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# Overview of the SERI Solar Energy Storage Program

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# OVERVIEW OF THE SERI SOLAR ENERGY STORAGE PROGRAM

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## ABSTRACT

This paper gives an overview of the Solar Energy Storage Program at the Solar Energy Research Institute. The program provides research, systems analyses, and economic assessments of thermal and thermochemical energy storage and transport. Current activities include experimental research into very high temperature (above 800°C) thermal energy storage and assessment of novel thermochemical energy storage and transport systems. The applications for such high-temperature storage are thermochemical processes, solar thermal-electric power generation, cogeneration of heat and electricity, industrial process heat, and thermally regenerative electrochemical systems. The research results for five high-temperature thermal energy storage technologies and two thermochemical systems are described.

## INTRODUCTION

Within the thermal energy storage program of the DOE Division of Energy Storage Technology, the Solar Energy Research Institute has the lead responsibility to conduct systems analyses, assessments, and research in thermal and thermochemical storage and transport for solar thermal power and process heat applications. The overall objective of the solar energy storage program at the Solar Energy Research Institute is to develop cost-effective advanced thermal energy storage and transport technologies for use in solar-powered systems to make such systems cost-competitive with fossil-fuel-powered systems in the 1990-2010 time frame. The emphasis of the program is on thermal energy storage for solar thermal power and process heat applications and on thermal energy transport. In 1982 our research was redirected from lower-temperature storage to high-temperature (above 800°C) storage and associated direct-contact heat exchangers as a result of value and cost analyses performed in prior years (Refs. 1, 2, 3). We also identified new areas for thermochemical energy storage and transport that have considerably greater energy densities than previously studied systems.

The rationale for focusing the research on storage at temperatures above 800°C is that (1) high-temperature storage provides a good potential for significant conservation of premium fossil fuels; (2) systems below 600°C are already fairly well developed; (3) high-temperature storage represents high-risk, high payoff research not likely to be sponsored by industry; and (4) high temperature is the direction of the solar central receiver work within the DOE Solar Thermal Technology Division for improved energy conversion efficiency and our storage program is partially in support of their work. The high-temperature thermal storage systems offer the potential for 30% cost reduction for solar hydrogen production (Ref. 4) and for 12% cost reduction for solar electric power generation (Ref. 5).

The applications for high-temperature (above 800°C) energy storage are (1) thermochemical processes, such as fuels and chemicals production; (2) solar thermal-electric power generation topping cycles using turbine equipment; (3) cogeneration of heat and electricity; (4) industrial process heat, such as cement and glass production and petroleum refining; and (5) thermally regenerative electrochemical systems.

## SYSTEM ANALYSES

The choice of storage technologies for advanced research is based on value and cost analyses. Value calculations have been made for both electric power generation applications (Ref. 1) and industrial process heat applications (Ref. 2). The value for a given application represents a cost goal. Storage concepts are then assessed relative to these cost goals using a consistent costing methodology and taking into account the performance of each system (Ref. 6).

The costs of a number of advanced storage concepts have been estimated. Some of these systems for which the original cost estimates compared favorably with the value were then selected for research either in-house by the Solar Energy Research Institute or under subcontracts. This research included concepts having storage temperatures ranging from 385°C to 1450°C. The storage technologies covered by this research are shown in Table 1. The cost data in the table are the latest projections based on the costing methodology described in Ref. 3. In some cases these projections are considerably higher than the original projections. Consequently, in FY 1983 we have abandoned research on concepts that have value-to-cost ratios below unity.

The results of the work on the abandoned concepts are given in Ref. 7. Here I will describe the status of those concepts for which research was continued in FY 1983.

## ADVANCED RESEARCH IN THERMAL ENERGY STORAGE

### High-Temperature Molten Salt Storage

The objective of this project is to research key issues in advanced, high-temperature molten salt thermal storage. Systems analyses at SERI have shown that high-temperature (800° to 1100°C) molten salts are potentially attractive as both receiver coolants and storage media, but they may require direct-contact heat exchange, new kinds of storage tank insulation, and new ways to maintain a sharp thermocline (Ref. 4). The salts could be sodium hydroxide, carbonates, or chlorides. They are all inexpensive and stable up to 1100°C. Other storage media candidates are

Table 1. **Value-to-Cost Ratio for Advanced Thermal Storage Concepts with Appropriate Advanced Central Receivers**

| Storage Technology | Storage Capacity (hours) | Application | Value ($/kWh$_t$) | Cost ($/kWh$_t$) | Value/Cost Ratio |
|---|---|---|---|---|---|
| Molten slag | 6 | electric power | 20-25 | 28 | 0.7-0.9 |
| High-temperature molten salt | 6 | electric power | 25 | 20 | 1.2 |
| Draw salt/air rock[a] | 48 | process heat | 10-20 | 6.7 | 1.5-3.0 |
| Phase-change salt/ ceramic pellets | 1-15 | process heat | 20 | 25-30 | 0.7-0.8 |
| Metal/phase-change salt | 1-15 | process heat | 20 | 10 | 2 |

a) With direct-contact heat exchanger. Draw salt: $KNO_3$ + $NaNO_3$.

silicates, sulfates, and boron oxide. Applications for solar thermal-electric power generation using combined energy conversion cycles have been identified for maximum temperatures ranging from 900° to 1100°C.

The problems with such high-temperature salt storage are how to contain the hot storage medium, how to achieve high storage efficiency, and how to accomplish the containment and high efficiency in a cost-effective manner. The approach to solving these problems is to use a single-tank thermocline storage subsystem, submerged internal insulation, and an insulating platform floating at the thermocline between the hot and cold salt. Because of the internal insulation, this approach allows use of a low-cost structural container at a 1100°C salt temperature. The design is such that at a 2% daily heat loss, the temperature drop through the insulation, results in a tank wall temperature of 350°C. In one design concept, the internal insulation is porous to reduce the insulation weight and cost. Trapped molten salt acts as insulation in its own right. There are a number of potential mechanisms that tend to degrade a thermocline (Ref. 8). At the high temperatures involved here, there is also a radiation exchange from the hot salt and wall insulation at the top of the tank to the cooler salt at the bottom. Many of these degradation mechanisms are eliminated or reduced by the use of a floating insulating platform between the hot and cool salt regions. The platform is intended to ensure a sharp thermocline and thus high storage efficiency.

In FY 1983, two of the key issues were addressed: dynamic stability of a free-floating platform (raft) and compatibility between various molten salts and candidate insulation materials. The raft must follow the interface of the hot and cold fluids and be stable at all states of charge and discharge. Such a device has not previously been demonstrated in practice. The structural and insulating materials must be compatible with the molten salt since they are in direct contact. Three mechanisms could cause incompatibility: chemical reactions, corrosion, and solution. The need for a long life and minimal replacement costs permits only very low rates of material degradation (Ref. 5).

During FY 1983 dynamic stability tests were performed on rafts floating in a water themocline. Water was used to minimize costs for the initial feasibility tests. Stability tests were done for various fluid inlet duct locations and for a range of Richardson numbers. The thermocline effectiveness was also determined for three rafts having a range of thermal resistances. The thermocline effectiveness did not vary significantly as a function of raft thermal resistance. In all cases the effectiveness of the thermocline was equal to or better than that of a natural thermocline (Ref. 9). Raft experiments using a molten salt are planned for FY 1984 now that the concept feasibility has been established.

Sixteen metal alloys and eight ceramic materials were tested for corrosion. Coupons of these materials were exposed at 900°C for up to 96 hours to molten sodium hydroxide; up to 384 hours to a low-melting-point mixture of Na, K, and Mg chloride; and up to 144 hours to eutectic sodium-potassium carbonate. None of the materials were compatible with the sodium hydroxide. None of the metal alloys were compatible with chloride, but all ceramics showed minimal corrosion rates in the chloride. Also, none of the metal alloys were compatible with carbonate, but selected ceramics, viz., 99.8% $Al_2O_3$, $ZrO_2$, and high alumina fused-cast materials with $Na_2O$ (3.9% and 5.6%), corroded minimally in the carbonate (Ref. 10).

### Draw Salt/Air Rock Energy Storage

Research was initiated in 1982 for molten nitrate salt storage at 550°C in combination with air/rock storage, where the heat is transferred from the molten salt to the rock using an air loop. The objective of the research in FY 1983 was to reduce the heat-transfer-related costs of such thermal energy storage systems. Direct-contact heat exchangers were believed to have cost advantages over conventional finned-tube indirect heat exchangers and would be used to couple short-term molten salt storage to longer-term air/rock storage to obtain long-duration storage (Ref. 11).

A second use for such direct-contact exchangers would be in very high temperature (800° to 1100° C) molten salt receiver/storage systems using molten carbonate salt. Analyses have shown that these systems can produce electricity for 12% lower cost than nitrate salt systems (Ref. 5). At these high temperatures, the direct-contact exchangers would compete even more favorably with conventional heat exchangers because conventional exchangers would need ceramic tubes, which are expensive and difficult to fabricate. The expected cost differences are so great that they would have a direct bearing on the system practicality (Ref. 12).

In FY 1983 we conducted experiments to determine the volumetric heat transfer coefficients between molten nitrate salt and air. The experiments were conducted using two types of packings (Rashig rings and Pall rings) for a range of air and salt flow rates. It was found that the heat transfer coefficient is independent of the salt flow over the range investigated but is a power function of the air flow. The Pall rings had a considerably lower (approximately one-half) pressure drop than the Rashig rings for corresponding air flow. Heat transfer coefficients in the range of 1800 to 3500 $W/m^2\ ^\circ C$ were measured. An economic analysis, using the experimentally obtained heat transfer coefficients, showed that direct-contact heat exchangers would cost one-half to one-fifth the cost of corresponding finned-tube heat exchangers, depending on the operating temperature, for the range of 360° to 800° C (Ref. 13).

### Metal/Phase-Change Salt Heat Exchange and Energy Storage

This system is described in detail in Ref. 7. Construction of experimental equipment was completed in FY 1983 and heat transfer measurements will be conducted in 1984. A subcontract for such measurements was awarded in June 1983.

## THERMOCHEMICAL ENERGY STORAGE AND TRANSPORT

Two areas of potentially cost-effective thermochemical energy storage and transport of high-quality thermal energy were identified in FY 1982: (1) carbon dioxide splitting for open-loop carbon monoxide transport, and (2) thermochemical heat pumping using the strong exothermic reaction of molten anhydrous materials with water. Previously assessed thermochemical transport systems all had energy densities of 11 to 13 $MJ/m^3$. These systems were not as cost-effective as molten draw salt transport for distances up to 50 km. However, they are cost-effective relative to fossil fuel systems using natural gas or residual oil at medium to high fuel cost escalation rates (Ref. 14). A reduction in cost by a factor of 2 would make thermochemical transport systems more cost-effective than molten draw salt for short transport distances.

Carbon monoxide has an energy density of 56 $MJ/m^3$, which is a factor of 4.3 to 4.6 higher that the systems previously studied. Furthermore, carbon monoxide transport would potentially require a lower capital investment than the other systems studied. The exothermic portion of the chemical plant is eliminated and only a one-way pipeline is required, whereas a two-way pipeline is needed for closed-loop systems. Finally, very high temperature heat (above 1500° C) is available from combustion of carbon monoxide.

The low-temperature chemical heat pump system under study is shown in Figure 1. This system can be used for either storing or transporting solar energy. We initially investigated simple hydration reactions; e.g., solutions of hydroxides in water. Heat is generated by mixing a hot concentrated hydroxide solution with steam under vacuum conditions①.

The heat of hydration causes a temperature rise, followed by heat removal to the industrial user②. The reactor is a heat exchanger with staged hydroxide addition. The user heat transfer fluid is heated in the heat exchanger. Heat is generated by the reactor from three sources: (1) hydration of the hydroxides, (2) cooling of the hydroxides (sensible heat), and (3) condensation of the steam used to hydrate the hydroxide (latent heat).

Such a heat pumping system has high energy densities (1.8-2.2 $GJ/m^3$) because the system is liquid rather than gaseous; low capital costs because the reactors are simple heat exchangers and the liquid system requires small equipment; and very high thermal efficiencies, in excess of 100% when the heat pumping effect is included.

In FY 1983, the $NaOH-H_2O$ hydration-dehydration system was studied for production of up to 50 psig saturated steam. Analysis indicates that the $NaOH-H_2O$ heat

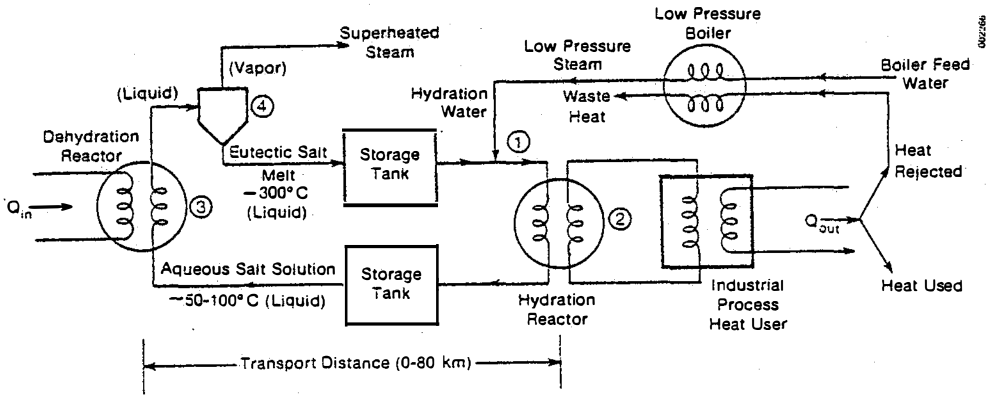

Figure 1. Generic Heat Pump for Thermochemical Energy Storage and Transport

pumped solar system produces atmospheric-pressure steam at a lower cost than a conventional hot oil solar system, whereas the hot oil system is more cost-effective for 50 psig steam production. The analysis was made for 1000 lb/h steam production and indicated that the NaOH-$H_2O$ system scales up economically more favorably than the hot oil solar system. Work is underway to identify and analyze high-temperature heat pumped systems. One system under consideration involves reactions of CaO, $Ca(OH)_2$, and phenol. This system is similar to the CaO, CaOH, and $H_2O$ systems previously analyzed, but it should be much more efficient and may be substantially more cost-effective. These studies have shown that an increase in efficiency significantly affects cost-effectiveness by reducing the size of the solar collector field (Ref. 15).

Work is underway to identify and analyze thermochemical systems to reduce carbon dioxide to carbon monoxide. The literature has been thoroughly reviewed and several processes have been appraised as technically feasible. Work is continuing to determine which processes are economically feasible and what experiments are required to validate the processes on a small scale.

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## PROJECT SUMMARY

**Project Title:**

SERI Solar Energy Storage Program

**Performing Institution:**

Solar Energy Research Institute
1617 Cole Blvd.
Golden, Colorado 80401

**Project Manager:**

Werner Luft, (303) 231-1823

**Project Objectives:**

The overall objective of this program is to gain a better understanding of advanced thermal energy storage and transport technologies and obtain information that allows developers to select the most promising thermal energy storage technologies. The emphasis of the program is on thermal energy storage for solar thermal power and process heat applications and on thermal energy transport. Research is performed on direct-contact heat exchange, thermocline maintenance, and thermochemical storage and transport processes to provide a basis for the selection of these promising technologies.

**Project Status:**

Experiments have been performed on direct-contact heat exchange between molten salt and air at 350°C for various packings and on a raft method of thermocline maintenance. Screening tests of 16 metal alloys and 8 ceramic materials have been performed to establish the compatibility with NaOH and carbonate and chloride salts at 900°C. Analyses have been completed of the economic and technical potential of thermochemical energy storage and transport.

A subcontract has been awarded to make heat transfer measurements for direct-contact heat exchange between molten salt and molten metal.

**Plans and Objectives for FY 1984:**

The objectives for FY 1984 are to investigate (a) technologies for thermal storage above 800°C to meet the needs for process heat applications, electric power generation, and the manufacture of fuels and chemicals; (b) associated direct-contact heat exchange; and (c) thermochemical transport and storage of thermal energy.

**Major Publications Related to Project:**

Luft, W. et al.: "SERI solar energy storage program: FY 1982 annual report." SERI/TR-231-1876, Golden, Colorado, Solar Energy Research Institute, March 1983.

**Contract Number:**

EG-77-C-01-4042

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Department of Energy, Division of Energy Storage Technology

**FY 1983 Funding:**

$850,000.