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Diurnal Cool Thermal Energy Storage: Research Programs, Technological Developments, and Commercial Status

M. A. Wise

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ABSTRACT

This report presents an overview of the major federal and private research and development efforts in diurnal cool thermal energy storage for electric load management in buildings. Included are brief technical descriptions and research histories of the technologies and applications of cool thermal storage. The goals, accomplishments, and funding levels of major thermal storage research programs also are summarized. The report concludes with the results of recent field performance evaluations of cool thermal storage installations and a discussion of the current commercial status of thermal storage equipment, including utility participation programs.

This report was sponsored by the Technology and Consumer Products (TCP) Division within the Office of Conservation of the U.S. Department of Energy. This report is part of TCP's ongoing effort to examine and evaluate technology developments and research efforts in the areas of lighting, space heating and cooling, water heating, refrigeration, and other building energy conversion equipment. Information obtained through this effort is used as an input in developing the U.S. research agenda in these areas.

EXECUTIVE SUMMARY

Thermal energy storage (TES) bridges the gap between periods of best thermal energy availability and thermal energy demand. Applications currently being researched and developed include the storage of solar heat collected during the daytime for night heating, aquifer storage of seasonal heat or chill, thermal storage for increased use of industrial reject heat, and the diurnal storage of heat or chill in buildings for daily electricity demand peak shaving and off-peak load shifting. Government and private research projects in these application areas have been ongoing in the United States since the early 1970s, and some TES technologies have been commercially successful for more than a decade.

Pacific Northwest Laboratory examined the major federal and private research and development efforts in diurnal cool TES for daily electrical load management in buildings. Three major categories of diurnal cool storage technologies were examined: 1) chilled water tanks, 2) ice storage tanks, and 3) other phase change materials (PCMs).

In a thermally stratified chilled water tank, thermal energy is stored as the liquid sensible heat of water. This technology takes advantage of the relatively high specific heat of water as well as its wide availability, low cost, and environmental acceptability. Cool storage is achieved by operating a compressor to generate and store chilled water (at approximately 40°F) at night during the off-peak hours. During the daytime, space conditioning and cooling loads are met using the stored chilled water. The bulk of the electricity demand for cooling is therefore shifted to the less expensive, off-peak time of day.

Ice storage tanks are operated on basically the same principle for diurnal cool storage as chilled water tanks. The main difference with using ice for cool storage is that the water is chilled to the point of freezing. Ice storage tanks have a higher thermal storage density than water tanks because the thermal energy is stored in the ice as the latent heat of fusion of water. Ice tanks therefore require less volume than water tanks to store an equivalent amount of thermal energy. The drawback with ice storage

systems, however, is that the lower evaporator temperatures necessary for creating ice result in lower refrigeration efficiencies and consequently more energy consumed by the compressor.

PCMs are substances that store thermal energy as latent heat. Water (ice) is the most widely used PCM for cool storage, so it has been discussed separately. Examples of PCMs studied for TES applications include salt hydrates, eutectic salts, paraffin, and clathrates. The goal of research into PCMs as thermal storage media is to find a substance that stores thermal energy as latent heat at a temperature higher than that required to form ice (32°F). An ideal PCM would thus have the advantages of both chilled water and ice (i.e., high thermal storage density at a relatively high evaporator temperature). Currently, the United States has at least one manufacturer of eutectic cool storage systems with a freezing point of 47°F (International Thermal Storage Advisory Council 1990a).

COOL STORAGE RESEARCH PROGRAMS

The DOE's TES program grew out of the increased concern about energy supply caused by the energy crisis of the 1970s. The program's original goal was to develop technologies for reducing energy consumption. This goal has since changed as national priorities have evolved. However, it continues to apply to certain TES technologies, such as those used as enabling mechanisms for solar and industrial reject heat.

From 1975 to 1982, the DOE and its predecessor, the Energy Research and Development Agency, emphasized the development of TES methods for reducing energy consumption. Special emphasis was placed on reducing oil consumption because of its importance in the energy crisis. The TES program was focused on relatively near-term technologies and supported a number of field tests and demonstration projects. Many of the concepts and technologies were still at an early stage of development when the philosophy of the TES program changed along with the rest of the national energy program in the early 1980s. With the apparent stability of fuel prices and supplies and the federal budget

reductions of the 1980s, research and development emphasis has shifted to long-term, high-risk research concepts beyond the scope of commercial industries (DOE 1989).

The subprogram under which the DOE conducts research in diurnal thermal storage is called the Diurnal TES program. The Diurnal TES program is one of the three major DOE TES subprograms, along with Industrial TES and Seasonal TES, under the broader TES program of the DOE Office of Conservation and Renewable Energy. Annual funding for the TES program has dropped from about \$9.5 million in 1981 to just \$1.125 million in 1990 as a consequence of the adjustment of federal research priorities.

The Diurnal TES program is primarily devoted to advancing technologies that use off-peak electrical energy to provide space cooling and heating. This shifting or leveling of the daily electrical load does not directly serve the original TES goal of reducing total energy consumption (although peaking units are generally less efficient than baseload generating units and therefore do use more energy). Instead, the focus of diurnal thermal storage research is reducing peak electrical demand, which has increased disproportionately nationwide with the total electrical demand. Oak Ridge National Laboratory has been the principal research laboratory for the Diurnal TES program since the program's inception in 1976.

The early focus of the TES program was on near-term technologies. Many of the projects were field tests and technical and economic assessments of the cool storage equipment and markets that existed at that time. During the 1980s, the program's focus was redirected to long-term concepts thought to be beyond the scope of private and industrial research. Progress was made in developing TES concepts with refrigerant clathrates and ammoniated complex compounds. Since 1986, other research efforts have included the development of ice self-release mechanisms and the study of TES using the heats of mixing of conjugating liquids.

The Electric Power Research Institute (EPRI) has also been a major player in diurnal cool storage research and development. EPRI has used its affiliation with utilities throughout the United States to foster the transfer of thermal storage technologies from the research laboratories to commercial

markets. EPRI has also sponsored major field tests of cool storage equipment, and, in the last few years, has heightened its efforts in developing state-of-the-art cool storage technologies with improved ice-making techniques and phase change eutectic storage systems.

CURRENT STATUS OF DIURNAL COOL STORAGE TECHNOLOGIES

Although the commercial viability of TES depends almost entirely on favorable economics for the end-use customer, the utilities stand to gain directly from widespread use of cool thermal storage. Some potential benefits of cool storage to utilities are improved load factors, decreased transmission and distribution system requirements, and less reliance on peak generating capacity. Several utilities have undertaken programs to encourage implementation of cool storage systems by their commercial customers. Cool storage can be mutually beneficial to utilities and customers, but the utilities are usually responsible for encouraging customer participation through subsidies and favorable rate schedules.

EPRI has sponsored field tests of commercial cool storage installations (EPRI 1990, 1989). The cool storage systems in the field tests in general consumed considerably more energy than simulated conventional air-conditioning systems for the same sites. Contrary to the expectations of some authors, the low-temperature air distribution system used in conjunction with a cool storage operation was also found to consume more energy than a conventional system. The cool storage systems were successful, however, in reducing peak electrical demands and shifting a significant portion of the electrical demand for space cooling away from the more expensive peak hours.

The first major nationwide survey of commercial thermal storage installations was performed by the Franklin Research Institute in 1981 and published by American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) (ASHRAE 1984). This study found that approximately 270 thermal storage installations were in place and operating at that time. The cool storage systems in the survey were evenly distributed among ice and chilled water storage systems. The survey also found that a few installations were already in place as early as 1974. The International Thermal Storage Advisory

Council (ITSAC) maintains a database of current thermal storage installations, which includes about 1000 installations. ITSAC cautions, however, that the database is not yet complete and that the true number of installations may be much higher. A 1990 ITSAC survey lists over 20 U.S. manufacturers of ice and eutectic storage systems (ITSAC 1990a).

CONTENTS

ABSTRACT	iii
EXECUTIVE SUMMARY	v
1.0 INTRODUCTION	1.1
1.1 PURPOSE AND SCOPE	1.1
1.2 ORGANIZATION OF THIS REPORT	1.2
2.0 DESCRIPTION AND STATUS OF DIURNAL THERMAL ENERGY STORAGE TECHNOLOGIES	2.1
2.1 OVERVIEW OF RELATED THERMAL ENERGY STORAGE TECHNOLOGIES	2.1
2.1.1 Aquifer Thermal Storage	2.2
2.1.2 Earth Thermal Storage	2.2
2.1.3 Industrial Thermal Energy Storage	2.3
2.1.4 Domestic Hot Water Storage	2.3
2.1.5 Advanced Storage Building Materials	2.3
2.1.6 Technologies for Hot Thermal Storage in Buildings	2.4
2.1.7 Enhanced Heat Transfer and Transport Systems	2.5
2.1.8 Annual Cycle Energy Storage	2.5
2.2 DIURNAL COOL STORAGE TECHNOLOGY DESCRIPTIONS	2.6
2.2.1 Chilled Water Tanks	2.6
2.2.2 Ice Storage Tanks	2.8
2.2.3 Phase Change Materials	2.10
2.3 CHEMICAL THERMAL ENERGY STORAGE	2.11
3.0 DIURNAL THERMAL ENERGY STORAGE RESEARCH PROGRAMS	3.1
3.1 THERMAL ENERGY STORAGE PROGRAMS AT THE U.S. DEPARTMENT OF ENERGY	3.1

3.1.1	DOE Diurnal TES Program Overview	3.4
3.1.2	Chronology and Technical Results of DOE Diurnal TES Projects	3.6
3.2	THERMAL ENERGY STORAGE PROGRAMS IN OTHER FEDERAL AGENCIES	3.12
3.3	THERMAL ENERGY STORAGE PROGRAMS AT THE ELECTRIC POWER RESEARCH INSTITUTE	3.13
3.4	THERMAL ENERGY STORAGE PROGRAMS AT THE AMERICAN SOCIETY OF HEATING, REFRIGERATION, AND AIR- CONDITIONING ENGINEERS	3.14
4.0	COMMERCIAL STATUS OF DIURNAL COOL THERMAL ENERGY STORAGE	4.1
4.1	UTILITY PARTICIPATION IN DIURNAL COOL STORAGE	4.1
4.2	PERFORMANCE RESULTS OF EXISTING COOL STORAGE SYSTEMS	4.3
4.2.1	Field Test of Cool Storage Installations	4.3
4.2.2	Field Test of a Low-Temperature Air Distribution System	4.8
4.3	COMMERCIAL STATUS OF COOL STORAGE TECHNOLOGIES	4.10
5.0	REFERENCES	5.1
	APPENDIX A - UTILITIES WITH COOL STORAGE INDUCEMENT PROGRAMS	A.1
	APPENDIX B - MANUFACTURERS OF ICE AND PHASE THERMAL CHANGE MATERIAL THERMAL STORAGE SYSTEMS	B.1

FIGURE

3.1	Chemical and Thermal Storage Program Structure	3.2

TABLES

3.1	DOE and ERDA Funding for Thermal and Chemical Storage, 1976-1990	3.3
3.2	Approximate Funding for the DOE Thermal Energy Storage Programs, 1980-1990	3.4
3.3	Assessment of Energy Consumption of Conventional Heat Pump vs. Storage Heat Pump Systems	3.9
4.1	Cool Storage Installations in the SCE's Program	4.3
4.2	Cool Storage System Test Sites	4.4
4.3	Energy Use of Cool Storage Systems by System Component	4.5
4.4	Comparison of Energy Use by Cool Storage Systems and Conventional A/C Systems	4.6
4.5	Electricity Peak Demand Reduction of the Cool Storage Systems	4.7
4.6	Fan Energy Consumption of Conventional versus Low-Temperature Air Distribution Systems	4.9

1.0 INTRODUCTION

Thermal energy storage (TES) is a method for bridging the gap between periods of thermal energy availability and thermal energy use. Applications currently being researched and developed include the storage of solar heat for night heating, aquifer storage of seasonal heat or chill, thermal storage for increased use of industrial reject heat, and the diurnal storage of heat or chill in buildings for daily electricity demand peak shaving and off-peak load shifting. Government and private research projects in these application areas have been ongoing since the early 1970s, and some TES technologies have been commercially successful for more than a decade.

Situations favoring TES are those in which the period of best energy availability does not coincide with the period of energy demand. For energy sources such as solar and industrial reject heat, thermal storage allows the use of energy that would otherwise be lost to the environment. Thermal storage can also function as an inventory stock of energy much like an inventory stock of manufactured items in an industrial plant. In an industrial plant, inventory is used as a buffer to smooth production demands over time. Analogously, diurnal thermal storage is used to distribute the electricity demand of a building more uniformly over a 24-hour period. The smoothing of demand in both examples has the additional benefit of reducing the peak demands. Diurnal thermal storage is also of particular interest to electric utilities as a load management tool because it can potentially decrease the reliance on inefficient peak generators and defer the need to create additional generating capacity.

1.1 PURPOSE AND SCOPE

The objective of this report is to provide an overview and summary of current and historical TES research programs and technological developments. Pacific Northwest Laboratory (PNL) focused this study on the diurnal physical and chemical TES technologies that are used to reduce peak electricity demands for space conditioning and cooling by shifting a portion of the daily electrical load to the off-peak time of day. Major public and private research

programs are discussed, including primary objectives, significant accomplishments, and funding levels, when available.

The coverage of private research and development (R&D) may not be complete because some of the commercial technologies are proprietary. Data concerning the government-funded research programs are often publicly available, so these programs can be described in greater detail. Information about private research programs has been obtained through the cooperation of the involved program managers.

This report is not intended to serve as a technical document. No original evaluation of the technical credibility or of the inherent value of the research efforts described is implied. The assessments of the technological and commercial status of the areas discussed are taken from published technical reports and, in some cases, from personal contact with the principal researchers.

1.2 ORGANIZATION OF THIS REPORT

This report consists of five sections and two appendices. Section 2 includes brief technical descriptions, research histories, and current assessments of the major technologies and applications of TES. Section 3 provides an overview of the major public and private TES research programs. Section 4 describes in more detail the commercial and economic status of the predominant cool thermal storage technologies, as well as utility programs that have been developed to encourage cool storage installations in commercial buildings. Section 4 also summarizes the results of two recent field testing and evaluation projects of commercial cool storage installations. Section 5 contains the report's references.

Appendix A lists the utilities with cool storage inducement programs, and Appendix B lists the manufacturers of ice and phase change thermal storage systems.

2.0 DESCRIPTION AND STATUS OF DIURNAL THERMAL ENERGY STORAGE TECHNOLOGIES

Before any of the specific thermal storage technologies are discussed, a few broad definitions of the predominant modes of TES are necessary. The first mode defined is sensible heat storage. In sensible heat storage, the temperature of the solid or liquid storage medium is raised or lowered to perform the storage operation. The thermal energy is thus stored as a temperature difference between the storage medium (e.g. water, bricks) and the environment. Another common mode of thermal storage is latent heat storage, which involves a physical change in the storage medium and usually refers to a change of phase. Typically, the thermal energy is stored as the latent heat of fusion (energy required to melt or freeze) of water (ice) or some other phase change material (PCM). The third mode included in this report is chemical heat storage. In this mode, the thermal energy is stored as the heat of reaction of a reversible chemical reaction.

Each of these three categories of TES can be used for storing either a heat source or a heat sink (storing cool or the absence of heat). In this report, a stored heat source will be referred to as hot storage, while a stored heat sink will be referred to as cool storage.

Although this report is primarily concerned with diurnal thermal storage for electricity load management in buildings, this application is just one of the many potential and developed end uses of TES. Several of the different technology areas, referred to as thermal storage, involve similar basic research, so the research cannot always be easily separated into categories by end use. Therefore, this section begins with brief descriptions of technologies and applications across the spectrum of TES before the diurnal cool storage technologies are discussed in more detail.

2.1 OVERVIEW OF RELATED THERMAL ENERGY STORAGE TECHNOLOGIES

This section briefly summarizes the major thermal storage technologies other than those used for diurnal cool storage (which is presented in detail throughout the remainder of this report). Where applicable, the technical and

commercial status of these technologies is briefly summarized. The technologies are not presented in any particular order.

2.1.1 Aquifer Thermal Storage

Aquifers, which are bodies of groundwater in deposits of permeable rocks located just below the earth's surface, can be used for either hot or cool storage. Although some diurnal applications have been identified and researched, aquifer TES is primarily considered to be a method for seasonal TES. Because of the large amount of energy required in aquifer storage, its best potential end use is in community or district heating systems in which a cheap source of thermal energy (e.g., solar heat, industrial waste heat, winter chill) is readily available. The U.S. Department of Energy (DOE) sponsors aquifer storage research, with PNL as the principal research facility.

2.1.2 Earth Thermal Storage

In earth thermal storage, the ground is used as the medium for storing heat from a solar collector or other heat source. As part of DOE's Solar-Assisted Heat Pump (SAHP) program, earth thermal storage in the form of ground-coupled heat pumps was studied in the late 1970s and early 1980s as a mechanism for maintaining a sufficient evaporator temperature during periods of high heating demand. The goal of the ground-coupled SAHP research effort was to minimize or eliminate the large amounts of backup electric resistance heating necessary for SAHP system operation. The driving idea behind this research was that the ground temperature is more stable than the air temperature and would therefore maintain a predictable minimum value for which the SAHP system could be designed (Andrews 1981). Much of the DOE-sponsored research in SAHPs was conducted with the Brookhaven National Laboratory (BNL). After inconclusive field performance tests in the early 1980s (Zimmerman 1987), further research efforts in ground-coupled SAHP systems under the DOE SAHP program have not been pursued.

Another type of earth TES studied is the crawl-space-assisted heat pump system in which an underground crawl space between buildings serves as the ambient heat source for a conventional heat pump. The heat from the ground

provides a higher ambient temperature for the heat pump than the outdoor air temperature. A drawback of earth thermal storage is that some indoor heat is lost from the buildings to the ground because of the crawl space. A DOE study conducted by the Oak Ridge National Laboratory (ORNL) in 1982 showed that higher floor insulation levels must be provided to make earth thermal storage energy-efficient (Martin et al. 1983).

2.1.3 Industrial Thermal Energy Storage

Industrial TES is the storage of industrial reject or waste heat that, in the absence of storage, would otherwise be lost to the environment. The DOE currently conducts research in industrial TES through ORNL. Much of this research involves identifying and testing high-temperature PCMs that store the reject heat as the latent heat of fusion. An example of a recent development in high-temperature thermal storage is the encapsulation of metallic alloys in which the core melts to absorb the thermal energy while the shell remains solid to facilitate heat transfer (Tomlinson and Kedl 1989).

2.1.4 Domestic Hot Water Storage

The objective of domestic hot water storage is to shift the energy demand for heating water to an off-peak time of day. The storage is performed by using a larger-than-conventional water tank or a system of dual hot water tanks. Under the sponsorship of the Electric Power Research Institute (EPRI) in 1981, ORNL undertook a study of domestic hot water storage systems in residential buildings (Kuliasha et al. 1984). The study showed that the energy demand period for water heating could be shifted off-peak, but the potential savings from doing so are limited because of the small contribution from domestic water heating to a utility's peak electrical demand.

2.1.5 Advanced Storage Building Materials

The concept of advanced storage building materials involves installing wallboards filled with a PCM into the walls of a building. The PCM wallboards can then be used for latent heat storage in passive solar heating applications. An ideal PCM for this application has a high heat of fusion (absorbs a large quantity of energy when melting) and a melting point in the comfortable-room-temperature range. This system can then function as a thermal storage

device; however, because the phase change is isothermic (changes phase at a constant temperature), it also serves as a temperature moderator for the building. The DOE has conducted research in advanced storage building materials through ORNL since 1981; currently, licensing and manufacturing of PCM wallboards with paraffin encased in gypsum are planned [American Society of Mechanical Engineers (ASME) 1989].

The Florida Solar Energy Center (FSEC) has begun conducting research aimed at exploiting the thermal capacitance of a PCM used in combination with the moisture capacitance of a desiccant material in a wallboard. The goal of this research is to construct a thermal storage system that will maintain human comfort levels by moderating room humidity as well as temperature. This system, which FSEC refers to as "enthalpy storage," has potential for application in hot, humid climates where air conditioning is a major component of peak electric loads. A daily cycle would consist of operating the air conditioner during the off-peak hours and allowing the enthalpy storage system to provide the cooling load in the peak hours. During air-conditioning operation, the PCM serves as the thermal storage medium, while the desiccant desorbs moisture. With the air conditioning turned off during the peak hours, the PCM acts as a heat sink to moderate room temperature, while the desiccant material absorbs moisture to mitigate increases in relative humidity. With DOE funding, FSEC has conducted an experiment demonstrating proof-of-principle for the enthalpy storage concept using a simple prototype system of water as the thermal storage medium and silica gel as the desiccant material.^(a)

2.1.6 Technologies for Hot Thermal Storage in Buildings

With the exception of some research conducted in PCMs for hot storage at residential temperatures, thermal storage for managing electric heating loads and for using solar heat is mainly accomplished with liquid- or solid-sensible heat storage. Pressurized hot water tanks, in which the water is superheated

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(a) Kamel A. A., M. V. Swami, S. Chandra, and P. W. Fairey. "An Experimental Study of Building-Integrated Off-Peak Cooling Using Thermal and Moisture ("Enthalpy") Storage Systems." Forthcoming in ASHRAE Transactions.

beyond its conventional boiling point, are the most common mode of liquid-sensible heat storage. Room storage heaters are electric resistance heaters with brick cores that exploit the bricks' solid sensible heat capacity. A brick core can also be coupled with a central air heater. The brick cores can be heated to temperatures above 1400°F and can store more energy than a pressurized water heater on a per-volume basis. Storage heaters have been used successfully as load-shifting and management tools in Europe for several years and are commercially available in the United States. Packed rock or pebble beds are another common medium for solid sensible heat storage. Although they can be used for either cool or hot thermal storage, packed rock bed storage units are typically used to store solar heat captured during the daylight hours for space heating at night.

2.1.7 Enhanced Heat Transfer and Transport Systems

Adding a PCM into the working fluid of heat transfer and heat transport systems could increase the thermal capacity of the fluid, thereby reducing sizing requirements of piping systems and other associated hardware. This increased thermal mass is the additional energy stored as the latent heat of the added material as it changes phase. The DOE has studied phase change slurries of cross-linked high-density polyethylene (x-HDPE) in a water glycol mixture for high temperature (270°F) heat transfer and transport. Because the molecular structure of the x-HDPE is cross-linked with electron beam irradiation, the particles retain their shape during the phase transition and are, thus, especially suited for use in a slurry (Tomlinson and Taylor 1988). The DOE has constructed an experimental facility at Argonne National Laboratory to test phase-change slurries (DOE 1989).

2.1.8 Annual Cycle Energy Storage

The Annual Cycle Energy Storage (ACES) concept was studied by the DOE from 1976 through 1981 as a method for seasonal TES in residential buildings. The program was sponsored by DOE's Office of Buildings Equipment Research and Development and had cumulative funding over those years in excess of \$5.1 million (Zimmerman 1987). The main objective of the ACES program was not to manage electric load but to reduce overall energy consumption; however, some of the technology and systems studied were quite similar to those investigated

for use in diurnal TES (Minturn 1983). In an ACES system, a one-directional heat pump is used to provide space heating and domestic water heating during the winter. What makes the ACES concept unique from conventional heat pump systems is that the reject side of the heat pump creates a large pool of ice that is stored in an insulated tank and used to provide summer cooling (Brunton et al. 1979). When designed correctly, the summer cooling load could be met very efficiently by circulating cold brine from the ice tank to the fan coil without ever having to operate a compressor.

With ORNL serving as the lead laboratory, DOE constructed an ACES test facility (referred to as "TECH") near Knoxville, Tennessee. The ACES test building achieved an annual COP (coefficient of performance) exceeding 3.0, while a control home that provided the same services but used a conventional system had an annual COP of 1.7. Annual energy savings of 40% to 50% were demonstrated at the ACES site. However, ACES was not found to be an economically viable consumer product because of the capital expense of the storage tank, which could be as large as several thousand cubic feet for some applications (Minturn 1983).

2.2 DIURNAL COOL STORAGE TECHNOLOGY DESCRIPTIONS

The cool storage technologies discussed in this section are primarily used on the customer side of the meter for shifting the electrical demand for space cooling and conditioning. In a typical diurnal cool storage application, the storage medium is charged (cooled) at night to minimize the electric demand for space cooling during the daytime. Commercial space cooling is certainly a significant, if not always the largest, contributor to summer peak electrical demand, so cool storage can potentially play a major role in reducing both utility and customer peak electricity demand requirements.

2.2.1 Chilled Water Tanks

The term "liquid" in liquid-sensible cool storage almost exclusively refers to chilled water stored in thermally stratified tanks. In a thermally stratified tank, the cooler water, because of its higher density, occupies the bottom portion of the tank while the warmer water resides at the top. Thermal stratification will occur naturally in a well-designed tank that is used

properly. In a typical cool storage application, a cylindrical steel tank is used for containing the stratified water. During the off-peak hours, cold water is generated and pumped into the bottom of the tank while warm water is drawn from the top. The direction of flow is reversed during the building cooling operation, as the cold water is drawn from the tank's bottom while the warmer return water is pumped into the top.

Water has a higher specific heat than most common materials. It can store approximately 18 Btu (British thermal units) per pound as sensible heat when chilled to 40°F in an efficiently operating storage tank (EPRI 1984). Water also enjoys the benefits of wide availability, low cost, and environmental acceptability. However, an additional consideration is that the water must be filtered and treated with chemicals to prevent corrosion and mildew growth.

Cool storage with chilled water tanks is a relatively simple technical concept that has had commercial applications for some time, so it has not recently been an area of emphasis in the major research programs. However, some research issues may remain concerning the best method of separating and preventing thermal mixing of the cold outlet water with the warmer return water. The separation of the cold water (typically 40°F) from the warm water (typically 60°F) in the stratified tank has been demonstrated to be relatively easy to maintain passively because of the density difference between the cooler and the warmer water (Hiller 1987). Alternative chilled water storage system designs that have been designed in attempts to improve the storage efficiency of single stratified water tank systems include baffle, labyrinth, and multiple tank systems. A DOE research project that concluded in 1982 tested a storage system with a permeable membrane placed inside the water tank to serve as a thermal barrier at the thermocline between the cooler and warmer water regions. The equipment used in the experimentation had operating problems, and the tests were not able to demonstrate a significant improvement in storage efficiency over conventional stratified water tanks (Martin et al. 1983).

Diurnal cool storage with stratified chilled water tanks is a technologically viable method for electricity demand peak reduction and has been available commercially for several years. In spite of the relative disadvantage of larger volume requirements, chilled water storage systems continue to maintain a share of the thermal storage market. A chilled water storage system is often chosen when sufficient space is available or when the storage system is also to be used to store heat in the cooler months. The design of stratified water tank systems has become standard practice for heating, ventilation, and air conditioning (HVAC) engineers with design standards published by research and trade associations, including EPRI and ASHRAE (Hiller 1987).

2.2.2 Ice Storage Tanks

Although ice is a PCM, it is presented separately because of the technological importance and commercial success of ice storage tanks as load management tools. Ice has many of the same advantages as chilled water in that it is cheaply available and presents no environmental threat. As with chilled water systems, ice tanks also require chemical water treatment and filtration. Electric load shifting is accomplished by charging the ice tank during the off-peak time of day and using the stored ice as a heat sink during the peak cooling hours.

Some comparisons between chilled water tanks and ice storage tanks are appropriate because they are the two most prevalent types of cool storage. Compared with ice, chilled water has a lower TES density. Therefore, a chilled water tank requires more volume than an ice storage tank to achieve the same amount of TES. In practice, the volume savings of ice storage systems are about a factor of five (EPRI 1984). However, chilled water tanks do have some advantages over ice tanks. For example, in a chilled water tank, the storage water is typically cooled to approximately 40°F. Because the temperature in an ice tank must be lowered to the freezing point of water (32°F), the higher evaporator temperature of the chiller used in a chilled water system results in a higher refrigeration efficiency than can be achieved with the ice storage method.

Ice storage tanks have a higher thermal storage density than chilled water tanks because the thermal energy is stored in the ice as the latent heat

of fusion of water. Ice stores thermal energy as latent heat at a storage density of approximately 144 Btu/lb of ice (about 162 Btu/lb when factoring in the sensible heat difference created as the water is cooled). As discussed above, ice tanks have the relative disadvantage of the lower evaporator temperatures that are required to make ice. This low evaporator temperature decreases the refrigerating efficiency of the cooling device, and the efficiency problem is intensified during the charging process as more ice forms in the tank. The most common method of ice-making is the direct expansion method in which the water freezes to form ice directly on the evaporator coils that pass through the storage tank. As the layer of ice on the coils thickens, it forms a thermal barrier that further lowers the evaporator temperature required to freeze the surrounding water.

The problem of ice "stickiness," which causes it to remain affixed to the refrigerant coils, has been the focus of research conducted by the DOE with ORNL and others. Although the ice can be removed from the coils through agitation, doing so requires adding energy to the storage tank, which correspondingly diminishes the net energy efficiency of the storage system. Ice self-release mechanisms that allow the formed ice to passively detach itself from the coils have been studied as a method to improve the efficiency of ice storage tanks. The DOE has conducted research on dynamic ice harvesters in which ice is formed on plates with glossy, non-stick surfaces, and ice self-release has been accomplished in this manner using vertical plates (Tomlinson and Kedl 1989).

Ice storage tank systems have been used in with low-temperature air distribution systems, which have recently come into prominence in building design. An early survey and evaluation sponsored by EPRI in 1986 estimated that using cold air can reduce the first costs and the operating costs by 20% to 30% for new installations of air distribution systems (Dorgan 1987). EPRI has continued to pursue research and disseminate information about the advantages of low-temperature air distribution systems, which have been a major factor in the popularity of ice storage tanks in the buildings' market.

2.2.3 Phase Change Materials

PCMs are substances that store thermal energy as latent heat. For cool storage applications that use PCMs, the thermal energy is stored as the latent heat of fusion as the PCM changes from a liquid to a solid. As noted previously, water (ice) is the most widely used PCM but is usually classified separately because of its importance. In general, TES with PCMs has a distinct advantage over heat-sensible storage in the higher thermal storage capacity that results in smaller storage volume requirements.

Much of the focus of PCM thermal storage research applies more to hot storage and advanced building materials than to cool storage for electric load management. Salt hydrates, eutectic salts, and paraffin are examples of substances studied as thermal storage media. Salt hydrates, which are compounds of salts with water, tend to have high latent heats because of their water content. A eutectic is a solid solution of two or more substances mixed in such a way that the freezing point is the lowest freezing point possible for any possible combination of the substances. Paraffin is an organic wax extracted from petroleum. As a group, these PCMs undergo isothermic phase changes at desirable temperatures. They do have a tendency, however, to melt and refreeze incongruently; subsequently, their desirable physical characteristics degrade over time. Many of the PCMs are also corrosive and must therefore be separated from the heat transfer medium by encapsulation or some other means.

As discussed previously, a significant disadvantage of ice storage tanks is the low evaporator temperature required to freeze the water. An ideal medium for cool thermal storage would be a PCM with a freezing temperature higher than that of water and closer to the delivery temperature of an air conditioning system. This substance would act as a "warm ice" (ASME 1989), providing the benefits of latent heat storage at higher refrigeration temperatures. A class of substances that has shown promise as "warm ice" cool storage media is the clathrate inclusion compounds of refrigerants and water.

Clathrates are structures composed of two compounds in which the molecules of the "guest" compound are enclosed in the crystalline lattice of the molecules of the "host" compound (Martin et al. 1983). The DOE has

studied the use of clathrates for cool storage with heat pumps with ORNL since the early 1980s. Clathrates of water with refrigerants such as CFC-11 and CFC-12 have been successfully developed and tested through the DOE programs. Clathrates with these refrigerants were found to have latent heats of fusion comparable to water (about 125 Btu/lb) with freezing points around 50°F (Martin 1986). Using these clathrates as a storage medium would also potentially allow a more efficient heat transfer mechanism because of the possibility of direct contact between the storage medium and the refrigerant. Although clathrates were considered a promising class of PCMs for cool storage, their further development has been slowed by other factors such as cost and environmental concerns. Mixtures of CFC-11 or CFC-12 with water were found to be the most practical clathrates, but their cost and operating equipment were determined to be prohibitive for practical use (Tomlinson and Taylor 1988). The environmental concerns about clathrate cool storage systems requiring large inventories of chlorofluorocarbons (CFCs) are another major hindrance to their development. Both CFC-11 and CFC-12 are stratospheric ozone-depleting substances and are scheduled to be phased out by the year 2000 under the Montreal Protocol.

During the last few years, EPRI has studied cool storage for load management with phase-change eutectic salts. Eutectics of sodium sulfate and water, which melt at 47°F, have been developed and tested; currently, the United States has at least one manufacturer of eutectic cool storage systems with this freezing point [International Thermal Storage Advisory Council (ITSAC) 1990a]. The higher freezing temperature allows for a better refrigerating efficiency than ice; however, the discharge temperature is too high to take advantage of low-temperature air distribution. Further research is being pursued to develop eutectics that melt from 38° to 40°F, which would allow compatibility with low-temperature air distribution systems (Wendland 1987).

2.3 CHEMICAL THERMAL ENERGY STORAGE

TES by chemical means, sometimes referred to as thermochemical energy storage (to distinguish it from the chemical storage of electrical energy as

in batteries), has not been developed for diurnal load management to the extent of the other technologies discussed here. Using the heat of reaction of a reversible chemical reaction to store heat or cool is analogous to the latent heat storage of ice and other PCMs, but chemical energy storage has not been a major area of study in the DOE Diurnal TES research program. However, potentially related research in chemical heat pumps and chemical energy systems has been conducted by the former DOE Office of Energy Storage and Utilization for industrial applications and for enhanced recovery of solar heat energy.

Chemical energy storage for diurnal load management has been developed by the DOE's TES program at low temperatures suitable for the food processing industries. Since 1986, the DOE has conducted research through ORNL on ammoniated complex compounds that store thermal energy from -60° to 0°C . Ammonia sorption storage systems were found to have high storage densities and high cycle efficiencies. The food freezing and storage industry is a major contributor to the peak electric power generation problems, and utilities are implementing electric rate incentives to encourage off-peak refrigeration. Ammonia is already widely used as a refrigerant in the food processing industry, so the code restrictions for ammonia are not seen as the hindrance that they would be for building air-conditioning applications (DOE 1989).

3.0 DIURNAL THERMAL ENERGY STORAGE RESEARCH PROGRAMS

This section summarizes the major research programs in diurnal cool TES. Program objectives, accomplishments, and funding levels are included when available. Although this report concentrates on diurnal technologies for building space cooling, the research cannot always be categorized into distinct end-use categories. Therefore, funding amounts have been included for research areas that may not apply directly to this specific end use but grow out of the same fundamental research areas. Most of this section is devoted to federal government research programs, for which information is publicly available. Research program information is also provided for private research efforts conducted by EPRI and ASHRAE.

3.1 THERMAL ENERGY STORAGE PROGRAMS AT THE U.S. DEPARTMENT OF ENERGY

DOE's TES program grew out of the increased concern about energy supply during the energy crisis of the 1970s. The Solar Heating and Cooling Demonstration Act of 1974 and the Non-Nuclear Research and Development Act of 1974 provided the original legislative mandates for developing the TES program. The program's original goal was to develop technologies for reducing energy consumption. This goal has since changed as national priorities have evolved. However, the goal continues to apply to certain TES technologies, such as those used as enabling mechanisms for solar and industrial reject heat.

DOE's TES program has been managed by the Office of Energy Storage and Distribution, which is under DOE's Office of Conservation and Renewable Energy. Current goals for the TES program include the following (DOE 1989):

- to reduce peak electrical demand
- to improve industrial, commercial, and residential energy efficiency
- to facilitate the use of renewable resources and widely available domestic fuels
- to reduce the production of pollutants that contribute to global warming, acid rain, and ozone depletion.

From 1975 to 1982, the DOE and its predecessor, the Energy Research and Development Agency (ERDA), emphasized the development of TES methods for reducing energy consumption. Special emphasis was placed on reducing oil consumption because of its importance in the energy crisis. The TES program focused on relatively near-term technologies and supported a number of field tests and demonstration projects. Many of the concepts and technologies were still at an early stage of development when the philosophy of the TES program changed along with the rest of the national energy program in the early 1980s. With the apparent stability of fuel prices and supplies and the federal budget reductions of the 1980s, R&D emphasis has shifted to long-term, high-risk research concepts beyond the scope of commercial industries (DOE 1989).

The TES program at ERDA and DOE has been funded as part of a larger program called Chemical and Thermal Storage. As Figure 3.1 shows, this program includes Chemical Energy Systems and Hydrogen Production subprograms. While funding for the overall Chemical and Thermal Storage effort has been clearly delineated in the Congressional budget process, budgeted amounts for the subprogram areas are less firmly documented. Table 3.1 shows the total funding for the combined program in current dollars and in 1989 constant dollars.

FIGURE 3.1. Chemical and Thermal Storage Program Structure

TABLE 3.1. DOE and ERDA Funding for the Chemical and Thermal Storage Program (in thousands of dollars), 1976-1990^(a,b)

Year	Funding in Current Dollars	Funding in 1989 Constant Dollars ^(c)
1976	13,113	26,247
TQ ^(d)	4,938	9,267
1977	28,800	54,048
1978	22,455	39,281
1979	30,560	49,106
1980	31,000	45,686
1981	32,300	43,399
1982	12,450	15,724
1983	7,000	8,509
1984	7,000	8,209
1985	2,285	2,602
1986	2,945	3,268
1987	3,950	4,249
1988	3,800	3,957
1989	2,050	2,050
1990	1,464	1,464 ^(e)

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- (a) The years 1976 through 1978 represent funding by ERDA.
 (b) Source: U.S. House of Representatives, Hearings Before a Subcommittee of the Committee on Appropriations, 1976-1990.
 (c) Constant dollars calculated using the GNP deflator.
 (d) TQ refers to the Transition Quarter that occurred between fiscal year 1976 and fiscal year 1977. The funding amount shown for the Transition Quarter is not included in either the preceding or the following years.
 (e) 1990 dollars.

The subprogram under which the DOE conducts research in diurnal thermal storage is called the DOE Diurnal TES program. The Diurnal TES program is one of the three major DOE TES subprograms along with Industrial TES and Seasonal TES. These divisions are not mutually exclusive in terms of basic science or potential end uses, but the inherent economic and institutional issues involved differ. This breakdown is considered to be consistent with the current DOE philosophy of advancing technologies rather than specific end uses (ASME 1989).

Table 3.2 gives approximate funding amounts in current dollars for projects within the DOE Diurnal, Industrial, and Seasonal TES subprograms. The figures given may not be exact because this breakdown represents a finer level of detail than that for which the appropriations are based. Also, some research may overlap the boundaries among the categories. PNL is the principal DOE research facility for Seasonal TES. ORNL is the lead laboratory for both the DOE Diurnal and Industrial TES programs, and historical funding amounts for these two areas have not been maintained separately.

3.1.1 DOE Diurnal TES Program Overview

The Diurnal TES program is primarily devoted to advancing technologies that use off-peak electrical energy to provide space cooling and heating. This shifting or leveling of the daily electrical load does not directly serve the original TES goal of reducing total energy consumption (although peaking units are generally less efficient than baseload generating units and therefore do use more energy). Instead, the focus of diurnal thermal storage research is on reducing peak electrical demand that has increased disproportionately nationwide with the total electrical demand. High peak demands

TABLE 3.2. Approximate Funding for the DOE Thermal Energy Storage Programs (current dollars, in thousands) 1980-1990^(a)

Year	Seasonal TES	Diurnal & Industrial TES	Total TES
1980	Unknown	3000	Unknown
1981	5200	4200	9400
1982	2200	3000	5200
1983	1500	2000	3500
1984	900	1200	2100
1985	600	1500	2100
1986	400	1500	1900
1987	800	1300	2100
1988	1300	700	2000
1989	1300	740	2040
1990	900	225	1125

(a) Source: Personal communication with Landis Kannberg at PNL and John Tomlinson at ORNL.

present problems for both utilities and consumers because equipment must be designed to meet the peaks. Typically, 75% of utilities experience their annual peak demands during the summer. Therefore, the initial market for TES appears to be in cool storage to shift electrical loads for air conditioning (DOE 1989).

ORNL has been the principal research laboratory for the Diurnal TES program since the program's inception in 1976. The overall goals of the Diurnal TES program are as follows (Tomlinson and Taylor 1988):

1. create the technology base required for developing efficient, cost-effective TES concepts in diurnal heating and cooling and industrial applications
2. work with industry, universities, technical societies, and trade associations to transfer the technology to the private sector.

Several of the highlights of the DOE Diurnal TES program have already been discussed as part of the explanations of the different technologies. During the 1980s, the Diurnal TES program focused on high-risk technologies considered to be beyond the scope of commercial R&D programs. In 1989 a peer review of the DOE TES program was conducted by an expert panel assembled by the ASME. The panel, which concluded that the DOE program was highly deserving of continued support, summarized the major technological accomplishments of the program. Some of these accomplishments that relate to diurnal cool storage are listed below (in no particular order) (ASME 1989):

- identified the critical Richardson number (a dimensionless ratio directly proportional to tank fluid depth and tank top-to-bottom temperature difference while inversely proportional to the square of the inlet velocity) of 0.25 for a stable thermocline in stratified water storage, which is now used as the basis for stratified water thermal storage tank design
- identified and developed clathrates as thermal storage media
- developed encapsulation technique for pelletized PCMs
- developed cross-linked high density polyethylene (x-HDPE) pellets as a form-stable PCM for heat transport systems
- demonstrated residential ice storage systems as a utility load management tool

- developed PCM wallboards
- developed a low-temperature chill storage system for the food processing industry
- developed ice harvesting technique as a basis for developing a commercial dynamic ice maker.

3.1.2 Chronology and Technical Results of DOE Diurnal TES Projects

This section describes the diurnal cool storage R&D projects performed under the DOE Diurnal TES program. The project descriptions are divided into five-year periods from 1976 to 1990. These chronological divisions are somewhat arbitrary and are not intended to represent points of major program changes. Within each period, the major projects under the Diurnal TES program are listed. The projects relating to diurnal cool storage for electrical load management in buildings are then discussed in more detail.

Most of the project information included in this section is taken from the annual TES Technical Progress Reports compiled and published by ORNL. Historical funding records for the individual projects within the program have not generally been maintained and are not available for inclusion in this report.

DOE Diurnal TES Projects, 1976 to 1980

The early focus of the TES program was on near-term technologies. Many of the projects were field tests and technical and economic assessments of the cool storage equipment and markets then in existence. Because of the evolution of the technology and the market conditions since the 1970s, many of the results of these tests and assessments are not as pertinent today as they were at that time. The following projects or major project areas were conducted by the DOE (and ERDA) Diurnal TES program for building heating and cooling load management from the program's inception in 1976 through 1980:

- Evaluation of Functional Requirements for a Cost-Effective TES/Heat Pump System
- Evaluation of Olivine Ceramic Bricks for Hot TES
- Simulation of Latent Heat TES Systems Performance

- Design and Field Demonstration of a Residential Cool Storage System
- Earth Thermal Storage with a Crawl-Space-Assisted Heat Pump
- TES Commercialization Readiness Assessment
- Survey of TES Installations (eventually published by ASHRAE)
- Construction of Test Facility for Room Storage Heaters.

DOE Diurnal TES Projects, 1981 to 1985

This time period contains the budget reductions and the shifts in research priorities that occurred in the TES program during the early 1980s. The focus was redirected to long-term concepts such as new storage materials, which were thought to be beyond the scope of private and industrial research.

The following projects or major project areas were conducted by the DOE Diurnal TES program from 1981 through 1985, but for this report are not considered to be directly related to diurnal cool storage for electric load management in buildings:

- Advanced Storage Building Materials with PCM Wallboards
- Earth Thermal Storage with a Crawl-Space-Assisted Heat Pump
- Solid Sensible Heat Storage with Olivine Bricks
- Passive Solar Building Modeling.

The following projects are directly related to diurnal cool storage in buildings for load management, and the progress of each is discussed below:

- Heats of Mixing of Conjugating Liquids
- TES with Ammoniated Complex Compounds
- TES with Refrigerant Clathrates
- Technical and Economic Assessment of Heat Pump TES
- Water Storage Tank Stratification Techniques.

Heats of Mixing of Conjugating Liquids. Certain liquids, when mixed over a particular temperature range, experience a heat of mixing in addition to the sensible heat capacities of the component liquids. A two-phase study

was initiated in 1985 to study the potential of using a pair of liquids with high heats of mixing as a thermal storage medium. The objective of the first phase was to identify potential liquid-liquid systems. The objective of the second phase was to make empirical measurements of the thermodynamic properties of the liquid-liquid systems identified in the first phase. It was believed that conjugating liquid systems having temperature regions of complete miscibility, both below some lower critical temperature and above some upper critical temperature, were potential dual-temperature (capable of storing either hot or cold) thermal storage media.

TES with Ammoniated Complex Compounds. Feasibility studies and computer simulations were performed in 1984 and 1985 to demonstrate the potential of dual-temperature thermal storage using ammoniated complex compounds. An ammoniated complex of sodium bromide was identified as a promising storage medium.

TES with Refrigerant Clathrates. A new project to study potential dual-temperature clathrates began in 1982. In support of this effort, a search was begun for a clathrate that would form at temperatures suitable for heat pump storage temperatures. An experimental crystallizer was constructed at ORNL in 1983, and the formation of a clathrate of CFC-12 and water was demonstrated using this facility. This clathrate formed at a relatively high pressure of 449 kPa (65.1 psia), indicating that a storage system using this clathrate would require containment in a pressurized vessel. A clathrate of CFC-11 was formed at 59 kPa (8.6 psia), which is considerably below atmospheric pressure (where standard atmospheric pressure is 101.3 kPa or 14.7 psia). CFC-21 formed a clathrate at atmospheric temperature but was considered too chemically active for practical use. By 1985 no suitable system for dual-temperature thermal storage was identified, and follow-up research was considered to be beyond the resources of the TES program.

Technical and Economic Assessment of Heat Pump TES. In 1982, the potential energy use and cost savings of thermal storage with heat pumps were assessed for hypothetical buildings in Boston, Nashville, and in Miami. Table 3.3 summarizes the results of the assessment of the potential annual energy use for both conventional and storage systems at the three sites. It

TABLE 3.3. Assessment of Energy Consumption of Conventional Heat Pump vs. Storage Heat Pump Systems (Martin et al. 1983)

Location/ System Type	Annual Electric Consumption (kWh)			Percent On Peak
	On Peak	Off Peak	Total	
Boston				
Conventional	13,507	18,710	32,217	42%
Hot Storage	3,135	21,888	25,023	13%
Cool Storage	12,501	19,837	32,338	39%
Hot & Cool Storage	2,129	23,015	25,144	8%
Nashville				
Conventional	9,267	12,759	21,846	42%
Hot Storage	4,197	16,425	20,622	20%
Cool Storage	6,344	15,873	22,217	29%
Hot & Cool Storage	1,274	19,539	20,813	6%
Miami				
Conventional	9,082	13,161	22,243	41%
Cool Storage	2,571	19,918	22,489	11%

should be stressed that these assessments were used to judge the potential applicability of TES and that the energy consumption comparisons were not supported by field tests with actual equipment.

As expected from the climates, hot storage was more effective in Boston for shifting energy consumption off-peak, while cool storage was more effective in Miami. However, the study determined that neither hot or cool storage would be cost-effective for reducing peak energy use in the more moderate climate of Nashville. The study concluded that only a system capable of providing cool storage in the summer and hot storage in the winter would be cost-effective in areas with moderate and seasonally varying climates. This finding became the impetus for much of the research into dual-temperature storage media, which was conducted over the next several years (e.g., dual-temperature clathrates and dual-temperature ammoniates).

Water Storage Tank Stratification Techniques. Three projects were completed in 1982 and 1983 that addressed the problem of maintaining the separation of cold and hot water in a water storage tank. The first project was an analytical and experimental study of natural thermal stratification

processes and verified that stratification will occur naturally when the Richardson number exceeds 0.25. This is an important finding for water storage tank design. A second project studied a labyrinth stratification technique and found that the additional internal barriers in the tank are not necessary to achieve thermal stratification. Finally, a third project tested the use of a permeable membrane as a thermal barrier to separate the cold and warm water in a tank. Operating problems with the experimental equipment were reported, and no conclusions were drawn as a result.

DOE Diurnal TES Projects, 1986 to 1990

The following projects or major project areas were conducted by the DOE Diurnal TES program from 1986 through 1990, but are not considered to be directly related to diurnal cool storage for electric load management in buildings for the purposes of this report:

- Heat Transfer with Phase Change Slurries
- Advanced Storage Building Materials with PCM Wallboards
- Evaporative Heat Transfer.

The following projects are directly related to diurnal cool storage in buildings for load management, and the progress of each is discussed below:

- Heats of Mixing of Conjugating Liquids
- TES with Ammoniated Complex Compounds
- TES with Refrigerant Clathrates
- Ice Self-Release Mechanisms
- Direct Contact Ice-Making Systems.

Heats of Mixing of Conjugating Liquids. Phase 1 (identification phase) of this project was initiated in 1986. Among the promising liquid systems identified for further study were aniline-n-hexane, propylene carbonate-water, and methyldiethylamine-water. In 1987, the Phase 2 empirical testing of the thermodynamic properties of the chosen liquid-liquid systems began. The heats of mixing of these mixtures were measured over various temperature ranges with a calorimeter. The methyldiethylamine-water mixture had an effective heat

capacity about 30% greater than that of water from 118° to 131°F, which gives it potential for heat storage systems. A propylene glycol mixture with a glycol weight fraction of 0.4 had an effective heat capacity 20% greater than water from 50° to 59°C. The project was completed in 1989 with the conclusion that the heat capacity of the fluid mixtures is enhanced by the heats of mixing and that such systems may have potential as liquid-based latent heat TES and heat transport systems.

TES with Ammoniated Complex Compounds. A study was begun in 1986 to evaluate the existing ammonia regulations to judge their impact on developing ammoniated TES systems in commercial buildings. The study found that ammonia, which is a combustible, corrosive, and toxic substance, could not be used under the current regulations. In 1987 the focus of study in ammoniated complex compound systems was shifted to the refrigeration and food-processing industries, where ammonia is already in wide use. The project's objective then became to develop a cost-effective ammoniated complex compound chill storage system for the temperature range of -76° to 320°F. Plans for 1991 include constructing a 30 ton-hr storage system and completing the heat exchanger optimization studies.

TES with Refrigerant Clathrates. The concept of forming clathrates at suitable temperatures and pressures for TES with a mixture of two refrigerants and water was formulated and tested. A mixture of CFC-11 (which forms a clathrate below atmospheric pressure) and CFC-12 (which forms a clathrate at a pressure above atmospheric) was empirically tested. A mixture of 0.88 mole fraction of CFC-11 and 0.12 mole fraction of CFC-12 formed a clathrate at a pressure of 1 atmosphere and at 48.6°F. In 1986 and 1987, however, a technical and economic assessment of clathrate cool storage systems was undertaken. The study concluded that the significant costs and environmental concerns of the large inventories of CFCs that would be required in clathrate systems critically hampered their further development. No further research into clathrate cool storage has been performed in the DOE TES program.

Ice Self-Release Mechanisms. The objective of the Ice Self-Release project, which began in 1987, was to define the physical and chemical mechanisms in the self-release of ice from submerged evaporator (cooling) plates in

open tanks. Passive ice self-release was considered to be a potential solution to the ice "stickiness" problem of direct expansion ice-on-coil systems, in which the ice forms an undesirable insulating layer on the evaporator coils. Using glossy surface coatings on the evaporator plates with electrolyte solutions in the surrounding water reduced ice adhesion to the evaporators. Ice self-release was achieved and verified for vertical evaporator plates but was not achieved with horizontal plates. The concept of Advanced Ice Release Mechanisms, which use the mutual repulsion of current-carrying conductors to achieve ice-release from evaporator surfaces, began to be studied in 1990.

Direct Contact Ice-Making Systems. The objective of this project is to develop an advanced direct contact, open-refrigeration cycle ice production and storage system based on liquid ring compressor technology. This project, which began in 1988 and was still ongoing in 1991, also seeks to solve the problem of the insulating layer of ice that forms on the evaporator surface and lowers the required evaporator temperature needed to form ice in the tank. In a direct contact ice-making system, the subcooled refrigerant comes in direct contact with the water and thus eliminates this problem completely. Plans for 1991 are to build and test a 30-ton, 250 ton-hr system.

3.2 THERMAL ENERGY STORAGE PROGRAMS IN OTHER FEDERAL AGENCIES

Although the DOE has clearly been the principal focus of federal research in TES, the National Aeronautics and Space Administration (NASA) and the Department of Defense (DOD) have both conducted TES research for some specialized applications, such as microclimate cooling systems for tanks, aircraft, and spacecraft. Since the 1960s, NASA has been testing and developing PCMs as thermal capacitors to passively buffer the temperature of orbiting satellites. The DOD has conducted research through the Wright Research and Development Center on using TES systems in conjunction with chemical heat pumps for applications on spacecraft.^(a)

(a) Source: project summary data base maintained by the Interagency Advanced Power Group, Washington, D.C.

3.3 THERMAL ENERGY STORAGE PROGRAMS AT THE ELECTRIC POWER RESEARCH INSTITUTE

EPRI is a national research consortium of electric utility companies. EPRI has used its affiliation with utilities throughout the United States to foster the transfer of thermal storage technologies from the research laboratories to commercial markets. In the last few years, EPRI has become a national leader in cool storage research and technology transfer, with annual research funding in excess of \$2 million.^(a)

EPRI has fostered the technology transfer of TES by sponsoring several thermal storage seminars, which brought together experts from the nation's research institutions, consulting firms, and electric utility companies. EPRI also supplied the initial funding and support for the founding of the ITSAC in 1985 (McCannon 1989). ITSAC, which began issuing publications in June of 1986, serves as an information clearing house for TES technology developments and market developments. ITSAC membership includes consultants, engineers, utilities, and research institutions.

EPRI has also developed and published several cool storage design manuals for utilities and building HVAC engineers. These design guides provide building engineers with step-by-step procedures for sizing storage systems and determining the economic payback under various utility rate structures. EPRI also publishes manuals to help educate the utilities about the benefits of thermal storage and the design rate schedules appropriate for the thermal storage commercial markets within their jurisdictions. Computer programs have also been developed to automate the procedures and calculations found in the manuals. Some examples of these EPRI software packages are COOLAID, COMMEND, and LMSTM (McMenamin 1987).

EPRI has sponsored and been involved with several major field-testing efforts of TES equipment and systems. In 1981 and 1982, EPRI and the DOE conducted a nationwide field test of TES systems in residential buildings. The technologies tested included ice storage tanks and stratified water tanks used for electric load management. The study determined that the electricity demand peak from residential air conditioning significantly lagged behind the

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(a) Personal communication with Ronald Wendland of EPRI, October 31, 1990.

utilities' peak demand period by several hours. This finding suggests that the benefits to utilities from thermal storage in residential buildings may be limited. In general, the study concluded that peak reductions were obtained but that substantially more energy was consumed (as much as an 118% increase) by the storage buildings than by the buildings in the control group (Kuliasha et al. 1984). EPRI has also evaluated cool storage installations in commercial buildings. In 1986, EPRI initiated an effort with the ORNL to develop an ice storage test facility. The goals of this facility are to test commercially available ice storage systems under uniform laboratory conditions so that performance areas requiring improvement can be identified (Tomlinson 1987). The results of two recent field tests of cool storage installations sponsored by EPRI are presented in Section 4.2 of this report.

During the last few years, EPRI has heightened its efforts in the R&D of state-of-the-art cool storage technologies. EPRI is currently conducting research in improving ice-making techniques and in developing cool storage systems using phase-change eutectics with freezing temperatures higher than water but low enough to be compatible with low-temperature air distribution systems.

3.4 THERMAL ENERGY STORAGE PROGRAMS AT THE AMERICAN SOCIETY OF HEATING, REFRIGERATION, AND AIR-CONDITIONING ENGINEERS

ASHRAE is a professional society of HVAC engineers. Thermal storage is one of the 88 technical areas under which ASHRAE research and technical programs are conducted, and a section describing thermal storage and thermal storage systems design is included in the ASHRAE handbook. Like EPRI, ASHRAE has played an important role in disseminating information about thermal storage through its conferences and technical publications.

Thermal storage is just one of ASHRAE's research areas, and ASHRAE has not had a thermal storage research program on the scale of EPRI. During the last five years, ASHRAE has sponsored research projects in the containerization of PCMs and in improved ice-making techniques. ASHRAE has also conducted

performance modeling and field testing of ice and chilled water thermal storage systems. The cumulative ASHRAE budget devoted to thermal storage projects over the last five years is approximately \$250,000.^(a)

(a) Personal communication with Bill Seaton of ASHRAE, November 20, 1990.

4.0 COMMERCIAL STATUS OF DIURNAL COOL THERMAL ENERGY STORAGE

The commercial viability of thermal energy storage depends almost entirely on favorable economics for the end-use customer. Low-temperature air distribution systems used in conjunction with ice storage systems might reduce long-term energy consumption (although current efforts have not reached this level of performance), but cool storage's economic benefits to commercial customers will not generally be sufficient without additional incentives from the utilities. It is the utilities that stand to gain directly from widespread use of cool thermal storage, and several utilities have undertaken programs to encourage their commercial customers to implement cool storage systems.

This section first describes utility programs that encourage cool storage and then includes results from recent field tests and information about the commercial status of cool storage systems.

4.1 UTILITY PARTICIPATION IN DIURNAL COOL STORAGE

Several utilities view cool thermal storage as a technologically proven method of managing generating loads and abating problems of growing peak electrical demands. Commercial space cooling is widely cited as the largest single contributor to summer peak demand in the United States. The advantages of cool storage for electric generating utilities include the following (EPRI 1983):

- improved capacity use or load factors
- decreased required peak-generating capacities, which in turn defers the need for building additional baseline and peak generating capability
- decreased transmission and distribution system capacity requirements
- improved energy efficiency by decreased use of less efficient peak generating capacity
- decreased reliance on the more expensive fuels such as oil and gas, which are used by peak generators.

Implementing cool storage systems typically cannot be justified economically to utility customers unless the utility adopts rate structures that

encourage off-peak electricity use by its customers. By doing so, the utilities share some of their eventual savings with their commercial customers. Cool storage can be mutually beneficial to utilities and customers, but the utilities typically must initiate customer participation.

Two common rate devices that utilities use to discourage on-peak electricity use are peak demand tariffs and time-of-day rates. Demand tariffs and surcharges for large commercial customers are standard for U.S. utilities and are not limited to cool storage promotion programs. A demand surcharge is simply a fee based on the largest demand registered by the customer in the billing period. A significant demand surcharge encourages customers to improve load management and helps make cool storage more economically attractive to them. A time-of-day or time-of-use rate structure means that the per-unit cost of energy charged by the utility is higher during the peak periods and lower during the off-peak periods. Again, this rate differential encourages the use of cool storage to generate cool thermal energy at night for space cooling during the day.

Some utilities have found that conventional rate strategies do not by themselves result in the full commercial realization of cool storage systems. To further stimulate the market penetration of cool storage, several utilities have begun to offer additional monetary inducements or subsidies to customers willing to implement new cool storage systems. This inducement is usually stated in terms of dollars of subsidy per kilowatt (kW) of load shifted. An ITSAC survey in 1990 (ITSAC 1990b) listed from across the United States 33 utilities that are currently offering cool storage inducements. The subsidies listed range from about \$50 to \$500 per KW of load shift, although many utilities have ceilings on the maximum award that can be offered. The complete ITSAC listing of participating utilities is included in Appendix A.

In 1983 Southern California Edison (SCE) became the first utility to adopt a cool storage inducement program, which at that time was \$200 per shifted KW with a \$100,000 maximum. The total amount of peak electricity demand shifted with cool storage by SCE's customers grew from approximately 5 MW (Megawatts) of installed capacity in 1984 to over 22 MW in 1986 (McCannon 1987). Table 4.1 shows the distribution by type of cool storage systems installed by SCE's customers by 1986. Note that the relatively high

TABLE 4.1 Cool Storage Installations in the SCE's Program
(installations and agreements as of July 31, 1986)
(McCannon 1987)

Type of System	Number of Installations	Total Peak Shift (MW)	Percent of Total Peak Shift
Chilled Water	25	10.7	40%
Ice	25	8.9	33%
Eutectic Salts	18	7.4	27%
Total	68	27.0	100%

percentage of eutectic salt systems is not considered to be representative of the total market share of these systems for the United States, but is instead a regional concentration.

4.2 PERFORMANCE RESULTS OF EXISTING COOL STORAGE SYSTEMS

In this section, the results of two recent cool storage field tests and evaluations sponsored by EPRI are summarized. The first program evaluated the performance of cool storage systems installed in commercial buildings. The second field test is of a low-temperature air distribution system designed for a new commercial building. Both testing projects were completed in 1988; therefore, some allowances for improved performance in the last two years may be appropriate in interpreting the results.

4.2.1 Field Test of Cool Storage Installations

EPRI sponsored a major field testing and evaluation program that monitored cool storage installations at 19 sites around the United States during 1987 and 1988 (EPRI 1989). The project's objectives were to validate the performance of cool storage systems and to recommend design and operating improvements for these systems. The program was administered by Science Applications International Corporation using the automated Data Acquisition and Evaluation System developed by EPRI for monitoring cool storage systems. Of the 19 sites, performance analyses were conducted for 7 sites for 1988. Table 4.2 lists and describes the characteristics of 6 of these sites.

TABLE 4.2 Cool Storage System Test Sites (EPRI 1989)

Site Code	Building Location	Building Size (sq. ft.)	Storage Medium	Storage Capacity (ton-hr)
AP	Southern California	190,000	Eutectic Salt	2800 (full)
AZ	Arizona	60,000	Eutectic Salt	1600 (full)
GT	Southern California	269,000	Ice	7925 (full)
MD	Montgomery, Alabama	25,000	Ice	400 (partial)
PK	New York City	1,200,000	Chilled Water	3600 (full)
WE	Westchester, New York	152,000	Chilled Water	3100 (full)

The "site codes" in Table 4.2 are the abbreviations assigned to each site that are used in subsequent tables. The size of the storage system is given in "ton-hours," which is a standard measuring unit of cooling load energy (1 ton-hour equals 12,000 Btu). The designation of storage systems as either "full" or "partial" refers to the designed mode of operation of the cool storage system. In a full storage system, the entire cooling load is generated off-peak. In a partial storage system, a portion of the cooling load is generated during the peak hours. A partial storage system allows for a smaller storage capacity requirement but, as a consequence, results in a higher electrical peak than a full storage system. The eutectic storage systems referred to in Table 4.2 have freezing points of 47°F.

A cool storage system's performance is judged both by its total energy use and by the reduction of on-peak electric demand resulting from using the system. For monitoring purposes, the cool storage systems were divided into three basic system components: the chiller (cooling mechanism), auxiliary equipment (e.g., pumps and fans), and the storage tank. Total cool storage system energy use then consists of the energy consumption of the chiller and

auxiliary equipment along with the standby thermal energy losses incurred by the storage tank and the rest of the system.

Table 4.3 shows the breakdown of energy use by system component at the tested cool storage sites. The standard performance measure of electric energy use for space cooling is kWh/Ton-Hr (number of kilowatt-hours of electrical energy required to deliver a ton-hour of cooling load). As expected from the lower evaporator temperatures, the ice storage systems in general experienced higher chiller energy use. The ice systems in the study also had more energy storage losses than the chilled water and eutectic systems. The eutectic salt storage system at the Arizona site experienced extremely low storage energy losses because the storage tank's thermal efficiency was measured as being virtually 100%.

The electricity demand and energy use for the cool storage systems in the study were compared with the simulated electricity demand and energy use for a simulated conventional air conditioning (A/C) system at each site. Table 4.4 shows the total cooling energy use for the storage and conventional A/C systems at the test sites. In general, the storage systems in the test consumed considerably more energy than conventional A/C systems.

TABLE 4.3 Energy Use of Cool Storage Systems by System Component
(EPRI 1989)

Site and Year	Chiller (kWh/Ton-Hr)	Auxiliary (kWh/Ton-Hr)	Storage (kWh/Ton-Hr)	Total System (kWh/Ton-Hr)
Chilled Water				
PK 1987	0.79	Not Measured	0.09	0.88
PK 1988	0.75	Not Measured	0.06	0.81
WE 1988	1.11	0.63	0.03	1.77
Eutectic Salt				
AP 1987	1.14	0.50	0.08	1.72
AP 1988	0.84	0.40	0.05	1.29
AZ 1988	0.93	0.54	0.01	1.47
Ice				
GT 1987	0.99	0.64	0.73	2.36
GT 1988	1.04	0.55	0.42	2.01
MD 1988	1.06	0.22	0.16	1.44

TABLE 4.4 Comparison of Energy Use by Cool Storage Systems and Conventional A/C Systems (EPRI 1989)

Site and Year	Cool Storage (kWh/Ton-Hr)	Conventional A/C (kWh/Ton-Hr)	Percent Increase
Chilled Water			
PK 1987	0.88	0.79	11%
PK 1988	0.81	0.80	1%
WE 1988	1.77	1.39	27%
Eutectic Salt			
AP 1987	1.72	1.42	21%
AP 1988	1.29	1.22	6%
AZ 1988	1.47	1.55	-5%(a)
Ice			
GT 1987	2.36	1.42	66%
GT 1988	2.01	1.14	76%
MD 1988	1.44	1.43	1%(a)

-
- (a) Decrease in energy use partly the result of differences in assumptions between the storage and conventional cooling systems (discussed below).
- (b) Storage system is used for partial storage and therefore shifts a smaller portion of the cooling load compared with the full storage systems.

Some caution is necessary in interpreting the performance comparisons shown between the conventional and cool storage systems. Because the conventional A/C systems were simulated and not actually implemented at the various test sites, their performance results do contain an unknown amount of uncertainty. But even without this uncertainty, it is not always possible to construct a complete "reference" cooling system scenario for each site to use as a basis for an objective comparison of the two types of systems because of the inherent differences between the conventional and storage systems. For example, at the Arizona site the installed cool storage system operated with two 160-ton centrifugal chillers and a cooling tower. Because of the study's ground rules, however, it was assumed that the conventional system at the Arizona site would use two 90-ton air-cooled reciprocating chillers because they were considered more common in practice for cooling loads the size range

(180 tons) of the Arizona site (EPRI 1989). The larger centrifugal chillers used by the cool storage system consume less energy than the smaller chillers of the conventional system, so a direct before-and-after comparison between the two strategies leads to misleading results. The additional cost of the larger chillers is also a significant factor that is not captured in the energy use comparison.

Table 4.5 compares the peak electrical demand and on-peak energy use for the simulated conventional A/C systems and the cool storage systems at the test sites. As the results indicate, the cool storage systems were generally successful in reducing the peak electrical demands of the buildings and shifting a portion of the daily electrical load to the off-peak time of day.

TABLE 4.5 Electricity Peak Demand Reduction of the Cool Storage Systems (EPRI 1989)

Site and Year	Reduction of Peak Demand with Cool Storage (kW)	On-Peak Energy Use of Conventional A/C System (kWh) ^(a)	On-Peak Energy Use of Cool Storage System (kWh)
Chilled Water			
PK 1987	300	75	0 ^(b)
PK 1988	396	145	5 ^(b)
WE 1988	-52	140	10
Eutectic Salt			
AP 1987	479	70	15
AP 1988	329	150	25
AZ 1988	210	50	10
Ice			
GT 1987	242	45	15
GT 1988	92	75	65
MD 1988	Not Applicable ^(c)		

(a) Energy in kWh used for cooling in an average daily on-peak period for each site.

(b) Energy for auxiliary equipment at the PK site was not measured.

(c) The MD site was designed as a partial storage system for uniform load-leveling because its utility had no peak rate period.

The field testing and evaluation program concluded with recommendations for improving cool storage systems performance (summarized here briefly). First, the cool storage system must be integrated with the operations of the building HVAC system in order to achieve optimal performance. The cool storage system should also be subjected to thorough and regular maintenance. Finally, proper insulation must be considered in the storage tank design, and the tanks should not be charged in excess of the cooling requirements of the next day. A more detailed discussion of the performance of the cool storage systems at the various sites in the referenced EPRI document (EPRI 1989).

4.2.2 Field Test of a Low-Temperature Air Distribution System

In 1988, EPRI sponsored a field test of a low-temperature air distribution system used in conjunction with an ice storage system for electric load management. The testing and evaluation were performed for EPRI by Dorgan Associates, Inc., of Wisconsin. The test facility was a 12-story, 265,000 square foot office building in southern California. The building was completed in 1987 and uses an ice storage system to shift its cooling load off peak. The cooling load peak capacity of the building's A/C system is 600 tons, and the cool storage system has a capacity of 7,900 ton-hours of cooling energy. The cool storage system is designed for a weekly full storage cycle in which the weekend off-peak hours are used to generate the stored cooling load. The primary air supply temperature for the air distribution system is set at 45°F (compared with a conventional supply temperature of 55°F). The ceiling space of the building is severely limited, and the designer stated that only using a low-temperature air distribution for the building would allow the design of a reasonable duct system in the limited space provided (EPRI 1990).

EPRI sponsored this study in support of its philosophy that cool storage systems still need additional refinements to become more cost-effective. The use of low-temperature air distribution systems in conjunction with ice storage is considered a potential mechanism for reducing the net costs and energy requirements of a building's A/C and air distribution systems. The objectives of the study were as follows (EPRI 1990):

- demonstrate the viability of cold air distribution technology
- identify opportunities to improve design and operation of cold air distribution systems
- compare system energy consumption to that of a conventional air distribution system.

Included in the results of the study are descriptions of system performance parameters such as space temperatures, relative humidity, and indoor air quality. Detailed results are included in the field test report; however, for this report the results are generally comparable to conventional air distribution systems. The main performance criterion of interest here is the system energy use compared with conventional air distribution systems.

Table 4.6 compares the observed fan energy use of the low-temperature air distribution system with the calculated fan energy use of a conventional system if it were installed in the test building. The fan-powered mixing boxes represented in the table are run continuously during the building occupied periods to mix the cold supply air (about 45°F) with room return air to produce an outlet temperature of 55°F to 60°F. As expected, because of the lower supply air temperature, the low-temperature system uses less supply fan energy than the conventional system. However, the system's higher energy use from the mixing box more than offsets the supply fan's reduced energy so that the total fan energy use for the low-temperature system exceeds that of the conventional system by approximately 9%. The conjecture that low-temperature

TABLE 4.6 Fan Energy Consumption of Conventional versus Low-Temperature Air Distribution Systems (from March 14, 1988, to October 2, 1988) (EPRI 1990)

System	Supply Fan Energy (kWh)	Mixing Boxes Energy (kWh)	Total Fan Energy (kWh)
Conventional (55°F)	11,720	1,861	13,581
Cold Air (45°F)	7,794	7,000	14,794

air distribution systems use less energy than conventional systems is therefore not supported by the results of this field test.

The study concluded by identifying alternative system configurations that would potentially minimize the energy penalty of the continuously operating fan-powered mixing boxes. It is acknowledged that further research is required to develop improved methods of delivering cold supply air to occupied spaces before the full potential benefits of low-temperature air distribution systems can be realized (EPRI 1990).

4.3 COMMERCIAL STATUS OF COOL STORAGE TECHNOLOGIES

The first major nationwide survey of commercial thermal storage installations was performed by the Franklin Research Institute in 1981 and published by ASHRAE (1984). This study found that approximately 270 thermal storage installations were in place and operating at that time. Of that total, 50 were cool storage systems and 55 served both cool and hot thermal storage. The rest of the thermal storage installations were classified as hot storage systems. The cool storage-only systems were about evenly distributed among ice and chilled water systems. The hot-and-cold storage systems almost exclusively used water as the storage medium. The main reason stated for implementing thermal storage systems was peak electrical demand reduction and the use of off-peak electricity rates. The survey showed that a few installations were already in place by 1974 which means they were installed before the DOE thermal energy storage research program was initiated.

ITSAC maintains a database of current thermal storage installations that incorporates information from past surveys as well as new installations. The ITSAC database currently contains information describing approximately 1000 thermal storage installations. However, ITSAC believes the database underestimates the true number of installations by as much as 50%. As of this writing, ITSAC is working to complete its database and to develop sales data and trends for the thermal storage industry.

Although published figures are not yet available, ice storage and stratified chilled water are generally considered to be the most common types of systems installed. Both types have their relative technical and economic

advantages and disadvantages in terms of size and operating efficiency, and neither type dominates the market share for cool storage. EPRI estimates that an equal number of chilled water and ice storage systems are operating, but that chilled water systems represent about 70% of the total installed cool storage capacity in the United States.^(a) Chilled water storage systems are especially applicable for large installations where the economies of scale counteract the lower thermal storage density. Ice storage systems, because of their lower volume requirements, are more favorable for retrofit installations where space is at a premium. They are also gaining popularity because of their use in conjunction with low-temperature air distribution systems. A 1990 ITSAC survey listed over 20 manufacturers of ice storage systems in the United States (ITSAC 1990a). The complete ITSAC list is included as Appendix B of this report.

(a) Electric Power Research Institute. "Commercial Cool Storage: Reduced Cooling Costs With Off-Peak Electricity." EU.3024, Palo Alto, California.

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APPENDIX A

UTILITIES WITH COOL STORAGE INDUCEMENT PROGRAMS

APPENDIX A

UTILITIES WITH COOL STORAGE INDUCEMENT PROGRAMS

The following is a list of utilities that have cool storage inducement programs.^(a) The utilities are listed in chronological order of program adoptions.

Southern California Edison	New England Electric
San Diego Gas & Electric Co.	City of Denton, TX
TU Electric Co.	Consolidated Edison Co.
Pacific Gas & Electric Co.	Jersey Central Power & Light Co.
Arizona Public Service Co.	Northern States Power
City of Austin, TX	Riverside Public Utilities
City of Palo Alto, CA	Anaheim Public Utilities
Public Service Electric & Gas	Orange & Rockland Utilities, Inc.
Salt River Project	United Illuminating Co.
Boston Edison	Madison Gas & Electric Co.
Long Island Lighting Co.	Metropolitan Edison
Los Angeles Dept. of Water and Power	Houston Lighting & Power
Sacramento Municipal Utility	Potomac Electric Power Co.
Oklahoma Gas & Electric Co.	Ontario Hydro
El Paso Electric Co.	Philadelphia Electric
Wisconsin Electric Power Co.	Cincinnati Gas & Electric Co.
Pennsylvania Electric Co.	

(a) Source: International Thermal Storage Advisory Council. April 1990.
"Thermal Storage Bulletin." File Code: B.4004, San Diego, California.

APPENDIX B

MANUFACTURERS OF ICE AND PHASE CHANGE MATERIAL STORAGE SYSTEMS

APPENDIX B

MANUFACTURERS OF ICE AND PHASE CHANGE MATERIAL STORAGE SYSTEMS

This appendix lists the manufacturers of ice and phase change material thermal storage systems.^(a)

<u>Manufacturer</u>	<u>Location</u>	<u>Type of System</u>
BALTIMORE AIRCOIL CO.	Baltimore, MD	Ice
CALMAC MFG. CORP.	Englewood, NJ	Ice
CBI NA-CON, INC.	Oak Brook, IL	Ice
CRYOGEL	Del Mar, CA	Ice
EVAPCO INC.	Baltimore, MD	Ice
FAFCO, INC.	Menlo Park, CA	Ice
HENRY VOGT MACHINE CO.	Louisville, KY	Ice
INTERNATIONAL ICE INDUSTRIES	San Marcos, CA	Ice
LENNOX INDUSTRIES, INC.	Dallas, TX	Ice
MORRIS & ASSOCIATES	Raleigh, NC	Ice
NORTH STAR ICE EQUIPMENT CORP.	Seattle, WA	Ice
O.E.M. PRODUCTS, INC.	Plant City, FL	Ice
PAUL MUELLER COMPANY	Springfield, MO	Ice
PHENIX HEAT PUMP SYSTEMS	Elk Grove, CA	Integrated heat/ cool residential system

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(a) International Thermal Storage Advisory Council. 1990. "Manufacturers of Cool Storage Products." ITSAC Thermal Storage Bulletin. File Code: A.3003, San Diego, California.

REACTION THERMAL SYSTEMS	Mapa, CA	Ice
REFRIGERATION ENGINEERING COMPANY	San Antonio, TX	Ice
SUNWELL ENGINEERING CO.	Woodbridge, Ontario	Ice
THERMAL ENERGY STORAGE, INC.	San Diego, CA	Clathrate Direct Contact Ice
TRANSPHASE SYSTEMS, INC.	Huntington Beach, CA	Eutectic with 48°F Freeze Point
TURBO REFRIGERATION CO.	Denton, TX	Ice
UHR CORPORATION	Alexandria, VA	Integrated heat/ cool residential system
YORK INTERNATIONAL CORP.	York, PA	Ice

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