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Evolution of Thermal Energy Storage for Cooling Applications

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Thermal energy storage (TES) for cooling can be traced to ancient Greece and Rome where snow was transported from distant mountains to cool drinks and for bathing water for the wealthy. It flourished in the mid-1800s in North America where block ice was cut from frozen lakes and shipped south in insulated rail cars for food preservation and health-care facilities.

Block ice (*Photo 1*) was initially used for cooling in theaters, where a 4 ft × 4 ft × 2 ft (1.22 m × 1.22 m × 0.61 m) slab of ice would weigh 1 ton (907 kg) and, with the heat of fusion of 144 Btu/lb (907 kg), would provide 12,000 Btu/h (334 kJ/kg) over 24 hours, hence our industry terminology. The dairy industry was the first to employ mechanical ice making to rapidly cool milk and frugal farmers would build ice all night long to reduce equipment size and cost.

First Generation of Thermal Energy Storage

Cooling of commercial office buildings became widespread after World War II, and its availability contributed to the rapid population growth in the southern and western United States. Window units, split DX, rooftop packages, and central chiller plants filled their respective niches. Utilities recognized that air conditioning was contributing to peak demand growth and initially promoted conventional air conditioning and refrigeration to increase revenues. Since the generating plants were underused at night, the utilities looked for ways to build additional off-peak load. Thermal energy storage for cooling office buildings and factories was embraced and many demonstration projects were initiated. However, due to the regulatory environment, these programs had to be "revenue neutral" and not

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subsidize one rate class at the expense of another. This meant that the TES project would shift its peak kWh at $0.05/kWh to off-peak at $0.025/kWh, but it had to consume twice as much energy at night. There was no customer savings, but the utility could provide an incentive to balance its load profile. These technical requirements favored ice storage and particularly "ice harvesting" systems (see later section, "Cool TES Technology Family Tree.")

The equipment manufacturers, utilities, and engineering firms saw a value in design guides and technical information. Sizing tanks, estimating weekly load profiles, and performance of ice slurries was neither well understood nor documented. ASHRAE established Technical Committee (TC) 6.9, Thermal Storage, in 1981. TES activity had previously been part of TC 6.1, Heat Pumps; but the research focus did not align across two very different markets.

Electric Utility Impacts and Second Generation of TES

In 1979, the electric industry fundamentally changed when the Three Mile Island (TMI) nuclear plant experienced an incident. Previously, nuclear power was supposed to be so inexpensive, it would not have to be metered. Safety concerns and public opposition rapidly increased the cost of nuclear plants with utilities pushed to the brink of bankruptcy. Utilities actually looked at ways to reduce growth to avoid additional construction costs. Demand-side management (DSM) was embraced to address peak electric demand. As a secondary result of the TMI accident, the Electric Power Research Institute (EPRI)—established by the utility industry to conduct collaborative research—began to take a closer look at advanced technologies for using electricity. As part of its research into DSM, EPRI invested in a portfolio of technology developments involving TES.

The new generation of TES systems had a new focus—reduce peak demand. The systems did not have to be revenue-neutral, which had mandated less efficient solutions such as ice harvesting. Simple ice tanks and chilled water storage were allowable. Chilled water storage was seen as the preferred technology by the chiller manufacturers as their existing product lines required no changes; but the challenge was to avoid mixing the supply and return chilled water to maximize capacity and maintain cool supply temperature. The TES industry experimented with various designs

PHOTO 1 Block ice farming. (courtesy of Wisconsin Historical Society)

(see later section, "Cool TES Technology Family Tree") before settling on thermal stratification as the simplest strategy. Extensive research was conducted at the University of New Mexico and separately by tank manufacturers to develop theories affecting diffuser designs to create and maintain stratification. EPRI funded studies and ASHRAE TC 6.9 produced the *Design Guide for Cool Thermal Storage.*

Ice storage tanks were also further developed in the early 1980s. These included ice-on-coil internal melt, ice-on-coil external melt, and encapsulated ice TES, as well as ice slurries and other phase change materials (PCMs), all described in the later section, "Cool TES Technology Family Tree."

A New Approach

The perceived energy penalty for ice-making was an impediment, especially as global warming concerns were emerging. The TES industry developed a novel alternative that radically departed from conventional HVAC design. Air is distributed through ductwork in most buildings at 55°F (12.8°C) in order to achieve ASHRAE Standard 55 comfort conditions of 76°F (24.4°C) and 50%RH. Chilled water is typically supplied to air-handling units at 44°F (6.7°C). An ice plant can provide chilled water temperatures at nominal 32°F to 36°F (0 to 2.2°C), and its larger Delta *T* is wasted. However, if the air-distribution system is designed for a much lower supply temperature of 45°F (7.2°C), the airflow can be cut in half for the same cooling capacity. Fan and duct size are reduced, offsetting the cost of the ice storage system. EPRI conducted studies and produced case studies documenting the energy savings and first cost savings of cold air distribution (CAD) systems. EPRI and Florida Power & Light (FP&L) funded one CAD/ice demonstration project at Brevard Schools.

EPRI was involved extensively in developing, evaluating, and promoting these different cool thermal energy storage technologies. It pursued a portfolio management approach, recognizing that there was not a one size fits all solution. One philosophical change was the use of partial storage to reduce first cost and limit the plant from bringing spare chillers on-line in future years. EPRI worked closely with ASHRAE TC 6.9 to disseminate information and fine-tune its research agenda (*Photo 2*). TC 6.9 had quickly grown to one of the largest technical committees due to its diverse membership of manufacturers, utility personnel, consulting engineers, academics, and facility managers seeking detailed performance data and design guidance. The TC was very active in research, handbook, and programs, sponsoring many forums, seminars, and papers.

EPRI recognized that it needed to centralize technical assistance to respond to its members' requests for training and support. In 1991, EPRI established the Thermal Storage Applications Research Center (TSARC) at the University of Wisconsin-Madison. The UW was selected due to its Engineering Professional Development program and its HVAC workshops on TES, HVAC controls, and cogeneration. Professor Charles E. Dorgan, Ph.D., P.E. was the director and quickly added staff to fulfill the training, communication, and technical assistance needs. TSARC conducted workshops throughout the United States for consulting engineers, sharing design experience and practical insight. TSARC established an advisory committee to guide its research programs and focus on technical resources. The committee included major utilities, manufacturers, researchers, and regulatory personnel.

The establishment of TSARC marks the height of utility industry promotion of cool TES. Utilities were offering incentives of up to $500 per kW avoided, sponsoring training workshops, and installing TES systems in their offices and operations facilities. That lit a fuse and TES systems were exploding throughout the United States. EPRI and TSARC also continued research into ice slurry TES and PCM TES.

Cool TES Technology "Family Tree"

Cool TES technologies can be divided into two main branches: those storing energy as a change in phase (latent heat systems) and those storing energy as a change in temperature (sensible heat systems).

PHOTO 2 TC 6.9 Programs Chuck Dorgan seminar. (courtesy U of Wisconsin-Madison)

Most latent heat TES systems employ water-ice as the phase change medium, though a minority of others have used other phase change materials (PCMs). Primary benefits are high energy density (low volume per stored ton-hour) and modularity, while drawbacks include complexity, the need for heat transfer to charge and discharge TES, high energy consumption due to low temp chiller operation, and little economy-of-scale. Ice TES has taken the form of a variety of configurations, each discussed below.

Latent Heat TES

Ice Harvester TES

Many manufacturers, including Paul Mueller, Turbo Refrigerating, Henry Vogt, and others offered ice harvesting systems that produced sheet ice, tube ice, or ice cubes on vertical heat transfer surfaces. A periodic defrost cycle was used to shuck the ice into storage tanks below, where water was later circulated through the piles of ice to meet cooling loads. Due to the high unit cost ($/ton) of the ice harvesters, they were generally configured as weekly-cycles in which ice was produced all weekend and each weeknight, and melted each weekday; thus, the ice makers were smaller and less expensive, while the ice tanks became several times larger. The complexity of these "dynamic" ice systems led to O&M issues, with simpler "static" ice options coming to dominate the Ice TES market.

Ice-on-Coil—Internal Melt

This approach generally takes one of two forms. In the first version, as long practiced by BAC, Evapco, and others for modules of roughly 500 to 1,500 ton-hours (1.8 to 5.3 MWh), a rectangular storage tank flooded with water contains a serpentine coil of metal pipe through which water-glycol is circulated. Cold glycol from chillers serves to chill the pipes, forming ice on the pipe exterior; later warm glycol from cooling loads serves to melt the ice, from the inside-out. In the second version, as long practiced by Calmac and Fafco for modules of roughly 150 to 200 ton-hrs (0.5 to 0.8 MWh, a plastic tank flooded with water contains small plastic tubing (or other heat transfer means) through which water-glycol is circulated. Again, cold glycol from chillers serves to chill the pipes, forming ice on the pipe exterior; later warm glycol from cooling loads serves to melt the ice, from the inside-out. In some cases, nearly 100% of the water can be converted to ice.

Ice-on-Coil—External Melt

This is a modified approach of the first type of internal melt ice-on-coil equipment described above. In early examples, practiced by BAC, Evapco, and others for modules of roughly 500 to 1,500 ton-hrs (1.8 to 5.3 MWh), a rectangular storage tank flooded with water contains a serpentine coil of metal pipe through which refrigerant is circulated and vaporized, forming ice on the pipe exterior. In later examples, water-glycol is circulated within the pipes to form ice. In both cases, warm water from cooling loads flows through the tank to melt the ice via direct contact, from outside-in. This permits a cooler supply water temperature to cooling loads and is especially applicable to district cooling applications where the cooler supply temp can reduce distribution pipe size and cost. In all cases, much less than 100% of the water can be converted to ice, as channels between the ice must be kept free for water flow during ice melting.

Encapsulated Ice TES

Similar to ice storage tanks, encapsulated ice systems were developed. Small plastic balls or lenses were filled with water and placed in a storage container. A water/glycol solution (or other secondary fluid) would flow around the balls or lenses and freeze the water. Later, warm return fluid from the cooling loads would flow to melt the ice and provide chilled water through a heat exchanger. Manufacturers included Cristopia, Cryogel, Reaction Ice, and others. Some manufacturers offered phase change materials (PCMs) other than water to raise the freezing temperature, allowing conventional chillers to be used and minimizing the energy penalty of making ice.

Ice Slurry TES

The production of pumpable ice slurries has long been explored, as the potential benefits from reductions in pipe and pump sizes and pump energy are quite substantial. Various attempts have been made, including using scraped-surface ice-makers (in Canada), Liquid Ice by CB&I in the late 1970s/early 1980s, and Slippery Ice by EPRI in the late 1980s, the latter two using falling-film HXs with electropolished stainless steel tubes and mylar heat transfer surfaces, respectively; however, limitations of low heat flux and high unit cost ended further development. A system operating at the triple-point of water (with all three phases: solid, liquid and vapor in equilibrium) was developed by IDE Technologies in Israel in the 1970s, and has the benefit of direct contact between the refrigerant (water vapor) and the water-ice, operating at 32°F (0°C) and a deep vacuum; subsequently, it has found occasional niche applications in the cooling of very deep gold mines in South Africa, as a heat pump for district heating in Scandinavia, and as a means of warm-weather snow-making for ski resorts. But pumping ice slurries continues to be a largely unrealized “holy grail” due to issues of clogging in real-world piping systems.

Beyond the latent heat systems in which water-ice is the dominant choice for the storage medium, some have employed other phase change materials (PCMs).

Paraffin Wax Slurries

In the early 1980s, Drexel University performed ASHRAE-funded research of pumpable slurries of paraffin wax in water. Small globules of wax (with a freezing point between typical CHW supply and return temperatures) were suspended in water, becoming liquid at the cooling load heat exchangers and returning to solid globules at the chiller; however, issues with the wax clogging heat exchangers ended further development.

Passive PCM TES

In the 1980s, paraffin waxes embedded in building wallboards were also explored as passive PCM TES; however, issues of flammability ended further development.

Eutectic Salts

Also, in the 1980s, a eutectic salt PCM was marketed commercially by Transphase with a freezing point of 47 °F (8°C). It promised key benefits of Ice TES (having high energy density) and CHW TES (being charged with conventional CHW supply temperatures of 40°F to 42°F or 4°C to 6°C); however, during the discharge (melt) cycle of the encapsulated PCM, CHW supply temperatures quickly rose well above the phase change temperature, thus limiting the applications to partial shift TES with chillers necessarily running downstream of the TES. This, combined with system costs and material environmental issues, ended the commercial applications after a number of years.

Triple Point Carbon Dioxide

In the late 1980s, CB&I and Liquid Carbonic developed and demonstrated a very low-temperature TES phase change technology using carbon dioxide at its triple point (i.e., where all three phases, solid, liquid and vapor, are in equilibrium). Deemed $SECO_2$ (for Stored Energy in Carbon Dioxide) it used CO_2 vapor as its refrigerant to achieve a liquid-solid phase change at –70°F (–57°C) and 60 psig (4.1 atmg).

Sensible Heat TES

Most sensible heat TES systems employ water as the storage medium, though a minority of others have used other low temperature fluids (LTFs). Primary benefits are simplicity, energy efficiency, and high economy-of-scale, while drawbacks include low energy density (high volume per stored ton-hr). Chilled water (CHW) TES has taken the form of a variety of configurations, each discussed below, with different means for maintaining necessary separation between cool supply water and warm return water.

Empty Tank Method TES

In its simplest configuration, the "empty tank" method employs just two tanks: one to hold the cool supply water and one to hold the warm return water; this keeps the two temperature zones separate, but requires a 100% increase in tank volume versus the water volume. To minimize this excess tank volume and cost, systems were sometimes configured with more than two tanks, sometimes as many as six, ten, or more tanks, always with all but one of the tanks being adequate to hold the full water volume; in this manner cool supply water and warm return water could still always be kept separate, as once a given "empty tank" had been filled, another tank had become empty and available to receive the subsequent flow of water. The larger the number of tanks, the smaller the required excess tank volume; however, smaller tanks have a higher unit capital cost; and each additional tank requires full size inlet/outlet piping and valves to handle the peak charge and discharge flows. Installations occurred periodically in the 1970s and 1980s; but perhaps the last significant example was in 1990 at Arizona State University, where five (plus one) underground tank compartments contained 5.5 million gallons (20,800 m^3) for 54,000 ton-hrs (190 MWh) of TES.

Labyrinth Tank TES

Labyrinth tanks use a multitude of compartments in a horizontal layout with connections such that water flows in a long circuitous path from cell to cell, in one direction during charging and reversed during discharging. Dating to at least the 1970s, this technique was seen primarily in Japan in the sub-basements of high-rise buildings where the foundations already employed an "egg-crate" (horizontal grid) construction for reasons of seismic design. However, some temperature mixing would occur.

Baffle-and-Weir TES

Also dating to the 1970s, baffle-and-weir tanks were occasionally used, where internal walls separated compartments within a tank, with water flowing over a wall to one compartment then under a wall to the next, and so on, with the flow reversed between charging and discharging. However, again, temperature mixing would occur.

Membrane or Diaphragm Separation TES

During the 1980s, primarily in Ontario, often based on designs by Robert (Bob) Tamblyn of Engineering Interface, tanks used internal flexible membranes to separate the upper warm zone from the lower cool zone; however, operational problems such as failures of the membranes, blocked pump suctions, and convection causing temperature mixing, were common issues. The first district cooling utility, begun by Hartford Steam in Connecticut in 1964, added a 20,000 ton-hr (70 MWh) CHW TES tank in 1985 using a rigid horizontal diaphragm designed to move up and down during charging and discharging; however, the diaphragm quickly jammed and failed, resulting in the tank being converted to thermally stratified TES, as it has performed for the past 34 years.

Thermally Stratified TES

Thermal stratification relies on the density difference between the more dense, cool supply water and the less dense, warm return water to create and maintain separation of the temperature zones with no physical barrier; internal flow diffusers are required to slow the inlet and outlet flows to avoid mixing. Seminal laboratory testing was conducted by Professor Maurice "Bud" Wildin of the University of New Mexico in the late 1970s and early 1980s, while Professor William Bahnfleth,Ph.D., P.E., of the Pennsylvania State University subsequently conducted full-scale field testing and analysis, all of which contributed to past and current information in the thermal storage chapter of the *ASHRAE Handbook*. Just as the was case for the other configurations of CHW TES, thermally stratified CHW TES was occasionally seen in the 1970s and early 1980s as "one-off" designs by consultants for particular applications; common among these were automotive plants where firewater storage tanks were required, and for which insulation and flow diffusers were designed and specified by Gordon Holness at Albert Kahn Associates or William Harrison at Giffels Associates among others, to place these water tanks into dual-service as TES. At the start of the 1980s, CB&I (Chicago Bridge & Iron, now McDermott), which had built a number of the one-off tanks, developed "turnkey" design-built CHW TES tanks, for which owners and engineers could merely specify TES capacity, operating temperatures, and peak flow rates, with the complete design and thermal performance guarantees provided by the tank supplier. This procurement approach (similar to that used for chillers, cooling towers, or other key CHW system components) led to a dramatic increase in the use of CHW TES, with CB&I having subsequently executed hundreds of such installations with steel tanks, and other tank builders following suit over time, including Natgun (now DN Tanks) being an early entrant with concrete tanks, preferred especially for in-ground tanks.

Beyond the sensible heat systems in which water is the dominant choice for the storage medium, some have employed other low temperature fluids (LTFs). Aqueous calcium chloride brines were occasionally used for low temperature applications; however, chlorides are notoriously corrosive, and once environmental issues eliminated use of the only viable corrosion inhibitor in the early 1980s, this option became economically much less practical. D-Limonene is a hydrocarbon ($C_{10}H_{16}$) with a freezing point of –102°F (–74°C) and can thus be used as a fluid storage medium for very low temperature (generally specialized and rare) applications. One example dating to the 1960s or 1970s was a large aeronautical test facility at Eglin Air Force Base in Florida; a hangar-sized test chamber required that a massive make-up ambient airflow be cooled to about –40°F (–40°C) but for only a short test period. The solution was a staged TES system of a two-tank "empty tank" method of calcium chloride brine, in series with a two-tank "empty tank" method of D-Limonene in two spherical pressure vessels.

Aqueous Sodium Nitrite/Nitrate TES

One particular version of low temperature fluid (LTF) TES uses a patented, thermally stratified solution of sodium nitrite and sodium nitrate in water, marketed as SoCool fluid, developed by Trigen Energy Corporation, with the patents later transferred to CB&I. The chemicals not only lower the freezing point versus that of pure water, they also lower the temperature at which maximum density occurs. This allows thermal stratification below the limit for pure water which occurs at about 39.4°F (4.1°C). It also increases the supply-to-return Delta *T* in TES, thus reducing the volume per ton-hr versus that of conventional CHW TES. First employed in 1994, over the next 15 years there were a dozen installations totaling nearly 300,000 ton-hrs (1055 MWh), with supply temperatures ranging from 29°F to 36°F (–2°C to +2°C). Applications include Chicago's McCormick Place convention facilities (1994), DFW International Airport (2002), and Princeton University (2005).

Pioneering Utility Programs

TU Electric was experiencing incredible growth in and around Dallas in the late 1980s, and needed to manage its peak demand (*Photo 3*). It offered customer incentives of $250/kW for the first 500 kW shifted to off peak and $125/kW thereafter. Texas Instruments (TI) installed a 2.7 million gallon (10,200 m^3) stratified CHW TES tank in 1990 to supplement its 4,200-ton (14 771 kW) chiller plant at its 1.1 million square foot (100 000 m^2) electronics manufacturing facility. TI invested $1.6 million for 24,500 ton-hours (86 MWh). Two more CHW TES installations followed at

PHOTO 3 Texas Instruments CHW TES. (courtesy DN Tanks)

PHOTO 4 San Francisco Marriott Hotel Ice TES. (courtesy PGE)

PHOTO 5 Ice Tank Installation at Brevard Schools, 2019. (courtesy Brevard Schools)

other TI facilities.

The 40-story, 1.5 million ft^2 (140 000 m^2) convention hotel in San Francisco included 1,500 guest rooms and 125,000 ft^2 (11 600 m^2) of meeting space. It had a peak electric load of 3,764 kW and a design cooling load of 920 tons (3236 kW). The chilled water plant consisted of two 900-ton (3165 kW) chillers. In 1993, the hotel was retrofitted with a supplemental 180-ton (633 kW) chiller (108 tons in ice-making mode) and six 500 ton-hour (1.8 MWh) ice-on-coil TES tanks (*Photo 4*). The ice TES plant was operated to take advantage of Pacific Gas & Electric real time pricing (RTP), consisting of a base \$0.04/kWh, a "transmission and distribution adder" up to \$0.30/kWh, and a "generation and bulk transmission" adder up to \$0.80/kWh.

Florida Power & Light targeted the k–12 school market to promote cool TES in the early 1980s. It successfully convinced the School Board of Brevard County to adopt ice storage and cold air distribution (CAD). The district wanted to provide better humidity control and also reduce the size and cost of ductwork and fans. The initial systems were Mueller ice harvester TES. These were eventually converted to ice-on-coil tanks. FPL rebates funded 20 ice plants serving 21 schools, totaling 10,640 tons (37 419 kW) of peak reduction and over \$60 million. There were 17 CALMAC and 3 FAFCO tank farms. The systems performed well, taking advantage of a seasonal time-of-use demand rate that only charged demand charges between 3 and 6 p.m., Mon-Fri, for four summer months. All the schools were closed at 3 p.m., but the ice storage schools could continue operations without a penalty. In 2008, tax revenues fell drastically and the district was forced to implement budget cuts. Maintenance was neglected. Valves, actuators, and sensors failed; but there were not sufficient funds for repairs/replacements. In 2014, the taxpayers agreed to a massive facility renewal program stretched over six years. Most of the chillers have been or will be replaced, and the building automation systems upgraded, but the ice storage tanks were deemed serviceable. So far, only one school replaced its tanks, in March 2019 (*Photo 5*).

New Challenges for the HVAC Industry and Opportunities

The Clean Air Act of 1996 marked another milestone for the TES industry. The phaseout of CFC refrigerants put the focus on chilled water plants throughout the US. Facility managers were tasked with containing leaks, evaluating the costs of converting or replacing chillers, selecting future refrigerants, and considering other options. TES was one option with several different wrinkles. Many facilities integrated TES to supplement capacity while decommissioning a chiller to salvage the CFC refrigerant for future use. In Chicago, Commonwealth Edison's affiliate (Northwind Chicago) built a district cooling (DC) system using a massive ice storage system (*Photo 6*). The ice made it feasible to distribute very cold water throughout the city's downtown "Loop," raising Delta *T*, and reducing pipe diameter and pumping energy. The DC system aggressively marketed the service to buildings in the Loop as a simple way to sidestep the CFC phaseout and outsource chiller operations. Of course, Commonwealth Edison was pleased to sell off-peak power at night from its nuclear fleet on a long-term contract. DC with TES was quickly applied in other cities.

The DC system grew to five plants (four of which have ice TES).

PHOTO 6 Northwind Ice Storage Plant, Chicago. (courtesy Enwave Chicago)

PHOTO 7 Northwind Chicago Plant #2 under construction with external melt ice-on-Coil units. (courtesy Enwind Chicago)

PHOTO 8 Trigen-Peoples McCormick Place Stratified Low Temp Fluid (LTF) TES, Chicago. (courtesy Chicago Bridge & Iron Co.)

PHOTO 9 Thermal Energy Corporation (TECO), District Energy System, Houston, using stratified CHW TES. (courtesy TECO)

Plant 1, built in 1995, had 66,000 ton-hrs (232 MWh). Plant 2 has a TES capacity of 125,000 ton-hrs (440 MWh), using BAC ice-on-coil modules, and came on-line in 1996 (*Photo 7*). Plant 3, built in 1997, had 97,000 ton-hrs (341 MWh). Plant 4, expanded in 1997, has 26,000 ton-hrs (91 MWh) dating from c.1985 (when it served only the Merchandise Mart, prior to the start of the DC system). Plant 5 built in 2002, has no TES. All the ice TES are BAC ice-on-coil units.

The large gray tank in the left center of *Photo 8* is the first ever application of the thermally stratified aqueous sodium nitrite/nitrate low temp fluid (LTF) TES system. The TES tank was completed in 1994 by CB&I and serves the district energy system developed by Trigen-Peoples (now owned and operated by the City of Chicago). It serves all 4 large exhibit hall buildings comprising McCormick Place, plus nearby hotel, office, and internet server facilities. The 8.5-million gallon (32 200 m^3) tank stores 123,000 ton-hours (433 MWh) at LTF supply/return temps of 30/54°F (–1.1/+12.2°C), capable of discharge rates of up to 25,000 tons (88 MW) (up to an 18.75 MW peak electric load shift). The cold supply temp was chosen for two reasons:

- to maximize Delta *T*, thus minimizing tank volume in this urban setting and
- to provide low temp air-distribution in much of the then newly-constructed exhibit halls, thus minimizing the size and costs of (miles of) air-ducts and fans, and minimizing fan power.

The low temp fluid also provides all on-going water treatment necessary for corrosion inhibition and microbiological control.

The TECO (Thermal Energy Corporation) district energy system provides steam and chilled water to 18 hospitals in the Texas Medical Center in Houston (*Photo 9*). The 8.8 million gallon (33 300 m^3) (100 ft D × 150 ft H [30.5 m D × 45.7 m H]) chilled water TES tank was provided by CB&I in 2010. It provides 70,000 ton-hours (246 MWh) at CHWS/R temps of 40/53°F (4.4/11.7°C). The TES can shift peak loads of up to 14,000 tons (10 MW electric). Due to excess nighttime wind power on the Texas grid, TECO is sometimes paid as much as $0.10/kWh to consume power to recharge the TES. And on extreme peak days, the TES allows TECO to avoid real-time power costs as high as several dollars per kWh.

Utility Transformation Continues

At the end of the 1990s, the US prepared for Y2K and the electric utility industry was transforming into a de-regulated, competitive, non-integrated bundle of different companies. There were GENcos, TRANScos, DIScos, and RETAILcos, and they were merging and divesting. Incentives and support for cool TES made a left turn. Why would a local distribution company pay an incentive to avoid building another organization's power plant? Power plants were cheap and plentiful. The retailers wanted to keep things simple and sold electricity at one price, with no on-peak, off-peak, or

A Cool TES Hall of Fame

Eight co-authors and contributors for this article nominated 27 individuals, in six categories, for an informal Cool TES Hall of Fame, and then voted based on individuals having provided a unique or pioneering contribution, which has proven to have had staying power over the years. These 14 inductees, listed alphabetically by category, each received between 50% and 88% votes.

Academics

William (Bill) Bahnfleth, Pennsylvania State University. He conducted field testing and analysis related to thermally stratified CHW TES, reflected in the *ASHRAE Handbook* and *Design Guide*. (50% of voters)

Charles "Chuck" Dorgan, The University of Wisconsin-Madison HVAC&R Center. He analyzed and championed the design and economics of ice TES and cold air distribution. (88%)

Maurice "Bud" Wildin, The University of New Mexico. He performed seminal lab-scale testing of thermally stratified CHW TES, reflected in the *ASHRAE Handbook* and *Design Guide*. (63%)

Consultants

Ian Mackie, Mackie Associates. He designed diffusers for thermally stratified CHW TES and helped engineer the first TES for utility turbine inlet cooling in 1991 (using ice harvesters). (63%)

Robert (Bob) Tamblyn, Engineering Interface Ltd. He developed and applied CHW Membrane Tank TES for numerous applications in Ontario in the 1980s. (50%)

Verle Williams, Utility Services Unlimited. He designed and applied Ice and CHW TES, each uniquely chosen and configured to best suit a variety of early applications in the Western United States. (69%)

Equipment Suppliers

John Andrepont, CB&I (Chicago Bridge & Iron Co.). He pioneered and championed performance-guaranteed, thermally stratified CHW (and LTF) TES in the 1980s and early 1990s, leading to >250 projects and >4.5 million ton-hrs, later using TES as an owner, and then consulting for >100 TES projects. (88%)

Calvin (Cal) MacCracken, Calmac Manufacturing. The Babe Ruth of TES, he was an inventor (~70 patents) and entrepreneur who developed small (~150 ton-hr) internal-melt ice-on-coil modules, which have ultimately been applied in over 4,000 projects in 60 countries, and total 6 million ton-hrs. (88%)

William (Bill) McCloskey, BAC (Baltimore Aircoil Company). He led the marketing and sales effort for large (~1,500 ton-hr) internal and external-melt, ice-on-coil TES, including urban district cooling systems in the United States, Canada and East Asia, ultimately applied in >3,000 projects, totaling 7 million ton-hrs. (63%)

Owners

Donald (Don) Fiorino, Texas Instruments. He implemented and documented the use of TES, installing multi-million gallon thermally stratified CHW TES at several TI facilities in the early 1990s. (50%)

Edward (Ed) Knipe, California State University System. He advocated and oversaw the use of thermally stratified CHW TES on a dozen CSU campuses in the 1990s, ultimately totaling >300,000 ton-hrs. (50%)

Utilities

Loren McCannon, San Diego Gas & Electric and ITSAC (Int'l Thermal Storage Advisory Council). He oversaw one of the first utility TES incentive programs and edited/published the ITSAC newsletter. (63%)

John Nix, Florida Power & Light. He oversaw one of the longest lasting and most successful utility TES incentive programs, ultimately achieving ~400 projects and ~140,000 tons of peak load reduction. He also led development of an ASHRAE standard for TES testing. (75%)

Others

Ronald (Ron) Wendland, EPRI (Electric Power Research Institute). He was a chief advocate and central clearinghouse for all things TES-related for the utility industry and adeptly "herded the cats" comprising the many diverse TES equipment suppliers active during the 1980s and early 1990s. (63%)

demand charges. It had become very difficult to justify a cool TES investment with these uncertainties. EPRI shuttered its cool TES program due to a lack of funding. Then, the ENRON scandal occurred in October 2001. California power markets had gone insane.

Several events and market changes occurred in the following years. Natural gas prices spiked in 2005 after Hurricane Katrina dismantled the offshore piping network in the Gulf. That rapidly reversed as fracking was able to produce vast quantities of inexpensive natural gas and the utility industry discovered the allure of combustion turbines (CTs). The only problem with CTs is that they are rated at 59°F (138.2°C) and output de-rates dramatically on hot summer days when it is needed most. That generated a new application for cool TES. Chilled water or ice can pre-cool the inlet combustion air and regain the full output of the CT. TC 6.9 sponsored programs on this new opportunity and development of the *Combustion Turbine Inlet Air Cooling Systems Design Guide*.

In 1991, the Lincoln Electric System (LES) in Lincoln, Nebraska, with assistance from EPRI, installed the first utility Turbine Inlet Cooling (TIC) system to use TES (*Photo 10*). A weekly-cycle ice harvester TES system was installed to pre-cool the CT inlet air, recovering 20% of the lost, hot weather output for 4 hours/day. Other similar TES-TIC systems were subsequently installed in Nebraska, North Carolina, Wisconsin, and Saudi Arabia during the 1990s; however, by the late 1990s, CHW TES became the dominant choice for TES-TIC, being used in capacities of up to 700,000 ton-hrs (2462 MWh) at a single plant in Saudi Arabia, for an increased hot weather output of 30%.

In 2005, the Saudi Electricity Company (SEC) in Riyadh, installed a 192,800 ton-hr (678 MWh) daily-cycle CHW TES system for TIC, achieving a hot weather output increase of 30% during six hours/day. More and often larger CHW TES-TIC installations have followed in Saudi Arabia, Pennsylvania, Virginia, Texas, New Mexico, California, and Florida, serving both simple cycle (peaking) CTs and CT combined cycle plants.

PHOTO 10 LES Peaking Plant with Ice TES for Inlet Air Pre-Cooling. (courtesy LES)

20 Years Later (21st Century Postscript)

Cool TES is still a viable (and growing) technology today. Early cool storage technology was inspired and significantly funded by the electric utility industry and supported technically by EPRI and ASHRAE. The utility industry has changed. Cool TES has evolved. In addition to US installations of ice TES numbering in the many thousands, and CHW TES (on average much larger) and numbering in the many hundreds, there have been many and growing Ice and CHW TES applications around the world, including Canada, Mexico, Brazil, Europe, East Asia, Southeast Asia, the Middle East, South Africa, and Australia. The cool TES industry, in many ways mature and thriving, exhibits increasing numbers of applications for traditional peak electric load management. Those applications primarily use either small- to large-scale ice-on-coil TES or large-scale thermally stratified CHW TES. But additionally, there has been significant growth in new types of TES applications or new markets, notably:

- Large District Cooling (DC) systems in East Asia (using CHW TES or mostly ice-on-coil TES),
- Very large DC systems in the Middle East (using ice-on-coil TES or mostly CHW TES); note that DEWA (Dubai Electricity & Water Authority) requires that new DC systems employ TES for at least 20% of peak capacity,
- Small-scale "rooftop" TES (using ~30 to 50 ton-hr [105 500 to 175 843 Wh] direct-refrigerant Ice TES units),
- Emergency back-up cooling for Mission Critical Facilities, such as data centers (using mostly small- to medium-scale CHW TES),
- Turbine Inlet Cooling (TIC) of Combustion Turbine power plants (using mostly large- to very large-scale CHW TES),
- The use of hot TES, as many district heating systems are converted from steam to hot water (using thermally stratified HW TES), and
- Support for increased deployment of intermittent renewable power sources, such as wind and solar (using all types of TES, as TES unit capital costs, life expectancy, and other performance characteristics are often far superior to those of batteries or other energy storage technology options).

Also, new TES technologies have continued to be developed, some beginning (or targeted) to capture new or niche market applications, e.g.:

- Ice slurry for cooling of human bodies and organs

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during surgery (using secondary aqueous fluid-ice production), developed by the U.S. Department of Energy at the Argonne National Laboratory,

- Ice slurry for warm weather production of snow for ski-resorts (using triple-point production of water-ice), and
- Various non-water phase change material (PCM) technologies, including bio-based (plant-based), non-toxic, non-corrosive PCMs that change from solid-to-solid phase or solid-to-"gel" as heat is added/removed. Phase change temperatures can range from approximately –50°C to +170°C (–58°F to +338°F), from a number of manufacturers. They can be used in passive or active systems including in traditional internal melt ice-on-coil tanks. The advantage of selecting a temperature to suit specific applications, is often offset by high material cost compared to that of water-ice or eutectic salts.

And although some TES installations are still driven by varied utility incentives (such as demand charges, time-of-use rates, real-time pricing, grid-wide coincident peaks, and even some cash incentives, with ConEd of NYC offering $2,520/kW still!), many applications are primarily justified by avoided capital investments in conventional (non-TES) chiller plant capacity when that capacity can be downsized through the use of TES, specifically during times of:

- New construction,
- Retrofit expansions, or
- Retirement/replacement of aging chiller plant equipment.

The evolution of TES has been rich with technologies, firms, and individuals. And the future of TES is bright with the continuing promise of solutions for HVAC, the electric grid, microgrids, and energy storage challenges.

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