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CONSERVATION

THERMAL ENERGY STORAGE APPLICATION AREAS

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SEASONAL THERMAL ENERGY STORAGE FOR BUILDING HEATING AND COOLING

Thermal energy storage enables the capture and retention of heat energy (or cold) during one period in time for use during another. Seasonal storage involves a period of months between the input and recovery of energy. When applied to building heating and cooling, it enables efficient use of alternative energy from such diverse sources as solar-thermal collectors, industrial waste streams, utility and industrial cogeneration facilities, and winter-chilled air. The exploitation of these energies supports national energy goals by reducing the consumption of fossil-fuel resources, particularly petroleum and natural gas.

Seasonal storage of thermal energy involves very large quantities of heat. Thermal energy may be stored as sensible heat by raising or lowering the temperature of the storage medium, as latent heat by freezing or melting the storage medium, and as thermochemical heat by causing a change in the chemical composition of the storage medium. Sensible-heat storage is a mature technology. The only major remaining engineering problems are those associated with cost-effective containment of large volumes of storage media, specifically heated water. The candidate techniques involve natural structures such as aquifers (underground, water-bearing geologic formations), constructed ponds, and earth, rather than manufactured devices such as water tanks and rock beds. The primary focus of the DOE seasonal storage effort is developing technology for aquifer storage and conducting large-scale demonstrations. Compared to sensible-heat technology, latent-heat storage is more expensive and does not offer a technical advantage sufficient for seasonal-duration storage. Thermochemical storage, however, offers a large reduction in storage volume and eliminates time-dependent energy losses. It is an emerging technology, currently at the bench-scale level of development, and is seen as a long-term prospect.

PURPOSE AND AREA OF APPLICATION

Seasonal thermal energy storage is a means of matching the needs of building heating and cooling systems to alternative energy sources. It will enable more efficient use of continuously-available energy sources in satisfying these essentially seasonal demands. In addition, it will enable the capture and use of resources which are only available during the off-season. The energy sources which are being considered for seasonal storage are:

- Solar-thermal energy
- Industrial waste heat
- Cogenerated heat
- Energy of availability such as winter-chilled air

POTENTIAL IMPACT

Seasonal storage of thermal energy could impact national energy consumption in the near- to mid-term. The suggested schemes for seasonal storage require no technological breakthroughs.

Seasonal storage in aquifers is expected to displace or conserve 10 MBOE* (0.06 Quads**) per year in 1985 and 350 MBOE (2 Quads) per year in 2000.

TECHNICAL DISCUSSION AND KEY PARAMETERS

Seasonal storage of energy for building heating and cooling will permit the more efficient use of continuous, alternative energies from sources such as solar-thermal, industrial waste, and utility or industrial cogeneration. It will also enable the use of "energies of opportunity" for seasonally-displaced end-uses, such as the capture of winter cold for use in summer air conditioning. A cost-effective thermal mass which is large enough to retain the energy needed for an entire heating or cooling season involves natural structures such as aquifers (underground, water-bearing geologic formation), constructed ponds, and earth, rather than manufactured devices such as water tanks and rock beds. The primary focus of the DOE seasonal storage effort is developing technology for aquifer storage and conducting large-scale technical demonstrations.

During 1977, heating, cooling, and hot water for residential and commercial buildings accounted for 25 percent of our national energy budget (approximately 3400 MBOE or 19 Quads), primarily as natural gas and petroleum distillates. These fuels are high-quality energy sources, whereas the real need in heating applications is for low-quality thermal energy, i.e., temperatures on the order of 30°C to 70°C (80°F to 160°F.) The use of fossil fuels is an accommodation to logistic, economic, and environmental factors, rather than a technological requirement.

There are alternative sources of energy which are both available and applicable to building heating and cooling, including solar-thermal energy, reject and cogenerated heat from utilities and industry, and energies of opportunity (e.g., winter cold). The availability of these sources is not always compatible with seasonally fluctuating heating and cooling demands, however. By bridging the time gaps between source and demand, thermal energy storage can enable effective capture and use of these alternative energies. A system for collection, transportation, storage, and distribution of these energies is illustrated in Figure 1.

*MBOE = million barrels of oil, equivalent

**1 Quad = 1 quadrillion Btu
= 1,000,000,000,000,000 Btu

Figure 1. System Concept for Seasonal Storage in Building Heating and Cooling

Source

The sources of low-quality thermal energy which are technically suitable for the heating and cooling of buildings include industrial reject heat, cogenerated heat from a utility or industrial power plant, solar-thermal energy, and "energy of opportunity" such as winter-chilled air. These sources are diverse, but may be characterized as generally continuous over the annual cycle, except for the seasonal variation in solar-derived heat and the intermittent nature of winter cold. The source temperatures are such that the energy may be used directly or may be adjusted in temperature for use in heating or cooling applications. While the ultimate decision to use a given source will be based on the economics of the whole system, the main technical factors for screening potential candidates are temperature, ($>150^{\circ}\text{F}$ for heating $<45^{\circ}\text{F}$ for cooling) and availability (quantity versus time).

Industrial Reject Heat. Many industrial sites have an excess of waste heat which is continuously available at or above the 100°C (212°F) minimum required for economic district heating. The system for collection and transport of this energy (e.g., heat exchanger and working fluid) must integrate fully with the specific process to follow its hourly and daily load fluctuations. Because of variation between and within industries, it is impossible to generalize their properties as an energy source. The examples given in Table 1, however, illustrate this potential.

Table 1. Industrial Reject Heat Sources

GENERIC INDUSTRY	WASTE-HEAT TEMPERATURE RANGE	SPECIFIC SITE	TEMP. OF RECOVERED HEAT	MAGNITUDE OF RESOURCE (EQUIVALENT* HOMES HEATED)
Aluminum	$90-980^{\circ}\text{C}$	Primary Aluminum Plant in Northwest U.S.	150°C	12,000
Cement	$400-700^{\circ}\text{C}$	Hypothetical 1/2-Million Ton/Year Dry-process Kiln in Albany, NY	$200-620^{\circ}\text{C}$	10,000

*Quantity of reject heat expressed in terms of the number of local, single-family homes which could be heated for one year.

Cogenerated Heat. Simultaneous generation of thermal energy and electric power by a single power plant (cogeneration) can result in conservation of fossil fuel. While the characteristics of a given facility will determine the relative quantities of heat and electrical energy produced, the capabilities of "typical" systems are illustrated in Table 2. The energy will be available as steam at temperatures exceeding 165°C (325°F). The source is essentially continuous over the annual cycle because the reliability of utility plants are greater than 95 percent.

Table 2. Sources of Cogenerated Heat

SYSTEM	MAGNITUDE OF THERMAL RESOURCE (EQUIVALENT* HOMES HEATED)
100 MMW Steam-Rankine Cycle (Conventional, Medium-size Utility Power Plant)	280,000 Homes
8 MMW Resid-fired Diesel Generator (Medium-size Industrial Diesel Engine)	2000 Homes

*Quantity of heat expressed in terms of the number of single-family homes which could be heated. Geographic location is assumed to be the Northeastern United States.

Solar-Thermal Energy. State-of-the-art flat-plate solar collectors are capable of producing thermal energy at 90°C (195°F) and concentrating collectors at 150°C (300°F). This energy source is subject to a regular, short-term variation as the result of the day-night cycle, with a superimposed random variation resulting from changes in the weather. An overall long-term variation is caused by seasonal effects. Figure 2 illustrates the daily availability of solar-thermal energy as measured over an annual cycle in the Washington, D.C. area. The effect of the geographic location is demonstrated in Table 3. Solar-derived thermal energy is usually available in the form of a hot working fluid such as water.

Table 3. Solar-Thermal Energy Availability

LOCATION	SUMMER ENERGY AVAILABILITY*	WINTER ENERGY AVAILABILITY*
Washington, D.C.	135%	45%
Seattle, Washington	155%	21%
St. Cloud, Minn.	100%	30%

*Daily energy production of a fixed (400 ft²) solar collector expressed as a percentage of the daily demand for January heating of a local, single-family dwelling.

Figure 2. Daily-Averaged Insolation Over One Annual Cycle at a Site in the Washington, D.C. Area*

Energies of Opportunity. These are sources of thermal energy which are available spontaneously as the result of the local climate. Practical applications are restricted to sources of "cold," such as winter-chilled air or cold water from rivers or the ocean. The temperature of these sources depends on local conditions, but Table 4 illustrates the general availability. The practical magnitude of this resource is determined by the size and cost of the heat exchange used for its collection. The energy would likely be available as a chilled working fluid such as water or brine.

*Source: Yuan, S. W., and Bloom, A. M. "Technical and Economical Aspects of Solar Energy Earth Storage." Presented at the International Solar Energy Symposium. Belgrade, Yugoslavia: October 25-30, 1978.

Table 4. Availability of Naturally-Occurring Energy Sources

LOCATION	SOURCE	RANGE OF TEMPERATURE	AVAILABILITY
New York City	Winter Air	0°C-5°C (32°F-40°F)	Dec-March
Chicago, Ill.	Winter Air	-3°C-5°C (27°F-40°F)	Nov-March

Demand

The demand element shown in Figure 1 consists of a mix of buildings with a net heating and cooling requirement determined by the local climate, the types of individual heating systems used, and the density of building types, sizes, and principal uses. The demand is characterized by a minimum and maximum allowable supply temperature, a total seasonal energy requirement, and a peak energy demand rate.

Temperature. The temperature at which energy is returned from storage affects the operation of the space conditioning system. For heating purposes, there is a lower limit for effective operation of an existing delivery system (e.g., hydronic baseboard radiators or forced hot air); an upper limit is established by the materials, safety, and local heating codes. In direct cooling applications, a maximum cooling temperature is set by individual air conditioning systems. For indirect cooling with an absorption-type heat pump, the minimum temperature is set by the specific equipment. Representative temperatures are given in Table 5. Specific temperatures are fixed by the individual systems, with appropriate allowances made for losses in heat exchangers, transfer equipment, and the distribution system.

Table 5. Temperature Requirements of Several Energy Demands

SYSTEM/APPLICATION	TYPICAL MINIMUM TEMP.	TYPICAL MAXIMUM TEMP.
Heating: Residential-Commercial	50°C	125°C
Heating: Commercial-Industrial	—	175°C
Heating: District	—	225°C
Hot Water: Residential	49°C	65°C
Cooling: Direct	—	3°C-10°C
Cooling: W/Absorption-type Heat Pump	77°C	96°C

Total Energy Requirement. The seasonal energy demand of a specific system is the sum of the requirements of the individual buildings; it is estimated from historical climatic data and the type, size, age, and principal use of the buildings. The relative energy requirements of a single-family dwelling in several geographic locations are presented in Table 6. Table 7 illustrates the relative energy requirements of different building types as a function of geographic area.

Table 6. Effect of Geographic Location on Energy Requirements of a Single-Family Dwelling*

LOCATION	RELATIVE* ENERGY REQUIREMENT				TOTAL
	HEAT	HOT WATER	COOLING	LIGHT & POWER	
Northeast	77	9	2	12	100
North Central	83	13	3	12	111
West	30	7	9	12	58
South	20	7	4	12	43

Table 7. Effect of Building Type and Geographic Location on Energy Requirements**

BUILDING TYPE	RELATIVE** ENERGY REQUIREMENT			
	NORTHEAST		SOUTH	
	HEAT	COOLING	HEAT	COOLING
Single Family Residence	100	3	26	5
Low-rise Apartment	129	6	142	11
Office Building	108	11	100	15
Retail Store	37	25	22	34
School Building	59	5	61	6

*Relative Energy Requirement: Individual and total energy requirements have been expressed as a percentage of the total requirement for a dwelling in the Northeast. (Source: "An Impact Assessment of ASHRAE Standard 90-75." Conservation Paper No. 43B. Federal Energy Administration.)

**Relative Energy Requirement: Heating and cooling requirements per square foot of building area have been expressed on a relative basis as a percentage of the value for heating a single-family dwelling in the Northeast. (Source: "An Impact Assessment of ASHRAE Standard 90-75." Conservation Paper No. 43B. Federal Energy Administration.)

Peak Energy Demand Rate. The effects of weather fluctuations and established patterns in the use of buildings combine to produce peak energy demands, which are frequently 2 to 2 1/2 times the average rate. Figure 3 illustrates this effect through a graph of the average daily energy requirement (winter) of a single-family dwelling in the Washington, D.C., area. All buildings exhibit a similar type of demand behavior, as determined by the specific building type, use patterns, and local climate. The ability to meet peak demands represents an inherent requirement for "surge" capacity in the building's energy system, similar to an automobile's need for "passing power." The energy system must be capable of delivering energy from either the source or the storage unit to meet the peak demand; otherwise a backup energy system (e.g., fossil-fueled boiler or electric resistance heater) will be required. System economics determines the backup system requirements.

Figure 3. Daily-Averaged Demand for Space Heating for a Typical Single-Family Dwelling in the Washington, D.C. Area*

*Source: Yuan, S.W., and Bloom, A. M. "Technical and Economical Aspects of Solar Energy Earth Storage." Presented at the International Solar Energy Symposium. Belgrade, Yugoslavia: October 25-30, 1978.

Storage

Thermal energy may be stored as sensible heat by changing the temperature of the storage medium, as latent heat by changing the physical state of the medium (e.g., freezing or melting), and as thermochemical heat by changing the chemical composition of the medium. The glossary provides more specific details of each mechanism. Sensible-heat storage is a mature technology, with rock beds and water tanks providing short-term storage in state-of-the-art solar heating systems. Latent-heat and thermochemical systems are in the developmental stages.

For near- and mid-term applications in new and retrofit seasonal thermal storage systems, the dominant technology will be sensible-heat storage with an inexpensive, readily-available medium such as water. A major consideration in the engineering of such a system is the sheer magnitude of the requirement. The "reference" building, a 1700 ft.² single-family dwelling in the Washington, D.C., area, requires about 96 million Btu (100 GJ) of thermal energy for annual heat and hot water. A practical hot-water storage unit for this system could involve about 90,000 gallons of water, a volume equal to the entire living space in the house. The space requirements for thermal storage to support multi-family dwellings, large commercial buildings, and district heating systems are proportionately larger, and involve multi-million gallon quantities of hot water. Storage in conventional tanks is physically impractical and economically unattractive. Alternative methods include storage in aquifers, earth, or engineered ponds; storage in tanks which are integrated with the building structure or foundation at the time of construction; and storage in advanced thermochemical devices known as chemical heat pumps for the longer term.

Aquifer Storage. An aquifer is a naturally-occurring, underground porous rock formation which contains water. The map in Figure 4 demonstrates the relative abundance of aquifers in the United States; they are frequently tapped as a source of water for household and irrigation purposes. Because they are an existing water-filled structure, aquifers represent a logical alternative to large, man-made thermal storage facilities. The concept involves using commercial well-drilling techniques to penetrate the aquifer with two separate wells, called a doublet. Water is withdrawn from one well, heated or chilled using an existing energy source, and re-injected into the aquifer through the second well, as shown in Figure 5. Reversing the flow of water permits recovery of the heat (or cold) on demand. The concept is attractive for near-term applications, because the technologies for well-drilling and production are established; aquifer storage will require, however, the solution of specific engineering problems. The application of an aquifer storage system to district heating with an industrial waste-heat energy source is shown schematically in Figure 6.

At the outset of a thermal storage project, the relevant properties of the aquifer, unlike a fabricated tank, are generally ill-defined. Each aquifer must be evaluated and a system developed to adapt it to specific source and demand elements, as shown in Figure 7. The existence of natural geothermal reservoirs confirms the possibility of storing pressurized water at 175°C (350°F), at least in a number of specific aquifers. The use of

Figure 4. Prospective Areas for Aquifer Storage

Figure 5. Heat Storage in a Doublet Aquifer System

Figure 6. Aquifer Storage Applied to Recovery of Industrial Reject Energy for District Heating

other aquifers for large-volume irrigation purposes is an indication that there are some very porous structures, capable of exchanging the quantity of water required for seasonal storage. The properties of a specific aquifer will establish limitations on each well doublet as a storage unit (e.g., magnitude of stored energy, maximum rate at which energy is input and withdrawn, rate of energy loss, and maximum storage temperature). The interface needs of the source and demand will determine the number of such doublets required. Because of the cost and relative complexity, aquifer storage is best suited to large applications such as district heating or industrial systems rather than individual homes.

Storage in Engineered Ponds. Surface reservoirs may provide an alternative means for seasonal storage with heated water for locations where the aquifers are unsuitable. The concept is under investigation in Europe for district heating and makes use of the stratification of hot and cold water in the heated reservoir. Hot water at up to 80°C (180°F) is withdrawn from the top, used in a hydronic heating system,

Figure 7. Development Process for an Aquifer Storage System

and returned somewhat cooler to the bottom of the reservoir. The flow is reversed during the heat-storage phase. System size is restricted only by the ability to construct a large, lined reservoir in the local earth. Like aquifer storage, the economy of scale favors application to larger systems such as district heating.

Storage in Damp Earth. Another proposed alternative to aquifer storage involves pumping water or other heat transfer media through a coil of pipe which is buried in water-soaked earth. In the charge mode, hot water from the energy source warms the ground to temperatures as high as 82°C (180°F). Energy is recovered by pumping water from the building heating system through the buried coil of pipe. The water is heated by the thermal energy which is stored in the earth, and is returned to the building to provide space heat and hot water. This concept is proposed for use with solar heating of single-family dwellings. System size is restricted only by the availability of land.

Engineered Tanks. The use of state-of-the-art fabricated tanks for seasonal storage of heated water is economically unattractive. Integration of the storage vessel with the building structure, using existing foundation walls and excavations in new construction, is seen as a means of reducing this cost. The concept is under consideration as a cost-effective means of extending simple, tanked hot-water storage from daily to seasonal applications.

Chemical Heat Pumps. This is an emerging technology for heating and cooling applications in solar-thermal energy systems. Its development emphasizes the interface of a solar-thermal source with a space-heating demand, making it well suited for all building heating and cooling applications. The storage capability of the chemical heat pump comes from the conversion of thermal energy to chemical bond energy in a "mobile" chemical compound such as water, ammonia, or methanol. These chemical compounds can be accumulated in a reservoir, thus effectively storing thermal energy. This form of storage is accomplished at ambient temperature with no time-dependent energy loss from the system. Storage as thermochemical energy is much more compact than storage as sensible or latent heat, and is a potential cost-effective alternative for areas not suitable for aquifer storage.

The operation of a chemical heat pump, based on sulfuric acid dilution with water vapor as the mobile chemical compound, is shown in Figure 8. The system operates with a charging temperature from 65° to 205°C (150° to 400°F), and is compatible with a broad range of solar, industrial waste, and cogeneration heat sources. Sulfuric acid is an inexpensive, readily-available commercial chemical. A wealth of experience with practical handling, use, and storage has been acquired from applications in automobile batteries, industrial plants, and petrochemical operations. The chemical heat pump concept is also being developed for systems involving methanolated salts, ammoniated salts, and metal hydrides.

Energy Storage Charging Cycle

Energy Storage Discharge Cycle

Figure 8. Operation of a Chemical Heat Pump Based on Sulfuric Acid Dilution

STATE OF DEVELOPMENT

Aquifer Storage

The technologies for well drilling and production are established; aquifer storage will require no breakthroughs, but some specific engineering problems need to be resolved. A major investigation of aquifer storage for air conditioning at JFK Airport in New York is proceeding through detailed engineering studies, and detailed aquifer geology is being established through test drillings. A second major demonstration is planned for Bellingham, Washington, as part of a project to capture industrial waste heat from an aluminum plant for use in a district heating system. Further demonstrations are planned for 1979 to 1984.

The DOE aquifer storage program also includes a variety of projects to increase the understanding of the basic processes which will affect the use of aquifers for thermal storage, including mechanisms of energy loss, mechanical and hydraulic effects, and environmental impacts. Experimental support work includes operation of wells at Auburn University and at Texas A&M that are intended to provide data for cyclic storage of heated (Auburn) and chilled (Texas) water.

Engineered Ponds

Storage of heated water in man-made ponds is under investigation in Europe, and information from these studies is being sent to the United States under a multi-national agreement with the relevant countries.

Damp Earth

An analytic study has indicated the technical-economic feasibility of this technique. The next stage in its development is a demonstration project, which is being considered for future emphasis.

Engineered Tanks

A study performed for DOE has indicated the feasibility of achieving reduced storage cost through unconventional construction techniques and integration with the building structure. The results of the study are being evaluated for their impact on total system economics.

Chemical Heat-Pump Storage

Much work remains to be done before chemical heat pumps can be commercialized: full-size systems must be built, tested, and proved reliable; the economics must be shown to be favorable; and any safety questions, such as possible dangers from sulfuric acid, must be resolved.

Laboratory-scale systems have been built for methanolated salts, ammoniated salts, sulfuric acid, and metal hydride heat pumps, and computer models have been developed for each system.

MAJOR HURDLES/PROBLEM AREAS

Thermal energy storage for seasonal applications is not expected to encounter significant problems, other than those normally associated with the engineering, design, and installation of new technologies. The sole institutional problem involves the regulation of aquifer exploitation and the resolution of potential conflicts over underground water rights.

ENVIRONMENTAL AND RESOURCE IMPACTS

Seasonal thermal storage will have no significant impacts on the environment or resource availability, because the materials involved are neither toxic nor scarce. Storage of heated or chilled water in aquifers involves some possibility of adverse environmental effects, such as subsidence (sinking) of the surface or disruption of local water-supply wells. A tendency towards adverse effects can be identified during the exploratory stage of developing the aquifer storage system, however, as will be shown during the numerous, planned demonstration projects.

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GLOSSARY

The following general glossary of terms contains definitions which are applicable to all five thermal storage fact sheets.

Active Solar System

A solar-thermal heating system which employs discrete components for collection, storage, and distribution of solar energy. The heating system is distinct from the building structure, much like a conventional furnace, and heat is moved through the system by the active circulation of a fluid such as air or water.

ASHRAE

American Society of Heating, Refrigeration, and Air-Conditioning Engineers.

Baseload Power Plant

In an electric utility system, baseload power plants supply the majority of total electric energy demand. They operate continuously except when shut down for planned maintenance or equipment failure. They are designed to provide the combination of capital cost and efficiency which enables power to be generated at minimum cost.

BOE

Barrels of oil, equivalent; a means of expressing a quantity of energy by relating it to the amount of petroleum which must be burned to produce the equivalent thermal energy. (The daily energy consumption in the United States is about 38 million BOE.)

Boiler Feed Water

The preheated water which is converted to steam in a boiler.

Btu

British thermal unit; a small unit of energy, equivalent to the thermal energy required to raise the temperature of one pound of water by one degree Fahrenheit.

Chemical Heat Pump

A heat pump is a device which extracts thermal energy from a low-temperature source and rejects it to a higher temperature demand. The seemingly impossible task of moving heat "uphill," i.e., from a low temperature to a higher temperature, may be accomplished only by expending energy to "drive" the process. Heat pumps based on the mechanical compression and expansion of a fluid such as ammonia or Freon are in common use in home

refrigerators, air conditioners, and heat pump heating-cooling systems. In a chemical heat pump, the mechanical process is replaced with a thermochemical one, involving two separate reactions in which a solid or liquid is decomposed to form a vapor and another solid or liquid. The vapor (or gas) must be common to both reactions, as it is the movement of this vapor which accomplishes the heat pumping action. The process is illustrated in the following sketch:

Chubs

A type of packaging for latent-heat storage materials which involves sealing in tubular, sausage-like containers.

Closed System

A process or device which maintains a constant amount of material within itself, neither accepting matter from nor rejecting matter to its surroundings.

Conversion Efficiency

A figure of merit for energy conversion devices such as a steam turbine-generator. It consists of the amount of energy produced expressed as a percent of the energy consumed.

COP

Coefficient of performance; a figure of merit for heat pump systems. In heating applications, it is the amount of heat supplied to the end-user per unit of energy consumed (either electric or thermal). In cooling applications, it is the amount of heat removed from the building per unit of energy consumed.

DOE

Department of Energy

Heat Engine

A machine which converts thermal energy to useful, mechanical work, e.g., a steam turbine.

Insolation

The rate at which the sun's energy reaches the earth's surface, usually expressed as an energy rate per unit area, e.g., Btu/ft²

Intermediate-Load Power Plant

In an electric utility system, intermediate-load power plants operate during normal and peakload demand periods, but not at low demand periods.

kWh

Kilowatt-hours; an engineering unit of measure for energy and the customary unit for electric bills. A subscript "th" or "e" is used to differentiate between thermal and electric energy (e.g., kWh_{th} and kWh_e).

Latent Heat

Latent heat is the energy associated with a change in the physical condition of a material, such as melting or freezing. The harvest of natural ice during the winter for use in summer refrigeration is an historical example of energy storage as latent heat. Storage as latent heat has the advantage that energy is stored and recovered at nearly constant temperature. This temperature is a unique property of the storage material and will govern the selection of a storage material for a specific application. Solid-liquid processes are the most practical for near-term applications, and include both melting of salt mixtures and crystallization of salt solutions. Latent-heat storage technologies are significantly less advanced than those for sensible heat. Continued development is expected to verify the lower cost and higher performance potential of phase-change materials for energy storage.

Macroencapsulation

A means for containing latent-heat storage material in small easily-handled packages, such as cans or plastic chubs.

MBOE

Million barrels of oil, equivalent; a means of expressing a quantity of energy by relating it to the amount of petroleum which must be burned to produce the equivalent thermal energy. (The daily energy consumption for the United States is about 38 MBOE).

Microencapsulation

A type of containment for latent-heat storage material which involves dispersion of the substance throughout a "host" material, such as ceiling tile, wallboard, or concrete block. The materials of construction then become effective heat storage devices.

MWh

Megawatt-hours; a large engineering unit of measure for energy, equal to 1000 kWh. A subscript "th" or "e" is used to differentiate between thermal and electric energy (e.g., MWh_{th} and MWh_e).

Passive Solar System

Literally, a solar-thermal heating system with no moving parts. The collection, storage, and distribution of solar-thermal energy is accomplished by static components, frequently built into the structure of the building.

PCIV

Prestressed cast iron vessel; a novel construction technique for pressure vessels which allows the use of low-cost cast iron to replace steel alloys.

Peakload (or Peaking) Power Plants

In an electric utility system, peakload power plants operate only during periods of peak or near-peak demand. Because they operate only for relatively short fractions of the day, peakload power plants produce relatively little energy compared to the total capacity and tend toward minimum capital cost. Low utilization of capacity and the use of expensive fuels cause the electric power produced by peaking plants to be more expensive than power from base-load power plants.

Phase-Change Material

A material which is used to store thermal energy as latent heat.

Power Tower

A high-temperature solar collector system which involves a large array of flat, individually-moveable mirrors (heliostats), which focus the sun's energy on a central receiver unit. The receiver is located in a tower, above the field of mirrors. This configuration was selected for development to a 10 MW scale under a DOE-funded program.

psi

Pounds per square inch, a unit of pressure.

Quad

Quadrillion Btu; an extremely large engineering unit of energy, equal to 1,000,000,000,000,000 Btu. The total energy consumption of the United States during 1978 was 77.7 Quads, the equivalent of nearly 14 billion barrels of oil.

Sensible Heat

Sensible heat is the energy associated with changes in the temperature of a material. Thermal storage as sensible heat is the most mature concept, with tanks of hot water and beds of hot rocks used in both active and passive solar-thermal systems. The quantity of material required to store a given amount of thermal energy depends on a property of the material known as specific heat and a characteristic temperature change determined by the system. Typical values are on the order of 10 to 100 Btu of energy storage per pound of material. As a storage technique, sensible heat has a major disadvantage in that energy is returned at an ever-decreasing temperature. Its major advantages are low cost and relative simplicity.

Thermal Load

A demand for thermal energy (heat).

Thermodynamic Cycle

The engineering description of a heat engine in terms of the series of compressions, expansions, heatings, and coolings to which a working fluid is subjected (e.g., Rankine cycle or Brayton cycle).

Thermochemical Heat

Thermochemical heat is the thermal energy associated with a change in the chemical composition of a mixture of materials. The heat released during combustion of a fuel is one example of thermochemical heat. For application to energy storage, however, the chemical reactions must be controlled and reversible. That is, the products of the reaction can be recombined at will to recreate the starting mixture. The concepts of reversibility and controllability are illustrated by an automobile storage battery, although that device stores electric rather than thermal energy. In a storage battery, the input of electric energy (charging) causes chemical changes to occur and, once the battery is charged, the higher energy products within the battery remain a source of energy on demand. The battery may be connected to an electric motor or a light bulb, in which case the stored electric energy will be returned, accompanied by chemical changes within the battery the reverse of those which occurred during charging. Thermochemical storage follows the same pattern, except that energy is supplied and returned as heat. Relative to sensible and latent-heat storage, thermochemical concepts have the advantage of permitting storage at ambient temperature with essentially no time-dependent heat losses. In addition,

the energy storage density is very high. Thermochemical energy storage is a relatively immature technology, with program emphasis focused on exploratory development and applied research for characterizing candidate storage reactions.

Thermocline

A specific configuration for sensible heat storage with a heated liquid such as water or oil. A single containment vessel is used to store both hot and cold fluid. Hot fluid remains at the top of the vessel and is added or withdrawn by displacement of (by) cooler fluid at the bottom of the vessel. The hot and cool fluid layers remain stratified because of the difference in density and because the containment vessel is filled with granular solid to impede mixing currents.

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THERMAL ENERGY STORAGE FOR RECOVERY OF INDUSTRIAL PROCESS AND WASTE HEAT

Approximately 40 percent of the total energy demand in the United States is used in industrial applications. Both energy savings and displacement of fossil fuels can result from the capture and reuse of rejected heat from industries. In many cases, this energy may be reused within the industrial facility to improve the process efficiency. In other cases, the heat may be exported to a heating system, thereby reducing residential fuel consumption.

Thermal energy storage is needed when there is a mismatch between heat availability and heat demand. For example, recovery of waste energy from industrial processes represents a relatively continuous source of energy which may be used for space heating of buildings. The building heating demand is strongly seasonal, however, and a direct link with a continuous source will cause a large fraction of the total energy resource to be wasted, especially during the warmer seasons when demand is low. Thermal energy storage can increase the economic feasibility of the recovery process by capturing energy on a year-round basis and enabling service to a larger number of customers during winter. Thermal storage is developed to bridge short-term gaps in supply and demand as well as the longer term and seasonal ones.

Twenty industrial categories have been identified as areas where heat recovery, using thermal energy storage, appears to be economically and technically feasible. The five industries selected for a more detailed investigation included: food processing, aluminum, cement, paper and pulp, and iron and steel. The analysis indicated that annual savings in the near-term (1985) of about 12 million barrels of oil, equivalent (0.07 Quads) appear possible through nationwide implementation of thermal energy storage in these five industries.

Industrial energy recovery includes a diverse range of demands, as demonstrated by the five specific case studies. For industrial thermal energy storage applications, a case-by-case analysis is required, because a cost-effective installation will likely require the use of local materials for storage and an evaluation of all internal and regional energy needs (e.g., space and process heat, peakload electricity, and thermal-mechanical conversion).

PURPOSE AND AREA OF APPLICATION

Energy conservation and fossil fuel displacement are the key objectives of retrofitting (modifying) an existing industrial site for waste heat recovery with thermal energy storage. Modern technology for energy management will be incorporated with new construction as necessary. However, the majority of existing industrial installations were designed and erected when energy was readily available and inexpensive. The use of cost-effective technology for heat recovery in existing plants will result in a near-term energy savings. It will also provide a proof-of-concept demonstration that will

accelerate recognition of improved recovery methods for new construction markets.

POTENTIAL IMPACT

The use of thermal energy storage in industrial waste heat recovery could have a major impact on national energy conservation. Table 1 indicates the projected near-term (1985) impact of industry-wide implementation of thermal energy storage in five industrial categories.

Table 1. Potential Near-Term (1985) Impact of Industrial Waste-Energy Recovery Involving Thermal Storage

INDUSTRY	ANNUAL ENERGY SAVINGS IN THE NEAR-TERM (1985)	
	QUADS	MILLION Bbl OIL
Food	0.0023	0.5
Aluminum	0.0014	0.3
Cement	0.04	7
Paper and Pulp	0.017	3
Iron and Steel	0.006	1
TOTAL	Approx. 0.0667	Approx. 11.8

TECHNICAL DESCRIPTION

Industrial production currently accounts for about 40 percent of the total energy consumed in the United States. A large portion of this energy is rejected to the environment, because its quality (temperature) is no longer high enough to be used elsewhere or because recovery is not economical. Retrofitting energy-intensive industrial sites with technology for recovering thermal energy will increase overall energy conservation, enable displacement of petroleum and natural gas imports, and reduce thermal pollution.

Heat recovery in an industrial process links two operations, one as a source of energy and the other as an element of demand. Frequently, the rate or timing of energy availability and energy demand are such that it is not practical to attempt a direct link. In other cases, the rate and time factors are compatible. A direct link, however, restricts the independent operation of the process elements involved, e.g., scheduling maintenance shutdowns, changing production rates, and optimizing in real-time processing conditions. Finally, in the case of energy export as for district heating, both short-term and seasonal fluctuations in demand could force "dumping" of excess energy or ineffective use of the potential waste-heat resource. In each case, thermal energy storage could eliminate the barrier to cost-effective heat recovery. The system concept for storage as a part of the

energy management operation is shown in Figure 1. An effective operational analysis will consider the properties of the source, demand, and conversion elements in selecting an optimum recovery storage system.

Figure 1. System Concept for Industrial Waste Energy Recovery

Source

The key parameters of potential energy sources are the rate of energy availability and the quality (temperature). Each will vary depending on the specific industry and individual plant site. Table 2 indicates the range of temperatures associated with waste heat from five energy-intensive industries. The magnitude of the waste-heat resource is difficult to quantify because of the variation between and within industries. In the extreme case, the waste energy from a typical cement kiln is estimated to be 50 to 80 percent of the energy input. Similarly, between 35 and 55 percent of the electrical energy consumed in the production of aluminum is lost as waste thermal energy.

Table 2. Temperature of Several Industrial Waste-Energy Sources

INDUSTRY	ENERGY USE AS A % OF NATIONAL TOTAL	WASTE HEAT TEMPERATURE RANGE (° C)
Primary Aluminum	2.8	90-980
Cement	3.5	430-730
Paper and Pulp	10.0	150-320
Food Processing	7.9	40-150
Primary Iron and Steel	10.9	260-1540

The physical form of industrial waste energy sources also is varied. Many well-defined streams are available at the heat exchangers which are used to cool process streams or products. Water and air are frequently used as the cooling medium, and rejected thermal energy can be recovered directly from these streams. A majority of thermal losses are not so well-defined, however. Among these are the heat lost in aluminum and steel refining processes, where direct thermal loss and hot fume gases are swept away from the equipment by large volumes of ventilation air. Depending on the physical and chemical characteristics of the effluent stream, not every potential energy source will be economically recoverable. Gas streams from chemical processes may be highly corrosive or dust-laden and tend to foul or attack heat exchangers. Waste-water streams may cause similar problems as the result of dissolved or suspended solids. The physical form of a specific waste stream affects its use as an energy source.

Demand

Industrial sites present a broad range of energy demands, from low temperatures for space heating to high-quality heat for process applications or generation of electric power. There are also off-site demands for space heating and hot water for local communities, which can be integrated as a single district-heating demand. The temperature requirements of several generic energy demands are given in Table 3. The magnitude of the demand depends on the specific type and size of installation being considered.

Table 3. Temperature Requirements of Several Energy Demands

ENERGY DEMAND	TEMPERATURE REQUIREMENTS
Space Heating	60° – 125°C
District Heating	60° – 225°C
Industrial Process Heat	
• Drying	40° – 760°C
• Sterilization	120° – 175°C
• Hot Water	40° – 70°C
On-site Power Generation	225° – 530°C

Storage

Thermal energy storage is an interface technology which permits the coupling of otherwise incompatible energy sources and energy demands. Thermal energy may be stored as sensible heat by changing the temperature of the storage medium, as latent heat by causing a phase change (melting or freezing) in the storage medium, and as thermochemical energy by changing the chemical composition of the storage medium. Sensible-heat technology is mature and requires only site-specific analysis for near-term uses. Latent-heat

technology is less mature and could be developed for mid-term industrial applications. Thermochemical technologies are in the very early stages of development and will not be a viable alternative for either near-term or mid-term industrial applications. A more detailed discussion of each mechanism is given in the glossary.

In near-term or mid-term industrial heat recovery applications, thermal storage as sensible heat is the primary technology. Water is an excellent storage medium for low-temperature uses and for those involving steam as the transport fluid. For high-temperature applications, any readily-available solid inexpensive material may be used, provided it has adequate heat capacity, physical strength, chemical stability, and temperature resistance. There is a strong advantage in selecting a material which is generic to the industry of interest, such as slag, gravel, ceramic brick, crushed stone, or scrap metal. Most industrial applications require only short-duration storage (buffering and daily), where the volume of the storage material is moderate and time-dependent losses (heat leaks) are easily controlled. Fabricated tanks are used to contain the storage medium in these cases. The export of thermal energy for district heating may be increased by long-duration (seasonal) storage; however, new containers must be developed because of the magnitude of the storage requirement. For this application, a technique for storing heated water in underground rock formation, known as aquifers, is being developed.

Industrial heat recovery with thermal storage encompasses a broad range of energy sources, demands, and storage needs. To illustrate this diversity, five industries were selected, which represent the most energy-intensive areas of the U.S. industrial sector. Subsequently, detailed case studies of thermal storage applications in these industries (aluminum, food processing, pulp and paper, cement, and primary steel) were conducted for the DOE Division of Energy Storage Systems. The emphasis was on near-term retrofit of existing industrial operations to conserve energy.

Primary Aluminum Industry

Aluminum production consumes about 8.5 percent of the U.S. total industrial electric power. The bulk of this energy is consumed by Hall electrolytic reduction cells which produce aluminum metal from refined bauxite ore. Because of the efficiency of these cells, approximately 35 to 55 percent of the electric energy consumed is converted to heat, which must be rejected from the cells to maintain the cell operating temperature. The heat is rejected to the ventilation air which sweeps past the cells and carries the hot, noxious gases away. This vent gas is subsequently scrubbed and filtered, and discharged to the atmosphere at 150°C (300°F). The magnitude of this potential thermal energy resource is on the order of 55 million Btu per ton of aluminum produced.

Recovery of this potential resource was evaluated by a team consisting of Rocket Research Company, Intalco Aluminum Corporation, and the Bonneville Power Administration. Their study focused on the Intalco plant at Ferndale, Washington, but has direct implications for the 30 other primary aluminum plants in the United States. Within the Ferndale plant, the need for large quantities of low-temperature thermal energy is not sufficient to justify the cost of recovery. Outside the plant, there are not immediate uses for

the resource, but its magnitude is so great that development of an application, such as a district heating system, is in the best interest of national energy conservation. The study team proposed using the hot exhaust gas to heat water for distribution in the district heating system of Ferndale and Bellingham, Washington. District heating of single-family homes is a concept which has not been adopted in the United States, but has been widely used in Europe, particularly the Scandinavian countries.

The Ferndale-Bellingham district heating system concept involves a continuous source and a strongly cyclic demand (daily and seasonal). Without thermal storage interposed between the two, the daily demand fluctuation would be accommodated by either "wasting" excess heat or using a backup (fossil-fired or electric) source to fill the shortfall. Figure 2 shows the minimum system required to avoid these daily excesses and permit cost-effective operation. The proposed storage unit is a multi-million gallon tank for accumulating heated water during periods of excess supply. The supply of heated water is used to buffer short-term peak demands, thus reducing reliance on the back-up system. Energy recovered from the Intalco plant

Figure 2. District Heating System Employing Waste Heat from the Aluminum Industry

could meet the space heating and hot-water requirements of 12,000 single-family dwellings in the nearby communities. The estimated system cost is 63-million dollars (1977 dollars), and a net displacement of 250,000 barrels of oil per year is projected.

Cost-effective seasonal storage for heated water would enable maximum recovery of the plant's energy, specifically, that which would be "wasted" during the summer. However, storage requirements are in the multi-billion gallon range, which is too large for fabricated tanks. Underground storage in natural, water-bearing rock formations known as aquifers is an emerging technology, which will enable cost-effective seasonal storage. The future development of district heating for Ferndale-Bellingham will include this alternative.

The economic driving force for heat recovery in primary aluminum plants is weakened by the siting of the 31 existing plants close to cheap hydro-electric power. At these sites, district heating must compete with relatively cheap electric heat. This recourse is heavily exploited, however, and new aluminum refining capacities might use more expensive energy sources. The ability to offset part of this cost through revenues from exported energy could become an important factor. In addition, an on-site demand for the recovered energy could develop as the result of the integration of the total aluminum process. Figure 3 shows the major energy requirements of the total process from bauxite ore to an aluminum metal. In practice, the Hall process is geographically separate from the Bayer and calcining stages. Rising energy prices might force closer thermal integration of the total process, and heat recovery with energy storage could play an important role.

Food Processing Industry

The food processing industry accounts for approximately 8 percent of the U.S. industrial energy consumption. According to one estimate, 85 percent of the fuel consumed by this industry is for the production of steam and hot water for cooking, washing, sanitizing, and cleanup operations at or below 120°C (250°F). Because of the nature of the operations, much of the energy is lost through the discharge of hot dirty water to local sewers.

A team consisting of Westinghouse Electric Corporation and the H. J. Heinz Company has evaluated the possibility of recovering this thermal energy. Their study focused on the Heinz canned and bottled food plant in Pittsburgh, Pennsylvania, and is believed to be representative of the capacity for energy recovery and conservation throughout the food processing industry. The Pittsburgh facility is characterized by two production shifts followed by a cleanup shift. It discharges a variety of individual waste streams to a central drain system at temperatures in the range of 50° to 95°C (120° to 200°F). The combined hot-water effluent stream averages 63°C (145°F), with a flow rate of 720 gallons per minute during the first shift and 550 gallons per minute during the second shift. Relative to 24°C (75°F) make-up water, the energy content of this steam is equivalent to 12,400 barrels of oil annually.

Figure 3. Total Process for Aluminum from Bauxite Showing Energy Requirements (Basis: 1 Ton of Aluminum Metal)

Low-temperature heat recovered from the factory can be used to satisfy three internal demands, i.e., preheating of boiler make-up water, heating of fresh water for food processing, and heating of factory clean-up water. The first two are production-shift demands which generally coincide with the time at which energy is available. The third demand occurs four to eight hours following energy availability. The storage needs of the heat recovery system include buffering storage to level surges in the need for boiler make-up and process water, as well as short-term storage to accumulate hot water for clean-up operations.

Figure 4 shows the heat recovery and storage system proposed for the Pittsburgh facility. Hot waste-water streams, those above 60°C (140°F), are accumulated in an insulated storage tank which buffers surges in demand. The hot waste water is used to heat fresh water for food processing on demand, with any excess accumulated in a large, insulated tank for subsequent use during third-shift clean-up operations. The warm waste-water streams, those below 60°C (140°F), are accumulated in an insulated storage tank before being used to preheat boiler make-up water. The system shown in Figure 4 is capable of recovering energy equivalent to 6 percent of the factory's current demand. The estimated cost of the retrofit system is \$413,000 (1977 dollars), and using current energy prices, the system economics are favorable (34 percent ROI). The annual energy savings for the entire food products industry, projected from the results of the Heinz study, is equivalent to over one-million barrels of oil or enough to supply heat and hot water to over 70,000 homes*.

*Typical, single-family dwellings in the Washington, D.C., area.

Figure 4. Thermal Energy Storage for Waste Heat Recovery in the Food Processing Industry

Pulp and Paper Industry

The forest products industry accounts for 10 percent of the national industrial energy consumption and is one of the largest users of fossil 150-million barrels of oil annually. The industry does supply more than 40 percent of its energy needs through the use of generic fuels, such as hog-fuel (wood waste) and recovered pulping liquors (effluent streams from wood pulping processes). In a typical pulp and paper mill, these generic fuels are used to fire the boilers that provide baseload steam generation, with fossil fuels used only to complete the supply. In certain mills, the hog-fuel boilers are unable to follow rapid fluctuations in process steam demand. In this case, the quantity of fossil-fired steam generation must be increased to the point where the fossil-fired boilers are capable of following the demand transients. The result is an increase in fossil-fuel consumption, in spite of an excess of cheap hog-fuel at the mill.

A study team consisting of Boeing Engineering and Construction Company, Weyerhaeuser Corporation, and SRI International has assessed the potential for energy conservation in the pulp and paper industry through heat recovery with thermal storage. The team focused on the incomplete use of hog-fuel resources in the Weyerhaeuser pulp and paper mill at Longview, Washington. The existing supply-demand characteristics of the Longview plant are shown in Figure 5. Steam demand varies from 975,000 to 1,125,000 pounds per hour, with the majority of demand swings occurring for an hour or less. A fossil-fired boiler supplies the load-following capacity, while excess

EXISTING SUPPLY/DEMAND CHARACTERISTICS

OPERATION WITH THERMAL STORAGE

Figure 5. Thermal Energy Storage Applied in the Pulp and Paper Industry to Achieve 50 Percent Reduction in Use of Fossil Fuel for Load-Following Boilers

hog-fueled baseload capacity remains unused. A shift to more hog-fueled steam generation requires some means of buffering the rapid fluctuations in demand to produce a match with the steady supply of steam from the hog-fueled boiler.

Direct storage of steam from the hog-fueled boiler can serve as the necessary buffer as shown in Figure 5. Steam accumulators are commercially available hardware which have the necessary quick charge-discharge capabilities. Excess steam from the hog-fueled boiler is charged to storage during periods of reduced demand by injecting it directly into hot water contained under pressure in a large steel tank. The steam condenses, and the energy released is stored as sensible heat by further increasing the temperature of the water in the tank. During periods of high demand, the boiler output is augmented by steam withdrawn from storage. The withdrawal process is accomplished by venting the accumulator to a lower pressure, causing the contained hot water to boil. Steam is supplied, and the water temperature in the accumulator decreases as the sensible energy of the hot water provides the energy required to revaporize the steam. This concept is known as variable-pressure steam accumulation and, for high charge-discharge rates and short cycle times, is superior to sensible-heat storage in solid media (rock beds) with a separate heat-transport fluid.

Figure 5 shows the conceptual arrangement of source, storage, and demand elements for the Longview mill, along with process flows which illustrate a 50 percent reduction in fossil-fuel demand for the upgraded system. The retrofit system would employ established technology and commercially-available equipment with a system cost of \$560,000 (1977 dollars). Based on current energy prices, system economics are very favorable (63 percent ROI). The resulting increase in the use of wastes as fuel at the Longview mill could displace fossil fuels by 118,000 barrels of oil, or enough to provide the annual heat and hot-water requirements of 7300 homes*. On a national basis, the estimated annual fossil-fuel savings are 3-million barrels of oil equivalent (MBOE) for the near-term (1985) and 13 MBOE in the far-term (2000).

Cement Industry

The cement industry consumes 3.5 percent of the national industrial energy budget and is the sixth-largest industrial energy user in the United States. With an annual energy consumption equivalent to 99-million barrels of oil, it is the most energy-intensive industry in the country, in terms of energy cost as a percentage of the total product cost. Over 80 percent of the energy consumed in a cement plant is used to fire the kilns, which convert the raw materials to cement "clinker." Fifty to eighty percent of that energy is lost from the kiln and subsequent processing stages. A study team consisting of Martin Marietta Aerospace Company, Martin Marietta Cement Company, and the Portland Cement Association has evaluated the potential for recovering a portion of this waste energy.

*Typical, single-family dwellings in the Washington, D.C. area.

The dry-kiln process for manufacture of cement involves heating the raw materials to 1480°C (2700°F) in a large rotary kiln (oven). Process heat is supplied by direct contact with hot gas from the controlled combustion of coal, oil, or natural gas, and hot gas exits the kiln at 380° to 825°C (720° to 1500°F). The hot, solid product from the kiln, known as clinker, is discharged to a cooler where it is reduced to a manageable temperature by a stream of air. Waste air exits the clinker cooler at 180°C to 230°C (350° to 450°F.) These two gaseous waste streams represent a significant thermal energy resource. If recovered in a waste-heat boiler, steam could be generated for on-site electric power production, and could supply 75 percent of the plant's requirements. However, during unscheduled maintenance periods for the kiln and clinker cooler, this waste heat is not available. Power must be obtained from a utility, auxiliary power must be produced by backup generators, plant operations must be curtailed, or an auxiliary source of thermal energy must be provided. The latter option, relying on thermal energy storage as a short-term source of energy, proves to be the most cost-effective.

The system proposed by the study team is shown in Figure 6. Two storage units are involved, both based on sensible-heat storage using solid materials such as magnesite brick, granite, limestone, or cement clinker. During normal operation, the storage units are charged independently, one by the medium temperature waste air from the clinker cooler and the other by a portion (10 to 20 percent) of the high-temperature kiln exit gas. The majority of the kiln exit gas is passed directly to the heat recovery boiler, producing steam which is used to generate 5 to 10 MWe of electric power. During heat recovery, when the kiln and clinker cooler are shut down for maintenance, ambient air is first passed through the medium temperature unit where it is heated to 200°C (400°F), then through the high-temperature unit where it is heated to 650°C (1200°F), and finally to the waste-heat boiler to generate steam for the turbine-generator. For a typical 70 ton per hour kiln system, the storage units are sized to contain the thermal energy equivalent of 780 barrels of oil and are capable of providing 10 MWe of power for a 24-hour period. The high and medium temperature thermal storage units are large, each one containing about 6,000 tons of storage medium (rocks). The system requires one week to charge to the full 240 MWe capacity.

A preliminary economic analysis set the cost of a complete storage, heat recovery, turbogenerator system at \$10-million (1977 dollars). Based on current energy prices and a 30-year life, the system economics are very favorable (70 percent ROI). The potential annual energy savings from retrofitting 118 dry-kiln installations is equivalent to 7-million barrels of oil.

Primary Iron and Steel Industry

The primary iron and steel industry accounts for slightly less than 11 percent of the total national industrial energy consumption, and is second only to the chemicals industry in the use of electric power. Like the primary aluminum industry, a large portion of the energy consumed by reduction and refining operations is lost or deliberately wasted. A study

Figure 6. Thermal Energy Storage for Waste-Heat Recovery in the Cement Industry

team consisting of Rocket Research Company, Bethlehem Steel Corporation, and Seattle Light Company has analyzed the iron and steelmaking processes for economically-recoverable sources of thermal energy. The electric arc steelmaking furnace was selected as the primary candidate for energy recovery.

Electric arc furnaces account for 25 percent of the U.S. steelmaking capacity. It is a batch process in which cold scrap iron and raw materials are melted by an electric arc which is struck directly from carbon electrodes to the scrap charge. Once molten, the charge is processed for 3 hours by subjecting it to multiple oxygen "blows" of 1 to 5 minutes. The gaseous effluent from the furnace, known as fume gas, is collected by a large furnace hood and quenched with a water spray. The fume gas temperature fluctuates from 27° to 1650°C (80°F to 3000°F) during a complete processing cycle, and averages 700°C (1300°F) for the 3-hour period. The total thermal energy of the fume gas analyzed is equivalent to the space heating demand of 3,900 homes*. If converted to on-site electric power, the energy could reduce purchases of utility power by about 3 MWe.

*Typical, single-family dwelling in the Washington, D.C., area.

The system for recovering thermal energy, including conversion to electric power, is shown in Figure 7. The energy source has two distinct temperature fluctuations which require the use of thermal storage to allow continuous power generation. Thermal energy is stored in beds of inert solid material (e.g., refractory brick, slag, or scrap steel) capable of withstanding the 1650°C (3000°F) maximum temperature. The short-duration fluctuations from oxygen blows are "smoothed" by a buffering storage unit through which the entire fume gas stream passes, resulting in a relatively uniform 700°C (1300°F) gas going to the waste-heat boiler. A portion of the smoothed stream is diverted to charge a "peaking" thermal storage unit. This unit is discharged to provide thermal energy to the waste heat boiler during the longer term fluctuations resulting from batch operation of the electric arc furnaces.

Figure 7. Thermal Energy Storage for Waste-Heat Recovery in the Steel Industry

A retrofit system to displace 7 MWe of purchased peak power costing 10 cents per kwh would have a payback period of about 5 years. The projected annual energy savings resulting from conversion of all existing electric arc furnaces in the United States is equivalent to more than one-million barrerls of oil.

STATE OF DEVELOPMENT

Thermal energy storage as sensible heat is a mature technology, which is capable of meeting near-term applications in industrial energy recovery. Improvements in current thermal energy storage technologies and innovative new techniques in latent heat and thermochemical energy storage will lead to inexpensive, general-purpose storage devices with greater storage densities and improved efficiencies. These are, however, expected to be available for industrial applications only in the mid- and long-term.

Demonstration projects sponsored by DOE will confirm the results of specific case studies. A major demonstration is planned for Bellingham, Washington, involving the capture of industrial waste heat from an aluminum production facility for use in a district heating system. This system will provide storage of short duration and is scheduled for operation by 1983.

Further demonstration projects are in the planning stages, with major decisions regarding application and scope scheduled for 1979 and 1980.

MAJOR HURDLES/PROBLEM AREAS

The application of heat recovery with thermal energy storage is not expected to encounter significant problems, other than those normally associated with the engineering, design, and installation of new facilities. The sole unresolved institutional problem involves the administration and regulation of energy export to district heating systems. This hurdle has been overcome in European systems, however, and should not prove to be serious.

ENVIRONMENTAL AND RESOURCE IMPACTS

Thermal storage systems are generally closed and do not offer a significant potential for serious environmental impact. Economic considerations generally preclude the use of costly or scarce resources; many common materials which are generic to the industry of interest are used.

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GLOSSARY

The following general glossary of terms contains definitions which are applicable to all five thermal storage fact sheets.

Active Solar System

A solar-thermal heating system which employs discrete components for collection, storage, and distribution of solar energy. The heating system is distinct from the building structure, much like a conventional furnace, and heat is moved through the system by the active circulation of a fluid such as air or water.

ASHRAE

American Society of Heating, Refrigeration, and Air-Conditioning Engineers.

Baseload Power Plant

In an electric utility system, baseload power plants supply the majority of total electric energy demand. They operate continuously except when shut down for planned maintenance or equipment failure. They are designed to provide the combination of capital cost and efficiency which enables power to be generated at minimum cost.

BOE

Barrels of oil, equivalent; a means of expressing a quantity of energy by relating it to the amount of petroleum which must be burned to produce the equivalent thermal energy. (The daily energy consumption in the United States is about 38 million BOE.)

Boiler Feed Water

The preheated water which is converted to steam in a boiler.

Btu

British thermal unit; a small unit of energy, equivalent to the thermal energy required to raise the temperature of one pound of water by one degree Fahrenheit.

Chemical Heat Pump

A heat pump is a device which extracts thermal energy from a low-temperature source and rejects it to a higher temperature demand. The seemingly impossible task of moving heat "uphill," i.e., from a low temperature to a higher temperature, may be accomplished only by expending energy to "drive" the process. Heat pumps based on the mechanical compression and expansion of a fluid such as ammonia or Freon are in common use in home

refrigerators, air conditioners, and heat pump heating-cooling systems. In a chemical heat pump, the mechanical process is replaced with a thermochemical one, involving two separate reactions in which a solid or liquid is decomposed to form a vapor and another solid or liquid. The vapor (or gas) must be common to both reactions, as it is the movement of this vapor which accomplishes the heat pumping action. The process is illustrated in the following sketch:

Chubs

A type of packaging for latent-heat storage materials which involves sealing in tubular, sausage-like containers.

Closed System

A process or device which maintains a constant amount of material within itself, neither accepting matter from nor rejecting matter to its surroundings.

Conversion Efficiency

A figure of merit for energy conversion devices such as a steam turbine-generator. It consists of the amount of energy produced expressed as a percent of the energy consumed.

COP

Coefficient of performance; a figure of merit for heat pump systems. In heating applications, it is the amount of heat supplied to the end-user per unit of energy consumed (either electric or thermal). In cooling applications, it is the amount of heat removed from the building per unit of energy consumed.

DOE

Department of Energy

Heat Engine

A machine which converts thermal energy to useful, mechanical work, e.g., a steam turbine.

Insolation

The rate at which the sun's energy reaches the earth's surface, usually expressed as an energy rate per unit area, e.g., Btu/ft²

Intermediate-Load Power Plant

In an electric utility system, intermediate-load power plants operate during normal and peakload demand periods, but not at low demand periods.

kWh

Kilowatt-hours; an engineering unit of measure for energy and the customary unit for electric bills. A subscript "th" or "e" is used to differentiate between thermal and electric energy (e.g., kWh_{th} and kWh_e).

Latent Heat

Latent heat is the energy associated with a change in the physical condition of a material, such as melting or freezing. The harvest of natural ice during the winter for use in summer refrigeration is an historical example of energy storage as latent heat. Storage as latent heat has the advantage that energy is stored and recovered at nearly constant temperature. This temperature is a unique property of the storage material and will govern the selection of a storage material for a specific application. Solid-liquid processes are the most practical for near-term applications, and include both melting of salt mixtures and crystallization of salt solutions. Latent-heat storage technologies are significantly less advanced than those for sensible heat. Continued development is expected to verify the lower cost and higher performance potential of phase-change materials for energy storage.

Macroencapsulation

A means for containing latent-heat storage material in small easily-handled packages, such as cans or plastic chubs.

MBOE

Million barrels of oil, equivalent; a means of expressing a quantity of energy by relating it to the amount of petroleum which must be burned to produce the equivalent thermal energy. (The daily energy consumption for the United States is about 38 MBOE).

Microencapsulation

A type of containment for latent-heat storage material which involves dispersion of the substance throughout a "host" material, such as ceiling tile, wallboard, or concrete block. The materials of construction then become effective heat storage devices.

MWh

Megawatt-hours; a large engineering unit of measure for energy, equal to 1000 kWh. A subscript "th" or "e" is used to differentiate between thermal and electric energy (e.g., MWh_{th} and MWh_e).

Passive Solar System

Literally, a solar-thermal heating system with no moving parts. The collection, storage, and distribution of solar-thermal energy is accomplished by static components, frequently built into the structure of the building.

PCIV

Prestressed cast iron vessel; a novel construction technique for pressure vessels which allows the use of low-cost cast iron to replace steel alloys.

Peakload (or Peaking) Power Plants

In an electric utility system, peakload power plants operate only during periods of peak or near-peak demand. Because they operate only for relatively short fractions of the day, peakload power plants produce relatively little energy compared to the total capacity and tend toward minimum capital cost. Low utilization of capacity and the use of expensive fuels cause the electric power produced by peaking plants to be more expensive than power from base-load power plants.

Phase-Change Material

A material which is used to store thermal energy as latent heat.

Power Tower

A high-temperature solar collector system which involves a large array of flat, individually-moveable mirrors (heliostats), which focus the sun's energy on a central receiver unit. The receiver is located in a tower, above the field of mirrors. This configuration was selected for development to a 10 MW scale under a DOE-funded program.

psi

Pounds per square inch, a unit of pressure.

Quad

Quadrillion Btu; an extremely large engineering unit of energy, equal to 1,000,000,000,000,000 Btu. The total energy consumption of the United States during 1978 was 77.7 Quads, the equivalent of nearly 14 billion barrels of oil.

Sensible Heat

Sensible heat is the energy associated with changes in the temperature of a material. Thermal storage as sensible heat is the most mature concept, with tanks of hot water and beds of hot rocks used in both active and passive solar-thermal systems. The quantity of material required to store a given amount of thermal energy depends on a property of the material known as specific heat and a characteristic temperature change determined by the system. Typical values are on the order of 10 to 100 Btu of energy storage per pound of material. As a storage technique, sensible heat has a major disadvantage in that energy is returned at an ever-decreasing temperature. Its major advantages are low cost and relative simplicity.

Thermal Load

A demand for thermal energy (heat).

Thermodynamic Cycle

The engineering description of a heat engine in terms of the series of compressions, expansions, heatings, and coolings to which a working fluid is subjected (e.g., Rankine cycle or Brayton cycle).

Thermochemical Heat

Thermochemical heat is the thermal energy associated with a change in the chemical composition of a mixture of materials. The heat released during combustion of a fuel is one example of thermochemical heat. For application to energy storage, however, the chemical reactions must be controlled and reversible. That is, the products of the reaction can be recombined at will to recreate the starting mixture. The concepts of reversibility and controllability are illustrated by an automobile storage battery, although that device stores electric rather than thermal energy. In a storage battery, the input of electric energy (charging) causes chemical changes to occur and, once the battery is charged, the higher energy products within the battery remain a source of energy on demand. The battery may be connected to an electric motor or a light bulb, in which case the stored electric energy will be returned, accompanied by chemical changes within the battery the reverse of those which occurred during charging. Thermochemical storage follows the same pattern, except that energy is supplied and returned as heat. Relative to sensible and latent-heat storage, thermochemical concepts have the advantage of permitting storage at ambient temperature with essentially no time-dependent heat losses. In addition,

the energy storage density is very high. Thermochemical energy storage is a relatively immature technology, with program emphasis focused on exploratory development and applied research for characterizing candidate storage reactions.

Thermocline

A specific configuration for sensible heat storage with a heated liquid such as water or oil. A single containment vessel is used to store both hot and cold fluid. Hot fluid remains at the top of the vessel and is added or withdrawn by displacement of (by) cooler fluid at the bottom of the vessel. The hot and cool fluid layers remain stratified because of the difference in density and because the containment vessel is filled with granular solid to impede mixing currents.

THERMAL ENERGY STORAGE FOR SOLAR-THERMAL POWER GENERATION

Solar-thermal power generation replaces the fossil-fueled boiler of a conventional power plant with a sophisticated collector system for concentrating and capturing the sun's energy. Given the national goal of reducing our consumption of fossil fuels, particularly imports, there is a strong incentive to develop solar-thermal power.

Solar energy is both diffuse and intermittent. The power level of a solar-thermal generator is dictated by daily and seasonal cycles, as well as local weather conditions. To provide baseload utility generating capacity, solar-thermal facilities must include thermal energy storage. High-temperature thermal energy is accumulated during fair weather and daylight hours. It is then recovered to generate power at night or during short periods of inclement weather. Therefore, cost-effective storage is needed for periods as short as a few minutes or as long as a day.

Thermal energy storage for solar-thermal power involves the transfer of large quantities of high-temperature heat, typically 500° to 750°C (930° to 1380°F). The technologies involved are in the developmental stage, and include storage as sensible heat in hot oil, latent heat in molten salts, and thermochemical heat in reversible chemical reactions.

PURPOSE AND AREA OF APPLICATION

Without thermal storage, solar-thermal power plants would reduce the consumption of fossil fuels by producing power only when the sun shines. To be cost effective, the capital cost of the solar plant must be less than the value of the fossil fuel displaced, or about 150 to 300 dollars/kW of solar power plant capacity (1975 dollars)*. Given the high cost of solar technology, economic conditions in the mid-term will not favor this mode of operation.

With thermal storage, power from a solar-thermal plant is available continuously, and may be used to reduce the utility's need for conventional baseload and intermediate-load capacity. Under these conditions, the capital cost of the solar-thermal plant must be less than the conventional plant it replaces, or about 1000 to 1500 dollars/kW of solar power plant capacity (1975 dollars)*. This will make the development of solar-thermal power

* Energy Technology Handbook. ed. D.M. Considine (New York: McGraw Hill Book Company, 1977), p. 6-6.

economically feasible. Large-scale, high-temperature thermal energy storage for buffering (several minutes to an hour) and short-term (several hours to a day) applications will enable solar-thermal power to displace conventional, fossil-fired generating capacity at locations with adequate year-round insolation rates.

POTENTIAL IMPACT

The development of solar-thermal power plants for commercial service on electric utility power grids is a long-range, but essential, contribution to the use of renewable energy resources. It is estimated that a vigorous development and commercialization program could displace annually 175 million barrels of oil (MBOE) or 1 Quad of fossil fuel by 2000. A technology for thermal energy storage in solar-thermal plants will greatly accelerate the market penetration rate by enabling the plants to operate continuously as baseload or intermediate-load plants.

TECHNICAL DESCRIPTION AND KEY PARAMETERS

Thermal energy storage will enable solar-thermal power plants to supply baseload capacity on a utility power grid. Short-duration (daily) storage, using sensible-heat and latent-heat technologies, will satisfy a need to provide thermal energy to the plant's turbines when darkness or inclement weather reduces the energy produced by the solar collectors.

Solar-thermal power generation replaces the fossil-fired boiler of a conventional baseload or intermediate-load power plant with a source of solar-derived heat. (See Figures 1 and 2.) Solar energy is collected by a large array of mirrors which focus (concentrate) the energy onto a central-receiver-boiler which absorbs the heat and turns water to high-pressure steam. This steam, superheated by absorbed solar energy, is used to drive a conventional heat engine (turbine) connected to an electric generator. A solar-thermal power generator, which replaces a fossil-fired boiler, can operate in either of two modes. It can displace fossil fuel by generating power only when solar energy is available, or it can displace power plant capacity by generating power continuously. The latter mode is possible only if energy storage is available to supply thermal energy to the turbines during periods of darkness or inclement weather.

Figure 1. Solar-Thermal Electric Utility Power System

Figure 2. Conventional Fossil-Fired Electric Utility Power System

A conceptual solar-thermal power system consists of an energy source (solar-thermal receiver), a thermal energy storage system, and a means of converting thermal energy into electricity (turbine-driven generator). The relationship among these components is illustrated in Figure 3. During periods of high insolation, the source is expected to supply enough thermal energy for electric conversion to meet the demand for power, with sufficient excess capacity to charge the thermal energy storage system. The storage system must be capable of supplying the necessary power for periods of time when solar energy is unavailable. The interface requirements between source and storage and demand/conversion and storage will be discussed in the following sections.

Figure 3. System Concept for Thermal Energy Storage in a Solar-Thermal Power Plant

Source

Efficient electric power generation requires high energy source temperatures. One promising design to meet the high-temperature requirement is the solar tower energy collector. In this design, a field of concentrating mirrors focuses sunlight on an absorber mounted on a high tower which produces temperatures of about 730°C. In France, the CNRS system being developed uses a large parabolic reflector instead of a tower to collect the energy. An absorber in the focal region of the reflector produces about 1000 kW of thermal power.

For any type of receiver, the power output of the source varies directly with the amount of incident solar radiation. The daily variation in thermal power generated by a specific receiver during a clear, sunny day is illustrated by the solid curve in Figure 4. The shape of this curve is determined by natural factors, i.e., the daily cycle of sunlight and darkness, as well as the seasonal variation in local insolation. The magnitude of the curve is determined by the size and specific design of the solar collector-receiver. Larger, more expensive receivers will increase the magnitude of the availability curve, while smaller, less expensive receivers will decrease it.

Figure 4. Daily Availability of Solar-Thermal Energy Relative to Daily Demand for Electricity by Utility Customers

The seasonal fluctuation in average daily thermal power production is illustrated by the solid curves of Figures 5(a) and 5(b). Again, the shape is determined by the annual cycle in local insolation, while the magnitude is set by receiver geometry and size. The solid curve in Figure 5(a) represents a larger, more expensive receiver than the solid curve in Figure 5(b).

Conversion and Demand

Thermal energy is converted to electric power in a heat engine-generator system. The mainstay conversion device of modern electric utility power plants is the turbine based on the steam-Rankine cycle. This is a sophisticated technology with reliable commercial-scale equipment available. The steam-Rankine cycle is capable of thermodynamic conversion efficiencies* approaching 40 percent. Modern equipment operates with a cycle-top (input) temperature of about 530°C (980°F), well within the capabilities of a concentrating collector like the "power tower."

Heat engines based on the Brayton cycle are considered to be an advanced alternative to the steam-Rankine cycle for solar power applications. The Brayton cycle is the basis for the familiar aircraft "jet engine." The basic gas turbine has a conversion efficiency* of only 20 percent, but advanced technology, known as recuperation or regeneration, may be used to achieve substantial increases. The Brayton cycle conversion efficiency increases, achieving a value of 45 percent for the 730°C (1350°F) thermal energy from the power tower. Further increases in temperature (efficiency) are limited by materials of construction.

* Conversion efficiency is a figure of merit for devices which transform thermal energy to mechanical or electrical energy, e.g., a steam turbine-generator. It is the amount of energy produced per unit of energy consumed.

- (a) Large, expensive solar collector-receiver system; sized to supply entire customer energy demand.

- (b) Smaller, less-expensive solar collector-receiver system; sized to share customer demand with non-solar generating units.

Figure 5. Daily-Averaged Availability of Solar-Thermal Energy Relative to Seasonal Demand for Electricity by Utility Customers

An electric utility produces and converts thermal energy in response to the customers' demand for electric power. This demand fluctuates on a daily and a seasonal cycle. It is determined by the mix of customers, geographic location, and weather conditions. The broken curve in Figure 4 shows the daily variation in customer electric demand, and the broken curve in Figures 5(a) and (b) shows the seasonal cycle for a system with a moderate requirement for winter heating. In general, utilities follow the daily fluctuations by operating two types of power plants, baseload and peakload units.

Baseload generators are large units which operate continuously at a fixed power level to satisfy the majority of the demand. Their capacity must be available 95 percent of the time. Baseload solar-thermal power plants will require sufficient energy storage to provide thermal energy to the turbines during the night and during periods of inclement weather. A reliable estimate of this requirement will be determined by analysis of long-term weather statistics for the proposed power plant site. Twenty-five hours of energy storage is a common estimate for this requirement.

Peakload generators are smaller units which are operated intermittently to follow the daily load fluctuations. They are characterized by quick response following moderately long idle periods (daily basis), and will require sufficient energy storage to bridge peak demands and solar energy availability (Figure 4). The estimated requirement is 4 to 16 hours storage of the thermal equivalent of peakload power demand.

It is possible to design a baseload solar-thermal power plant such that its daily-averaged output exceeds the demand for electric power over the entire annual cycle. This is illustrated in Figure 5(a), where the seasonal supply curve is always above the demand curve. It is clear that this system will have excess capacity (shaded area between the curves) over most of the annual cycle, and that the solar receiver-collector system is oversized. Unless the excess power can be sold to another utility system, the power plant will operate below its full capacity and power costs will be high. A more likely power plant configuration will involve sizing to achieve a closer match between the supply-demand curves, as shown in Figure 5(b). Through rational sizing of the power plant, excess capacity can be reduced to exportable levels or eliminated altogether. The utility system will rely on fossil-fired or other non-solar generating capacity to make up the deficit between supply and demand shown in Figure 5(b).

Storage

Thermal energy storage is a key element for cost-effective application of solar-thermal power generation. Buffering storage, up to an hour in duration, is necessary to smooth the abrupt changes in insolation caused by intermittent cloud cover during the day. It prevents potentially damaging system transients in the same manner that an automobile's shock absorbers isolate the passengers from road bumps. Short-term storage, up to a day in duration, is necessary to supply thermal energy to the turbines during the night and during short periods of inclement weather. The daily interchange of thermal energy to and from storage is illustrated by the shading between

the supply and demand curves of Figure 4. The solar receiver is sized so that the total excess thermal energy produced during daylight hours balances the deficit incurred at night. This concept is illustrated by the equally shaded areas of excess and deficit in Figure 4. Storage is therefore seen as a necessary element of utility-scale, baseload solar-thermal power generation.

Thermal energy may be stored as sensible heat by changing the temperature of the storage medium, as latent heat by causing a phase change (e.g., melting or freezing) in the storage medium, and as thermochemical energy by changing the chemical composition of the storage medium. Sensible and latent heat technologies are being advanced for buffering and short-term storage. The basic technology of these mechanisms is well known, but application to large-scale, high-temperature storage for solar-thermal power plants requires development, scale-up, and system integration. Thermochemical energy technology is proposed for seasonal storage applications, and is currently in the early stages of development.

The magnitude of thermal storage required for even a moderate-sized utility power plant is enormous. Table 1 illustrates the order of magnitude for three durations of storage, assuming a 100 MWe solar-thermal plant with a steam-Rankine turbine.

Table 1. Relative Thermal Storage Requirements for Daily, Short-Term, and Buffering Applications in a 100 MWe Power Plant.

TYPE OF STORAGE	EQUIVALENT STORED CAPACITY	EQUIVALENT THERMAL ENERGY	RELATIVE MAGNITUDE OF TOTAL ENERGY*
DAILY (24 hrs)	1600 MWhe	2500 BOE**	150 homes
SHORT-TERM (6 hrs)	600 MWhe	925 BOE**	60 homes
BUFFERING (30 mins)	50 MWhe	75 BOE**	5 homes

* Expressed as number of Washington, D.C., area single-family homes which could be supplied with heat and hot water for one year.

**BOE — barrels of oil, equivalent.

Storage Based on Sensible Heat. Thermal energy is stored as sensible heat by raising the temperature of an inert storage medium. Recovery involves cooling the storage medium and energy returns at a continuously decreasing quality (temperature). The medium may consist of a solid material, such as crushed stone, or it may be a large "thermal mass" of the working fluid, such as oil or water, which is used to transport heat through the system. The size of the storage unit is based on a property known as heat capacity and a temperature change which is set by the source-demand system. The medium

must be able to withstand repeated exposure to the temperature required to power the turbine generators (up to 530°C or 980°F for steam-Rankine and 730°C or 1350°F for Brayton). High temperatures and relatively large storage volume make cost-effective containment of the storage medium a major concern.

Water is an excellent storage medium and working fluid, but it must be maintained under pressure to prevent boiling at elevated temperatures. State-of-the-art pressure vessels are too expensive for thermal energy storage, and a new concept known as the prestressed cast iron vessel (PCIV) is being evaluated. In this concept, cylindrical cast iron blocks are stacked to the desired height and are held in compression by external tie rods for strength. A sample PCIV has been designed with an energy storage capacity of 300 MWhe and a containment of 8000m³ (2.1 million gallons) of water at 275°C (530°F) at up to 1160 psi pressure. The cost of the vessel is estimated at 10 million dollars, or 33 to 50 dollars/kWhe of stored energy. The cost of a standard, steel alloy, welded construction pressure vessel with similar capabilities is 20 million dollars, or 66 to 100 million dollars/kWhe of stored energy.

As an alternative to large fabricated vessels, storage of hot water in natural underground geologic formations known as aquifers has been evaluated. However, at the high temperatures involved in solar-thermal power generation, storage must be accomplished at depths of 5,000 feet to achieve the pressure required to prevent boiling. At this depth, the energy requirements for pumping can be as high as 25 percent of the stored energy. The use of underground storage with water as the storage medium does not appear to be economically feasible for high temperature applications, i.e., those above 150°C (300°F).

The use of underground storage cavities, engineered in natural salt formations to contain non-volatile oils for sensible heat storage, is being investigated. As shown in Figures 6 and 7, the cavities are excavated deep within existing salt formations, and oil is used as the medium for both heat storage and heat transfer. Figure 6 illustrates a "thermocline" system with two well penetrations into a single gravel-filled cavern; hot oil is injected and recovered through the well into the upper portion, and cool oil is injected and recovered through the second well into the lower portion. Figure 7 illustrates a doublet cavity system in which oil is pumped from a hot well to a cold well during energy withdrawal, and vice-versa during energy storage. The thermocline approach appears to be the better system for first-generation power plants. The characteristics listed below have evolved from a preliminary analysis of one potential thermocline system:

Storage capacity: 1500 MWh_{th}

Capital cost: 4.6 million dollars

Size: 30,000 m³ (8 million gallons) cavity volume
7,500 m³ (2 million gallons) of captive oil

The salt-cavern concept could be applied to salt deposits and rock salt formations which are distributed throughout the United States.

Figure 6. Hot-Oil Thermocline System for Thermal Storage in Solar-Thermal Power Generation

Figure 7. Doublet Cavern System for Thermal Storage in Solar-Thermal Power Generation

Storage Based on Latent Heat. In a latent-heat system, energy is stored and released at constant temperature through a change in the physical state (phase) of a storage medium, for example through melting and freezing. Most latent-heat concepts are based on melting specialized salt mixtures known as eutectics, although use of metal alloys is possible. In addition to constant-temperature operation, latent-heat systems offer the potential advantage of smaller physical size. A more detailed discussion of storage as latent heat is given in the glossary.

The integration of a salt-based latent-heat storage unit with a solar-thermal power system involves matching the melting point of the mixture to the needs of the power turbine. For example, a conventional steam-Rankine turbine will require a salt mixture which freezes and returns thermal energy at 450° to 530°C (840° to 980°F). This requirement is met by a variety of salt mixtures involving inexpensive, commercially-available materials, such as chlorides and carbonates. Salt cost is an important factor, and the candidate materials must not exhibit any significant difficulties in handling, containment, or stability.

The magnitude of thermal storage required and the thermal properties of the salt mixture (heat of fusion) determine the volume of storage. The energy storage density for typical salt mixtures is such that a cubic foot of molten salt will contain sufficient thermal energy to generate 2 to 3 kWh of electricity. Daily storage (16 hours) for a nominal 100MWe power plant will require 4 to 6 million gallons of molten salt. Considering only the volume of storage medium, the latent-heat system will be about one-half the size of an equivalent PCIV system, which stores sensible energy as pressurized hot water.

Latent-heat storage units are coupled to solar receivers and the steam turbine by a heat-transfer fluid which passes through heat exchangers immersed in the molten-salt medium. The maximum rate of storage and withdrawal is determined by the size and type of these heat exchangers. Analysis of the heat-transfer system is complicated by the melting and freezing processes which occur at the exchanger surface. Successful development of latent-heat storage systems, therefore, will depend on the evaluation of a durable, cost-effective means for incorporating heat exchangers within the containment vessel.

Storage Based on Thermochemical Effects. Thermochemical energy storage is an advanced concept which offers the potential for significant reduction in system size through increased storage density. It also eliminates time-dependent energy losses because storage is accomplished at ambient temperature. For daily storage applications (up to 24 hours) in solar-thermal power generation, thermochemical storage could eliminate the major drawbacks to sensible heat and latent heat technologies, i.e., physical size and time-dependent energy loss (heat leaks).

Thermochemical energy storage uses reversible chemical reactions to store thermal energy as chemical-bond energy by changing the chemical composition of the storage medium. In a sense, the use of fossil fuels represents an application of thermochemical energy storage over millions of years. Solar energy and atmospheric carbon dioxide caused the growth of vegetable matter during early geologic ages of the earth. Subsequent burial and conversion of this matter to fossil fuels have provided man with a concentrated source of stored chemical energy, which may be burned to recover thermal energy. The carbon dioxide released during combustion re-enters the cycle with solar energy to form vegetable matter which, given the proper conditions and time, will form more fossil-fuel deposits. The concept of an advanced thermochemical energy storage cycle employs controllable chemical reactions in a closed cycle, with a net exchange of thermal energy and no net gain or loss of material. The cycle of energy storage and recovery will take place over a period of hours instead of centuries.

Development of thermochemical methods for daily storage of thermal energy in solar-thermal power plants involves identifying a chemically reacting system which is rapid and controllable and which accepts and returns thermal energy in the temperature range of 400° to 800°C (750° to 1475°F). The three systems shown below are promising candidates:

Thermal energy from the receiver causes decomposition of the starting material to form a series of high-energy products, such as CaO (lime) and H₂O (water) in system (3). Separation and containment of the high-energy products at ambient temperatures result in energy storage with no time-dependent loss. The products are recombined on demand to recover the stored energy and to retrieve the starting material. While the equipment for reacting, treating, and storing the chemical products is complex, thermochemical storage is best-suited to seasonal storage because of the increased storage density (2 to 10 times that of sensible or latent technologies) and the absence of a time-dependent energy loss.

STATE OF DEVELOPMENT

Sensible-Heat Technology

The materials for this technology are well known, but the application on a utility scale has never been demonstrated. Cost-effective containment is now the major focus of DOE programs. Prestressed cast iron vessels are being evaluated at the design stage, and underground concepts are being evaluated at the preliminary design phase.

Latent-Heat Technology

A variety of salt mixtures are known to have suitable thermal properties and are therefore undergoing laboratory evaluation. The DOE programs have a strong emphasis on containment, including compatibility of materials and techniques for exchanging heat with the storage system. Testing currently is limited to bench-scale experiments.

Thermochemical Technology

Reaction systems have been identified, and experimental work is proceeding at the laboratory scale to identify key parameters. The DOE programs will advance promising candidates to a proof-of-concept, bench-scale test of a complete cycle.

MAJOR HURDLES/PROBLEM AREAS

Latent-heat systems have difficulties with containment, because molten salts are very corrosive at high temperatures. Adequate containment for both sensible and latent-heat systems has yet to be demonstrated in large-scale applications, and more efficient heat-exchange methods are needed.

More detailed scientific information must be gathered on catalysts and reagents for thermochemical storage. Side reactions, which cause a loss of efficiency with time, reaction reversability, product separation, and corrosion of high-temperature system components are all problems that must be solved. In addition, thermochemical systems must be simplified before commercialization.

ENVIRONMENTAL AND RESOURCE IMPACTS

The environmental impacts of thermal energy storage systems are minimal. The construction of salt caverns will pose some problems of water availability and brine disposal. Once in place, however, all systems are closed and should pose no serious threat to their environment.

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GLOSSARY

The following general glossary of terms contains definitions which are applicable to all five thermal storage fact sheets.

Active Solar System

A solar-thermal heating system which employs discrete components for collection, storage, and distribution of solar energy. The heating system is distinct from the building structure, much like a conventional furnace, and heat is moved through the system by the active circulation of a fluid such as air or water.

ASHRAE

American Society of Heating, Refrigeration, and Air-Conditioning Engineers.

Baseload Power Plant

In an electric utility system, baseload power plants supply the majority of total electric energy demand. They operate continuously except when shut down for planned maintenance or equipment failure. They are designed to provide the combination of capital cost and efficiency which enables power to be generated at minimum cost.

BOE

Barrels of oil, equivalent; a means of expressing a quantity of energy by relating it to the amount of petroleum which must be burned to produce the equivalent thermal energy. (The daily energy consumption in the United States is about 38 million BOE.)

Boiler Feed Water

The preheated water which is converted to steam in a boiler.

Btu

British thermal unit; a small unit of energy, equivalent to the thermal energy required to raise the temperature of one pound of water by one degree Fahrenheit.

Chemical Heat Pump

A heat pump is a device which extracts thermal energy from a low-temperature source and rejects it to a higher temperature demand. The seemingly impossible task of moving heat "uphill," i.e., from a low temperature to a higher temperature, may be accomplished only by expending energy to "drive" the process. Heat pumps based on the mechanical compression and expansion of a fluid such as ammonia or Freon are in common use in home

refrigerators, air conditioners, and heat pump heating-cooling systems. In a chemical heat pump, the mechanical process is replaced with a thermochemical one, involving two separate reactions in which a solid or liquid is decomposed to form a vapor and another solid or liquid. The vapor (or gas) must be common to both reactions, as it is the movement of this vapor which accomplishes the heat pumping action. The process is illustrated in the following sketch:

Chubs

A type of packaging for latent-heat storage materials which involves sealing in tubular, sausage-like containers.

Closed System

A process or device which maintains a constant amount of material within itself, neither accepting matter from nor rejecting matter to its surroundings.

Conversion Efficiency

A figure of merit for energy conversion devices such as a steam turbine-generator. It consists of the amount of energy produced expressed as a percent of the energy consumed.

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DOE

Department of Energy

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MWh

Megawatt-hours; a large engineering unit of measure for energy, equal to 1000 kWh. A subscript "th" or "e" is used to differentiate between thermal and electric energy (e.g., MWh_{th} and MWh_e).

Passive Solar System

Literally, a solar-thermal heating system with no moving parts. The collection, storage, and distribution of solar-thermal energy is accomplished by static components, frequently built into the structure of the building.

PCIV

Prestressed cast iron vessel; a novel construction technique for pressure vessels which allows the use of low-cost cast iron to replace steel alloys.

Peakload (or Peaking) Power Plants

In an electric utility system, peakload power plants operate only during periods of peak or near-peak demand. Because they operate only for relatively short fractions of the day, peakload power plants produce relatively little energy compared to the total capacity and tend toward minimum capital cost. Low utilization of capacity and the use of expensive fuels cause the electric power produced by peaking plants to be more expensive than power from base-load power plants.

Phase-Change Material

A material which is used to store thermal energy as latent heat.

Power Tower

A high-temperature solar collector system which involves a large array of flat, individually-moveable mirrors (heliostats), which focus the sun's energy on a central receiver unit. The receiver is located in a tower, above the field of mirrors. This configuration was selected for development to a 10 MW scale under a DOE-funded program.

psi

Pounds per square inch, a unit of pressure.

Quad

Quadrillion Btu; an extremely large engineering unit of energy, equal to 1,000,000,000,000,000 Btu. The total energy consumption of the United States during 1978 was 77.7 Quads, the equivalent of nearly 14 billion barrels of oil.

Sensible Heat

Sensible heat is the energy associated with changes in the temperature of a material. Thermal storage as sensible heat is the most mature concept, with tanks of hot water and beds of hot rocks used in both active and passive solar-thermal systems. The quantity of material required to store a given amount of thermal energy depends on a property of the material known as specific heat and a characteristic temperature change determined by the system. Typical values are on the order of 10 to 100 Btu of energy storage per pound of material. As a storage technique, sensible heat has a major disadvantage in that energy is returned at an ever-decreasing temperature. Its major advantages are low cost and relative simplicity.

Thermal Load

A demand for thermal energy (heat).

Thermodynamic Cycle

The engineering description of a heat engine in terms of the series of compressions, expansions, heatings, and coolings to which a working fluid is subjected (e.g., Rankine cycle or Brayton cycle).

Thermochemical Heat

Thermochemical heat is the thermal energy associated with a change in the chemical composition of a mixture of materials. The heat released during combustion of a fuel is one example of thermochemical heat. For application to energy storage, however, the chemical reactions must be controlled and reversible. That is, the products of the reaction can be recombined at will to recreate the starting mixture. The concepts of reversibility and controllability are illustrated by an automobile storage battery, although that device stores electric rather than thermal energy. In a storage battery, the input of electric energy (charging) causes chemical changes to occur and, once the battery is charged, the higher energy products within the battery remain a source of energy on demand. The battery may be connected to an electric motor or a light bulb, in which case the stored electric energy will be returned, accompanied by chemical changes within the battery the reverse of those which occurred during charging. Thermochemical storage follows the same pattern, except that energy is supplied and returned as heat. Relative to sensible and latent-heat storage, thermochemical concepts have the advantage of permitting storage at ambient temperature with essentially no time-dependent heat losses. In addition,

the energy storage density is very high. Thermochemical energy storage is a relatively immature technology, with program emphasis focused on exploratory development and applied research for characterizing candidate storage reactions.

Thermocline

A specific configuration for sensible heat storage with a heated liquid such as water or oil. A single containment vessel is used to store both hot and cold fluid. Hot fluid remains at the top of the vessel and is added or withdrawn by displacement of (by) cooler fluid at the bottom of the vessel. The hot and cool fluid layers remain stratified because of the difference in density and because the containment vessel is filled with granular solid to impede mixing currents.

THERMAL ENERGY STORAGE FOR DAILY APPLICATIONS IN BUILDING HEATING AND COOLING

Daily thermal energy storage for building heating and cooling is primarily an enabling technology for solar space-heating, solar water-heating, and solar space cooling systems. Thermal storage is an integral and essential part of these solar-powered systems, with the energy generally stored for no more than a few days.

Daily or short-term thermal energy storage involves accumulating heat (or cold) during part of the day or during several days, followed by using the accumulated energy over a similar time period. Thermal energy can be stored as sensible heat, latent heat, or thermochemical energy. Sensible-heat storage is a mature technology, which involves raising or lowering the temperature of the storage medium. Latent-heat storage is a less mature technology, and involves a change in the physical state of the medium, generally through freezing and melting. Latent-heat storage is more compact than sensible-heat storage, and has the advantage of storing and returning energy at constant temperature. Thermochemical energy storage is an emerging technology for capturing thermal energy as chemical bond energy through reversible chemical reactions. Chemical heat pump storage for solar heating and cooling systems offers the potential of compact storage as well as a heating and cooling operation in one unit.

Thermal energy storage enables solar energy to supply building needs for space heat, hot water, and space cooling, thereby replacing fossil and nuclear-derived energy with a clean, inexhaustible source.

PURPOSE AND AREA OF APPLICATION

Daily storage will enable the widespread use of solar-derived energy. The source of energy, solar radiation, is intermittent and must be collected while it is available and stored for later use. Since the energy is collected and used as heat (thermal energy), it is best stored as thermal energy.

Thermal energy storage is used in solar systems in a variety of ways. Solar water-heating systems generally use a separate preheat tank to store solar-heated water. This tank then feeds into a conventional water heater. Thermal storage for solar space heating depends on the particular system. Passive systems often use building components and collect the energy (solar heat) directly in the storage device, where active systems employ a separate storage device, often located in a basement, and use air ducts or liquid in pipes to transfer heat into and out of storage. Solar cooling systems generally use separate high-temperature storage units to drive an absorption-type air conditioner, but can also use cold storage to store the output from the air conditioning unit directly.

POTENTIAL IMPACT

Space heating, water heating, and space cooling account for approximately one-fourth of the total national energy consumption. Cost-effective daily thermal storage could increase the rate of market penetration for solar technologies in these areas, thereby displacing the use of prime fossil fuels. Solar space heating and water heating are mature technologies and could become widely used. Solar space-cooling systems are available but are not cost effective, a situation which could change with technology improvements and rising electricity prices. The estimated annual oil savings which will result from implementation of these technologies is expected to be 15 MBOE by 1985 and 230 MBOE by 2000.

The impact of solar energy systems will vary from region to region. Those areas with the highest insolation, generally in the southern part of the United States, have the greatest potential for solar water heating. Solar space heating will have the most impact where both insolation and heating loads are high. The Rocky Mountain States are generally well suited for solar heating, while the Pacific Northwest is not because of its low insolation. Solar cooling is best suited for sunny climates with long, hot summers, such as the Southwest.

TECHNICAL DESCRIPTION AND KEY PARAMETERS

Daily or short-term thermal energy storage is needed to use intermittent solar energy for building heating and cooling. The basic mechanisms for thermal storage are sensible heat, latent heat, or thermochemical heat. Sensible heat storage is the simplest concept and is widely used today. Latent-heat storage offers much more compact storage and is moderately well developed. Thermochemical storage, using chemical heat pumps, offers compact heat storage as well as heating and cooling operation. It is in the early stages of development.

The principal application of daily (or short-term) thermal energy storage is for solar heating and cooling systems. The energy source, solar radiation, is unavailable during the night, and during bad weather it may not be available for several days. The heating and cooling needs of buildings are more continuous, however, depending primarily on the outdoor temperature. For a solar-thermal system to supply a reasonable fraction of a building's demands without heavy reliance on fossil-fired backup systems, energy storage is needed to bridge the gaps between periods of supply and demand.

Figure 1 shows the system concept for an active solar-thermal system which supplies space heating and hot water. The three separate elements of an active solar-thermal system are the collector, the storage unit, and the demand. Energy is collected whenever available and stored for recovery as needed. Figure 1 also shows the system concept for a passive solar-thermal system in which storage capability has been physically integrated with the energy source (the solar collector), avoiding the need for an active energy transfer system.

ACTIVE SYSTEM

PASSIVE SYSTEM

Figure 1. System Concept of Daily Storage for Solar Space Heating

Source

The source of thermal energy is solar energy (insolation) gathered by a solar collector. Insolation depends on geographic location, with sites at latitudes closer to the equator receiving relatively more insolation. Local climate affects the percentage of solar radiation actually reaching the solar collector. For example, New York City receives less than 75 percent of the insolation received at Laramie, Wyoming, even though both cities are located at essentially the same latitude. The difference is a result of more frequent cloud cover and greater atmospheric haze in the New York area.

Insolation at a given location varies considerably over the course of a day, and the total daily insolation varies greatly from day to day, with the average insolation higher in summer than in winter. Figure 2 shows the average daily insolation for a site near Washington, D.C., over a period of one year. The very dramatic swings over a few days are caused by changes in the weather. On days with a heavy cloud cover, rain, or snow, the insolation is drastically lower than for a clear, sunny day. The trend in the short-term swings shows the seasonal variation, with the highest average insolation occurring in summer.

The amount and temperature of the thermal energy derived from the solar source depend on the amount of sunlight (insolation) and on the design of the solar collector. Flat-plate solar collectors, the mainstay design for solar heating applications, will produce temperatures up to 90°C (200°F). Less-expensive, low-performance collectors used as swimming pool heaters will perform only up to 40°C (100°F), while high-technology stationary concentrating collectors are capable of temperatures up to 150°C (300°F). The fraction of available insolation actually retained by a given collector is known as the collector efficiency. It decreases under conditions of increased insolation or increased collection temperature. In typical installations, a state-of-the-art flat-plate solar collector will capture 50 percent of the available insolation.

Figure 2. Daily-Averaged Insolation Over an Annual Cycle at a Site Near Washington, D.C.

Demand

The system energy demand is for space heating, water heating, and space cooling. These needs constitute approximately one-fourth of our total national energy consumption; the substitution of solar energy in a fraction of the available buildings could displace a substantial amount of fossil-fuel derived energy.

Almost all buildings require space heating and hot water, including houses, apartment buildings, office buildings, schools, and industrial plants. In addition, air conditioning is used in most buildings in hot climates and in some buildings (office buildings, certain industrial plants, etc.) in cooler climates. Because there is a diversity of building types, this discussion will use a detached home as an example. However, solar heating and cooling are applicable to almost all building types.

Heating and Hot Water. Building heat demands are determined by weather conditions (primarily temperature), geographic location, construction (insulation and infiltration), and quantity of people and heat-producing equipment inside. The heating demand varies during the day and from day to day, depending on the weather. For a well-insulated 1500 square foot residence in Washington, D.C., the peak heating demand is about 7.5 kW (25,600 Btu per hour), while the average demand for January, the coldest month, is only 4.8 kW (16,200 Btu per hour). The peak requirement will generally occur in the early morning when the solar input is zero and the heating load can only be met by stored solar-thermal energy.

Residential hot-water demands average about 22 gallons per day per person, and occur as two or three daily surge periods for showers, laundry, and cleaning. The hot-water needs of other buildings depend on the type of facility; a laundromat requires a large amount of hot water and an office building requires a very small amount. Most conventional water heaters employ a nominal amount of storage to meet normal surges in household demand. A solar water heater requires additional storage, primarily because of the daily and other short-term variations in insolation.

Temperatures required for space and water heating are relatively low. Efficient space heating requires a temperature greater than 30°C (85°F), while water heating generally requires temperatures above 60°C (140°F). However, water may be preheated to considerably lower temperatures, reducing energy consumption in the conventional heating system. These temperature requirements are easily met by state-of-the-art flat-plate collectors.

Cooling. Building cooling demands, like heating demands, are determined by the weather (primarily temperature, solar gain, and humidity) and building characteristics. Cooling demands are increased by the internal load of people, lights, and machinery. In an office building, these internal loads can be greater than those caused by the weather. The cooling loads, like the heating loads, vary throughout the day, over a period of several days, and with geographical location. In Washington, D.C., a well-insulated 1,500 square foot residence has a maximum cooling demand of almost 5.9 kW (1.7 tons) with an internal temperature of 22°C (72°F) and an external temperature of 33°C (92°F). However, the average July cooling load is only about 2.4 kW (.69 tons). Like solar heating, there is frequently a difference between peak demand and peak energy availability, with the highest cooling loads generally occurring later than the period of highest insolation. High cooling loads can also occur during overcast, humid days when the insolation is low. Thus, storage of solar energy is an essential part of solar space cooling.

Solar space cooling is generally accomplished by an absorption-type air conditioner which is similar to a conventional gas air conditioner, but modified to run on lower input temperatures. The temperature required to drive the units is 82°C (180°F), which is within the capabilities of a high-quality state-of-the-art flat-plate collector with a selective coating and double glazing. More expensive stationary concentrating collectors such as Argonne National Laboratory's CPC (a collector with the absorber placed in rows of cusp-like troughs) are applicable also. Solar space-cooling equipment is currently quite expensive and its market penetration will lag behind solar heating equipment.

Storage

The use of energy storage is essential for cost-effective application of solar energy to building heating and cooling and hot water supply. This is because of the intermittent nature of the source of energy (insolation) and the variations in the energy demand (building heating, cooling, and hot water). Several factors influence the need for storage capacity: the size of the demand, the economics of providing a backup source (such as electricity), and the cost of the storage system. The optimum storage size is determined by trading off the various factors to find the most economical system. The economic optimum for most solar systems occurs when there is sufficient storage to supply demand for between one and three days.

Sensible-Heat Storage. Sensible-heat storage is the simplest form of daily or other short-term heat storage. The technology is mature and requires no development to achieve full-scale commercialization. Heat is stored by raising the temperature of a storage medium, such as water or rocks, and recovered by cooling the storage medium.

The most common types of sensible-heat storage for use with active solar heating and cooling systems are water tanks and rockbeds. Water has a higher heat capacity and thus the storage is more compact than a rockbed. Storage for a solar heating system in a typical single-family home involves 1,000 gallons of water (a volume equivalent to a medium-size clothes closet) or 380 cubic feet of rockbed (about the size of an average bathroom). Heat storage in a given system will vary over a range of temperatures, for example 35 to 65°C (95 to 150°F). The lower limit is determined by the heating requirement and the upper limit by the efficiency of the solar collectors. The lower limit for heat storage to drive an absorption-type air conditioner is 82°C (180°F). Costs for water and rock-heat storage systems are quite low. The tank cost of a water system is about 0.30 to 5.00 dollars per gallon, with the lower value achieved in very large systems. A 1,000 gallon tank can be obtained for 700 dollars. A thermally-equivalent rockbed storage system is considerably larger and will cost between 1 and 2 times as much as the water storage system.

In passive solar heating systems, sunlight is absorbed directly by the storage unit, thus eliminating the need for separate solar collectors. Three site possibilities for the storage unit include: (1) part of the building structure, such as brick or concrete walls or brick floors; (2) part of the building components, such as a phase-change material enclosed in ceiling tiles or cinder blocks; or (3) simply placed inside or on top of the building, such as water-filled drums or roof ponds.

The controlled release of stored heat is accomplished through vents which are opened or closed to control air circulation. Due to their simplicity, passive solar heating systems are more cost-effective than active systems in areas of relatively high insolation.

Latent-Heat Storage. Latent-heat storage takes advantage of a change in the phase of the storage medium, generally the freezing-melting process. Thermal energy is absorbed as a material melts and is released as the material solidifies

or freezes. The heat effect accompanying a change in phase is much larger than that associated with nominal changes in temperature (sensible heat). Storage as latent heat is more dense, and may be accomplished in a smaller volume. It has the added advantage of accepting and returning energy at a constant temperature. Ice is a perfect example and has many historical applications as an energy storage medium.

Mixtures of inorganic salts and a form-stable organic polymer (polyethylene) are viable candidates for phase-change storage media. Table 1 illustrates the properties of some media, with melting point and unit cost as the most important parameters for storage applications. Melting points in the range of 30° to 100°C (85° to 212°F) are most applicable to solar heat and hot water, with those in the 82° to 100°C (180° to 212°F) range applicable to absorption air conditioning. A storage unit to replace the sensible-heat unit in an active solar home-heating system would be much smaller, about the size of a refrigerator.

Table 1. Properties of Latent-Heat Storage Media

MATERIAL	MELT-FREEZE TEMPERATURE C°	RELATIVE STORAGE DENSITY*	STORAGE COST**
Glauber's Salt	32°C	7300 lb.	\$280
Form-stable polyethylene	125°-135°C	4500 lb.	\$1200
Commercially-available material (based on anhydrous sodium hydroxide.)	280°C	5000 lb.	\$1000

*Mass of material required to retain the 24-hour demand for space heating of a typical home in the Washington, D.C., area (average January day; 115kWhth.)

**Cost of storage medium only.

Much of the development for phase-change thermal storage emphasizes containment and heat transfer, the process of getting thermal energy in and out of the melting-freezing mixture. Because the medium is a solid or a mixture of solid particles in a syrupy liquid, it remains stationary in the system, and an inert fluid such as air or water is used to circulate thermal energy between the source, storage unit, and demand. Direct contact of the transfer fluid with the storage medium is not practical because many of the storage materials are either water-soluble or are not form-stable without external support. The need for additional equipment or structures to enable heat transfer between storage and the end use increases system cost. An important aspect of latent-heat storage is, therefore, the development of cost-effective means for containment with heat transfer.

Phase-change materials can be added to conventional building materials through microencapsulation, the dispersion of a medium throughout the physical structure of concrete blocks, wall panels, and ceiling tiles. In this manner, the building serves as the storage unit and stored heat is

transferred directly to the living area. The walls, floors, and ceilings involved will be maintained at a temperature slightly above ambient, and the warming of the living space will be accomplished through natural thermal convection and radiation. Due to the radiant heat, occupants may experience a physiological perception of comfort at less than normal ambient temperatures. This form is especially suitable for passive solar systems, as shown in Figure 3, but also can be used in active systems.

Figure 3. Passive Solar Heating System with Microencapsulated Latent-Heat Storage

Phase-change materials may be used in a central storage unit, either in bulk or in a macroencapsulated form. Macroencapsulation involves containment in cans, bottles, and chubs (sausage-like tubes), which are in turn arranged within a central enclosure. This technique provides both physical containment and surface area for heat transfer, by flowing the thermal transport fluid (air or water) through the matrix of capsules. Macroencapsulation is attractive, because it enables the medium to be packaged in easily-handled containers at a central factory with existing, automated machinery.

Bulk containment involves a single tank full of a molten (or frozen) phase-change materials. Thermal energy is added or withdrawn by means of coils of tubing which are immersed in the medium through which an appropriate heat transport fluid is passed. Conceptually, it is a less-complicated physical arrangement than macroencapsulation, because one layer of containment has been eliminated. However, the need for effective heat transfer tends to offset this advantage. Both macroencapsulation and bulk containment are applicable to active solar-thermal heating systems, as shown in Figure 4.

Figure 4. Latent-Heat Thermal Storage in an Active Solar-Thermal Heating System

Thermochemical Storage. Thermochemical energy storage uses the large heat input or output which accompanies a change in the chemical composition of the storage medium. A particularly useful application of thermochemical technology for daily heating and cooling of buildings is the chemical heat pump. (Technical aspects are described in the glossary.) Chemical heat pumps can provide thermal energy storage with an even greater energy density than latent-heat storage. In most cases, chemical heat pumps integrate storage with a capability for heating and cooling, thus eliminating the absorption air conditioner. Chemical heat pumps also can provide heating with a coefficient of performance (COP) greater than one. In essence, more heat can be delivered to the building than is supplied directly from the solar collectors, with the additional heat taken from the outdoor air like electrically-driven heat pumps. The storage capability of chemical heat pumps is based on the conversion of thermal energy to thermochemical energy. The chemical products which result from the charging cycle may be accumulated in small reservoirs and recombined to release heat on demand. The chemical heat-pump systems considered for building heating and cooling include those which use sulfuric acid, methanolated salts, ammoniated salts, and metal hydrides.

The sulfuric acid heat pump is based on the movement of water vapor between a high-temperature sulfuric acid reservoir and low-temperature water reservoir. The charge-discharge cycle for a sulfuric acid heat pump used for space heating is shown in Figure 5. The charging temperature of this device is from 65° to 205°C (150° to 400°F), which is much broader than commercial absorption units. It may be used effectively with either flat-plate or concentrating solar collectors. The storage density of a sulfuric acid heat pump is 6 to 12 times that of sensible and latent-heat systems. A practical unit could be the size of a console television. Sulfuric acid is an inexpensive, readily available commercial chemical. A wealth of experience with practical handling, use, and storage has been acquired from applications in automobile batteries, industrial plants, and petrochemical operations.

Energy Storage Charging Cycle

Energy Storage Discharge Cycle

Figure 5. Operation of a Chemical Heat Pump Based on Sulfuric Acid Dilution

Methanolated salt-based heat pumps use methanol as the transport fluid. During charging, methanol is disassociated from a salt in the high-temperature unit and is condensed to form liquid methanol in the low-temperature unit. A solar charging temperature of 150°C (300°F) can be used to give a heating COP of approximately 1.6 with an outdoor temperature of -10°C (15°F). Commercial electric heat pumps are considerably less effective when outdoor temperatures fall this low.

Ammoniated salt chemical heat pumps use ammonia as the transport fluid. An ammoniated salt is used in the high-temperature unit with a different compound, like ammonium chloride, used in the low-temperature reactor. Such a heat pump could be operated with a solar charging temperature of 80°C (175°F).

A metal hydride-based heat pump uses two dissimilar metal hydride materials in the high- and low-temperature reservoirs, and hydrogen gas as the transport fluid. The device is capable of high performance for heating and cooling with charging temperatures in the range of 120° to 140°C (250° to 280°F). The economic application of hydride heat pumps requires laboratory development of less-expensive metal hydride materials with high storage capacity and long life.

The development of chemical heat pumps is at an early stage. The only working systems are laboratory models, and good cost estimates are not yet available.

STATE OF DEVELOPMENT

Sensible-Heat Storage

Sensible-heat storage for use in solar heating systems is commercially available today, with water tanks and rockbeds the most popular. There is no major development required for near-term use.

Latent-Heat Storage

Latent-heat storage systems are nearing the stage of first use in commercial installation. Development is required, however, to improve the cost effectiveness of latent-heat technologies and increase their market penetration rate. Investigations into latent-heat storage systems involve studying methods for containment and heat transfer, determining the physical and thermal properties of improved phase-change materials, and performing computer modeling and detailed experiments on the melt/freeze process. Some of the studies involve building and testing of prototype units. The economics of mass production of latent-heat storage components and systems is also being investigated. Economics and reliability will be the major factors determining commercialization.

Current investigations into latent-heat storage systems have yielded data on the thermal performance of several salt hydrates and have produced useful, form-stable high-density polyethylene pellets for operation in the 120° to 140°C (250° to 280°F) range.

Chemical Heat-Pump Storage

Much work remains to be done before chemical heat pumps can be commercialized: full-size systems must be built, tested, and proved reliable; the economics must be shown to be favorable; and any safety questions, such as possible dangers from sulfuric acid, must be resolved.

Laboratory-scale systems have been built for methanolated salts, ammoniated salts, sulfuric acid, and metal hydride heat pumps, and computer models have been developed for each system. Economic and commercialization studies are underway.

MAJOR HURDLES/PROBLEM AREAS

Thermal energy storage systems for short-term solar applications generally face no major hurdles or problems, although development continues to solve minor problems, to develop systems, and to reduce costs.

Sensible-heat storage units are available commercially. Chemical heat-pump systems need comprehensive chemical and physical property data to allow the detailed analysis required for selection of an optimum system.

ENVIRONMENTAL AND RESOURCE IMPACTS

Environmental and resource impacts from short-term, sensible latent and chemical storage systems are minimal. All systems are closed and only exchange thermal energy with the environment. The release of chemicals, such as sulfuric acid, either due to a malfunction of the system or during its final disposal is not expected to be a major concern.

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GLOSSARY

The following general glossary of terms contains definitions which are applicable to all five thermal storage fact sheets.

Active Solar System

A solar-thermal heating system which employs discrete components for collection, storage, and distribution of solar energy. The heating system is distinct from the building structure, much like a conventional furnace, and heat is moved through the system by the active circulation of a fluid such as air or water.

ASHRAE

American Society of Heating, Refrigeration, and Air-Conditioning Engineers.

Baseload Power Plant

In an electric utility system, baseload power plants supply the majority of total electric energy demand. They operate continuously except when shut down for planned maintenance or equipment failure. They are designed to provide the combination of capital cost and efficiency which enables power to be generated at minimum cost.

BOE

Barrels of oil, equivalent; a means of expressing a quantity of energy by relating it to the amount of petroleum which must be burned to produce the equivalent thermal energy. (The daily energy consumption in the United States is about 38 million BOE.)

Boiler Feed Water

The preheated water which is converted to steam in a boiler.

Btu

British thermal unit; a small unit of energy, equivalent to the thermal energy required to raise the temperature of one pound of water by one degree Fahrenheit.

Chemical Heat Pump

A heat pump is a device which extracts thermal energy from a low-temperature source and rejects it to a higher temperature demand. The seemingly impossible task of moving heat "uphill," i.e., from a low temperature to a higher temperature, may be accomplished only by expending energy to "drive" the process. Heat pumps based on the mechanical compression and expansion of a fluid such as ammonia or Freon are in common use in home

refrigerators, air conditioners, and heat pump heating-cooling systems. In a chemical heat pump, the mechanical process is replaced with a thermochemical one, involving two separate reactions in which a solid or liquid is decomposed to form a vapor and another solid or liquid. The vapor (or gas) must be common to both reactions, as it is the movement of this vapor which accomplishes the heat pumping action. The process is illustrated in the following sketch:

Chubs

A type of packaging for latent-heat storage materials which involves sealing in tubular, sausage-like containers.

Closed System

A process or device which maintains a constant amount of material within itself, neither accepting matter from nor rejecting matter to its surroundings.

Conversion Efficiency

A figure of merit for energy conversion devices such as a steam turbine-generator. It consists of the amount of energy produced expressed as a percent of the energy consumed.

COP

Coefficient of performance; a figure of merit for heat pump systems. In heating applications, it is the amount of heat supplied to the end-user per unit of energy consumed (either electric or thermal). In cooling applications, it is the amount of heat removed from the building per unit of energy consumed.

DOE

Department of Energy

Heat Engine

A machine which converts thermal energy to useful, mechanical work, e.g., a steam turbine.

Insolation

The rate at which the sun's energy reaches the earth's surface, usually expressed as an energy rate per unit area, e.g., Btu/ft²

Intermediate-Load Power Plant

In an electric utility system, intermediate-load power plants operate during normal and peakload demand periods, but not at low demand periods.

kWh

Kilowatt-hours; an engineering unit of measure for energy and the customary unit for electric bills. A subscript "th" or "e" is used to differentiate between thermal and electric energy (e.g., kWh_{th} and kWh_e).

Latent Heat

Latent heat is the energy associated with a change in the physical condition of a material, such as melting or freezing. The harvest of natural ice during the winter for use in summer refrigeration is an historical example of energy storage as latent heat. Storage as latent heat has the advantage that energy is stored and recovered at nearly constant temperature. This temperature is a unique property of the storage material and will govern the selection of a storage material for a specific application. Solid-liquid processes are the most practical for near-term applications, and include both melting of salt mixtures and crystallization of salt solutions. Latent-heat storage technologies are significantly less advanced than those for sensible heat. Continued development is expected to verify the lower cost and higher performance potential of phase-change materials for energy storage.

Macroencapsulation

A means for containing latent-heat storage material in small easily-handled packages, such as cans or plastic chubs.

MBOE

Million barrels of oil, equivalent; a means of expressing a quantity of energy by relating it to the amount of petroleum which must be burned to produce the equivalent thermal energy. (The daily energy consumption for the United States is about 38 MBOE).

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In an electric utility system, peakload power plants operate only during periods of peak or near-peak demand. Because they operate only for relatively short fractions of the day, peakload power plants produce relatively little energy compared to the total capacity and tend toward minimum capital cost. Low utilization of capacity and the use of expensive fuels cause the electric power produced by peaking plants to be more expensive than power from base-load power plants.

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A material which is used to store thermal energy as latent heat.

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A high-temperature solar collector system which involves a large array of flat, individually-moveable mirrors (heliostats), which focus the sun's energy on a central receiver unit. The receiver is located in a tower, above the field of mirrors. This configuration was selected for development to a 10 MW scale under a DOE-funded program.

psi

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Sensible Heat

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THERMAL ENERGY STORAGE TO ASSIST ELECTRIC UTILITY LOAD MANAGEMENT

Electric utilities encounter daily, weekly, and seasonal variations in their system load because of established patterns for using electricity. Over the years, the utility industry has devised an economic way of meeting load variations by using separate plants to supply peakloads of up to several hours. Specialized peakload generating equipment is expensive, however, and the current cost of supplying peak energy is several times that of supplying energy on a continuous basis from "baseload" generating facilities. In addition, peakload generating systems usually require the combustion of petroleum distillates or natural gas as fuel. Given the national goal of reducing our consumption of these fuels, particularly imports, there is a strong incentive to develop other methods for managing utility peakloads.

Thermal energy storage offers a low-cost alternative to meeting utility system peakloads by storing thermal energy during off-peak hours (usually late at night) for use during peak periods. This thermal energy may be stored at either the customer site (load leveling) or at the utility power plant (load following).

Thermal energy stored at the customer site can be used to meet peak thermal demands without imposing additional electrical loads. Basically, off-peak electricity is converted to thermal energy, stored by the customer, and used to meet thermal demands during peak periods. Thus, the use of a thermal energy system reduces peak utility electric demand. Customer storage is applicable whenever electricity is used to provide a thermal service such as space conditioning or water heating. Commercial, energy-storing space heating units are used in Europe and are under evaluation in the United States. Off-peak water heating systems will be similar to existing units, except for an increase in storage capacity to meet an entire day's supply. In both cases, the incentive for customer acceptance is a rate structure which makes off-peak electric power an attractive option.

Thermal energy may be stored at the utility power plant as part of the plant's thermodynamic cycle. This stored energy is used to boost the plant's electrical output during periods of peak demand. A good example is a preheated store of boiler feedwater for a steam-driven turbine generator. When additional output is needed, this stored energy can be added rapidly to the system. Steam normally used to preheat boiler feedwater can be diverted to produce additional electricity. The advantage to the utility is that customer involvement is eliminated and the impact on operation is more certain.

PURPOSE AND AREA OF APPLICATION

Thermal energy storage may be incorporated into the utility system at either the residential or commercial site or directly into the thermodynamic cycle of a generating plant. When thermal storage is used at the customer site, it acts as a load-leveling system and can reduce the peak electrical demand that the generating plant must meet. If thermal storage is used in the generating plant, it increases the plant's capacity to meet peakloads in the load-following mode.

Customer thermal storage systems are used in conjunction with electrical hot water and space conditioning services in residential and commercial buildings. Utility plant thermal storage systems are designed for use in steam-electric generating plants, which supply about 80 percent of the electric energy in the U.S. utility industry. The application of thermal storage systems in either location is dependent on a variety of technical, economic, and institutional factors.

POTENTIAL IMPACT

By reducing utility capital costs, thermal storage systems potentially could save from 50 to 250 million dollars per year on residential and commercial energy bills by 1990. The major savings in using thermal storage comes from the reduced cost of meeting peak electrical loads. The high costs of peak period electricity are not seen by most users, because they pay a flat rate for electric energy regardless of when it is consumed. The technology for customer thermal storage systems for residential water heating and space heating is available. Current oil (and gas) savings, however, are likely to be small, because fuel savings from peakload plants are offset by increased fuel consumption at the baseload plant. As the percentage of baseload capacity (coal-fired or nuclear) increases relative to oil or gas-fired baseload capacity, larger savings in oil or gas will occur.

Nationally, increased use of customer thermal storage systems could reduce the utility peakload by up to 1 percent by 1990. Thermal storage space heating systems will tend to be used in colder parts of the country, where they can reduce the winter peakloads caused by electrical space heat. Space cooling systems utilizing thermal storage are likely to be practical in warmer climates, where they can reduce summer peakloads from space cooling. Therefore, thermal storage hot water systems are applicable regardless of climate.

TECHNICAL DESCRIPTION AND KEY PARAMETERS

Customer Thermal Energy Storage

Most customer thermal energy storage systems are based on storing energy as sensible heat in common materials such as water or ceramic bricks. The key elements to the successful application of customer thermal storage are relatively simple design, low capital and installation cost, high reliability, and long service life. Application of these systems is economically most favorable where the utility has baseload power available at 1.5 to 2.0 cents/kWh or less.

Customer thermal storage systems are designed to utilize off-peak electric energy from the utility to provide on-peak thermal services to residential and commercial buildings. This concept, known as load leveling, is shown schematically in Figure 1. The utility system (energy source) usually has surplus baseload capacity during the off-peak period, normally about 8 hours, from 10 p.m. to 6 a.m. This capacity may amount to as much as 10 percent of a utility's peak capacity, although this amount may not be available for the entire off-peak period.

Figure 1. System Concept for Customer Thermal Energy Storage to Accomplish Electric Utility Load Leveling

Figure 2 illustrates the goal of customer thermal storage for utility load leveling. The traditional demand curve (solid line) is smoothed considerably (dashed line) when electric power consumption is shifted from peak to off-peak periods. The shading used in Figure 2 represents energy stored and recovered by the storage units in the customers' buildings.

Figure 2. Customer Thermal Storage Smooths Demand for Electric Power

The demand characteristics of the thermal load vary with application. A typical household may require about 60 gallons (15 kWh) of hot water per day. Hence, a thermal storage water-heating system capacity of 25 to 30 kWh (thermal) is adequate for a daily cycle. The typical reduction in the peak load is about 2 to 4 kW. In contrast, the thermal storage system in a large commercial building may involve 1 MWh of storage for a typical peakload reduction of 100 kW. The storage system has to retain sufficient energy to meet the thermal demand over the entire 16-hour on-peak period. However, the demand is concentrated in an 8 to 10-hour segment of the on-peak period for many systems.

Customer thermal storage systems use sensible or latent-heat storage in common materials. Hot water and some space heating thermal storage systems use electrical energy to heat water with a resistance heater. The stored hot water may be consumed or released as heat to the building space via suitable radiators. Sensible heat from resistance heaters also may be stored in ceramic bricks with considerably higher energy density. Ice or chilled water may be used as "cool" storage to supply a heat sink for building air conditioning loads.

The key parameters of customer thermal storage technology are summarized in Table 1. Water is the most common storage medium. Hot-water storage at moderate temperatures requires only mild steel tanks and suitable insulation to reduce thermal losses. The ceramic materials used for heat storage operate at much higher temperatures, up to 1000°F, for which suitable low-cost containment systems have been devised. Chilled water for thermal storage cooling systems is stored in a low-cost poured concrete tank.

Table 1. Principal Characteristics of Customer Thermal Storage Systems

SYSTEM TYPE	STORAGE MEDIUM	TEMPERATURE RANGE (°F)	STORAGE DENSITY kWh/ft ³	CAPITAL COSTS \$/kWh *	SYSTEM LIFETIME (YEARS)
Residential Hot Water	Water	60° to 160°F	1.4	15-20	10
Commercial Hot Water	Water	60° to 200°F	2.1	20-80	20
Residential Space Heat (Central)	Ceramics	80° to 1000°F	2.6	12	15
Commercial Space Cooling	Water	38° to 53°F	0.27	15-35	25

* Additional costs are incurred for control systems and energy conversion devices in many cases.

In all cases as shown, the basic capital cost of the storage system is low, with the emphasis on systems costing less than 25 dollars/kWh. The operating costs for storage systems are the costs of lost thermal energy not delivered to the load. In most cases, this is 10 percent or less of the total energy placed in the storage system.

Successful use of customer thermal storage depends on the availability of large quantities of low-cost off-peak electric energy, under 1.5 to 2.0 cents/kWh. The cost of the off-peak electric energy has to be sufficiently low so that the difference saved over the on-peak energy price can pay the cost of the thermal storage system.

The key parameters for system success are low cost and operation and simple design. The simple design results in a reliable system with a long service life. Figure 3 shows a thermal storage heating system of British design using high-temperature ceramic storage material. The system is heated electrically by the resistance elements during the off-peak period. A thermostatically controlled fan transfers the stored heat to the room or entire house to maintain the internal temperature. This system can effectively store heat for 16 hours so that all heating may be supplied by off-peak electricity.

The Department of Energy (DOE) is actively developing advanced thermal storage systems for customer use. These systems will utilize phase-change materials to store thermal energy more compactly and at optimal temperatures. Optimal storage temperatures are usually chosen to be close to the temperature of the intended application and to minimize loss of energy availability through large temperature differences. This is especially important for integrating thermal storage with heat pumps and for more efficient heating and cooling systems.

Figure 3. Commercially Available, European Design for an Electric Space Heater With Thermal Storage

Improved methods of packaging thermal storage phase-change materials are being developed. One thrust is to develop the phase-change materials with normal building materials, so that they can be integrated into walls, ceilings, and floors. This approach lends itself to "passive" heating or cooling systems. Alternatively, the phase-change material may be packaged in small containers for use in thermal storage systems. The individual package then serves as a heat exchanger for thermal energy flowing in or out of the phase-change material.

Utility Thermal Energy Storage

Thermal energy storage can be used at the utility generating plant to boost generating capacity for meeting peak demand. This is accomplished either by operating the main turbine at an increased steam flow or by using an auxiliary turbine. Boosts of up to 50 percent of the main plant capacity are possible. Alternate designs for utility thermal storage systems are being examined for commercial potential. A major disadvantage to thermal storage at the utility is a result of the conversion efficiency of modern turbine-generators; more than 2.5 kWh of thermal energy must be stored to produce 1 kWh of peak electrical power.

Large baseload and intermediate-load utility power plants are unable to follow peakload demands, because the thermal energy source (fossil fired or nuclear boiler) is unable to respond to the changing need for steam to drive the turbine-generators. One concept for utility load following involves operating a main boiler at a steady rate, accumulating the excess thermal energy produced when electric demand is low, and recovering energy from storage to augment boiler output whenever electric demand is high. Figure 4 is a schematic of thermal storage applied to load following. Figure 5 is an illustration of the thermal energy supply and demand curves, with shading used to accent the transfer of energy to and from storage. Up to 10 percent of the utility system capacity may be available for as long as 8 hours during the off-peak period. On weekends, up to 15 percent of the system peak capacity may be available for up to 16 hours in the off-peak mode. Therefore, thermal storage at the utility generating site enables the utility baseload or intermediate-load generator to follow the normal fluctuations in electrical loads, minimizing the need for specialized peaking generators.

Figure 4. System Concept for Utility Thermal Energy Storage to Accomplish Electric Utility Load Following

During off-peak periods, excess thermal energy from the utility boiler is charged to thermal storage. The turbine and generator units must be sized large enough to use the stored energy and the full boiler output to generate peakload power. For example, a 1000 MWe baseload plant might accumulate thermal energy at a rate equivalent to 100 MWe during an 8-hour off-peak period, and then generate peak power at rates as high as 1300 MWe during peak demands.

Two alternative approaches have been devised for such utility thermal storage systems. In the first scheme, part of the boiler output is diverted to a steam accumulator (or alternative thermal storage). The surplus energy then is stored at a fairly high temperature. During a peak period, the steam accumulator serves as a auxiliary boiler, and its output is directed to a separate turbine generator system.

Figure 5. Utility Thermal Storage Enables Load Following by Baseload Power Plant

Alternatively, energy can be stored from steam extracted by bleeding intermediate stages of the turbine. Extraction steam is normally used for feedwater heating. During low-demand periods, additional steam is extracted to "charge" the thermal storage system. For peakload demands, the steam normally extracted is expanded through the entire turbine to produce additional electrical output. The thermal storage system provides energy for feedwater heating during this period. Figure 6 diagrams a typical steam plant using feedwater thermal storage. The storage temperatures for this system are lower, since the thermal storage does not generate steam. As an example, in a typical nuclear plant, the feedwater must be heated from about 38° to 215°C (100°F to 420°F). This feedwater could be stored directly in a pressure vessel at about 400 psi. Alternatively, the heat energy could be stored in a heat-transfer medium, such as oil, or a sequence of phase-change materials. These materials would operate in the 90° to 260°C (200° to 500°F) range.

Most designs for utility thermal storage systems use commonly available engineering materials. Costs for utility storage system vary with the specific system design. Total system costs generally exceed 100 dollars/kWh. The storage-related costs are usually 20 to 30 dollars/kWh with the

NORMAL OPERATION - 6 HOURS
(BLEED STEAM PREHEATS BOILER FEEDWATER.)

CHARGING EXCESS THERMAL ENERGY TO STORAGE - 6 HOURS
(BLEED STEAM PREHEATS BOILER FEEDWATER PLUS EXTRA WATER FROM COLD STORAGE. EXCESS PREHEATED FEEDWATER IS STORED.)

RECOVERY OF THERMAL ENERGY FROM STORAGE - 12 HOURS
(NO BLEED STEAM. FULL POWER FROM TURBINES. BOILER OPERATES ON STORED, PREHEATED FEEDWATER.)

Figure 6. Utility-Owned Thermal Energy Storage
(Arrows Indicate Flow of Steam and Feedwater)

balance of the cost for energy conversion capacity. The higher storage costs are a consequence of having to store 2.5 to 3.5 times as much heat energy per kWh as a customer thermal system. The additional heat storage is required to compensate for the conversion efficiency of the turbine generator, which is generally about 30 percent. Detailed data on operating costs of these systems are not readily available.

The potentially high costs for utility thermal storage systems are limiting interest in the development of experimental hardware. Research efforts sponsored by DOE are focusing on how to devise low-cost alternatives to the present designs. Advanced materials and structural design concepts are being considered. The use of thermal storage in conjunction with utility compressed air storage systems also is being investigated.

STATE OF DEVELOPMENT

Customer thermal storage systems for hot water and space heating are already widely used in Europe and are gaining recognition in the United States as an effective load management technology. The technology is being evaluated by DOE and the utility industry for application in this country. Concepts for utility thermal storage systems also are being studied. The DOE program is aimed at achieving cost-effective thermal storage systems using more advanced technology.

Customer thermal storage technology has been highly commercialized in Europe by nearly 20 years of experience. Adoption of the technology for the U.S. market has largely involved obtaining code acceptance and sizing the systems for larger U.S. homes. Hot water thermal storage systems have been used in large numbers, with about 200,000 such units in Detroit. Several other utilities in the Northeast have installed up to 100 storage heating units in residences as part of demonstration programs. Testing still is underway. DOE also is funding ASHRAE to develop standard test procedures for thermal storage systems.

Less is known about the use of thermal storage in the commercial sector, and well-documented test data on commercial thermal storage systems are not available.

Utility thermal storage system concepts are still being explored to find a suitable concept for further development. Since the estimated system costs for current alternatives are high, prospects for early commercialization are low.

MAJOR HURDLES/PROBLEM AREAS

The major barrier to more effective commercialization of customer thermal storage systems is utility rate reform to include off-peak electric pricing. Customer thermal storage systems require low-cost off-peak electric energy to be attractive economically. However, because of delays in instituting new electric rate structures, off-peak electric rates are not available

to most residential and small commercial users. Unless rate reform or time-of-day metering systems are allowed on a wide scale, commercialization of customer thermal storage systems will not be significant. The utility industry will have to find other means to achieve better load management.

Current research is focusing on advanced concepts which can potentially overcome this problem. This includes studies of hot water, oil, rock, iron, molten salts, sulfur and phase-change materials for energy storage. A wide variety of aboveground and underground containment vessels also are being studied.

ENVIRONMENTAL AND RESOURCE IMPACTS

Thermal storage devices are closed systems, generally using conventionally available materials. They have no emissions and can be recycled at the end of their useful life. Hence, they have minimal environmental and resource impacts.

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GLOSSARY

The following general glossary of terms contains definitions which are applicable to all five thermal storage fact sheets.

Active Solar System

A solar-thermal heating system which employs discrete components for collection, storage, and distribution of solar energy. The heating system is distinct from the building structure, much like a conventional furnace, and heat is moved through the system by the active circulation of a fluid such as air or water.

ASHRAE

American Society of Heating, Refrigeration, and Air-Conditioning Engineers.

Baseload Power Plant

In an electric utility system, baseload power plants supply the majority of total electric energy demand. They operate continuously except when shut down for planned maintenance or equipment failure. They are designed to provide the combination of capital cost and efficiency which enables power to be generated at minimum cost.

BOE

Barrels of oil, equivalent; a means of expressing a quantity of energy by relating it to the amount of petroleum which must be burned to produce the equivalent thermal energy. (The daily energy consumption in the United States is about 38 million BOE.)

Boiler Feed Water

The preheated water which is converted to steam in a boiler.

Btu

British thermal unit; a small unit of energy, equivalent to the thermal energy required to raise the temperature of one pound of water by one degree Fahrenheit.

Chemical Heat Pump

A heat pump is a device which extracts thermal energy from a low-temperature source and rejects it to a higher temperature demand. The seemingly impossible task of moving heat "uphill," i.e., from a low temperature to a higher temperature, may be accomplished only by expending energy to "drive" the process. Heat pumps based on the mechanical compression and expansion of a fluid such as ammonia or Freon are in common use in home

refrigerators, air conditioners, and heat pump heating-cooling systems. In a chemical heat pump, the mechanical process is replaced with a thermochemical one, involving two separate reactions in which a solid or liquid is decomposed to form a vapor and another solid or liquid. The vapor (or gas) must be common to both reactions, as it is the movement of this vapor which accomplishes the heat pumping action. The process is illustrated in the following sketch:

Chubs

A type of packaging for latent-heat storage materials which involves sealing in tubular, sausage-like containers.

Closed System

A process or device which maintains a constant amount of material within itself, neither accepting matter from nor rejecting matter to its surroundings.

Conversion Efficiency

A figure of merit for energy conversion devices such as a steam turbine-generator. It consists of the amount of energy produced expressed as a percent of the energy consumed.

COP

Coefficient of performance; a figure of merit for heat pump systems. In heating applications, it is the amount of heat supplied to the end-user per unit of energy consumed (either electric or thermal). In cooling applications, it is the amount of heat removed from the building per unit of energy consumed.

DOE

Department of Energy

Heat Engine

A machine which converts thermal energy to useful, mechanical work, e.g., a steam turbine.

Insolation

The rate at which the sun's energy reaches the earth's surface,² usually expressed as an energy rate per unit area, e.g., Btu/ft²

Intermediate-Load Power Plant

In an electric utility system, intermediate-load power plants operate during normal and peakload demand periods, but not at low demand periods.

kWh

Kilowatt-hours; an engineering unit of measure for energy and the customary unit for electric bills. A subscript "th" or "e" is used to differentiate between thermal and electric energy (e.g., kWh_{th} and kWh_e).

Latent Heat

Latent heat is the energy associated with a change in the physical condition of a material, such as melting or freezing. The harvest of natural ice during the winter for use in summer refrigeration is an historical example of energy storage as latent heat. Storage as latent heat has the advantage that energy is stored and recovered at nearly constant temperature. This temperature is a unique property of the storage material and will govern the selection of a storage material for a specific application. Solid-liquid processes are the most practical for near-term applications, and include both melting of salt mixtures and crystallization of salt solutions. Latent-heat storage technologies are significantly less advanced than those for sensible heat. Continued development is expected to verify the lower cost and higher performance potential of phase-change materials for energy storage.

Macroencapsulation

A means for containing latent-heat storage material in small easily-handled packages, such as cans or plastic chubs.

MBOE

Million barrels of oil, equivalent; a means of expressing a quantity of energy by relating it to the amount of petroleum which must be burned to produce the equivalent thermal energy. (The daily energy consumption for the United States is about 38 MBOE).

Microencapsulation

A type of containment for latent-heat storage material which involves dispersion of the substance throughout a "host" material, such as ceiling tile, wallboard, or concrete block. The materials of construction then become effective heat storage devices.

MWh

Megawatt-hours; a large engineering unit of measure for energy, equal to 1000 kWh. A subscript "th" or "e" is used to differentiate between thermal and electric energy (e.g., MWh_{th} and MWh_e).

Passive Solar System

Literally, a solar-thermal heating system with no moving parts. The collection, storage, and distribution of solar-thermal energy is accomplished by static components, frequently built into the structure of the building.

PCIV

Prestressed cast iron vessel; a novel construction technique for pressure vessels which allows the use of low-cost cast iron to replace steel alloys.

Peakload (or Peaking) Power Plants

In an electric utility system, peakload power plants operate only during periods of peak or near-peak demand. Because they operate only for relatively short fractions of the day, peakload power plants produce relatively little energy compared to the total capacity and tend toward minimum capital cost. Low utilization of capacity and the use of expensive fuels cause the electric power produced by peaking plants to be more expensive than power from base-load power plants.

Phase-Change Material

A material which is used to store thermal energy as latent heat.

Power Tower

A high-temperature solar collector system which involves a large array of flat, individually-moveable mirrors (heliostats), which focus the sun's energy on a central receiver unit. The receiver is located in a tower, above the field of mirrors. This configuration was selected for development to a 10 MW scale under a DOE-funded program.

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