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ABSTRACT

This paper presents a preliminary technical and economic analysis of various concepts for sensible heat storage at a temperature of 900°C.

INTRODUCTION

To make solar-thermal-energy systems, such as central receivers for power generation, viable, it is generally recognized that they must contain an energy storage subsystem. Copeland et al. (1) have made preliminary cost estimates for some high-temperature molten salt storage concepts. As shown in Figure 1, this work suggests that molten carbonate salt storage may have economic potential in power-plant-scale systems. Some early concepts for molten salt containment, such as an internal metal honeycomb (1), have not been feasible because of their high metal corrosion rates (2). Work is continuing at SERI to generate new molten salt containment concepts and to make preliminary economic and technical analyses to identify candidates for further research.

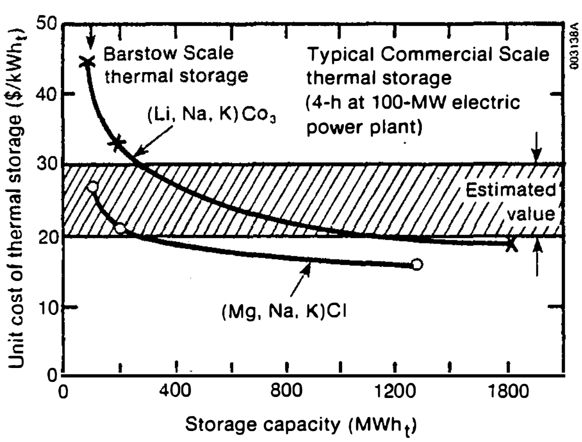

Figure 1. Projected Cost of Molten Salt Thermal Storage in Solar Thermal Applications

REQUIREMENTS AND DESIGN CONDITIONS

Early studies established some system design and performance criteria for thermal energy storage(1). A nominal maximum thermal storage temperature of 900°C was selected in consideration of power-generation efficiency, material properties, solar thermal collector performance, etc., but higher temperatures could be used if materials permit. Molten salts seem to be the storage medium with the fewest associated problems. Among these, alkali-metal carbonate salts show the most promise when cost and corrosiveness are taken into account (3). The lithium-sodium-potassium carbonate eutectic mixture (approximately 1/3 wt. fraction each) is recommended because of its low melting point (397°C), good stability at higher temperatures, and relatively low corrosiveness. With this salt mixture, a lower operating temperature of 425°C is attainable, providing a 425°C to 900°C overall temperature swing. A storage capacity of 1800 MWh_t (e.g., 300 MW for 6 hours) was selected and a heat-loss rate of 2% per day (36 MWh/day, 1.5 MW) was specified. The quantity of Li-K-Na eutectic required for this capacity is about 7.5×10^6 kg (8.2×10^3 tons). The volume of the medium is thus about 3.6×10^3 m^3 with tank dimensions of approximately 6.6 m in depth by 27 m in diameter for a cylindrical storage vessel.

GENERAL STORAGE TANK CONFIGURATION

There are two generic types of thermal storage tank designs: a two-tank system, with one tank for the hotter fluid and a second for the colder fluid; and a single-tank, thermocline system, wherein the density difference between the hot and cold fluids inhibits convective mixing and heat transfer. Thermocline storage has been proven for lower temperature systems (4), but a unique problem occurs with thermoclines at higher temperatures because radiant heat transfer becomes significant and a natural thermocline of a transmitting liquid provides no radiant transfer resistance. Two ways of reducing radiant transfer and maintaining a thermocline are proposed: a "raft," which uses a disc, impervious to radiation, with a density between that of the hotter and colder storage liquid so that it floats between them; and a dual-media system consisting of a packed bed of nontransparent solid particles with the liquid medium occupying the interparticle voids. The dual-media concept has been used as phase change thermal storage at temperatures up to 500°C (5), whereas the raft concept has been demonstrated only at near-ambient conditions (4).

Figure 2 shows a sketch of the general features of a raft-thermocline, molten salt system. The internal volume, the roof structure, and the insulation would be similar for each of the concepts. The floor, foundation, and the water-cooled layer also could be about the same for each concept so long as care is taken in the design to prevent higher temperature (above ~500°C) fluid from contacting these components. The sidewall design appears to have the strongest influence on containment cost and feasibility. The materials' strength at the operating temperature, corrosion resistance, and cost are the key factors. There have been some preliminary corrosion studies at 900°C (2), but more corrosion information is required.

Work is in progress at SERI to identify the most promising concepts for further research. This work considers corrosion resistance, strength at temperature, reliability of performance of the technical concept, and cost. Some preliminary results from that work are presented in this paper.

DESIGN CONCEPTS

In this section, characteristics of each of the three general storage types--the raft thermocline, the two-tank system, and the dual-media thermocline--are discussed.

Raft Thermocline System

The general features of a raft thermocline system are shown in Figure 2. The particular sidewall design considered here is shown in Figure 3. This concept features an inner layer

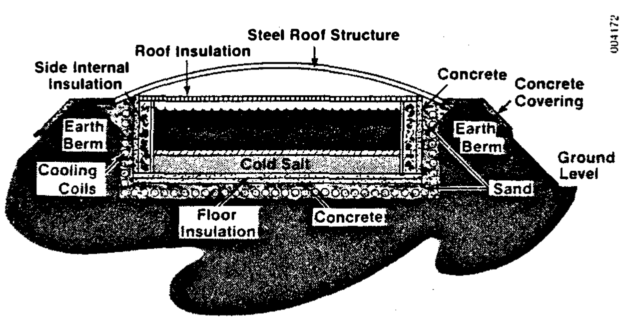

Figure 2. Raft-Thermocline, Molten Salt System

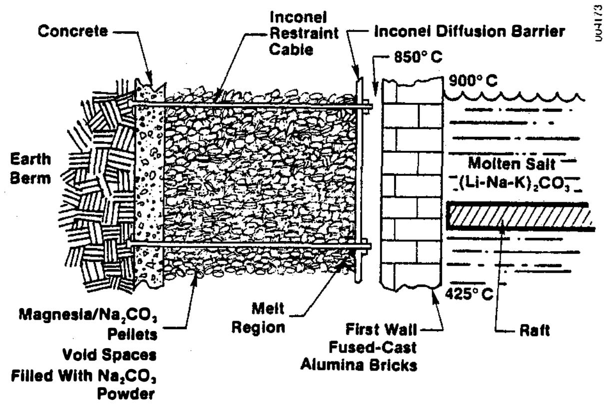

Figure 3. Sidewall Design Raft-Thermocline System

of high-purity, fused-cast-alumina bricks. This material appears to withstand 900°C molten carbonates, but it is very expensive (2). Across these insulating bricks the temperature decreases to below about 858°C (the melting point of sodium carbonate, a component of the insulation layer). The metal serves as a "diffusion barrier," not a structural member. The diffusion barrier consists of overlapping, but not joined, sheets of Inconel. These will inhibit, but not entirely prevent, movement of the molten salt into the next layer, a pelleted magnesia insulation. The vertical Inconel sheets are held in place by horizontal bars anchored in the outer structural wall. Sodium carbonate powder fills the voids between the magnesia pellets. As molten salt penetrates through the alloy diffusion barrier and into the magnesia/Na_2CO_3, it cools and dissolves Na_2CO_3 which increases the melting point. Thus, the salt will solidify after some distance, preventing further liquid penetration, and preventing further dissolution of sodium carbonate. The raft itself is envisioned to be similar in design to the sidewall but ballasted to float at the thermocline.

Table 1 shows results of some preliminary design and cost estimations for this concept. The values are approximate, but the results clearly indicate that the sidewall and raft are the dominant costs (~60%). In turn, the expensive fused-cast-alumina bricks contribute a major portion of these costs. Thus, it is desirable to avoid using this material.

The raft-thermocline concept has some other disadvantages. The raft concept has been demonstrated only in the laboratory at near-ambient conditions (4), but not for large-scale, high-temperature systems. So, there is an element of technical uncertainty regarding its performance. Also, in this design the sidewall is subject to frequent temperature cycling from 425°C to 900°C.

Table 1. Cost Summary for Raft Thermocline System

Item	Investment ($10^6$$)	Investment ($/kWh)	Percentage of Total
Sidewall	20.0	11.1	40.2
Raft	10.0	5.6	20.1
Top	3.4	1.9	6.9
Bottom	1.7	0.9	3.4
Medium	14.6	8.1	29.4
Total	49.7	27.6	100.0

Two-Tank System

The two-tank system uses one tank for high-temperature, 900°C, molten salt storage and a second for low-temperature, 425°C, storage. The major advantage is that the hot and cold fluids do not come in contact and do not exchange heat. Disadvantages are that two separate tanks of equal volume are required and that the sidewalls of both tanks are subjected to frequent pressure cycles, alternating between contact and no-contact with molten salt. Temperature cycling is not nearly as severe as with the other concepts.

The overall vessel design would be similar to that shown in Figure 2. The particular sidewall and bottom design considered is shown in Figure 4. A water-castable-alumina insulation is the basis of the sidewall. An outer concrete or steel wall provides the structural strength. The alumina is separated from the molten carbonate by an Inconel liner. The liner bears no load. The bottom layer is magnesia powder over a waffeled (for thermal expansion) Incoloy liner at 550°C. The Inconel and Incoloy can be joined (e.g., welded) near the bottom, below the solidus-line. The bottom is protected from high-temperature molten salt by having the hot-salt inlet and draw-off located above the bottom insulation.

Results of a preliminary analysis of the two-tank system are given in Table 2. Although the values are approximate, they do indicate that this hot-tank sidewall concept is less expensive than that used with the raft-thermocline in Table 1 or than the design for the dual-media considered later in Table 3. An equivalent wall design for the raft-thermocline or dual-media designs would then reduce their costs substantially. The results also show that the second, cold-fluid, tank contributes a significant amount (nearly 24%) to the total cost.

Dual Media System

The use of a solid packing as a second storage medium with a liquid is employed in the Solar One plant (300°C). This approach offers the advantages of a proven concept for maintain-

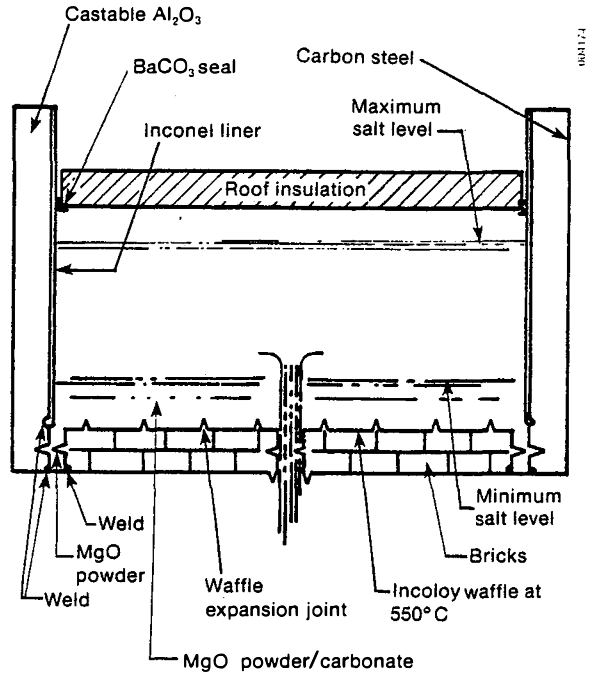

Figure 4. Sidewall and Bottom Design for a Two-Tank System

Table 2. Cost Summary for Two-Tank System

Item	Investment ($10^6$$)	Investment ($/kWh)	Percentage of Total
Hot Tank			
Sidewall	7.7	4.3	21.4
Top	3.4	1.9	9.5
Bottom	1.7	0.9	4.7
Medium	14.6	8.1	40.7
Cold Tank			
Sidewall	3.4	1.9	9.5
Top	3.4	1.9	9.5
Bottom	1.7	0.9	4.7
Total	35.9	19.9	100.0

Table 3. Cost Summary for Dual-Media System

Item	Investment ($10^6$$)	Investment ($/kWh)	Percentage of Total
Sidewall	13.9	7.7	41.9
Top	3.4	1.9	10.2
Bottom	1.7	0.9	5.1
Media	14.2	7.9	42.8
Total	33.2	18.4	100.0

ing a thermocline plus the suppression of radiant transfer so long as the solid is non-transparent In addition, the solid is often cheaper than the fluid medium (per unit of energy stored) and thus may offer a cost advantage as well. On the other hand, a solid must be found for this application that can withstand the molten salt at temperature, and such a material could be more expensive than the fluid. The solid medium, as well as the tank sidewall, is subject to frequent, large temperature changes and large gradients.

A potential sidewall design for the dual-media case is shown in Figure 5. An inner Inconel labyrinth seal (plates similar to the diffusion barrier of Figure 3) permits molten salt movement into a first layer of insulation consisting of, for example, magnesia pellets.

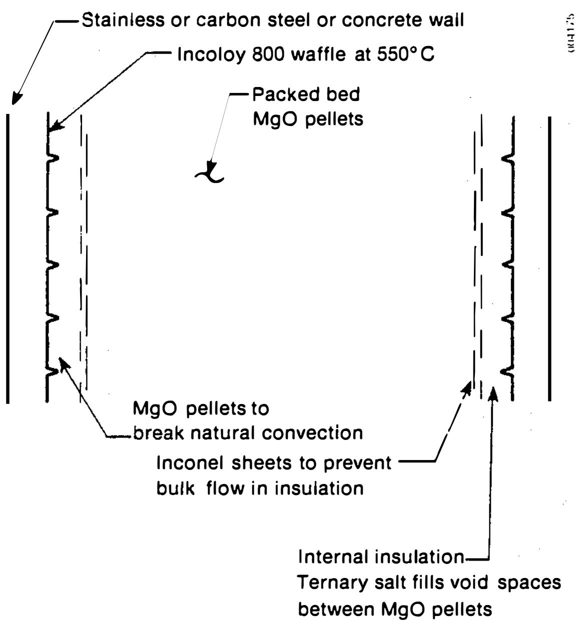

Figure 5. Sidewall Design for a Dual-Media System

The liquid can move into the magnesia, but the inconel barrier and the pellets inhibit liquid convection. The temperature is reduced to, say, 550°C through this layer. There is then a waffeled Incoloy barrier backed by silica insulation and a load-bearing wall. The solid packing in the bed is magnesia pellets (or other suitable material such as alumina). Such pellets have been fabricated and used at up to 800°C (5). Their stability in the carbonate salts at 900°C must be tested.

SUMMARY

Three concepts for thermal energy storage at 900°C--a raft-thermocline system, a two-tank system, and a dual-media thermocline system--are discussed, and design and performance criteria for these systems are presented. Preliminary design and cost analyses for three particular designs are included. Although they are by no means definitive, they do suggest the following:

- The use of high-purity alumina insulations should be avoided because of their high cost;
- Roof and floor costs are similar for each of the concepts;
- A two-tank system will be more expensive than one tank if a similar sidewall design is used for both;
- In the dual-media design, the solid magnesia pellets cost about the same as eutectic salt per unit of energy storage;
- An Inconel liner over cast-alumina insulation appears to be the most cost-advantageous sidewall design so far considered.

In this study the cost of construction was estimated by first determining the material mass requirements for the system based on corrosion and thermal properties and then multiplying them by the unit cost of each component. The materials cost was then multiplied by a construction cost factor of 1.8, media cost was added, and this total was multiplied by an investment factor of 1.95 to obtain the total capital investment (6). The material properties and their costs are shown in Table 4. A report documenting the summary presented here will be prepared in the near future, but it should be noted that more work is required to identify, design, and estimate the cost of the most promising concepts. The information needed includes the following:

- Stability and corrosion resistance of metals and ceramics exposed to carbonate-salt eutectic at 900°C and exposed to temperature or wet-dry cycling;
- Reliable cost estimates for fabricated metal alloys and ceramics;
- Performance reliability of a large raft at high temperature.

Table 4. Materials Properties and Costs

Metals	Approx. Max. Useful Temp. with Carbonates °C	Price, $/hg June 1980 Basis (6,7)
C-Steel	300	1.43
Stainless		
Steel-304	350	5.50
-316	400	8.80
Incoloy 800	550	11.00
Inconel	900	17.60
Ceramics	**Approx. Thermal Conductivity, J/S•m•k, (5,10)**	**Price, $/hg June 1980 Basis (5,8,9)**
Magnesia Powder	0.9	0.33
Magnesia Pellets	1.0	0.66
Magnesia Brick	2.4	1.10
Water-Cast Alumina	1.7	1.32
Fused-Cast Alumina	1.9	26.00
Medium		
Li-K-Na Carbonate Eutectic Salt	--	1.03 (6)

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