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Thermal Energy Storage Development for Solar Electrical Power and Process Heat Applications¹

Development of thermal energy storage technologies for solar thermal systems has been conducted since the mid-1970s. This paper presents an overview of past and present experimental activities for electrical power and process heat applications both within and outside the United States. The factors affecting the selection of a storage technology for these applications, as well as the nature of those applications, are discussed. Future research needs are also described.

Introduction

If solar thermal power systems are to be developed for commercial applications, these systems must be able to provide continuous operation during periods of variable insolation, extend operation into nonsolar hours, avoid the potentially harmful transients arising from abrupt changes in insolation, and ensure power availability in emergency periods. Two options exist for meeting these requirements: conventional fuel backup systems, and energy storage. Backup systems indeed provide a viable near-term solution. However, as conventional fuel supplies become more expensive or of limited availability, thermal energy storage will assume an increasingly significant role.

Recognizing the important potential of thermal storage, the U.S. Department of Energy (DOE) and several foreign governments have sponsored research and development activities to (a) establish technology readiness for various storage technologies, and (b) operate these technologies in solar systems. These solar systems comprise four related collector concepts: hemispherical bowls, parabolic troughs, heliostat fields with tower-mounted central receivers, and parabolic dishes. Each system uses reflective surfaces to focus or concentrate the sun's rays onto a small area where the radiant energy is converted to heat. The resulting heat energy can be used to run a conventional turbine-generator or to provide heat for an industrial process.

Thermal energy storage technologies are generally developed for these systems according to a stepwise technical approach. In the first phase, the technical feasibility of storage concepts is established. Small-scale laboratory experiments are included in this phase. In the second phase,

storage subsystems are defined for the most promising concept(s), and larger scale subsystem research experiments (SREs) are conducted. (An SRE is an experiment of sufficient size to insure the successful operation of the full-size subsystem.) In the final phase, the thermal storage subsystem is integrated into an on-line or new solar thermal power plant or test facility. At the completion of this last step, the storage subsystem is a proven alternative, ready for retrofit into existing solar thermal systems or for incorporation into future solar thermal systems.

Up to the present time, almost all storage research and development activities within the United States have been conducted under DOE sponsorship [1-3]. The DOE has also participated in foreign projects under the auspices of the International Energy Agency (IEA) [17]. Other projects have been sponsored by individual foreign governments [12-14, 26].

This paper presents an overview of major past and on-going experimental activities both within and outside the U.S. The factors affecting the selection of a storage technology for any application are described first. Next, several system applications are described, along with the experiments that were conducted to develop the storage technologies for those applications. To date, the majority of these applications have been for electrical power generation, although the developed storage technologies could also be used for other applications, such as industrial process heat. Finally, future research needs are described.

Factors Affecting Storage Technology Selection

The selection of a storage technology for any application depends on both cost and performance considerations. The total cost of a thermal energy storage subsystem (C_t) can be determined from energy-related costs (C_e) and power-related costs (C_p). The variable C_s includes the costs of the storage medium, container, insulation, and any other items associated with the actual storage of thermal energy; C_p comprises the

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price of heat exchangers, pumps, plumbing, heat transfer fluids, and any other items required to transfer heat to and from storage. For a storage capacity of h hours, $C_i = C_p + C_s h$. Thus accurate knowledge of C_p and C_s is needed to assess quantitatively the applicability of a storage concept.

Since C_i is usually a small fraction (approximately 10 to 20 percent) of the total cost of a solar thermal plant [4], C_i must be significantly reduced before it has a substantial impact on the cost of energy delivered from the system. Therefore, potentially large storage cost reductions are required to justify committing substantial resources to developing an advanced thermal energy storage concept.

However, the cost of delivered energy may be affected more by storage performance than by storage cost. If the quantity of thermal energy delivered from storage is less than that charged to storage, an extra price must be placed on the delivered energy to pay for the energy "lost" in passing through storage. This charge is beyond that needed to pay for the thermal storage system itself. Obviously, the greater the losses of energy from storage, the greater the delivered-energy cost penalty. Systems with low storage efficiencies (< 50 percent) will probably not be acceptable for most applications. High-efficiency storage systems (> 90 percent) will be desirable.

Another important performance consideration is the temperature of the thermal energy delivered from storage. Solar thermal systems are designed to produce output temperatures matched to application requirements. These requirements have led to two generic storage system configurations: direct and indirect. In the direct system, the same material is used for both the receiver working fluid and the storage medium. Thus no heat exchanger is required to charge storage, and the temperature of the thermal energy delivered either from storage or directly from the receiver can be nearly the same. In an indirect system, an intermediate heat exchanger is used to charge storage. Temperature drops must be provided between the receiver and storage and between storage and the load in order to transfer heat. Therefore, the receiver must be operated at a higher temperature to charge storage than is needed to operate directly to the load; or, a lower temperature must be produced at the load from storage than is produced directly from the receiver. To complicate matters further, some thermal storage systems may experience a continual drop in storage temperature with time (e.g., sensible heat storage), or the discharge cycle may occur at significantly lower temperatures than the charge cycle (e.g., thermochemical storage). Finally, the temperature of the energy delivered from storage is affected by those limits imposed by material properties (such as fluid degradation or media solidification temperatures).

All of these temperature limitations adversely influence the economics of the solar thermal system. If the temperature of the fluid from storage is lower than the temperature of the fluid available directly from the receiver, heat engines will run less efficiently; and less work will be produced per unit of energy delivered from storage than delivered directly from the receiver. Alternatively, the temperature of the fluid from storage may not be adequate for process heat applications. If the receiver temperature is raised to make higher outlet temperatures from storage possible, the receiver efficiency will drop; and less energy will be available from storage per unit of energy incident onto the receiver.

These selection considerations imply that the appropriate thermal storage system is efficient, low in cost, and able to provide high-quality thermal energy. Of course, due to practical constraints, trade-offs must be made among these factors to achieve the lowest possible cost of delivered energy from the integrated solar thermal/thermal storage system. Quantitative trade-offs among thermal storage characteristics are beyond the scope of this discussion, but a methodology

has been developed and studies have been performed to identify thermal storage systems that have the potential to deliver lower energy costs [5-8].

Applications Program Activities

Development activities directed to specific application areas have been conducted since the mid-1970s. Table 1 provides a summary of the major thermal storage subsystem/system experiments. All are sensible heat experiments, with the exception of a latent heat buffer storage experiment for parabolic dishes and a latent heat storage stage for a Japanese solar system experiment.

Early Storage Development. In 1975, the DOE funded several studies to develop solar thermal power systems which use water/steam-cooled central receiver technology [9-11]. As part of these studies, storage systems were developed for both a 10-MW_e pilot plant and a larger scale 100-MW_e commercial plant. Laboratory experiments investigated concept feasibility and the thermal stability, compatibility, and fouling of various storage media. Finally, two SREs were performed.³

The first experiment was designed by Martin Marietta and the Georgia Institute of Technology. A 1.6-MWh_t two-stage sensible heat storage system used oil in the main stage and HITEC, a eutectic mixture of NaNO₃, NaNO₂, and KNO₃, in the superheat stage. In operation, the media were heated when the colder fluid was removed from one tank, heated in a heat exchanger with steam from the receiver, and returned to a second tank. For heat extraction, the process was reversed. Operation of the oil and salt stages was similar. For this experiment, the receiver steam for charging storage and the feedwater for discharging storage were simulated by tapping into existing supply lines at the site of the experiment, the Georgia Power Company's Plant Yates in Newnan, Georgia.

A second experiment designed by McDonnell Douglas and Rockwell had a 4-MWh_t storage capacity and employed dual liquid (oil) and solid (rock/sand) storage media, with the thermocline principle applied to store both hot and cold storage media in the same tank. Using solid media in the tank increases the volumetric energy density, reduces the quantity of costly liquid, and impedes the mixing of the hot and cold fluids. Heating of the storage media was achieved by removing colder oil from the bottom of the tank, heating it in a heat exchanger with steam from the receiver, and returning the oil to the top of the tank. During heat extraction, the process was reversed. The receiver steam for charging storage was simulated by heating the oil directly with a fossil-fired heater. For discharging storage, a steam generator heat exchanger at the site of the experiment, Rockwell's Santa Susana Test Facility, was used.

Based on the results of these tests and cost/performance estimates for the commercial-size plant, the single-stage oil/rock thermocline concept was selected for the 10-MW_e Solar Central Receiver Pilot Plant located near Barstow, California [4]. The thermal storage tank at the pilot plant contains Exxon's Caloria HT 43 heat transfer oil, 1-in.-dia gravel, and sand. The oil is distributed over the rock/sand bed by the diffuser manifolds to ensure a sharp and uniform thermocline. The system operates over a temperature range of 218 to 304°C (425 to 580°F) and is sized to deliver 7 MW_e over a 4-hr period. Operation from storage occurs at reduced power because the temperature and pressure of steam generated from storage is less than that available directly from the receiver. Figure 1 shows a schematic of the pilot

³A third SRE, which was to test a NaNO₃-NaOH latent heat storage concept, was built but never tested. The concept used mechanical scrapers to prevent buildup of a frozen salt layer. This layer develops on the outside tube walls as the storage system is discharged. Numerous laboratory experiments were completed by Honeywell, but the SRE was canceled because of funding considerations and the lack of any significant advantages over the competing sensible heat concepts [10].

Table 1 Major thermal storage subsystem/system experiments

Subsystem/system experiment	Concept	Storage medium	Operating temperature range	Capacity
10-MW _e pilot plant SRE (Newnan, Ga.)	two stages, hot/cold tanks	Oil, molten HITEC salt	oil – 238 to 295°C (460 to 563°F) salt – 270 to 482°C (519 to 900°F)	1.6 MWh _t
10-MW _e pilot plant SRE (Santa Susana, Calif.)	dual-media thermocline	oil, rock/sand	218 to 302°C (425 to 575°F)	4.0 MWh _t
10-MW _e pilot plant (Barstow, Calif.)	dual-media thermocline	oil, rock/sand	218 to 304°C (425 to 580°F)	28 MWh _e
Shallow well irrigation pumping (Willard, N.M.)	single-medium thermocline	oil	116 to 216°C (240 to 420°F)	0.38 MWh _e
Deep well irrigation pumping (Coolidge, Ariz.)	single-medium thermocline	oil	200 to 288°C (392 to 550°F)	0.9 MWh _e
Midtemperature Solar Systems Test Facility (Albuquerque, N.M.)	cascaded tanks	oil	241 to 309°C (466 to 588°F)	0.86 MWh _t
Midtemperature Solar Systems Test Facility (Albuquerque, N.M.)	single-medium thermocline	oil	243 to 311°C (470 to 592°F)	0.21 MWh _t
Solar total energy (Shenandoah, Ga.)	single-medium thermocline	silicone oil	260 to 399°C (500 to 750°F)	3.3 MWh _t
IEA 0.5-MW _e power plant (Almeria, Spain)	single-medium thermocline	oil	225 to 295°C (437 to 563°F)	0.8 MWh _e
IEA 0.5-MW _e power plant (Almeria, Spain)	hot/cold tanks	liquid sodium	275 to 530°C (527 to 986°F)	1.0 MWh _e
Molten nitrate salt SRE (Albuquerque, N.M.)	hot/cold tanks with an internally insulated hot tank	molten NaNO ₃ -KNO ₃ salt	288 to 566°C (550 to 1050°F)	6.9 MWh _t
Checker stove power module (Nashua, N.H.)	air/refractory thermocline	cordierite	704 to 927°C (1300 to 1700°F)	20 kWh _t
Heat pipe receiver with thermal storage (Evendale, OH)	tube capsules	NaF-MgF ₂ phase change salt	827°C (1520°F)	2 kWh _t
THEMIS 2.5-MW _e power plant (Targassonne, France)	hot/cold tanks	molten HITEC salt	250 to 450°C (482 to 842°F)	12 MWh _e
CESA-1 1-MW _e power plant (Almeria, Spain)	hot/cold tanks	molten HITEC salt	220 to 340°C (428 to 644°F)	3 MWh _e
EURELIOS 1-MW _e power plant (Adrano, Sicily, Italy)	two stages, steam accumulator tank, and hot/cold tanks	pressurized water, molten HITEC salt	water – 210°C (410°F) salt – not available	0.36 MWh _e
Sunshine 1-MW _e power plant (Nio, Kagawa, Japan)	steam accumulator tanks	pressurized water	249°C (480°F)	3 MWh _e
Sunshine 1-MW _e power plant (Nio, Kagawa, Japan)	two stages, steam accumulator tanks and tube capsules	pressurized water, KCl-LiCl phase change salt	water – 232°C (450°F) salt – 361°C (682°F)	3 MWh _e

plant storage unit. Funded jointly by the DOE and utility companies, the plant will be operated by the Southern California Edison Company in its grid network. Construction of the plant was completed in early 1982, and plant start-up is underway.

Other storage-equipped, water/steam-cooled solar thermal power systems have been built in Japan, Italy, and Spain [12–14]. The Japanese Sunshine project consists of two 1-

MW_e pilot plants. One plant uses central receiver technology with pressurized water storage. When the plant is in operation, heated water from the receiver is pumped to pressurized storage tanks. For power generation, this water is flashed to steam and then routed to the turbine-generator. A second pilot plant uses flat mirrors and secondary parabolic concentrators to produce superheated steam that is routed to a two-stage storage system. The main-stage storage medium is

pressurized water, while the superheat stage contains a phase-change salt (KCl-LiCl). For power production, the main-stage water is flashed to steam and then superheated by passing over tubes containing the KCl-LiCl salt. Both pilot plants are sized to operate from storage for three hours. Construction of the plants is complete, and testing has begun.

The EURELIOS project, a 1-MW_e power plant of the central receiver type, is located in Sicily, Italy. This plant uses a two-stage storage system that contains features of both the Japanese and Martin/Georgia Tech two-stage storage systems. The main stage contains pressurized water, while the superheat stage contains molten HITEC salt. Water from the main stage is flashed to steam and superheated in a heat exchanger by the molten salt. For this system, the hot and cold molten salt are contained in separate tanks. The storage system is sized for 1/2-hr operation at a reduced plant output. Plant operation began in 1981.

The 1-MW_e Spanish CESA-1 power plant is also a central receiver project. Superheated steam from the receiver heats a single-stage storage system containing molten HITEC salt; the hot and cold salt are again contained in separate tanks. Heat exchangers are used to transfer energy from the steam to the salt or vice versa. The storage system is sized for 3 hrs of operation at a reduced plant output. Construction of this plant is scheduled for completion in 1982.

A second major application for thermal storage has been in the area of irrigation pumping. In recent years, two projects have been completed: the shallow well project at Willard, New Mexico, and a deep well project at Coolidge, Arizona [15]. Both of these projects use a single-medium (Caloria HT 43 hydrocarbon oil) thermocline storage system. The system relies on the density difference between hot and cold oil to store both oils in the same tank. Cold oil is removed from the bottom of a tank, heated in a parabolic trough collector, and then returned to the top of the tank. In contrast to the Barstow indirect storage system, no charging heat exchanger is required for these direct systems since the collector and storage fluids are the same.

The Willard facility began operation in 1977. The facility was upgraded in 1978 by adding troughs, a second thermocline storage tank, and other modifications. The storage system operated over a temperature range of 116 to 216°C (240 to 420°F) and was sized to deliver 19 kW_e (25 HP) for a period of 20 hrs. The facility, which was used to obtain operational and performance data on all subsystems and components, was deactivated in 1981.

The Coolidge facility began operation in late 1979. Designed and constructed by Acurex Corp., the system is operated by the University of Arizona. The Coolidge storage system operates over a range of 200 to 288°C (392 to 550°F) and is sized to deliver 150 kW_e for a period of six hours.

The storage development that preceded or paralleled the Willard and Coolidge projects consisted primarily of laboratory experiments and testing of hydrocarbon oil multitank and thermocline storage systems at the Mid-temperature Solar Systems Test Facility (MSSTF) in Albuquerque, New Mexico [15]. The multitank or "cascade" system had a capacity of 0.86 MWh_t. Three identical tanks could each be used either as a cold or hot tank. The test program, which was completed in 1980, investigated heat losses and the control strategies required to transfer the hot or cold storage fluid from one tank to another during operation.

A thermocline storage system was also installed at the MSSTF. Initially, a low-carbon-steel pressure vessel with 2.5-cm (1-in.) thick walls was evaluated for storing hot and cold fluid in the same tank. Conduction along the thick walls enhanced heat losses and thermocline degradation; thus additional development was necessary. A new thermocline tank, made of 0.48-cm (3/16-in.) low-carbon steel, replaced the old one during 1980. Having a capacity of 0.21 MWh_t, the

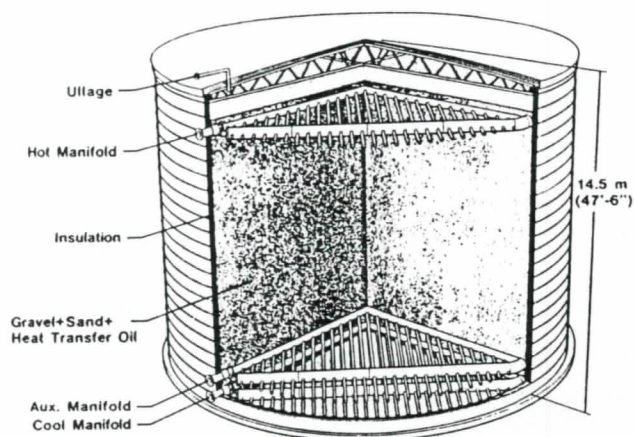


Fig. 1 Schematic of single-stage oil/rock thermocline thermal storage unit for the Barstow pilot plant

new tank was heavily instrumented to measure heat loss and thermocline performance. Subscale models of diffusers for distributing the fluid flow within the tank were also tested in the laboratory and then fabricated and tested full-scale in the tank. Testing of this system was completed in 1981, and the results are being incorporated into a process design handbook.

Single-medium thermocline systems are being constructed for such other applications as a solar total energy (cogeneration) project located in Shenandoah, Georgia, and an electrical power project located in Almeria, Spain. The Shenandoah project will supply 3 MW_e from a field of parabolic dish collectors to provide electricity, process steam, and space conditioning for a knitwear apparel factory. Initially, a trickle storage concept was proposed for the Shenandoah project. In this concept, storage is either charged or discharged by oil that trickles over a cold or hot storage bed, transferring heat between the oil and the bed. This approach uses a relatively low-cost, solid storage medium for essentially all storage. Because oil is used for only heat transfer, the inventory of high-cost oil is minimized. However, considerations for the overall project cost and the status of the technology development resulted in a reduced capacity storage subsystem and the selection of the single-medium thermocline concept for Shenandoah. The storage subsystem is now sized to provide about 1 hr of operation at the plant rated output. The dish working fluid and storage medium are the same: a silicone oil (Syltherm 800) heat transfer fluid operating over a temperature range of 260 to 399°C (500 to 750°F) [16]. Construction of the plant is complete, and start-up was initiated in early 1982.

The Almeria project is jointly funded by several countries under the auspices of the International Energy Agency. The project involves the construction and operation of two 0.5-MW_e plants, one using oil-cooled parabolic trough collectors and the other a sodium-cooled central receiver. The trough system includes single-medium oil thermocline storage that operates over a temperature range of 225 to 295°C (437 to 563°F). The central receiver system uses liquid sodium sensible heat storage that operates over a temperature range of 275 to 530°C (527 to 986°F), with the hot and cold fluids stored in separate tanks. Both systems are sized to provide about 2 hrs of storage at the plant rated output. Construction of these systems is complete, and plant start-up was initiated in mid-1981 [17].

Advanced Storage Development. The liquid sodium central receiver system is one of several advanced concepts under study for electrical power and process heat applications [18, 19]. These concepts also include molten-salt and gas-cooled central receivers [20, 21] and dish receivers in which the

storage system is either ground-based or mounted directly on the dish [22-24].

Compared to first-generation water/steam technology, the advanced central receiver concepts offer greater thermodynamic availability when the system is operated from storage. For example, the storage round-trip efficiencies of the Barstow, EURELIOS, and CESA-1 power plants are about 70 percent, while the storage round-trip efficiency of the IEA liquid sodium plant exceeds 90 percent⁴. These design-point values will be verified in tests that will be performed during 1982 and 1983. A high round-trip efficiency results from using receiver heat transport fluids, such as sodium or molten salt, that also serve as the storage medium or from using high-operating-temperature fluids and media, such as air and refractory brick.

Molten nitrate salt sensible heat storage is currently being singled out for development. A $\text{NaNO}_3\text{-KNO}_3$ salt mixture appears particularly attractive because of its low cost, high energy density, and potentially high operating temperature. Salt material studies are being performed to establish the physical properties and long-term stability and corrosion-inducing behavior of molten nitrate salts at elevated temperatures [25]. During 1980, the DOE funded Martin Marietta to begin development of a nitrate salt sensible heat storage subsystem. This effort includes a full-size subsystem design, laboratory experiments, and the design, construction, testing, and evaluation of an SRE. A major objective is to advance the state-of-the-art in high-temperature containment.

Martin Marietta's design approach is to contain the high-temperature (566°C or 1050°F) salt in a lined and internally insulated hot tank (Fig. 2) and to contain the low-temperature (288°C or 550°F) salt in a separate tank made of carbon steel. Because the hot tank is internally insulated, less-expensive carbon steel can be used for the shell material. The liner is a liquid-tight waffled membrane design of the type used in liquefied natural gas storage applications. The SRE, which used a propane-fired heater to heat the salt and an air-cooled heat exchanger to cool the salt, was conducted at the Central Receiver Test Facility (CRTF) in Albuquerque. Laboratory experiments to establish the fatigue life of the liner and testing of the SRE were successfully completed in 1982.

The SRE will be integrated into a molten salt electric experiment that is planned for the CRTF in 1983. This system experiment will integrate a molten-salt-cooled receiver, the thermal storage SRE, steam-generator heat exchangers, and a steam turbine to generate 0.75 MW_e of electrical power.

The French THEMIS project is another system experiment using molten salt technology [26]. THEMIS is a 2.5-MW_e power plant that uses molten HITEC salt both as the receiver working fluid and the storage medium. The storage system is sized to provide about 5 hrs of operation at the plant rated output. Perhaps the biggest difference between THEMIS and the DOE experiment is the upper operating temperature of the salt. The THEMIS system will operate at a temperature 116°C (208°F) lower than the CRTF experiment. At the lower temperature, salt stability and corrosion-inducing effects are of less concern, but system efficiency is also reduced. THEMIS is scheduled for completion in 1982.

Conceptual designs of storage systems for gas-cooled central receivers and parabolic dishes have been completed by Boeing and Sanders Associates, Inc., respectively [21, 24]. Both concepts use a porous ceramic matrix as the storage

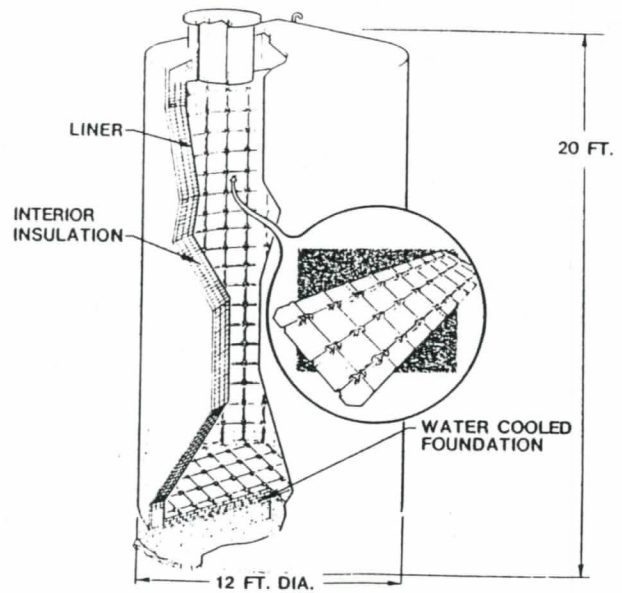


Fig. 2 Molten salt SRE hot tank

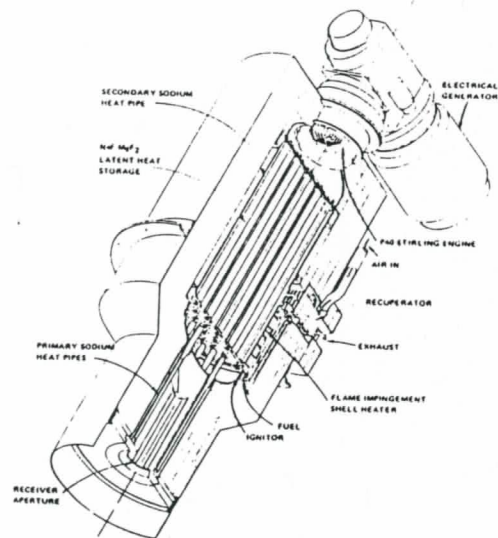


Fig. 3 Dish/Stirling buffer latent heat storage system

medium with air flowing through the matrix to add or remove heat. The ceramic material, typically aluminum oxide or magnesium oxide, is heated to a temperature of 816°C (1500°F) and is contained in a pressurized storage tank. No hardware development has been conducted for the larger central receiver storage system, but Sanders has successfully tested a smaller dish/Brayton storage system [24].

Storage development for parabolic dishes also includes dish-mounted latent heat storage systems for use with Rankine, Brayton, and Stirling engines. Since the engines are also mounted on the dish, the overall concept is generally a highly integrated receiver/storage system with storage sized to provide energy only for short durations or buffering. Conceptual designs and some hardware development have been completed for dish/Rankine and dish/Stirling systems (Fig. 3), and a dish/Brayton conceptual design was also recently completed. Work is also being performed at the Jet Propulsion Laboratory to determine the heat transfer and corrosive properties of the salts [1].

⁴ The round-trip efficiency of a storage subsystem is defined as:

$$N_{r.t.} = \frac{E_{out}}{E_{in}} \times \frac{N_{storage}}{N_{solar}}$$

where E_{out} = thermal energy out of storage; E_{in} = thermal energy into storage; $N_{storage}$ = power conversion efficiency when operating from storage; N_{solar} = power conversion efficiency when operating directly from solar.

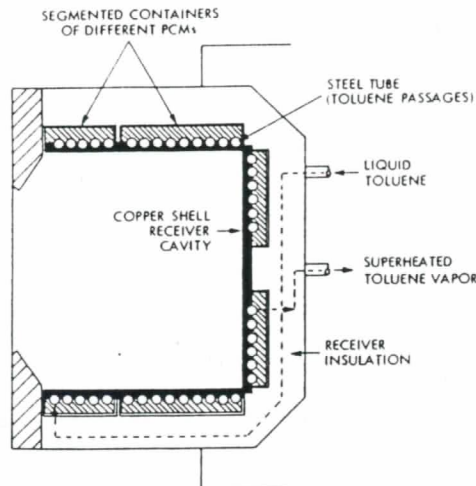


Fig. 4 Integrated receiver/storage design for dish/organic-Rankine system

A receiver/storage design which uses phase-change material (PCM) packaged integrally within the receiver walls (Fig. 4) has been proposed for the Small Community System Experiment [23]. This project, which will be located in Osage City, Kansas, will use a field of parabolic dishes with dish-mounted organic Rankine engines to generate about 0.1 MW_e of electrical power [27]. The use of the design is uncertain because recent funding constraints have limited the required hardware development.

Research Needs of the Program

Development activities not only have led to some promising options for near-term storage applications but also have pointed to areas for further work. For the first-generation storage technologies now being tested, the round-trip efficiencies are already quite high (70 percent for indirect systems and above 90 percent for direct systems) so significant improvements in performance are unlikely. The major emphasis therefore should be on a reduction in system costs. Sensible heat storage has immediate promise. However, for applications such as Barstow, Coolidge, IEA, and Shenandoah, even lower cost media are needed. Low-cost liquid and solid media are being sought to reduce the amount of the more costly liquid media. Even molten nitrate salt storage, which now has the best system cost potential if used with a salt-cooled receiver and a high operating temperature (566°C or 1050°F), could benefit from a low-cost solid medium like rock. Of course, the fluid-rock combination must be capable of reaching the maximum receiver temperature without significant degradation.

For sensible heat storage, direct storage systems provide a high thermodynamic availability, and this results in performance and potential economic advantages over indirect systems. In direct systems, the fluid employed in the receiver is stored in a large tank until heat is required. Heat exchangers are thereby not needed. The problem then is finding suitable low-cost fluids for both storing and collecting solar thermal energy. Molten nitrate salt appears suitable for both roles, while liquid sodium is suitable for collection but is less attractive for storage because of its lower density, lower heat capacity, and higher cost. Other collection fluids should be investigated for direct storage. In addition, inexpensive vessels for fluid containment are needed, as are low-cost options for providing high-temperature energy from storage to maximize the work production capability.

If direct storage is not cost-effective, low-cost heat exchange is required between the receiver heat transfer fluid and

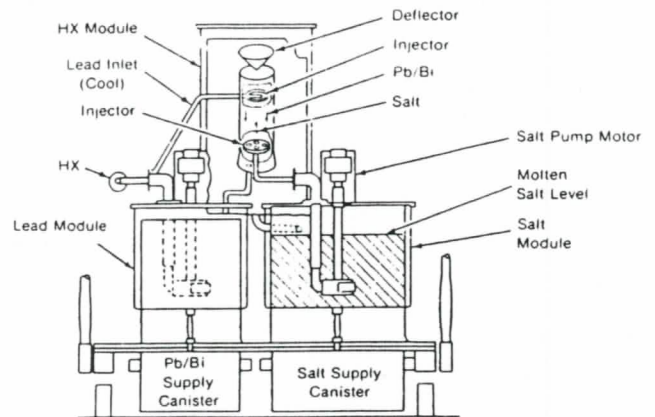


Fig. 5 High-temperature direct contact heat exchanger

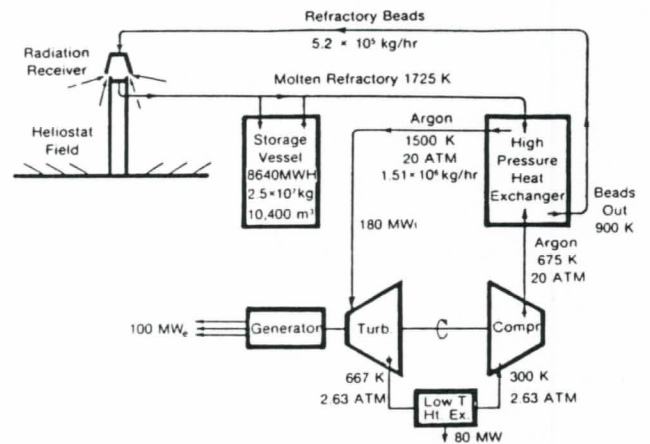


Fig. 6 Schematic of proposed high-temperature solar thermal power plant (temperatures are shown for a mixture of 40 percent SiO₂, 20 percent MgO, 35 percent CaO, and 5 percent Al₂O₃)

the storage medium. Since conventional heat exchangers generally require expensive alloys to withstand high-temperature corrosive environments, alternative modes of heat exchange are needed. One system under investigation uses direct contact between the storage media and the heat transfer fluid [28]. As illustrated in Fig. 5, three tank modules are coupled by two separate fluid loops: one for the molten salt latent heat thermal storage medium, and the other for the liquid metal heat transfer fluid. The liquid metal is injected at the top of the heat transfer column, becomes heated as it flows down through the column, and is pumped from the bottom of the column to the heat sink. Molten salt bubbles into the bottom of the column and transfers both latent and sensible heat to the countercurrent flow of liquid metal as the salt rises through the system. When the solidified drops of salt reach the top of the column, they are directed over the edges and fall to the bottom of the surrounding tank. During the next charging cycle, the solid salt is melted and drained back to the molten salt tank, ready for the next discharge cycle. Although the system now being studied employs a latent heat storage medium, the concept also has potential for reducing the cost of sensible heat storage. Preliminary indications are that a direct contact latent heat storage system has strong economic potential for producing saturated steam, but considerable research and development must still be completed to prove this concept's technical feasibility.

Significant thermal storage improvements are particularly needed at very high temperatures (approximately 816°C or 1500°F, or above). Thermal storage in this temperature range can be used to supply heat to high-efficiency Brayton and

Stirling cycle engines. The storage vessels and heat exchangers required to withstand such high temperatures are costly. If direct contact heat exchange is used between the heat carrier fluid and the storage medium (e.g., refractory brick), the containment vessel must also be capable of operating at the generally high pressures associated with the hot gas heat transfer fluids. Innovative system configurations, low-cost containment approaches, or new storage concepts might be devised to lower the cost of very high-temperature storage.

One proposal is a high-temperature (727 to 1727°C, or 1340 to 3140°F) combination storage and heat transfer system. A uniform aggregate of refractory oxide beads is injected directly into a solar receiver where it melts [29]. As shown in Fig. 6, the liquid refractory oxide, which is stable at high temperatures, is then piped to a storage vessel. When heat is needed, the melt is pumped into the high-pressure heat exchanger shown in Fig. 7. There the melt is sprayed as droplets through a countercurrent stream of high-pressure working gas, giving up heat by convection and solidifying in the process. The hot gas is then used to drive a heat engine while the solid beads are collected and stored at the bottom of the heat exchanger as an aggregate, ready for reinjection into the solar receiver. Although this concept has favorable economic potential, many of the basic ideas underlying the concept are unproven, and substantial research and development are required to determine its technical and economic viability.

Another potentially economical thermal storage concept for high-temperature applications uses a thermal storage medium with both sensible and latent heat components [30]. This concept involves the retention and immobilization of phase-change salts within a porous ceramic matrix. Discrete, submicron-sized particles may be distributed through the ceramic phase, or the dispersed phase may be interconnected in a partially sintered, porous body. Capillary forces are primarily responsible for retaining the latent heat storage salt within the ceramic void space. Experiments have demonstrated the feasibility of retaining 65 volume percent molten alkali carbonates at 700°C (1292°F). If the concept is proven feasible, composite pellets, bricks, or other shapes can be fabricated for use in direct contact with compatible fluids, thereby eliminating heat exchanger tubes. However, research must be performed to prove technical merits and limitations, and a system must be evaluated to determine the economic potential of the idea.

Latent heat energy storage suffers two major cost penalties. First, the cost of pure materials are high relative to those of competing sensible heat media, such as rocks. Second, heat exchange from the media requires extensive surface area (at high cost) to provide adequate heat transfer through the solidifying material by conventional shell-and-tube devices. The direct contact system described previously is a possible solution to this high-cost heat transfer, but other approaches to latent heat storage are also desirable to overcome these limitations.

One concept that has received recent attention is a latent heat storage unit which can be interfaced with a saturated steam receiver and a process heat application requiring saturated steam [31]. The latent heat storage module, shown in Fig. 8, is a rectangular, externally insulated carbon steel tank containing five tube assemblies. A tube assembly has 15 single tubes, each bent into a serpentine. (The figure shows an earlier design of six tubes per serpentine.) The serpentine tubes are supported by carbon steel channels and are separated horizontally by aluminum channels (not shown) which also enhance thermal conductivity. The storage medium is an 18.5 NaNO₃-81.5 NaOH (mole, in percent) salt eutectic with a melting point of 256°C (493°F). The storage module is charged by condensing 288°C (550°F) saturated steam into saturated liquid. On discharge, the storage module produces 232°C (450°F) saturated steam from saturated

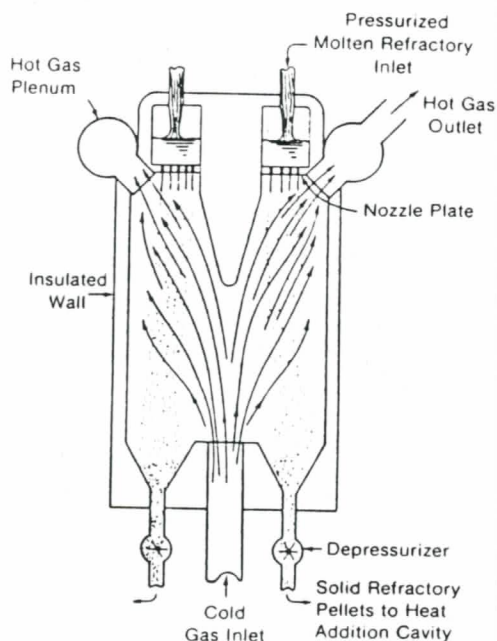


Fig. 7 High-temperature direct contact droplet heat exchanger

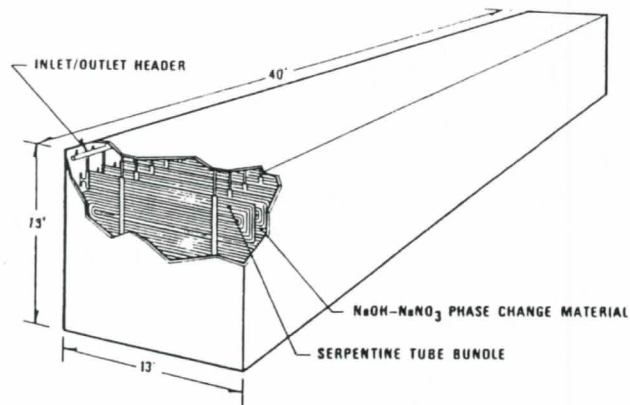


Fig. 8 Latent heat thermal storage module

liquid. The storage capacity of a module is 19.0 MWh_t. Hardware development is needed to assess further the technical and economic merits of this concept.

An area of interest in the far term is long-duration thermal energy storage subsystems. At this time, only two options are potentially low enough in cost to be reasonable candidates for baseload storage: air/rock storage, and thermochemical storage. For the air/rock system, the heat transfer limitations of air raise serious doubts about the ability to obtain low power-related costs. Thermochemical storage is conceptually attractive because high-grade heat could be stored at ambient temperature, but (a) only a few compounds have low enough material costs to be considered and (b) gases are produced during the known high-temperature reactions. Even if the gases can be easily condensed for storage at ambient conditions, the heat of condensation, a substantial fraction of the stored energy, is released at too low a temperature for use in the solar thermal system. Therefore, when the liquids are used to generate heat by the exothermic reaction, the quantity of thermal energy produced is far less than that used to drive the endothermic reaction [32]. If the gases do not condense, the cost of gas containment, with or without compression, is probably too high for thermochemical storage to be cost effective. Furthermore, serious questions have been raised about the cost of thermochemical storage [33]. New alter-

natives which meet the low cost requirements of long duration storage but overcome these difficulties are needed.

The thermal transport of energy is also of significant concern. As the temperature of receiver operation rises, movement of the thermal energy from the collector to storage or to the load, or to both, becomes increasingly difficult. Some research and analyses have been done in using reversible reactions with only gaseous reactants and products for ambient or near-ambient temperature transport. Although a few reasonably promising reactions have been identified, cost and efficiency problems have cast doubt on this approach. A need exists for new transport approaches for high-temperature applications. Such ideas might include better fluids, cheaper pipelines, low-cost insulations, or entirely new concepts.

Conclusions

Various thermal storage research and development activities have been conducted since the mid-1970s. In the sensible heat area, significant progress has been made. Laboratory experiments to study storage media stability and containment, and large-scale SREs to study storage performance, have been successfully completed for several storage concepts. Although system experiments that use these concepts for electrical power and cogeneration applications have been constructed, more testing remains to be done. At this stage, the main impediment to the commercial use of sensible heat storage appears to be cost. Technologies such as molten nitrate salts must be developed to reduce these costs.

In the latent heat area, salt stability and containment tests have also been carried out, and small-scale experiments have been performed to evaluate storage performance. These experiments identified areas for further work—in particular, a low-cost, effective means for getting the energy into or out of the storage medium. Several approaches that address this issue are under study, but the outlook for their success is still uncertain.

To date, the DOE thermal storage program has emphasized developing applications that require temperatures under 538°C (1000°F) and capacities of 1 to 6 hrs. Much work remains to be done for applications requiring (a) buffer storage with capacities less than one hour, e.g., dish-mounted engines for power generation; (b) storage temperatures above 538°C (1000°F), e.g., Brayton-cycle power generation; and (c) large-capacity storage, e.g., fuels and chemicals production or baseload power generation. However, since the DOE program is currently experiencing severe budget cuts, a large portion of the needed development will have to be funded through the private sector.

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