1. HISTORY OF THERMAL ENERGY STORAGE

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Abstract. This chapter discusses the history of thermal energy storage focusing on natural energy sources. Links are made to recent trends of using renewable energy to achieve greater energy efficiencies in heating, cooling and ventilating buildings. The Deep Lake Water Cooling development in Toronto is presented as a typical modern interpretation of past practices with an integration of municipal services of water supply and district cooling. Environmental concerns and restrictions have also stimulated thermal energy storage developments. Cold storage in aquifers originated in China where excessive groundwater extraction related to industrial cooling had resulted in significant land subsidence. To rectify the subsidence problem, cold surface water was injected into the aquifers. Subsequently, it was observed that the injected and "stored" water had maintained its cool temperature for months and was suitable for industrial cooling. Thus, aquifer thermal energy storage (ATES) was born. The Netherlands restricted groundwater mining for industrial cooling but left an exemption if reinjection using ATES for cooling were implemented. This stimulated interest in ATES and led to many implemented projects. In some areas such as Winnipeg, Manitoba, the natural groundwater temperature (6 °C) is suitable for direct cooling. The reinjection of warm waste energy results in a gradual warming of the aquifer, ultimately leading to lower system efficiency for cooling. Using the aquifer for ventilation air preheating in winter helped the WINPAK plant maintain the natural groundwater temperature. Ground source technologies combined with underground thermal energy storage are seen as the best current method of combining natural energy sources with modern energy efficient building design. The latest technical findings have been incorporated into codes, standards and guidelines. Some of these are briefly described. Storing freely available energy to meet the requirements of a later season is "seasonal storage". Three principal stimuli to the development of large-scale seasonal energy storage are: (1) the decoupling of electricity and heat production in cogeneration plants with heat storage increasing the fraction of the annual heat demand met by cogeneration; (2) seasonal storage-assisted central solar heating plants to enable solar energy to supply winter heating demands; (3) the storage of ambient winter air temperatures for summer cooling. Thermal storage associated with cogeneration

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and district heating is a standard application. Central solar heating plants have been investigated, constructed and monitored as part of the International Energy Agency, Task VII of the Solar Heating and Cooling Implementing Agreement "Central solar heating plants with seasonal storage". The storage of ambient winter air temperature is particularly suited to continental climates characterized by long cold winters with brief hot summers. Ice and snow are practical latent energy storage media for cold winter air. Snow and ice may be fabricated or gathered from natural sources. In larger commercial buildings, particularly those of energy efficient design, the energy expended for cooling can be a major proportion of the total energy requirement. This combination of a suitable ice-making climate with significant building cooling demands stimulated interest in seasonal thermal energy storage. Various design alternatives were investigated, tested, evaluated and demonstrated. These efforts originated in the USA and Canada but now have been applied successfully in Sweden.

Keywords: ATES; aquifer thermal energy storage; borehole thermal energy storage; BTES; building cooling; chiller; district cooling; hypolimnion water; ice; ice storage; lake water; PCM; phase change materials; seasonal energy storage; snow; thermal energy storage; TES; underground thermal energy storage; UTES.

1.1. Introduction

The history of thermal energy storage is a rich tale dating back to ancient civilizations. It is based on natural sources of energy complemented by human ingenuity. These natural sources include ambient air, sky, ground, and the evaporation of water with the storage materials of building mass, rocks, water, ground and phase change materials. Heat transfer includes radiation, convection and evaporation. This limited review of some historical themes may assist in current attempts to reduce energy intensities by taking greater advantage of natural energy sources.

Perhaps the oldest form of energy storage is the harvesting of natural ice or snow from lakes, rivers and mountains for food preservation, cold drinks and space cooling. The following extract from 350 years ago illustrates the popularity of ice in Persia:

> They use abundance of Ice in Persia, as I have been observing; in Summer especially every one drinks with Ice: But that which is most remarkable, is, That tho' at Ispahan, and even at Tauris, which is further North, the Cold is dry and penetrating more than it is in any part of France or England, yet the greatest part of the People drink with Ice as well in the Winter as the Summer.

> Ice is sold in the out-parts of the City in open places: Their way of making it is thus . . . In less than eight Days Working after this Manner, they have Pieces of Ice five or six Foot thick; and then they gather the People of that Quarter together, who with loud Shouts of joy, and Fires lighted upon the Edges of the Hole, and with the Sound of Instruments to Animate them, go down into it, and lay these Lumps of Ice one upon the other [1].

Some regions of Japan (Kyoto, Kanazawa and Kusatsu) still celebrate the Himuro tradition as the Ice House Festival on June 1. Natural ice was collected and stored in Himuro, an icehouse, for use in the summer. It is thought the ice was used for cold drinks and to relieve the summer heat. The townspeople of Kusatsu collected and stored the precious ice in Himuro, a kind of icehouse, for the summer. It was customary to offer guests some of the natural ice with a decorative rhododendron flower. This frozen offering was thought to ward off sickness and disease for the entire year.

Before mechanical refrigeration systems were introduced, people cooled their food with ice and snow, found or made on-site or gathered in the mountains. This practice survives today in the Taurus Mountains of Turkey. Ice was stored in icehouses usually partially buried in the ground and lined with straw or sawdust. Remains of these structures survive on many farms in Europe and North America. Ice has long been used for space comfort conditioning. In the early nineteenth century, ice was placed in air ducts to cool and dehumidify warm air blown by fans.

Conventional building HVAC design focuses on the peak load conditions to enable equipment sizing and the system efficiencies. The total energy usage determines energy costs but is not a major risk factor. But energy storage design must consider both the peak delivery of energy and the total amount of energy that can be stored. This is especially true in some recent applications in the Netherlands that have no conventional backup.

The first ground-source heat pump was installed in Indianapolis, Indiana in the home of Robert C. Webber, an employee of the Indianapolis Power and Light Company. It was a 2.2 kW compressor hooked to a direct expansion ground coil system in trenches supplying heat to a warm air heating system. The installation was monitored beginning October 1, 1945 and this is the first day of ground source heat pump operation documented in literature [2].

Although groundwater cooling has a long history, the deliberate storage of cold water in an aquifer for later use or Aquifer Thermal Energy Storage (ATES) has a history of about forty years. It originated in China where excessive groundwater extraction related to industrial cooling had resulted in significant land subsidence. To rectify the subsidence problem, cold water (from surface water) was injected into the aquifers. Subsequently, it was observed that the injected and "stored" water had maintained its cool temperature

Figure 1. Scarborough Town Centre: first building ATES combined heating and cooling in Canada.

for a long period of time and was suitable for industrial cooling. The development of ATES in North America and Europe focused on the independent storage of cold and heat energy, both through experimentation and industrial applications. Environmental impacts related to aquifer warming, as well as the need for both heating and cooling, called for a technology advancement that would allow the effective storage of both warm and cold energy at different times of the year. The first application in Canada of a combined heating and cooling ATES for a new building was at the Scarborough Centre [3] building of the Government of Canada (Figure 1).

In many areas, the natural groundwater temperature is suitable for direct cooling. For example, in Winnipeg, Manitoba, the natural groundwater temperature is 6 °C. However, the reinjection of warm waste energy may result in a gradual warming of the aquifer, ultimately leading to aquifer degradation and lower system efficiency for cooling. ATES can avoid the gradual warming of the aquifer by using the waste heat for ventilation air preheating in winter.

1.2. Seasonally-Charged Deep Lake Water Cooling (DLWC) For Downtown Toronto [4]

Toronto is located on the northern shore of Lake Ontario. This lake contains a large volume of seasonally replenished 4°C water some six kilometers from shore below the 80-m level in the hypolimnion layer. Toronto is the largest metropolitan area in Canada with a downtown core of high rise buildings adjacent to the lake. This downtown core has a large cooling requirement (720 MW thermal) supplied primarily by on-site vapour compression chillers. The Deep Lake Water Cooling (DLWC) project will tap this lake water for cooling downtown Toronto buildings through a district cooling network. The district cooling network has been constructed and the DLWC implemented beginning in 2001–2002. Extending the municipal water intake for the DLWC project provides Toronto with a new water supply source and solves summer taste and odour problems. DLWC has made a major impact on replacing electrically-driven vapour compression chilling, much of it still using CFC refrigerants, and has cut electrical use to power these chillers. DLWC is unique in the size of the cooling demand that can be served; in the integration with municipal services, specifically the water supply for metropolitan Toronto; and the positive impact on energy efficiency and reduced greenhouse gas emissions. The project has the capacity to cool 100 office buildings or 3 million square meters of building space eliminating about 60 MW from the Ontario electrical grid.

1.2.1. GENERAL DESCRIPTION OF DLWC

Toronto is located on the northern shore of Lake Ontario. The high average monthly maximum temperature occurs in July at 26.5 °C with an extreme historical high of 40.6 °C. Relative humidity levels of greater than 80% often accompany the maximum temperatures and determine the low chilled water temperatures needed for dehumidification. The mean daily temperature averaged over the year is 8.9 °C.

Early in this century some Toronto buildings used lake water for cooling. Toronto is now a large metropolitan area with a downtown core of high-rise buildings having a large cooling requirement peaking at roughly 720 MW thermal. Pepco became the first summer peaking utility in 1942. This is now the common situation even for utilities such as Toronto Hydro and Hydro Ottawa. This core is within close proximity to the lake. The cooling requirement is provided by on-site, electrically-driven vapour compression chillers requiring approximately 200 MW peak electrical demands. This electricity usage gives off 150,000 tonnes annually of carbon dioxide. The lake water pumps require only 5% of the electricity currently used by the electrically-driven chillers that would be replaced [5].

1.2.2. FREECOOL FEASIBILITY STUDY

Freecool was the original concept involving the use of permanently cold water from the 80-m depth of Lake Ontario as a substitute for water that is cooled mechanically by electric chillers. A feasibility report [6] was completed for the Canada Mortgage and Housing Corporation in 1982.

The study found that Freecool could result in significant energy conservation in electricity for cooling and in natural gas for steam generation. The general concept is applicable in whole or in part to other major metropolitan areas in Canada and the USA where the natural cooling source could be a lake, river, sea or aquifer. The results of this preliminary feasibility study indicated that the Freecool concept was both technically and economically sound. Negative reactions to the Project Freecool proposal included the view that it was an expensive megaproject; that it ignored cooling demand reduction opportunities at source; that it lacked an identified proponent; and that the dumping of large volumes of return water in the harbour would have negative environmental consequences [7].

1.2.3. DISTRICT COOLING

District cooling is prompted by two factors. One is the large and growing demand for cooling within modern large buildings, caused by growth in the use of heat-producing office equipment and trends towards greater occupant densities in buildings. The other factor is growing difficulty in the provision of on-site cooling posed by refrigerant restrictions. Large modern buildings in Toronto require at least some cooling for 365 days a year to offset heat build-up in their cores.

There are environmental and economic benefits from district cooling. There is the avoidance of use of chemicals that destroy the stratospheric ozone layer such as CFCs. Another advantage is avoidance of the increases in ambient temperature, humidity, and noise that occur outside buildings that have on-site chillers, largely on account of their fans and cooling towers. The major environmental and economic benefits of DLWC arise because pumping cold water in from the lake requires only 5% of the energy required to produce the same amount of cold water using conventional chillers. The adverse environmental impacts are negligible when DLWC is integrated with the municipal water supply.

1.2.4. DLWC AND THE MUNICIPAL WATER SYSTEM

The exciting feature of the DLWC's district cooling system is that it makes use of the huge reservoir of cold water at the core of Lake Ontario. The lake is more than 250 m deep in places. Below about 80 m in the hypolimnion layer, reached within five kilometers of downtown Toronto, the water is permanently at 4 °C. This is the result of a natural phenomenon present in all large deep bodies of water where winters are cold. Surface water sinks when it is cooled to

4 °C because water is at its most dense at this temperature. Summer warming penetrates only to about a 60-m depth. Thus, a deep lake such as Lake Ontario has within it a very large volume of naturally cold water that is seasonally replenished each winter.

1.2.5. FUTURE EXPANSION OPTIONS

DLWC will gradually expand its cooling customer base. As the district cooling demand exceeds the DLWC capacity other options are available. The existing steam network is available during the cooling season to produce ice from steam-driven compressors cascading to absorption chillers. A number of large distributed ice storages are foreseen. They would be charged during the off peak evening hours and discharged during the day to meet the peak cooling demands.

The first phase of DLWC has the potential to meet more than half the annual cooling demand for the whole of Toronto's downtown, and about a fifth of the peak demand. The chilled water will cost less to produce than by conventional means, but the overwhelming advantages are environmental. As noted, the downtown will be quieter and less humid in summer because there will be no need for noisy chillers or vapour-producing cooling towers, which can also be a source of bacterial contamination and cause a form of pneumonia known as Legionnaires' disease.

The DLWC concept has sparked interest elsewhere. Cornell University has proposed a $55-million project called Lake Source Cooling [8] would reduce Cornell's air-conditioning energy usage by 80% by tapping nearby Cayuga Lake.

1.2.6. DLWC CONCLUSIONS

The DLWC project was a success for several reasons. It finally gained a clear proponent; it is integrated into the existing municipal services of water supply and steam and chilling services. It also contributes in a major fashion to the environmental goals of the city of Toronto [9]. These aspects were missing in the original proposals that were large, expensive and add-ons. Future growth of the district cooling network will be determined by customer response, but environmental and economic trends favour a rapid growth. Potential applications at other lake sites exist, but are limited in number.

1.3. Ice For Thermal Energy Storage

The storage of ambient winter air temperature is, however, particularly suited to continental climates characterized by long cold winters with brief hot summers are ideal for the seasonal storage of cold to offset summer cooling peaks. Ice and snow are practical latent energy storage media for cold winter air.

Long-term storage of latent energy in Canada has involved the seasonal storage of winter's cold for use in cooling buildings. This combination of a suitable ice-making climate with significant building cooling demands stimulated a seasonal thermal energy storage program to investigate, test and evaluate various design alternatives and to demonstrate potentially cost-effective storage schemes.

Ice, including both natural and artificial snow, is the choice for the storage of cold as latent energy. In areas of heavy snowfall, where it is collected and transported to snow dumps, an existing supply system is in place. In this respect, the situation is very similar to refuse collection and disposal. Any use that can be made of the refuse or snow that reduces the volume and frequency of hauls to dumps has a cost saving. Thus a building-related snow storage facility could earn revenue from dumping charges. This revenue in some Canadian cities would be comparable to the energy savings. Snow making is also a possibility, as it extends the range beyond those cities receiving heavy snowfall and eases the problems related to annual variation of snowfall and temperature. However artificial snow making involves operational expenses. It was decided to begin with ice formed in situ based on the wider applicability of this approach, i.e., only cold temperatures are required, the volume of storage is less (about one-half that of snow), the storage is not contaminated with salt and dirt as is street snow, and the possibility of a completely automated process exists.

The objective was to develop an automated, efficient ice freezing, storage, and utilization technique with minimal operating and maintenance costs; to determine the height of ice that could be efficiently produced as a function of winter temperatures; and to develop a standard modular approach applicable at any site in a cost-effective manner. The application was to cool commercial and industrial buildings. A construction cost goal of \$150–\$200 (Canadian 1985) per cubic meter of ice was set for the system based on expected energy and chiller savings in comparison with conventional cooling techniques. All of the major technical objectives were achieved. Agricultural applications with a modified design were evaluated over several seasons with positive results.

1.3.1. FABRICATING ICE

Interest in long-term latent energy storage in the form of ice and snow dates back to 1975 [10]. The first field experiment was conducted in the winter of 1979–1980, referred to as Project Icebox because of the wooden structure in which the ice was formed, stored, and melted. The water layer was simply exposed to ambient conditions and allowed to freeze. Results indicated that

Figure 2. Fabrikaglace during cooling extraction.

a substantial volume of ice could be formed, but manual intervention was needed. The meltdown response of the ice to a varying cooling load was completely successful.

The height of ice that can be formed in any location is dependent on many factors, but is directly related to winter temperatures and the method employed. The ice is formed of thin water layers continuously refreshed as the previous layer is frozen. The frequency of water spraying is dependent on the outside temperature. The ice is formed at the point of demand, eliminating all collection and transportation from the production site to the point of use. The size of such a storage should be large enough to spread the costs over a sufficient volume to reduce the first costs to an acceptable level. This method of fabricating a large ice block layer-by-layer using a water spray and outside air distributed over the water surface was called *Fabrikaglace* (Figure 2).

The usable cooling energy content of the cubic meter of ice is about 100 kWh. Therefore, the cost avoidance based on Canadian commercial electricity rates was about $5–$50 per cubic meter of ice. Farmers pay about $25 per cubic meter for delivered ice used in harvesting operations. Fishermen pay about $10 per cubic meter for ice made in large quantifies, and cube ice sold primarily in summer for chilling of drinks sells for an equivalent of about $200 per cubic meter. Cost considerations led to an initial cost goal of $120 (1979 $) per cubic meter of ice [11].

A field trial during the winter of 1981–1982 employed a fully automated enclosed design. It utilized fans to deliver cold outside air onto the water surface. The air is conducted to the water surface within polyethylene tubes sewn from sheeting. The outside temperature controls the frequency of water spraying.

Spraying was used to form a thin water layer. The water spray was formed by directing water onto an attached plate, which spreads a fountain of water over the ice. This splasher provides an even distribution of water controlled by a timer to give the desired thickness. This same splasher was used to distribute water in the meltdown phase. The water layer thickness used was from 1 to 3 mm. Then the ice-making potential at any location can be estimated based on local temperature records. The overall system coefficient of performance, including formation and storage, of the ice and delivery of useful cooling to the building, was estimated to be 50–100.

Freezing degree minutes or FDM are the product of the temperature in degrees below 0 °C times the duration of the temperature in minutes. The original scheme of three temperature ranges controlling the frequency of spraying resulted in about 300 FDM needed on average to freeze a layer of water. The method of sensing temperature every minute gave a 150 FDM requirement, a doubling of efficiency.

In a typical Quebec City winter, Fabrikaglace based on FDM control, produced a 20-m height of ice. The system coefficient of performance for a reasonably sized application is many times that of competing conventional or other renewable designs. This conclusion is based on data from several seasons of operation. It may be possible to produce significantly more ice in exchange for a decrease in the coefficient of performance. This field trial was successful and supplied cooling to a nearby building.

1.3.2. TECHNICAL GOALS

The goal of a completely automated ice making technique was achieved gradually over five years. First, fans were introduced to bring in cold air when required. Air tubes were used to carry the air to the water surface. These tubes were originally shortened manually as the ice surface rose. The spraying of water interfered with these tubes, and ice formed where it was not wanted. A better method of spraying water was developed and multiple generations of "splashers" eventually led to an acceptable system that distributed water without problems. The plastic air tubes were replaced with collapsible tubing. They were fully extended at the beginning of the freezing cycle and gradually shortened during the winter. Air tubes and splashers were later integrated into one unit that was hoisted from the roof. The control originally was based on reading outdoor air temperatures and basing frequency of spraying on temperature. A method based on sensing temperature every minute and accumulating freezing degree minutes doubled the efficiency. Later, the separate tubes bringing air vertically onto the water surface were integrated into a header that uses angled vents to distribute air horizontally over the water surface.

1.3.3. COST GOALS

Costs estimates for a full-sized application, based on experimental costs, were competitive with conventional cooling. As technical development progressed, costs increased. While the goal of minimum operation and maintenance seemed secure, it was achieved by increased sophistication. Also, as the technique increased in efficiency and the height of ice that could be made increased, the importance of land area decreased. The demonstration chosen involved a building complex scheduled for replacement of the chiller for a cost of about \$250,000. The annual energy cooling costs had been dramatically reduced to about \$20,000 through modifications in building operation. Therefore, the combined capital cost and energy cost avoidance over ten years for the introduction of a Fabrikaglace would be about \$350,000 or \$115 per cubic meter of ice. Special R&D requirements for instrumentation and evaluation of about \$200,000 gave a rough cost of \$550,000. Higher cost for a first trial could only be justified if there was a reasonable expectation that future project costs could be reduced based on the experience gained in constructing and operating the demonstration. Major assumptions are that the designs are reliable enough to replace part or all of the conventional chilling capacity and that no additional maintenance and operational expenses are required. Commercialization was envisioned by involving prefabricated building manufacturers in the design of the demonstration. Such manufacturers may have general contracting capabilities and can therefore deliver the entire project. Local teams formed of such manufacturers with engineers and architects would be able to market the technology. Cost-effective trials have been completed for chilling of vegetable crops [12].

1.3.4. SWEDISH SNOW STORAGE

The Swedish tradition of using stored snow and ice for cooling is old. Ice barns were used for centuries for storage of food. The barns were normally well-insulated buildings kept cold by the stored ice. In some cases the barns were merely a storage room for ice in which case the ice was stored under a layer of sawdust. There are 6th century ice storage pits, which according to archaeologists were used for storage of meat and fish in summer time. Some old ice barns are still in operation. During the 19th century ice cooling became common in the Swedish cities. Ice was harvested from lakes and stored for later use. Ice cooling was a large industry and Swedish and Norwegian ice was exported to New York, London, and India. Norway exported more than 300,000 tons of ice to London in the year 1900.

Today there is a renewed interest in snow and ice cooling. The first large-scale plant for space cooling is now in its sixth year of operation. Several similar projects are now under evaluation. The Sundsvall Hospital [13] snow cooling plant, mainly used for comfort cooling, is located in central Sweden, where the annual mean temperature is 6 °C. The plant is designed for a cooling load of 1,000 kW (1,000 MWh), which requires 30,000 m^3 of snow. It consists of a watertight, slightly sloping asphalt surface, 140 m × 60 m. Cold melt water is pumped from the storage to heat exchangers in the hospital building. While cooling the building the water is warmed. The water is re-circulated to the storage to melt more snow, i.e., to produce cold water. The storage has no power limit. If a higher cooling power is needed more water is re-circulated and more melt water is formed.

Most of the snow is collected from nearby streets. If necessary, snow guns are used to produce additional snow. In April the snow deposit is thermally insulated by 0.2 m of wood chips. Some meltwater is evaporated through the sawdust, which gives an evaporative cooling effect that corresponds to 25% of the extracted cold. The wood chips in Sundsvall are reused several seasons before being burnt in a nearby cogeneration plant.

The operation of the snow cooling plant has so far been successful. During the year 2000—the first short cooling season—about 19,000 m^3 of snow was sufficient to supply 93% of the cooling demand. In 2001 about 27,000 m^3 of snow met 75% of the cooling demand. Some modifications were made on the storage as a result of experiences from the first two years of operation.

1.4. Underground Thermal Energy Storage (UTES)

1.4.1. INTRODUCTION TO ATES AND BTES

Underground Thermal Energy Storage (UTES) has been used to store large quantities of thermal energy to supply process cooling, space cooling, space heating, and ventilation air preheating, and can be used with or without heat pumps. UTES is used as an energy sink and source when supply and demand for energy do not coincide. Recognized energy sources include winter ambient air, heat-pump reject water (from cooling and heating mode), solar energy, process heat, etc. UTES may be used to meet all or part of the heating or cooling requirements of the building or process. Heat pumps may be employed to decrease or increase the storage temperature for cooling or heating.

Applications for UTES include space heating and cooling of all building types, agriculture (e.g., greenhouses), and industrial process cooling. UTES can be applied at sites presently using groundwater for cooling. UTES would assist in keeping aquifer temperatures from increasing and ensure that environmental safeguards such as aquifer recharge are employed. The cost-effectiveness of UTES is based on the capital cost avoidance of conventional heating or chilling equipment and energy savings. Heat rejection equipment, such as cooling towers, may be avoided if the earth is used as an energy store.

UTES encompasses both aquifer thermal energy storage (ATES) and borehole thermal energy storage (BTES).

ATES may be used on a short-term or long-term basis

(a) as the sole source of energy or as a partial storage;
(b) at a temperature useful for direct application or needing upgrade; and
(c) in combination with a dehumidification system, such as desiccant cooling.

Cold storage underground is now a standard design option in several countries. The duration of storage depends on the local climate and the type of building or process being supplied with cooling or heating. Aquifers, necessary for the implementation of ATES, can be discharged effectively through production wells to meet large cooling and heating demands. Aquifers are underground, water-yielding geological formations, and can be unconsolidated (gravel and sand) or consolidated (rocks). The temperature of aquifer water is related to, but usually slightly warmer than, the mean annual air temperature.

In Alabama, where the natural groundwater temperature (about 18 °C) is too high for direct cooling, ATES is used to store chilled water produced during the winter months. The wells are separated by a critical distance to ensure that the warm and cold stores remain separate and that thermal breakthrough does not occur within one season. This critical distance is primarily a function of the well production rates, the aquifer thickness, and the hydraulic and thermal properties that control the storage volume. A minimum separation distance is 30 m and distances of 100–200 m are common for commercial building applications. Multiple-well configurations, involving more that two wells, have been employed where large volumes of water are required and in systems where individual well yields are low. Single-well applications have also been employed using vertical separation of hot and cold groundwater where multiple aquifers exist. A number of software programs are available to simulate UTES systems.

The increasing use of groundwater source heat pumps for heating and cooling residential and commercial buildings has stimulated the demand for ATES applications with heat pumps. Facilities in northern latitudes may have roughly equal heating and cooling energy requirements. A groundwater source heat pump connected to a cold well and a warm well is a rudimentary ATES. The warm well can be used as a heat source for the heat pump evaporator in the heating season and the by-product chilled water stored in the cold well. The chilled water is stored until the cooling season when, for a time, it can be used directly, without the heat pump, to provide space and process cooling.

Cold storage water is normally injected at temperatures of 2–5 °C, with cooling power typically ranging from 200 kW thermal to 20 MW thermal, and with the stored cooling energy extending to 20 GWh. At a cogeneration waste heat project supplying direct heating to the Utrecht University campus in the Netherlands, hot wells have successfully stored water up to a temperature of 90 °C. Attempts to store water at temperatures of 250 °C have not been successful due to adverse water–rock geochemical interactions. A typical single-well flow rate is 3 l/s for a small application and 50 l/s for larger applications. Cost-effectiveness is enhanced when both heating and cooling energy are supplied.

UTES systems fall into two categories depending on whether the stored energy is actively gathered (e.g., the facility at the University of Alabama building in Tuscaloosa where the cooling tower was used in winter as a collector of chilled water) or whether the system stores waste or by-product energy (e.g., groundwater heat pump projects that store the by-product chilled water from the heating season). These double-effect storage projects are more likely to be economical.

Chemical changes in groundwater due to temperature and pressure variations associated with aquifer thermal energy storage may result in operational and maintenance problems. Fortunately, these problems are avoidable and manageable within the operating range of most common applications. Explicit guidelines on proper design, materials selection, and operation, which would decrease the likelihood of such problems, are now available. To maintain well efficiency, back flushing is recommended.

BTES applications involve the use of boreholes and are operated in closed loop (i.e., there is no contact between the natural groundwater and the heat-exchange fluid). Typically, a BTES system will include one or more boreholes equipped with borehole heat exchangers (e.g., U-tubes) through which waste heat or cold energy is circulated and transferred to the ground for storage. Borehole thermal energy storage has been extensively exploited in Sweden. Large systems are operating at Richard Stockton College in New Jersey and at the new University of Ontario Institute of Technology in Oshawa, Ontario.

Seasonal storage began as an environmentally sensitive improvement on the large-scale mining of groundwater. It has the potential to save large amounts of energy. The modern approach is characterized by the reinjection of all extracted water, minimal water treatment, and the attempt to achieve annual thermal balancing. The recent research, which is focused on community-based and aquifer-based use of aquifer thermal energy storage, perhaps integrated with other community services such as drinking water supply or aquifer remediation, will lead to large-scale storage implementation.

1.4.2. GUIDELINES AND STANDARDS

1.4.2.1. *C448.3-02—Design and Installation of Underground Thermal Energy Storage Systems for Commercial and Institutional Buildings [14]*

This Standard covers minimum requirements for equipment and material selection, site survey, system design, installation, testing and verification, documentation, and commissioning and decommissioning of Underground Thermal Energy Storage Systems for Commercial and Institutional Buildings. It is not a design guideline but rather a provision that the user is obliged to satisfy in order to comply with the Standard. It makes clear who is responsible for what and what expertise is needed.

The Standard covers Equipment and Materials, e.g., acceptable grouting materials; Site Survey Requirements, e.g., all wells shall be tested for their recharge rate up to the maximum recharge rate required; Design of UTES Systems, e.g., an ATES system shall be designed with due consideration being given to significant chemical changes due to warming or cooling based on water chemistry analysis and modeling; Installation of Systems, e.g., the engineer shall ensure that the water-supply and recharge well(s) and pumping equipment are installed, hydraulically tested, and sealed and grouted by a qualified contractor.

1.4.2.2. *Environmental Checklist for Earth Energy Heat Pumps and Underground Thermal Energy Storage (UTES) Systems*

Potential environmental concerns over the use of earth energy heat pumps and UTES are

- the possibility of leakage of the heat-exchange fluid into the natural environment;
- thermally induced biochemical effects on groundwater quality;
- ecological distress due to chemical and thermal pollution; and
- external contaminants entering the groundwater.

Potential environmental concerns should be addressed through system design and monitoring. The following items are provided as a guide:

(a) The antifreeze solution used for heat exchange shall not be toxic, as determined by the occupational safety and health provisions of the *Canada Labour Code*, Workplace Hazardous Materials Information System (WHMIS) Material Safety Data Sheets, and standard test methods.
(b) The antifreeze solution shall not adversely affect the physical, metallurgical, or chemical integrity of the piping system.
(c) The physical piping connections shall not allow leakage of the antifreeze solution under the anticipated maximum internal pressure of the system.

(d) A system-monitoring procedure shall be designed (including an emergency response plan) to handle any accidental leakages safely and effectively. Before installation, the entire system or randomly selected critical components of the system shall be tested under conditions resembling those that will prevail after installation of the system, to determine any flaws or shortcomings in design and manufacturing. The installation of the system shall be accompanied by a means for system integrity monitoring and for remediation in case of failure.
(e) The monitoring system shall be managed properly to prevent any leakages from spreading beyond property limits.
(f) Heat-exchange fluid spills or leakages in a soil-based heat sink whose base is located at least 1 m (3 ft) above the highest anticipated or known groundwater level are generally not a concern, except in those cases where the heat sink consists of soils with Darcy permeability coefficients greater than 10 cm/s. In such cases, consideration may be given to lining the heat sink base and sides with clay or artificial impermeable barriers.
(g) Where the heat sink consists of a prism of soil-containing vertical boreholes that penetrate the groundwater, some of the holes may be designed as pumping wells to confine accidental leaks and recover lost fluids.
(h) Vertical and/or inclined boreholes shall be properly sealed against contamination from external sources or from any contaminated stratigraphic units intersected by the boreholes.
(i) Any soil-based installation shall not permit the flushing of soil into aquatic habitat.
(j) Antifreeze released from a submerged earth energy heat pump system will be diluted immediately, but it will also change the quality of the surrounding water. The system design shall include mitigating measures to protect aquatic habitat and water quality.
(k) Potential thermal pollution of a water body shall be analyzed with respect to its impact on aquatic habitat and on the local or regional ecosystem. Temperature rises above certain critical limits can promote the growth of certain parasites or bacteria, which can affect fish. It has been suggested that the columnaris disease of salmon in the Columbia River was facilitated by a slight elevation in temperature.
(l) During well drilling, well development, water sampling, and in situ testing, care shall be taken to prevent the entry of contaminants from the surface and/or the subsurface stratigraphic units intersected by the well bore.
(m) Well bores and vertical boreholes shall not penetrate designated geological formations.

(n) The velocity and direction of groundwater flow shall be determined in order to maximize the thermal store retention time.
(o) Pumping from existing or new wells and injecting water into existing or new wells shall not affect the water rights of other well owners/users, and in no case should such withdrawal or injection affect the pre-use quality of the groundwater, except by mutual consent of the parties involved (and then only if the change in water quality satisfies local regulations and can be shown to be beneficial for the purpose intended).
(p) The UTES storage temperature should not result in unacceptable temperature changes in the groundwater being withdrawn from the storage aquifer by neighbouring groundwater users. In some jurisdictions a maximum change of +1 °C is considered acceptable.
(q) Groundwater treatments designed to improve the efficiency of UTES systems and/or components should not result in such changes to the groundwater quality as may be considered unacceptable for the supply aquifer or the aquifer into which the treated groundwater is injected.
(r) Groundwater injected into an aquifer shall meet the water quality criteria established for that aquifer.
(s) The impact of groundwater or ground-temperature changes on soil micro-organisms shall be investigated to ensure that pathogens (human or animal disease-bearing or—causing micro-organisms) are not encouraged to multiply.
(t) Ground-temperature changes shall not adversely affect surrounding structures and the natural habitat.
(u) The earth energy heat pump and UTES systems shall be designed to prevent the entry of allochthonous (external origin) bacteria, viruses, fungi, and spores into the human or animal hygiene domain served by the system.
(v) The earth energy heat pump and UTES system design shall include antiseptic measures and treatments that preserve and enhance hygiene, to counteract possible contaminants. For example, bacteria of the genus *Legionella* are associated with cooling towers.
(w) During extraction of groundwater, the quantity of dissolved gases released shall not be sufficient to change the groundwater quality from the standard established for the supply aquifer.
(x) During well drilling and/or development, the drilling muds used should not be of the type that can serve as nutrients to indigenous bacteria or viral species that may be present in a dormant state within the subsurface environment. Where such drilling muds are required to be used by the nature of the geological formations that are intersected by the

well bore, the well-development phase should include a thorough flushing of the well bore and its immediate surroundings to remove potential nutrients.

1.4.2.3. *Direct Use of the Underground as Heat Source, Heat Sink, Heat Storage Guideline VDI 46401 [15]*

The guideline is intended for planning and construction firms, manufacturers of components (e.g. for heat pumps, piping, thermal insulation materials, etc), licensing authorities, energy consultants and for persons providing instruction/training in this field. Proceeding from the current state of the art, the goal of the guideline is to ensure correct design, suitable choice of materials, and correct production of boreholes for UTES systems as well as their proper installation and incorporation into energy supply facilities. This will ensure that these systems operate trouble-free in an economically and technically satisfactory manner, also over long periods of time, without having a negative impact on the environment.

Direct Use of the Underground as Heat Source, Heat Sink, Heat Storage *GuidelineVDI 4640 Part4:* Thermal Use of the Underground: Direct Uses 02.08.2004 Editor: VDI Verein Deutscher Ingenieure (The Association of Engineers), Release: September 2004 Price: EUR 65,80 Released in German and English. Available from: Beuth Verlag GmbH, 10772 Berlin www.beuth.de.

The new publication of part 4 "Direct Uses" of the guideline series "Thermal Use of the Underground" describes how the groundwater or the underground can be used thermally as heat source, heat sink and heat storage without operating a heat pump or a cooling device in this process. Part 4 treats the direct thermal use of the groundwater, its design and installation, water economic and water legal aspects as well as environmental aspects. The direct thermal use of the underground with borehole heat exchangers, energy piles, etc forms a further main emphasis. The earth-to-air heat exchangers for heating up and/or cooling the air are described in detail. System descriptions with their design, installation, environmental and economical aspects are some of the topics of this chapter.

Under consideration of the status quo of the technological development, the guideline series of VDI 4640 "Thermal Use of the Underground" presents in four different parts a proper design, a suitable material choice and a correct execution of drillings, installation and system integration of plants for the thermal use of the underground:

Part 1: Fundamentals, approvals, environmental aspects.
Part 2: Ground source heat pump systems (GSHP).
Part 3: Thermal underground energy storage (UTES).
Part 4: Direct uses.

1.5. Conclusions

Thermal energy storage has had a long history extending from thousands of years ago to the present. These traditions have been modified to assist in the current need to achieve energy efficient building technologies. Thermal energy storage ranges through scales from the personal to the municipal. Integration of storage with other municipal services such as snow collection and water supply has been seen as giving promising results. Natural energy sources seem ready again to play a major role in the effort to achieve large reductions in energy intensity in existing and new buildings [16]. This requirement will be clear as the response to the post-2012, post-Kyoto world is formulated.

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