic acid, a strong, corrosive organic acid. Due to its high reactivity, Novec 1230 is the only clean agent that is classified as a volatile organic compound (VOC) (8–9).

As regard to the interaction in the body (8–9), unlike the HFC and inert gas agents, Novec 1230 undergoes reaction in the lungs. Novec 1230 reacts to form HFC-227ea and Perfluoropropionic acid when it crosses the lung-air interface. In contrast, FM-200 does not react to form potentially hazardous products; the toxicity of FM-200 is so low that it is approved for use as a propellant in metered dose inhalers (MDIs), where it is employed to propel a medicament down the throat of the patient into his/her lungs. As regard to the physical state, unlike the HFC and inert gas clean agents, which are all gaseous at room temperature, Novec 1230 is a high boiling liquid which increases the possibility of a liquid discharge with Novec 1230 compared to the other clean agents and also affects its performance. For example, recent studies within the aviation industry have indicated that Novec 1230 is ineffective in several civil aviation applications (8–9).

Human Safety Concerns with Clean Fire Extinguishing Agents (1–9)

NFPA 2001 does not recommend exposure to halon-carbon clean agents for more than 300 s with less exposure in higher concentrations, as shown on Tables 4, 5, 6 and 7. Designers of fire protection systems need to specially exercise care in the

Table 4 Time for safe egress for halocarbon clean agents (NFPA 2001 2004)

Time for safe human exposure at stated concentrations for HFC-125

S. No.	HFC-125 concentration		Maximum permitted human exposure time (min)
	%v/v	ppm	
1	7.5	75,000	5.00
2	8.0	80,000	5.00
3	8.5	85,000	5.00
4	9.0	90,000	5.00
5	9.5	95,000	5.00
6	10.0	100,000	5.00
7	10.5	105,000	5.00
8	11.0	110,000	5.00
9	11.5	115,000	5.00
10	12.0	120,000	1.67
11	12.5	125,000	0.59
12	13.0	130,000	0.54
13	13.5	135,000	0.49

Notes Data derived from the EPA-approved and peer-reviewed physiologically based pharmacokinetic (PBPK) model or its equivalent. Based on LOAEL of 10.0% in dogs

Table 5 Time for safe human exposure at stated concentrations for HFC-236fa (NFPA 2001 2004)

Time for safe human exposure at stated concentrations for HFC-236fa			
S. No.	HFC-236fa concentration		Maximum permitted human exposure time (min)
	%v/v	ppm	
1	10.0	100,000	5.00
2	10.5	105,000	5.00
3	11.0	110,000	5.00
4	11.5	115,000	5.00
5	12.0	120,000	5.00
6	12.5	125,000	5.00
7	13.0	130,000	1.65
8	13.5	135,000	0.92
9	14.0	140,000	0.79
10	14.5	145,000	0.64
11	15.0	150,000	0.49

Note Data derived from EPA-approved/peer-reviewed PBPK model on LOAEL of 15% in dogs

Table 6 Time for safe human exposure at concentrations for HFC-227ea (NFPA 2001 2004)

Time for safe human exposure at stated concentrations for HFC-227ea			
S. No.	HFC-227ea concentration		Maximum permitted human exposure time (min)
	%v/v	ppm	
1	9.0	90,000	5.00
2	9.5	95,000	5.00
3	10.0	100,000	5.00
4	10.5	105,000	5.00
5	11.0	110,000	1.13
6	11.5	115,000	0.60
7	12.0	120,000	0.49

Note Data derived from EPA-approved/peer-reviewed PBPK model on LOAEL of 10.5% in dogs

Table 7 Time for safe human exposure at stated concentrations for FIC-1311 (NFPA 2001 2004)

Time for safe human exposure at stated concentrations for FIC-1311			
S. No.	FIC-1311 concentration		Maximum permitted human exposure time (min)
	%v/v	ppm	
1	0.20	2000	5.00
2	0.25	2500	5.00
3	0.30	3000	5.00
4	0.35	3500	4.30
5	0.40	4000	0.85
6	0.45	4500	0.49
7	0.50	5000	0.35

Note Data derived from EPA-approved/peer-reviewed PBPK model on LOAEL of 0.4% in dogs design of clean agent systems for enclosures where human exposure to the agent is possible.

Of particular concern is human exposure to the decomposition byproducts formed by breakdown of the extinguishant when exposed to high temperatures or an open flame. For example, halocarbon agents containing fluorine have the potential to form toxic hydrogen fluoride. Inert gas agents do not create decomposition products, but care must be taken to avoid high application concentrations. Table 8 lists the toxicity of clean agents. Inert gas agents contain about 8% carbon dioxide, but the CO_2 is not a concern at normal inert gas concentrations. Care must be taken to avoid over-design which could result in excessive inert gas concentrations and reduce oxygen concentrations below 10%. NFPA 2001 (2004) prohibits the application of halocarbon agents into occupied rooms at concentrations greater than 24% and requires that the NOAEL limits listed in Table 1 not be exceeded for any clean agent.

Table 8 provides information for designers relative to NOAEL and LOAEL % ages for halocarbon clear agents and time for safe exposure for HFC-125, HFC-236fa, HFC-277ea, and FIC-1311.

The ALC is the approximate lethal concentration. The cardiac sensitization levels are based on the observance or non-observance of serious heart arrhythmias in a dog. The usual protocol is a 5-min exposure followed by a challenge with epinephrine. High concentration values are determined with addition of oxygen to prevent asphyxiation.

These tables enable clean agent system designers to consider methodologies for keeping human exposure to a minimum. Methods to protect personnel exposed to clean agents include

- Ensuring that exits are well situated, well marked, and well lighted, adequate number and width to allow rapid egress of all occupants, and are readily accessible with clear and unobstructed aisles or passageways to the exits.
- Consider the provision of extra egress doors; specifying that doors are required to swing in the direction of egress travel and to reclose automatically.

Table 8 Toxicity information for halocarbon clean agents (NFPA 2001 2004)

S. No.	Agent	LC_{50} or ALC (%)	NOAEL (%)	LOAEL (%)
1	FC-3-1-10	>80	40	>40
2	FIC-1311	>12.8	0.2	0.4
3	FK-5-1-12	>10.0	10	>10.0
4	HCFC Blend A	64	10	>10.0
5	HCFC-124	23–29	1	2.5
6	HFC-125	>70	7.5	10
7	HFC-227ea	>80	9	10.5
8	HFC-23	>65	50	>50
9	HFC-236fa	>18.9	10	15

Notes LC_{50} is the concentration lethal to 50% of a rat population during a 4-h exposure

- Providing adequate alarm notification before clean agent discharge.
- Providing training of personnel to ensure proper identification and response to an alarm; and providing continuous alarms during discharge and agent containment.
- Providing alarms, locks, signs and methods to prevent reentry to a room during agent containment.
- Specifying placement of breathing apparatus and room ventilation requirements.
- Specifying a plan for rescue of anyone who may become trapped within the room or otherwise overexposed to the suppressing agent and its combustion byproducts.

Consideration also must be given to the possibility of confusion or disorientation of occupants during discharge. Clean agent discharge may be noisy, and the force of discharge may create reduced visibility. It may produce a swirl of dislodged papers or other loose materials. The low temperature of discharging gas may be a shock to a personnel. Training of responsible personnel is a necessity, and the specification of clean agent systems should not be considered for "at risk" persons, such as in public and patient areas in hospitals and nursing homes.

Clean Agent System Design Consideration for Urban/Semi-urban Occupancies in India

The clean agent system design considerations for the halon-alternative fire extinguishing agents that must be planned and designed for urban and semi-urban occupancies in India such that the fire extinguishant containers should not be in the hazardous area, and it shall suitably be in a protected location as close as possible to the hazard. Piping and fittings must be of a pressure rating commensurate with expected system pressures, and must be corrosion-resistant. Piping and fittings must be metallic, and the fittings cannot be of cast iron and it may be of welded, brazed, or malleable iron. Fire suppression and detection shall be selected/designed to be appropriate for the anticipated class of fires and emerging fire load density pattern/layout with appropriately designed discharge flow rate, particle/droplet size distribution with respect to fire extinguishing efficiency parameters.

An existing detection system may possibly be reused when designing a clean agent system, provided that the characteristics of the anticipated fire have not been changed because local application has not been found to be effective by the committee responsible for the technical content of NFPA 2001 (2004), clean agent systems are to be specified and designed for total flooding of enclosures. The enclosure protected by a clean agent must be rendered amenable to the application and retention of agent by

- Arranging for the automatic closing of doors
- Sealing opening and cracks around doors and windows

- Clipping down and restraining ceiling tiles and sealing them where necessary
- Shutting down supply and return air to a room with dampers in ducts to prevent loss of clean agent
- Attempting to limit loss of clean agent through floor drains, trenches, pipe penetrations through walls, and other wall and floor penetrations
- Shutting down gas or other flammable supplies
- Shutting down electrical power to energized electrical components where necessary

Systems must be designed such that the agent containers are not in the hazard area, and are in a protected location as close as possible to the hazard. Piping and fittings must be of a pressure rating commensurate with expected system pressures, and must be corrosion-resistant. Piping and fittings must be metallic, and fittings cannot be cast iron. They can be welded, brazed, or malleable iron. Detection shall be selected to be appropriate for the anticipated fire, as discussed. An existing detection system possibly may be reused when designing a clean agent system for a room currently protected by halon, provided that the characteristics of the anticipated fire have not changed.

Designing Halocarbon Clean Agents Total Fire Suppression Quantitative Requirement (1–9)

Clean agent systems are designed to extinguish fires either by flame extinguishment or by inerting. For reduction of flammable concentration in an atmosphere, inerting is required to be done below one-half of its lower flammable limit. Flame extinguishment is designed to cease combustion of a combustible solid or a flammable liquid. Halogenated clean agents are required to possess the properties listed in Table 9, and their systems are required to be designed to operate within the working pressure as shown in Table 10. Halocarbon agent total flooding quantity, assuming normal leakage from a tight enclosure, is calculated by using the same formula being used for halon

$$W = \frac{(V).(C).(A)}{(s).(100 - C)}$$

Table 9 Halogenated agent quality requirements (NFPA 2001 2004)

S. No.	Property	Specification
1	Agent purity, mole%, minimum	99.0
2	Acidity, ppm (by weight HCl equivalent), maximum	3.0
3	Water content, % by weight, maximum	0.001
4	Nonvolatile residues, g/100 ml maximum	0.05

Table 10 Minimum design working pressure for halocarbon clean agent system piping (1–9)

S. No.	Agent	Agent container maximum fill density (kg/m^3)	Agent container charging pressure at 21 °C (kPa)	Agent container pressure at 55 °C (kPa)	Minimum piping design pressure at 21 °C (kPa)
1	HFC-227ea	1260.75	1029	1708.14	1372
		1210.32	2469.6	3567.2	2853.76
		1210.32	4116	7031.5	5625.2
2	FC-3-1-10	1344.8	2469.6	3087	2469.6
3	HCFC blend A	944.722	4116	5831	4664.8
		944.722	2469.6	3704.4	2963.52
4	HFC 23	806.88	4177.05[a]	11751.18	9405.06
		756.45	4177.05[a]	10701.6	8561.28
		672.4	4177.05[a]	9480.52	7587.16
		588.35	4177.05[a]	8629.88	6908.02
		504.3	4177.05[a]	7943.88	6359.22
5	HCFC-124	1243.94	1646.4	2428.44	1941.38
6	HCFC-124	1243.94	2469.6	3978.8	3183.04
7	HFC-125	907.74	2469.6	4218.9	3375.12
8	HFC-125	941.36	4116	7168.7	5734.96
9	HFC-236fa	1243.94	1646.4	2469.6	1920.8
10	HFC-236fa	1260.75	2469.6	4116	3292.8
11	HFC-236fa	1243.94	4116	7546	6036.8
12	FK-5-1-12	1512.9	2469.6	2833.18	2469.6

[a] Not super-pressurized with nitrogen

$$s = (K1) + (K2.T),$$

where W = weight of halocarbon clean agent (kg); V = net volume of protected enclosure (m^3); S = specific volume (m^3/kg); A = altitude correction factor as per Table 11 (NFPA 2001 2004).

C = halocarbon clean agent design concentration that represents percentage of clean agent per volume. For example, if the halocarbon clean agent concentration is 6%, C = 6, not 0.06, and if the concentration is 6.5%, C = 6.5, not 0.065. k_1 and k_2 = constants that relate to the specific volume of hydrocarbon agent used; these constants are listed in Table 12 (NFPA 2001 2004).

Alternatively, the required agent quantity can be determined using the flooding factors found in Annexure A of NFPA 2001. For each agent, the flooding factor multiplied by the room volume gives the agent quantity, which is multiplied by the altitude correction factor. This can be better illustrated from following examples for the general understanding of the readers for the clean agents: HFC-227ea and IG-541.

Table 11 Atmospheric correction factors (NFPA 2001 2004)

S. No.	Equivalent altitude (km)	Enclosure pressure (mm Hg)	Atmospheric correction factor
1	−0.92	840	1.11
2	−0.61	812	1.07
3	−0.30	787	1.04
4	0.00	760	1.00
5	0.30	733	0.96
6	0.61	705	0.93
7	0.91	678	0.89
8	1.22	650	0.86
9	1.52	622	0.82
10	1.83	596	0.78
11	2.13	570	0.75
12	2.45	550	0.72
13	2.74	528	0.69
14	3.05	505	0.66

Case 1: Design of HFC-227ea Halocarbon Clean Agent Concentration

A sophisticated instrumentation room of size: 3 m wide × 6 m long × 3 m height with an ambient temperature of 21 °C is protected by a halocarbon clean agent, HFC-227ea, at a 6% design concentration. Design HFC-227ea requirement by weight to protect the room, assuming an elevation at sea level?

Solution: As specific volume of superheated HFC-227ea vapor can be approximated by the formula:

$$s = (k1) + (k2.t),$$

where t = temp. (°C) given as 21 °C, $k_1 = 0.1209$ and $k_2 = 0.00049$ for HFC-227ea.

Therefore

$$\begin{aligned} s &= 0.1209 + 0.00049.t = 0.1209 + (0.00049 \times 21) \\ &= 0.1313\,\mathrm{m}^3/\mathrm{kg} \end{aligned}$$

Refer Table 11, approx. same value at 21 °C.

$$\begin{aligned} V &= (3\ \mathrm{m}) \times (6\ \mathrm{m}) \times (3\ \mathrm{m}) = 54\ \mathrm{m}^3 \\ C &= 6\ (\mathrm{given}) \end{aligned}$$

Table 12 HFC-227ea total flooding quantity (NFPA 2001 2004)

S. No.	Temperature, *t*	Specific vapor vol., s	Weight requirements of hazard volume, *W*/*V* (kg/m^3)[b] Design concentration (% by volume)[e]									
	(°C)[c]	(m^3/kg)[d]	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%
1	−12	0.1146	0.556411	0.657271	0.758131	0.862353	0.95817	1.079202	1.190148	1.304456	1.420445	1.539796
2	−6.6	0.1173	0.542963	0.640461	0.741321	0.842181	0.946403	1.052306	1.161571	1.272517	1.386825	1.502814
3	−1	0.1202	0.531196	0.625332	0.72283	0.822009	0.92455	1.028772	1.134675	1.242259	1.353205	1.467513
4	4.5	0.1230	0.519429	0.611884	0.707701	0.803518	0.902697	1.005238	1.107779	1.215363	1.322947	1.433893
5	10	0.1258	0.507662	0.598436	0.690891	0.786708	0.882525	0.981704	1.084245	1.188467	1.29437	1.403635
6	15.5	0.1285	0.495895	0.584988	0.675762	0.769898	0.864034	0.961532	1.060711	1.161571	1.265793	1.373377
7	21	0.1313	0.485809	0.573221	0.662314	0.753088	0.845543	0.94136	1.038858	1.138037	1.238897	1.343119
8	26.6	0.1340	0.475723	0.561454	0.648866	0.737959	0.828733	0.921188	1.017005	1.114503	1.213682	1.316223
9	32	0.1367	0.467318	0.549687	0.635418	0.72283	0.811923	0.904378	0.996833	1.09265	1.190148	1.289327
10	38	0.1395	0.457232	0.539601	0.623651	0.709382	0.796794	0.885887	0.976661	1.070797	1.166614	1.264112
11	43	0.1422	0.448827	0.529515	0.611884	0.695934	0.781665	0.869077	0.95817	1.050625	1.144761	1.240578
12	49	0.1449	0.440422	0.519429	0.600117	0.682486	0.766536	0.852267	0.94136	1.030453	1.122908	1.217044
13	54	0.1476	0.432017	0.509343	0.58835	0.669038	0.753088	0.837138	0.922869	1.011962	1.102736	1.195191
14	60	0.1503	0.425293	0.500938	0.578264	0.657271	0.73964	0.822009	0.90774	0.993471	1.082564	1.173338
15	65.5	0.1530	0.416888	0.492533	0.568178	0.645504	0.726192	0.80688	0.89093	0.976661	1.064073	1.153166
16	71	0.1556	0.410164	0.484128	0.558092	0.635418	0.714425	0.793432	0.875801	0.959851	1.045582	1.132994
17	76.6	0.1583	0.40344	0.475723	0.549687	0.623651	0.700977	0.779984	0.860672	0.943041	1.027091	1.114503
18	82	0.1610	0.396716	0.467318	0.539601	0.613565	0.68921	0.768217	0.847224	0.927912	1.010281	1.096012

(continued)

Table 12 (continued)

S. No.	Temperature, t	Specific vapor vol., s	Weight requirements of hazard volume, W/V (kg/m^3)[b] Design concentration (% by volume)[e]									
	(°C)[c]	(m^3/kg)[d]	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%
19	88	0.1637	0.389992	0.460594	0.531196	0.603479	0.679124	0.754769	0.833776	0.912783	0.995152	1.077521
20	93	0.1662	0.383268	0.452189	0.522791	0.595074	0.667357	0.743002	0.820328	0.899335	0.978342	1.060711

[a] The manufacturer's listing specifies the temperature range for operation

[b] W/V [agent weight requirements (kg/m^3)] = kilograms of agent required per cubic meter of protected volume to produce indicated concentration at temperature specified: $W = \frac{V}{s}\left(\frac{C}{100-C}\right)$

[c] t [temperature (°C)] = the design temperature in the hazard area

[d] s [specific volume (m^3/kg)] = specific volume of superheated HFC-227ea vapor can be approximated by the formula: $s = 0.1209 + 0.00049.t$, where $t = $ temp. (°C)

[e] C [conc. (%)] = Volumetric conc. of HFC-227ea in air at the temperature indicated

[f] For other halocarbon clean agents, refer to NFPA 2001

A = sea level, or 0 feet elevation, and the correction factor is therefore 1, per Table 10.

$$W = \frac{(V).(C).(A)}{s.(100 - C)} = \frac{(54).(6).(1)}{(0.1312).(100 - 6)}$$
$$= 26.23 \approx 27 \text{ kg}$$

An alternative method of determining that design flooding quantity is to use the tables contained in the Annex of NFPA 2001. The table for HFC-227ea is included as Table 12.

The weight requirement corresponding to 21 °C and 6% is shown as 0.4858. Multiplying this factor times the room volume gives

$$W = \left(0.4858 \frac{\text{kg}}{\text{m}^3}\right) \times \left(54 \text{ m}^3\right) = 26.23 \approx 27 \text{ kg}$$

It may be noted that for this Case-1, the results are identical whether using the formula or the table. NFPA 2001 (2004) includes a table for each clean agent recognized by the standard.

The value 0.4858 kg/m^3 is a flooding factor, representing the quantity of halocarbon clean agent required to achieve a selected design concentration (6%) at a specified temperature (21 °C).

Inert Gas Clean Agent Total Flooding Quantity

Inert gas agents are required to be used at the minimum working pressures shown in Table 13 (NFPA 2001 2004) and must possess the quality shown in Table 14 (NFPA 2001 2004).

Inert gas quantity is based on finding the volume of gas needed, as opposed to finding the weight, as we did with halocarbons.

The formula for determining the volume of gas required is

$$V_g = (2.303).(V).\left(\frac{V_S}{s}\right).\log 10\left(\frac{100}{100 - C}\right).(A)$$

where

s	$(k_1) + (k_2.T)$
V	net volume of protected enclosure (m^3)
S	specific volume of inert gas (m^3/kg) at specified temperature
C	inert gas clean agent design concentration (v%)
V_s	specific volume of inert gas at 21 °C
A	altitude correction factor, refer Table 11.

Table 13 Minimum design working pressure for inert gas clean agent system piping (NFPA 2001 2004)

S. No.	Agent	Agent container pressure at 21 °C (kPa)	Agent Container Pressure at 55°C (kPa)	Minimum design pressure at 21 °C of piping upstream of pressure reducer (kPa)
1	IG-01	16,341	18,271	16,341
		20,436	22,781	20,436
2	IG-541	14,997	17,755	14,997
		19,996	23,671	19,996
3	IG-55	15,320	17,065	15,320
		20,423	22,753	20,423
		30,634	34,130	30,634
4	IG-100	16,575	19,299	16,575
		22,312	26,015	22,312
		28,000	32,778	28,000

Table 14 Inert gas agent quality requirements (NFPA 2001 2004)

S. No.			IG-01	IG-100	IG-541	IG-55
1	Composition, % by volume	N_2 Ar CO_2	Minimum 99.9%	Minimum 99.9%	52% ± 4% 40% ± 4% 8% + 1% − 0.0%	50% ± 5% 50% ± 5%
2	Water content, % by weight		Maximum 0.005%	Maximum 0.005%	Maximum 0.005%	Maximum 0.005%

$k_1 + k_2$ constants that relate to the specific volume of inert gas clean agent used, as listed on Table 14.

Note that Table 14 provides constants for IG-541 only, and that NFPA 2001 should be consulted for other inert gas agents.

V_g = volume of inert gas added at standard conditions per volume of hazard space.

Case 2: Design of IG-541 Inert Gas Clean Agent Concentration

A compartment/room of size: 6.06 m wide by 15.15 m long by 2.42 m height with an ambient temperature of 21 °C, is protected by inert gas clean agent IG-541, with a concentration of 34%. Design the minimum volume requirement of IG-541 to protect the compartment/room, assuming an elevation at sea level? (Given: V_s for IG-541 at 21 °C is 0.675 m^3/kg.)

Solution: As specific volume of superheated IG-541 vapor can be approximated by the formula

Table 15 IG-541 total flooding quantity (NFPA 2001 2004)

S. No.	Temp, t	Specific vapor volume s	Volume requirements of agent per unit volume of hazard, $V_{agent}/V_{enclosure}$[b] Design concentration (% by volume)[e]							
	(°C)[c]	(m^3/kg)[d]	34	38	42	46	50	54	58	62
1	−40	0.5353	0.524	0.603	0.686	0.802	0.873	0.977	1.096	1.218
2	−34.4	0.5480	0.513	0.590	0.672	0.760	0.855	0.958	1.070	1.194
3	−29	0.5608	0.501	0.576	0.657	0.743	0.836	0.936	1.046	1.166
4	−23	0.5735	0.490	0.563	0.642	0.726	0.817	0.915	1.022	1.140
5	−17.7	0.5863	0.479	0.551	0.628	0.710	0.799	0.895	1.000	1.116
6	−12	0.5990	0.469	0.539	0.615	0.695	0.782	0.876	0.979	1.092
7	−6.6	0.6117	0.459	0.528	0.602	0.681	0.766	0.858	0.958	1.069
8	−1	0.6245	0.450	0.517	0.590	0.667	0.750	0.840	0.939	1.047
9	4.44	0.6372	0.441	0.507	0.578	0.653	0.735	0.824	0.920	1.026
10	10	0.6499	0.432	0.497	0.566	0.641	0.721	0.807	0.902	1.006
11	15.55	0.6627	0.424	0.487	0.555	0.628	0.707	0.792	0.885	0.987
12	21	0.6755	0.416	0.478	0.545	0.616	0.693	0.777	0.868	0.968
13	26.6	0.6882	0.408	0.469	0.535	0.605	0.681	0.762	0.852	0.950
14	32	0.7009	0.401	0.461	0.525	0.594	0.668	0.749	0.836	0.933
15	37.7	0.7137	0.393	0.453	0.516	0.583	0.656	0.735	0.821	0.916
16	43	0.7264	0.386	0.445	0.507	0.573	0.645	0.722	0.807	0.900
17	49	0.7392	0.380	0.437	0.498	0.563	0.634	0.710	0.793	0.884
18	54.4	0.7519	0.373	0.430	0.489	0.554	0.623	0.698	0.779	0.869
19	60	0.7647	0.367	0.422	0.481	0.544	0.612	0.686	0.766	0.855
20	65.5	0.7774	0.361	0.415	0.473	0.535	0.602	0.675	0.754	0.841
21	71	0.7902	0.355	0.409	0.466	0.527	0.593	0.664	0.742	0.827
22	76.6	0.8029	0.350	0.402	0.458	0.518	0.583	0.653	0.730	0.814
23	82	0.8157	0.344	0.396	0.451	0.510	0.574	0.643	0.718	0.801
24	87.7	0.8284	0.339	0.390	0.444	0.502	0.565	0.633	0.707	0.789
25	93	0.8412	0.334	0.384	0.437	0.495	0.557	0.624	0.697	0.777

Note The manufacturer's listing specifies the temperature range for operation

[a] Atoms of middle Carbon-Cl_2

[b] Atoms of middle Carbon-Cl, F

[c] Atoms of middle Carbon-F_2

[d] Atoms of middle Carbon-Cl, H

[e] Atoms of middle Carbon-H, F

[f] Atoms of middle Carbon-H_2

$$s = k_1 + k_2.t,$$

where t = temperature (°C); $k_1 = 0.6271$ and $k_2 = 0.00229$ for IG-541.

Therefore,

$$\begin{aligned} s &= (0.6271) + (0.00229 \times 21) \\ &= 0.675\ \mathrm{m}^3/\mathrm{kg} \end{aligned}$$

Refer Table 15, approx. same value at 21 °C.

$$V = (6.06) \times (15.15) \times (2.42) = 222.17\ \mathrm{m}^3$$

$$\text{Concentration } (\%), C = 34 \text{ (given)}$$

$$V_s = 0.675\ \mathrm{m}^3/\mathrm{kg}, \text{as per NFPA 2001}$$

A = sea level elevation, and the correction factor is, therefore 1, as per Table 11.

$$\begin{aligned} V_g &= (2.303).(222.17).\left(\frac{0.675}{0.675}\right).\log_{10}\left(\frac{100}{100-34}\right).(1) \\ &= (2.303) \times (222.17) \times (1) \times (0.1805) \times (1) = 92.35\ \mathrm{m}^3 \end{aligned}$$

In a manner analogous to the tabular solution presented in Case-1, designers can use Table 15 to obtain a solution. It may be very important to note that the flooding factor corresponding to 21 °C and 34% concentration is 0.416 $\mathrm{m}^3/\mathrm{m}^3$ which when multiplied with 222.17 m^3 gives rise to 92.42 m^3 of IG-541, which is slightly more than what was obtained using the design calculation method, which could be attributed to rounding of logarithmic functions.

- V_g [agent volume requirements ($\mathrm{kg/m}^3$)] = Kilogram of agent required per cubic meter of protected volume to produce indicated concentration at temperature specified.

$$V_g = 2.303 \times \left(\frac{V_S}{s}\right).\log_{10}\left(\frac{100}{100-C}\right) = \left(\frac{V_S}{s}\right) \times \ln\left(\frac{100}{100-C}\right)$$

- t [temperature (°C)] = the design temperature in the hazard area.
- s [specific volume (m^3/kg)] = specific volume of superheated IG-541 vapor can be approximated by the formula: $s = 0.6271 + 0.00229t$, where t = temperature (°C).
- C [concentration (%)] = Vol. Conc. of IG-541 in air at the temperature indicated.

Note: V_s = the term $V_g = \ln\,[100/(100 - C)]$ gives volume at a rated concentration (%) and temperature to reach air-agent mixture at the end of flooding time in a volume of 1 m^3.

Halocarbon and Inert Gas Discharge Time

Halocarbon clean agents must be discharged within 10 s. Inert gas agents that do not create decomposition products may be discharged within one minute. The room must hold the gas for a time sufficient to extinguish a deep-seated fire without re-ignition.

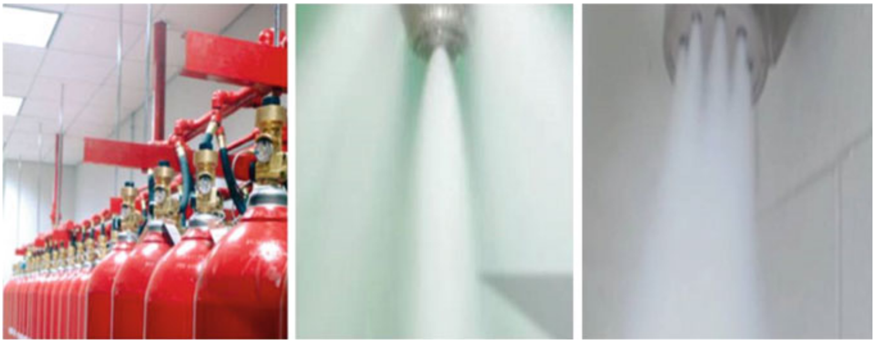

Fig. 2 A clean agent storage arrangement and discharge from nozzles

Clean Agent Storage and Nozzle Discharge Arrangement

A clean agent storage arrangement, clean agent nozzles and clean agent discharge are shown in Fig. 2 for suppression of fires in a room or compartment.

Pressure Relief Venting for Clean Agent Systems

NFPA 2001 (2004) requires that where clean agent valving arrangements on the pilot piping or on the discharge piping create closed piping arrangements where pressure could increase beyond the pressure rating of the piping, fittings, and nozzles, pressure relief devices are to be installed. The pressure relief devices are required to discharge in such a manner as not to be hazardous to personnel. The NFPA 2001 Annex describes pressure relief isometric diagrams for clean agent cylinders, showing pressure compatibilities for a variety of clean agent storage conditions. The Annex further recommends that pressure relief venting for closed piping sections follow the FSSA Pipe Design Handbook.

Novel and New Water-Based Options for Halon Replacement Options

Three water-based options for Halon replacement are

1. Water mist system
2. Double-interlocked pre-action Water Mist systems
3. Standard automatic water mist systems

Concluding Remarks

1. The design of new halon systems has been essentially halted as the result of cessation of production of halon in accordance with the Montreal Protocol, which prohibits the manufacture of halogenated agents in countries participating in the agreement. Although pure halon in concentrations between 5 and 10% is considered nontoxic to humans during brief exposure, the products of decomposition can be dangerous if breathed.
2. Clean agent systems may be considered as halon system replacements when designed in accordance with NFPA 2001.
3. From Case-1 study, it may be important to note that the value of 0.4858 kg/m^3 is a total flooding factor of HFC-227ea fire extinguishing agent representing the quantity of halocarbon clean agent required to achieve a selected design fire extinguishing concentration of 6% at a specified ambient temperature of 21 °C.
4. From Case-2 Study, it may be very important to note that the flooding factor for IG-541 clean agent fire extinguishing agent corresponding to ambient temperature of 21 °C and minimum fire extinguishing 34% concentration is 0.416 m^3/m^3, which is slightly more than that was obtained using the design calculation method, which could be attributed to rounding of logarithmic functions.
5. The clean agent containers should not be kept/mounted in the hazardous area, and it shall suitably be installed in a protected location as close as possible to the hazard. Piping and fittings must be of a pressure rating commensurate with expected system pressures, and must be corrosion-resistant. Piping and fittings must be metallic, and the fittings cannot be of cast iron and it may be of welded, brazed, or malleable iron.
6. Fire suppression and detection shall be selected/designed to be appropriate for the anticipated class of fires and emerging fire load density pattern/layout with appropriately designed discharge flow rate, particle/droplet size distribution with respect to fire extinguishing efficiency parameters.
7. An existing detection system may possibly be reused when designing a clean agent system, provided that the characteristics of the anticipated fire have not been changed
8. Clean agents include halocarbon and inert gas agents that are in conformance with NOAEL and EPA guidelines.
9. Halocarbon agents develop products of decomposition that may be harmful to personnel, hence such agents may be strategically used as per EPA and local government guidelines, rules, and regulations prevailing under Protocol Agreement.

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