SERI/TP-252-2569
UC Category: 62a
DE85000534

High Temperature Sensible Heat Storage Options

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November 1984

Prepared for the
Solar Energy 1985 ASME/ASES Conference
Knoxville, Tennessee
25-29 March 1985

Prepared under Task No. 4253.11
FTP No. 455

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401

Prepared for the
U.S. Department of Energy
Contract No. DE-AC02-83CH10093

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price:
Microfiche A01
Printed Copy A02

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ABSTRACT

Alkali-metal carbonate salts meet the requirements for high temperature solar central receiver systems, but due to their corrosiveness, special problems arise in the design of storage tanks. In particular, to reduce corrosion and temperature sufficiently to retain strength in the containing wall, internal thermal insulation is required. This paper presents design options and operation criteria for sensible heat molten salt storage with internal insulation.

INTRODUCTION

An energy storage subsystem is important for the continuous operation of solar central receiver systems[1]. Copeland et al.[2] identified a potentially large industrial market for solar systems able to deliver heat at approximately 900°C, preliminary cost estimates for some high-temperature storage concepts were also made, and established system design and performance criteria. Using a nominal thermal storage temperature of 900°C and considering power generation efficiency, material properties, solar thermal collector performance, and other issues, they concluded that molten salts are the storage medium with the fewest technical problems and among them alkali-metal carbonate salts show the most promise when cost and corrosiveness are taken into account. The lithium-sodium-potassium carbonate eutectic mixture (approximately 1/3 wt. fraction each) was selected for this study 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 for sensible heat storage.

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 or a single-tank, thermocline system, in which the density difference between the hot and cold fluids inhibits convective mixing and heat transfer. Thermocline storage has been proven for lower-temperature systems,[3,4] but a unique problem occurs with thermoclines at higher temperatures because radiant heat transfer becomes significant. Transparent liquid salt offers no resistance to radiant transfer, and radiation between a hot ceiling and a cooler bottom can induce convection currents that destroy the thermocline. Two ways of reducing radiant transfer and maintaining a thermocline are: a "raft" that uses a disc and is impervious to radiation with a density between that of the hotter and colder storage liquid so that it floats between them, and a two-media system consisting of a packed bed of nontransparent solid particles with the liquid medium occupying the interparticle voids. The two-media concept has been used at Solar One, the 10 MW_e central receiver power plant in Barstow, Calif., at temperatures up to 300°C[4] and as phase change thermal storage at temperatures up to 500°C[5], whereas the raft concept has been demonstrated only at near ambient conditions[6].

A study has been conducted at the Solar Energy Research Institute (SERI) to identify the most promising high temperature storage concepts, considering corrosion resistance, strength at high temperature, reliability of performance of the technical concept, and cost[6]. A summary of the material properties and costs used in this study are shown in Table 1. A storage capacity of 1800 MWh_{th} (e.g., 300 MW_{th} for 6 h) was selected and a maximum heat-loss rate of 2%/day (36 MWh/day, 1.5 MW) was specified. The quantity of Li-K-Na eutectic required for this thermal capacity is about 7.5×10^6 kg (8.2×10^3 tons) and the volume of the medium is about 3.6×10^3 m^3 with tank dimensions of approximately 8 m in depth by 24 m in diameter for a cylindrical storage vessel. Corrosion measurements have been made for the materials used in the various designs and the available data are summarized in Refs. 2 and 6.

DESIGN CONCEPTS

In this section the characteristics of raft thermocline systems, two-tank systems, and two-media thermocline systems are discussed. Only one typical design for each system will be presented. Additional information can be found in Ref. 6.

Table 1. Properties of Materials for Molten Carbonate Salt Storage

Material	Density, ρ kg/m³ (× 0.062 = lb/ft³)	Thermal Conductivity k, W/m•K (× 0.578 = Btu/hr•ft•°F) @900°C unless noted	Heat Capacity Cp, kJ/kg•K (× 0.239 = Btu/lb °F) Mean, 400–900°C	Price $/kg
Refractories				
High Purity Alumina (99.8%)	3.8×10^3	12.1 @ 400°C 6.3 @ 800°C	1.2	5.5
High Purity Alumina Bricks, filled with MgO powder	2.9×10^3	4.1 (dry) 4.4 (wetted with carbonates)	--	3.5 ($10,000/m³)
Alumina Bricks (95.1%)	3.0×10^3	1.7	--	1.6
Magnesia (95.5)				
Bricks	2.6×10^3	2.3	1.25	1.1
Powder	2.3×10^3 (bulk)	2.0	1.25	0.33
Pellets	2.1×10^3 (bulk)	1.8	1.25	0.66
Concrete				
Ordinary structural concrete	1.9×10^3	1.4	--	0.072 ($135/m³)
Ordinary insulating concrete	0.8×10^3	0.33	--	0.45 ($360/m³)
Castable Refractory	1.2×10^3	0.27	--	0.57 ($680/m³)
Salt				
$(Na\text{-}K\text{-}Li)_2\ CO_3$ Eutectic	--	--	--	1.03
Insulations				
Mineral Fiber				
Blanket (200°C max.)	--	0.051 (100°C)	--	$9.5/m² (0.1m)
Board (980°C max.)	--	0.116 (400°C)	--	$25./m²×(0.1m)
Calcium Silicate Board (650°C max.)	$.58 \times 10^3$	0.126 (200°C)	--	$45./m²×(0.1m)
Diatomaceous Earth (1000°C max.)	--	0.13 (540°C)	--	$4.3/m²(0.1m)

Raft Thermocline System

The general features of a raft thermocline system are shown in Fig. 1. and a suitable sidewall design concept is shown in Fig. 2. This sidewall has an inner layer of high-purity, fused-cast-alumina bricks that can withstand 900°C molten carbonates, but is very expensive[7]. Across the insulating bricks the temperature decreases to below about 858°C, the melting point of sodium carbonate, which is 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 into the magnesia/Na_2CO_3, it cools and dissolves Na_2CO_3 and increases its 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.

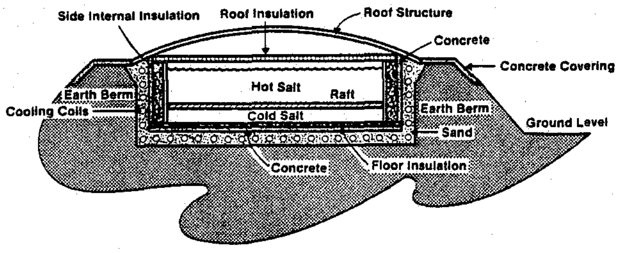

Fig. 1 Single-tank storage concept.

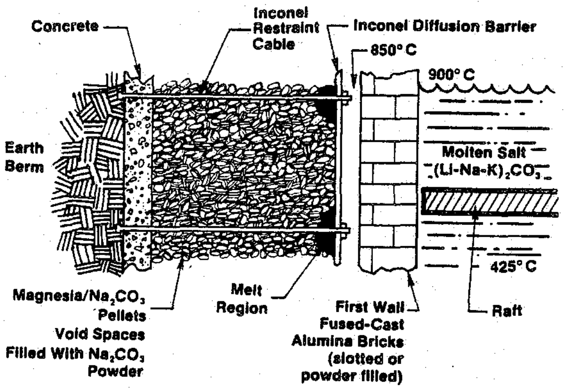

Fig. 2 Single-tank raft thermocline system with alumina bricks and pellet insulation.

Table 2 shows results of preliminary design and cost estimations for this concept. Optimistic and pessimistic refer to thermal performance and materials cost

Table 2. Cost Summary for Diffusion-Barrier Raft Thermocline System (Figure 2)

Optimistic

Item	Investment ($10^6$$)	Percentage of Total
Sidewall	9.6	31.0
Raft	3.1	10.0
Top	1.3	4.0
Bottom	0.4	1.0
Medium	16.3	54.0
Total	30.7 (17.1 $/kWh)	100.0

Pessimistic

Item	Investment ($10^6$$)	Percentage of Total
Sidewall	20.0	39.0
Raft	10.0	19.0
Top	3.4	7.0
Bottom	1.7	3.0
Medium	16.3	32.0
Total	51.4 (28.5 $/kWh)	100.00

assumptions. The values are approximate, but the results clearly indicate that the sidewall and raft are the dominant cost items. The expensive fused-cast-alumina bricks, in turn, contribute a major portion of these costs. It should be pointed out that the other two designs that will be presented later were done with the same approach and same basic data, so that the relative values are more dependable than absolute values. The cost does not include installation, operation, and maintenance expenses.

Two-Tank System

Two-tank systems use one tank for high-temperature molten salt storage at 900°C, and a second for low-temperature storage at 425°C. A major advantage of this design is that the hot and cold fluids do not contact each other 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. However, temperature cycling is not nearly as severe as with other concepts.

The overall vessel design is shown in Fig. 3 and the particular sidewall and bottom design considered is shown in Fig. 4. A water-castable-alumina insulation is the basis of the sidewall with an outer concrete or steel wall providing the structural strength. The alumina is separated from the molten carbonate by an Inconel liner which bears no load. The bottom layer is magnesia powder over a waffled (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.

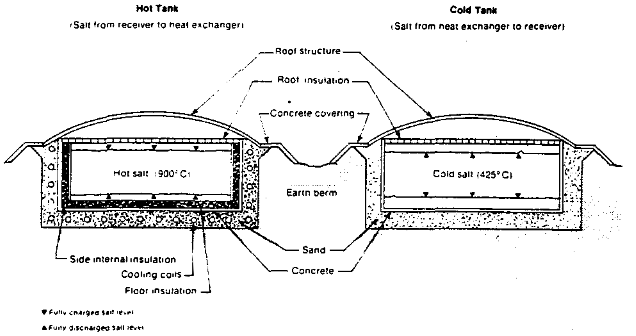

Fig. 3 Two-tank storage concept.

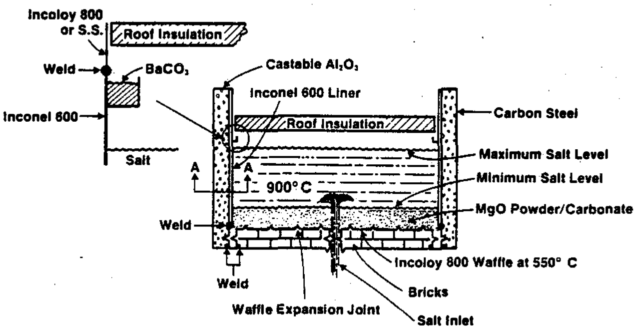

Fig. 4 Two-tank system with inconel-lined hot storage tank.

Results of a preliminary cost analysis for the two-tank system are given in Table 3. Although the values are approximate, they do indicate that the hot-tank sidewall concept in Fig. 4 is less expensive than that used with the raft-thermocline in Table 2. The results also show that the cold-fluid tank contributes nearly 7% to the total cost.

Two-Media System

In a two-media system solid packing is employed as a secondary storage medium with a liquid in the space between the solid particles. This approach is used in Solar One and is a proven concept for maintaining a thermocline which can effectively suppress radiant transfer when the solid is opaque. In addition, the solid may be cheaper than the fluid medium and thus this approach may offer a cost advantage as well. On the other hand, for high temperature applications a solid must be found that can withstand the molten salt at the operating temperature, and such a material could be more expensive than the fluid because the solid medium, as well as the tank sidewall, must withstand frequent, large temperature changes and large gradients.

The general features of a two-media storage system are similar to those shown in Fig. 1, but no raft is used. A schematic diagram which shows the details of the tank sidewall construction is given in Fig. 5. The inner Inconel sheets permit molten salt movement into a first layer of insulation consisting of, for example, magnesia pellets.

The liquid can flow into the magnesia, but the Inconel barrier and the pellets inhibit liquid convection. The temperature is reduced to about 550°C in this layer

Table 3. Inconel Lined Castable Refractory Two-Tank System (Figure 4)(pessimistic design only)

Item	Investment (10^6\$)	Percentage of Total
Hot Tank		
Sidewall	7.7	24.0
Top	3.4	11.0
Bottom	1.7	5.0
Medium	16.8	53.0
Cold Tank	2.0	7.0
Total	31.6 (17.6 \$/kWh)	100.0

which is surrounded by a waffled Incoloy barrier backed by silica insulation and a load-bearing wall. The solid packing in the bed may be magnesia pellets or some other suitable material, such as alumina. Such pellets have been fabricated and used at up to 500°C[5], but their stability in the carbonate salts at 900°C is not known.

A two-media tank design of particular interest is shown in Fig. 6. The container has the shape of the frustrum of a cone and is located within the ground, using earth as part of its foundation. An inexpensive carbon steel liner covers the MgO or Fe_2O_3 insulation powder to prevent the molten salt from entering the central bed section where the salt is mixed with the pellets. The thick, powder-insulation layer reduces the temperature sufficiently to permit use of a stainless steel shell between the powder and the outer sand layers. The advantage of the sloped-wall tank design is that thermal expansion may take place along the conical longitude.

The results of cost estimates for this design are shown in Table 4. Based upon initial laboratory tests, a 45° angle for the tank wall, called the angle-of-repose was used. The main costs, after the media, are for the magnesia powder insulation and the stainless steel liner. The difference between the optimistic and pessimistic cases is that the magnesia prices used in the optimistic case (\$0.33/kg for powder and \$0.66/kg for pellets) are half as much as in the pessimistic case. Thus, one sees the strong impact of the magnesia price on the capital cost of this design. Use of high-purity-alumina solid packing in high-void shapes, e.g., thin-wall cylinders, was also considered. This gave media costs which started at about the same level as the pessimistic case in Table 4-B and ranged upward. With information available at this time, a high uncertainty is associated with the solid medium cost.

A review of the cost estimates indicates that:

1. Pessimistic capital investment estimates are about 1.5 times as large as the optimistic ones for the tank plus storage media.

2. The cost of the sensible heat storage media is a significant portion of the total investment.

3. The raft-thermocline is significantly more expensive than the other concepts considered.

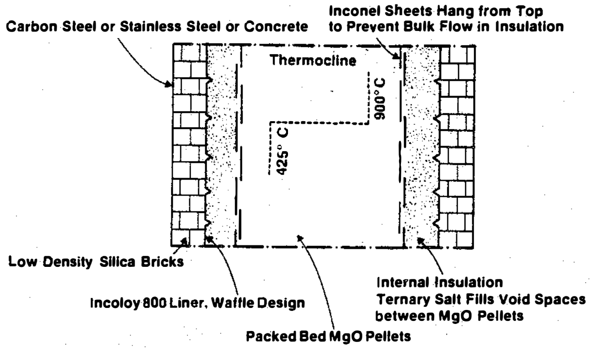

Fig. 5 Single-tank two-media thermocline system—cylindrical storage tank.

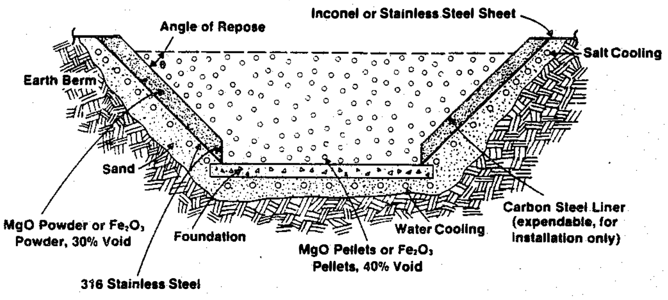

Fig. 6 Single-tank two-media thermocline system—conical storage tank.

4. The sloped wall, two-media system is the least expensive among the three concepts considered, but the difference is within the uncertainty of the estimates.

THERMAL ANALYSIS

General Consideration

The objective of the thermal analysis was to size the storage tank for the specified capacity and to prevent temperatures from exceeding safe limits at boundaries. The temperature limits depend upon the materials used in the design concept; they were 550°C at an Incoloy liner, 65°C at a concrete skin and 300° at a carbon steel skin. An analysis was made of heat loss and temperature distribution at the tank bottom to ascertain whether or not active water-cooling was necessary for foundation and soil protection. The efficiency of regenerative wall cooling with 425°C molten salt was also investigated.

The raft-thermocline and two-tank storage systems use only molten salt as storage medium. The minimum volume of salt required is the total energy stored, 1800 MWh (6.48 TJ), divided by the product of the mean heat capacity over the 425 - 900°C range, the density, and the temperature change (475°C) of the molten salt. Two percent additional salt was included to compensate for a two percent maximum rate of heat loss per day. But some additional salt is required because the thermocline itself takes some space and it is necessary to keep some 425°C salt in the bottom of a thermocline tank at all times, or to keep some 900°C salt in the

Table 4. Cost Summary for Sloped-Wall Two-Media System (Figure 6)

Optimistic

Item	Investment (10^6\$)	Percentage of Total
Sidewall	4.1	19.0
Top	1.5	7.0
Bottom	0.4	2.0
Media	15.4	72.0
Total	21.4 (11.9 \$/kWh)	100.0

Pessimistic

Item	Investment (10^6\$)	Percentage of Total
Sidewall	6.1	23.0
Top	1.5	4.0
Bottom	0.4	1.0
Medium	25.3	72.0
Total	33.3 (18.5 \$/kWh)	100.00

high temperature tank of a two-tank system. Four percent extra volume was allowed for these factors and three percent extra storage was allowed (as discussed later) when regenerative cooling was employed. Two-media storage requires that the average heat capacity and density of the solid pellets plus the eutectic salt in the bed be used. These were calculated using an estimated void fraction for the pellets and a averaged volume for the bed.

Since magnesia has a lower heat capacity per unit volume than molten salt, a larger storage tank is required for a system using salt and pellets than for a system using salt alone.

Initial calculations were based on an idealized "step-shaped" thermocline, with no heat transfer across it. Also transient effects were neglected. The optimistic assumptions were made for preliminary design and cost estimating; but in the final estimates 4% extra tank volume was allowed for. The rationale for this approach is discussed in the next section.

The heat loss rate of 2% per day is an average design value. On the average the storage tank will be filled with 900°C liquid for less than half the time of each day because even under favorable conditions the time required to thermally "charge" the tank is of the order of 9 hours while the discharge time is about 6 hours.

The hot tank of a two-tank system will always contain some hot liquid but will only rarely be quite full. The basis for the heat-loss calculations and insulation sizing is one steady-state 12 hour per day period with the tank full at 900°C and another 12 hour period with the tank full at 425°C. The insulation required is that which results in a daily average heat-loss rate equal to 1.5 MW. The actual situation is much more complex due to the transient nature of the conduction and due to thermal capacity, but since the above procedure is conservative, i.e., it over-estimates the insulation thickness required, it is satisfactory for design purposes.

The insulation-design procedure was to fix a required temperature difference (e.g., 900 to 550°C) and the heat-loss rate at that difference and then to calculate the insulation thickness required under quasi steady-state conditions to limit the heat loss to two percent of the maximum stored energy.

Regenerative Cooling

Since internal insulation materials are expensive any measures which can reduce the amount required are desirable. Regenerative cooling with 425°C molten salt is one such possibility. In this concept the heat transferred to the salt is not lost from the system, for the 425°C molten salt is returned to storage at a temperature slightly above 425°C. Regenerative cooling could be used with any of the tank design concepts, but it is only advantageous with the most expensive internal insulations and offers little advantage when there is a continuous metal liner in contact with the molten salt. An analysis to indicate when regenerative cooling might be useful was made under some simplifying assumptions.

The heat absorbed by the molten-salt regenerative coolant is not lost and although no additional energy needs to be collected, more liquid must be heated over a smaller temperature difference by the solar receiver. Moreover, it is necessary to provide additional storage volume, since more liquid at 900°C must be stored to make the same amount of heat available. Thus more capital is required because of the larger storage tank and the piping system for molten salt circulation while the investmanet is reduced because less internal insulation is needed. The extra storage tank investment was estimated from

Extra Capital Cost = (Rate of heat transfer to cooler salt) x (Capital Cost of storage)/(Rate of heat use from storage)

The hourly rate of heat use from storage was taken as the total energy stored divided by 12 hours. If heat were withdrawn from storage at a different rate, that would have some effect on this analysis. The capital cost of the storage tank was taken from preliminary storage investment estimates. Total capital cost of the pipe, the internal insulation, and the extra tank volume was approximately minimized with respect to the amount of heat absorbed by the cooler salt. It was found that regenerative cooling is cost effective when high-purity alumina brick insulation is used, but not for the other design concepts.

Bottom Insulation

A simple physical model was used to evaluate the thickness of the insulation layer on the tank bottom necessary to keep temperatures at specified values. The calculated thickness was then used as a guideline in deciding whether active cooling system in the foundation should be employed.

The foundation was assumed to be a semi-infinite domain, and the bottom of tank insulation, where heat loss to the ground occurs, was idealized as a "disk" heat source at a specified temperature. Little is known about soil or concrete properties at elevated temperatures and soil moisture trapped under the foundation may boil and produce unpredictable results. Thus, it was felt that the bottom of the insulation layer should be kept below 100°C, for safety. A certain thickness of insulation layer above this disk area is required to reduce temperatures from 900°C where the insulation is in contact with salt to 100°C across the layer. The tank was assumed to have a diameter of 24 m. A conservative estimate using 0.2 W/mK and 2 W/mK as the thermal conductivities of the insulation and foundation, respectively, yielded an insulation thickness of about 0.4 m.

Even in the case of a single tank system when the bottom tank temperature is about 425°C all the time, the required floor insulation thickness to prevent boiling in the foundation is over 2 m. Therefore, an active cooling system should be employed for the foundation in all tank systems.

Thermocline Stability

In estimating the volume required to store the specified amount of heat it was assumed that the actual thermocline would occupy approximately 4% of the tank volume. In order to verify the reasonableness of this assumption, calculations on the size of the thermocline were performed with a code developed by Sandia[8] for the design of the two-media cylindrical storage system used for the Solar One Power Plant, but using the best available property data for the carbonate salt working fluid and the magnesia pellets. The results of this calculation are displayed in Fig. 7 where the temperature distribution at various times after the hot fluid is introduced at the top is plotted against distance from the top in a cylindrical tank. Inspection of this figure shows that the thermocline in a carbonate molten salt-magnesia pellet, two-media storage system is sharper than for Solar One media due to the higher heat capacity of the carbonate salts and magnesia pellets[4]. On the basis of the calculations performed for the present design, the thermocline would occupy a height of approximately one meter or 12.5% of the volume. However, if we allow for a six percent temperature difference, less than 30°C on each side, the volume occupied by the thermocline is decreased by approximately a factor of three. Consequently, the assumption that the thermocline occupies roughly four percent of the volume appears to be reasonable.

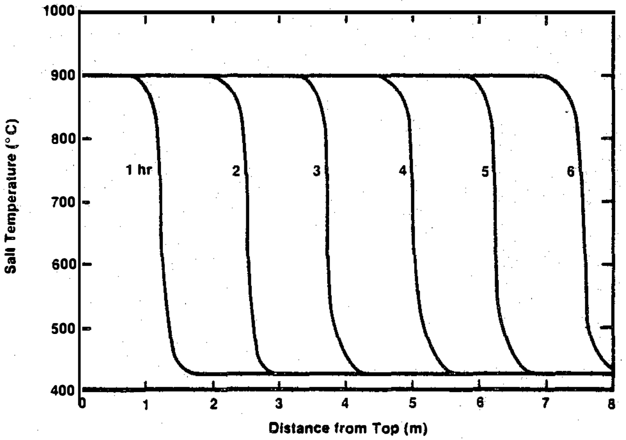

Fig. 7 **Molten salt temperature distribution in a packed magnesia-pellet bed.** Void fraction = 30%, pellet diameter = 2.54 cm., fluid superficial velocity = 0.03 cm/sec.

In a qualitative manner the effect of radiation is not expected to be appreciable, but it can be taken into account by increasing the thermal conductivity of the solid by an appropriate factor that accounts for a linearized radiation contribution. An estimate following the theory of radiative heat transfer through a participating medium[9] indicates that the equivalent radiative conductivity in a 1 m thick two-media zone and with a 475°C temperature difference between 900°C and 425°C is about 2 W/mK. This value is about the same as the conductivity through the media. Hence, to a first order approximation, both conduction and radiation can be neglected as compared to convective heat transfer.

DISCUSSION OF TECHNICAL RISKS

Risk Assessment

Table 5 summarizes the key design features, the cost estimates, as well as the technical risks in each of the designs covered in this study. This section will amplify on the remarks contained in the table.

Single-Tank Raft

The single tank raft concept (Fig. 1 and Fig. 2) was proposed to eliminate the effects of radiation in a thermocline system. Radiant heat transfer could result in significant heat losses and could destabilize a thermocline at a high-temperature. However, the raft concept turned out to be higher in cost than two-media or two-tank storage systems and the stability of the raft at higher temperatures for the large diameter (order 24 m) required is open to questions. Since there exist technical uncertainties with regard to the raft concept and the system appears to have no cost advantages, this particular idea does not appear to be promising.

Two-Tank Design Concept

The two-tank design concept displayed in Figs. 3 and 4. uses a castable alumina wall with an Inconel liner that is allowed to "creep" into position. However, there are no reliable data on the creep process and there is no adequate basis to design a tank for this concept. Consequently, the technical risk of this proposed design is unacceptably high and until this question is resolved, it is not recommended to pursue this design.

Single-Tank-Two-Media Systems

The two-media single tank concept is shown in Figs 5 and 6. A major technical risk in this concept is the integrity of the solid pellets in molten salts at 900°C which has not been demonstrated. In addition, there are also questions on thermocline stability which have been mentioned previously in this paper. The sloped wall concept has potentially a lower cost, because no expensive metal or ceramic liner is required. There also exists a question regarding the maximum permissible Rayleigh number because if that were to be exceeded, the insulation effectiveness of the media could be impaired by free convection currents set up across the thermocline region. The sloped wall concept has the advantage of ameliorating the effects of thermal expansion because the tank is not only constrained radially, but can expand freely along the top perimeter. Although the technical risks of the single-tank, two-media concept shown in Fig. 6 are high, because of the potential cost advantages of the sloped wall design, it is recommended that this concept be pursued. This concept is the least expensive of those considered here.

Table 5. Summary of Storage Tank Designs

Initial Design	Storage System	Design Features	Technical Risks or Disadvantages	Remarks	Cost Estimates			
					$10^6\$$		\$/kWh	
Figure					low	high	low	high
2	Single Tank Raft	Slotted or powder-filled alumina bricks, Inconel diffusion barrier	Very high cost in ceramic bricks Technical uncertainty about raft stability	Not recommended	30.7	51.4	17.1	28.5
4*	Two-Tank	Castable alumina wall, Inconel liner creeped into position, use $BaCo_3$ powder to solidify salt	No reliable data on creeping process	Not pursued		-31.6	-17.6	
6	Single Tank Two-Media	Sloped wall design, powder insulation, carbon steel liner	Integrity of solid pellets is a key question Slope stability of wall-powder insulation is uncertain		21.4	33.3	11.0	18.5

*Design concept for hot tank only. No internal insulation requirement for cold tank. Cost estimates include cold tank.

CONCLUSIONS AND FUTURE WORK

Three concepts for thermal energy storage at 900°C, a raft-thermocline system, a two-tank system, and a two-media thermocline system are discussed in this paper, and design and performance criteria for these systems are presented. Preliminary design and cost analyses for the three concepts indicate that:

1. Regenerative cooling is worthwhile when high-cost, high-purity alumina brick insulation is used, but not for the other design concepts.
2. Active cooling under the tank is necessary to reduce the need for solid insulation and prevent boiling in the ground in all concepts.
3. A thermocline is stable in a two media system according to an analysis that considers convective heat transfer only.
4. The single-tank raft system concept has technical uncertainties and the highest cost of the three systems.
5. The use of high purity ceramic brick internal insulation results in excessive cost.
6. The two-media single tank with sloped walls, shown in Fig. 6

has the potential of being the lowest cost system.

The following questions should be answered to remove technical uncertainties.

1. The compatability of the sensible heat storage solids with the molten salt in a two-media hot tank should be studied more thoroughly.
2. The stability of the insulated sloped wall should be further studied. On the basis of preliminary measurements it has been assumed that the angle of repose is 45°, but very little is known about this concept, especially in a molten salt at elevated temperatures.
3. The wet insulation layers must be designed in such a way that natural convective heat loss, due to circulation and heat conduction thorugh the insulation from above to below the thermocline inside the insulation can be suppressed. Experiments to provide design guidelines under high temperature conditions are recommended.
4. The effect of conduction and radiation on the stability of a thermocline should be analyzed rigorously. Also, the effect of sloped walls on the shape and the temperature distribution of thermoclines should be investigated.

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