SERI/TR-252-2490
DE85012152

May 1985

High Temperature Molten Salt Containment

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P. P. Lynn

Solar Energy Research Institute
A Division of Midwest Research Institute

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Operated for the
U.S. Department of Energy
under 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 A04

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issue of the following publications, which are generally available in most libraries: *Energy Research Abstracts. (ERA); Government Reports Announcements* and Index (*GRA* and I); *Scientific and Technical Abstract Reports (STAR);* and publication, NTIS-PR-360 available from NTIS at the above address.

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September 20, 1985

Scott Faas
Division 8452
Sandia National Laboratories
Livermore, CA 94550

Dear Mr. ~~Faas~~: Scott :

Enclosed for your information, please find a recently published report titled, "High Temperature Molten Salt Containment," by K. Y. Wang, R. E. West, F. Kreith, and P. P. Lynn. This report studies the feasibility of several design options for high-temperature sensible heat storage containment, recommends the most promising concepts for future engineering development and identifies some technical uncertainties that warrant further research efforts.

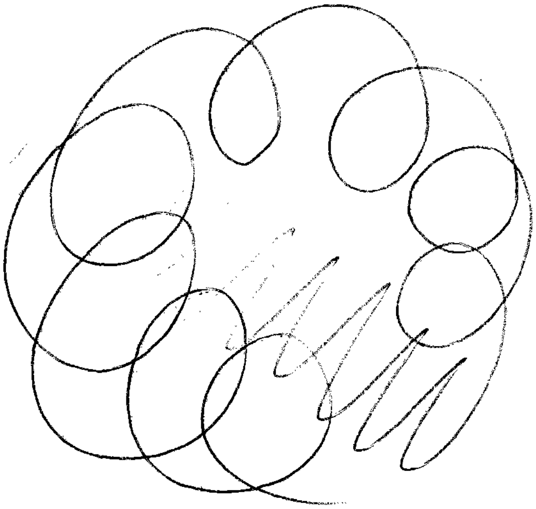
This research is part of DOE's Energy Storage Technology Program which attempts to identify economical energy storage and transport subsystems for the industrial sector and to bring the corresponding technologies to the point where they can be transferred from research to development. University and industry peer reviewers are encouraged to provide us with constructive and valuable feedback so that we can assist the DOE in achieving this goal, while maintaining our state-of-the-art knowledge.

Sincerely,

Kung Yu Wang

K. Y. Wang

cc: D. H. Johnson
S. Bull



SERI/TR-252-2490
UC Category: 59c
DE85012152

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K. Y. Wang
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Prepared under Task No. 4253.11
FTP No. 455

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PREFACE

This report studies the feasibility of commercial scale central receiver energy storage systems from both the technical and economical viewpoints, and identifies uncertainties that warrant further investigation. The design concepts in this report were generated by Robert J. Copeland of the Thermal Research Branch at the Solar Energy Research Institute (SERI).

The authors would like to thank Werner Luft for his leadership in this program and Ronald E. West and Paul P. Lynn for their valued assistance. Special thanks also go to Robert J. Copeland of SERI and Scott Faas of Sandia National Laboratories, Livermore.

The following persons have contributed valuable review comments to the completion of this report and their efforts are appreciated: R. W. Bradshaw, Sandia National Laboratories, Livermore, M. Olszewski, Oak Ridge National Laboratory, and L. Vant-Hull, University of Houston.

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SUMMARY

Objective

To study the feasibility of several design options for high-temperature sensible heat storage containment from both the technical and economic viewpoints; to recommend the most promising concepts for further engineering development; and to identify some technical uncertainties that warrant further research efforts.

Discussion

Alkali-metal carbonate salts meet the requirement for low-cost storage media, for high-temperature solar central receiver systems. However, because of their corrosiveness, special problems arise in the design of storage tanks. To reduce corrosion and temperature sufficiently to retain strength in the containing wall, internal thermal insulation is required.

A study has been conducted to identify the most promising high-temperature containment concepts. The study considers corrosion resistance, strength at high temperature, reliability of performance of the technical concept, thermal insulation requirement, and cost. Three storage systems were considered: single-tank raft, single-tank, two-media, and two-tank systems. A system with the fewest technical risks and lowest cost was chosen for further consideration.

Conclusions

The single-tank raft system concept has technical uncertainties and the highest cost. The two-tank system is also high in cost. The single-tank, two-media sloped wall tank has the potential of being lowest in cost. However, a number of technical questions must be answered before proceeding with prototype construction: natural convection in the insulation layer; the effect of radiative heat transfer; the thermocline stability; and the compatibility between two media.

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SECTION 1.0

INTRODUCTION

1.1 HIGH TEMPERATURE ENERGY STORAGE

A central receiver solar thermal power plant that uses molten salt as both the primary transport fluid and the thermal storage medium is being developed. One of the systems being used for generating electricity and for process heat [1] was designed by the Martin Marietta Corporation. This system has operating temperatures ranging from 288°C to 566°C. A solar energy system with temperatures above 900°C has a potential for higher efficiency in generating power (e.g., use combined Brayton/Rankine cycle instead of Rankine cycle only), lower hydrogen production cost, cost effective cogeneration of heat and electricity, and conservation of premium fossil fuels [2,3]. However, serious technical risks and uncertainties arise by attempting to increase the maximum salt temperature in the storage tank from about 600°C to 900°C (or even 1100°C). The problems of greatest concern are: more severe corrosive activity between container and salt, higher heat loss to the surrounding environment through the storage tank walls, unreliable structural integrity at high temperature, and uncertainties about durability of the storage system. These research subjects have been addressed independently at SERI and jointly with other research groups. This report presents several tank designs for energy storage tank designs and scrutinizes each of them from technical and economical viewpoints.

The capacity of the energy storage system for this study is 1800 MWh (thermal), and the daily heat loss from the storage tank is limited to 2%. The heat capacity determines the volume of salt required, or roughly the size of the tank. The load-bearing capacity of ground that constitutes the foundation of a storage tank limits the height of the tank. A 0.33 height/diameter ratio was selected for cylindrical tank designs, because a previous optimization study by Martin Marietta Corporation indicated that the cost optimal ratio is 0.3 to 0.4 [1].

1.2 APPROACH

Eight design concepts were considered for the energy storage system. A short description and illustration for each design is given in Section 2.0. The designs were subject to thermal and structural analyses; some of the design features were modified as a result of the analyses described in the following sections. Essential information on the components of the storage systems is in Section 3.0, the information includes physical properties of salt, insulation of brick and powder, and load-bearing steel and concrete. Price data are also furnished. The data are essential for the thermal and structural analyses and cost estimates presented in Sections 4.0, 5.0, and 6.0.

The thermal analysis thickness calculated the sizes of various thermal insulation layers of the sidewalls, top, and bottom of the storage tank, so the heat loss from inside the tank stays within the allowance. The above information, plus some rough calculations on the cost of tank structure, produced estimates good enough to eliminate less desirable designs from consideration, so a detailed structural analysis was not needed. Three of the designs were chosen for further consideration (see Section 5.0). Temperatures that were previously assigned at different locations of the tank had to be changed to accommodate structural allowance and safety factors.

The technical risks associated with the present designs are discussed in Section 7.0. These risks reflect the uncertainties in the areas of material strength, reliability, and durability. The most promising design, based on all the facts and arguments available, is recommended in Section 8.0 for further study. Topics that need further research and development efforts are identified.

SECTION 2.0

INITIAL DESIGNS

2.1 REQUIREMENTS AND DESIGN CONDITIONS

An energy storage system is important for the continuous operation of solar central receiver system. Copeland et al. [2] identified a potentially large industrial market for solar systems that are capable of delivering heat at temperatures of 900°C and made preliminary cost estimates for high-temperature storage concepts. A nominal thermal storage temperature of 900°C was used and a system design and performance criteria were established. Molten-salt storage media have the fewest associated problems, and among them, alkali-metal carbonate salts show the most promise when cost and corrosiveness are taken into account [4]. The lithium-sodium-potassium carbonate eutectic mixture is recommended because of its low melting point (397°C), good stability at higher temperatures, low vapor pressure, 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(th) (e.g., 300 MW for 6 hours) was selected and a heat-loss rate of 2%/day (1.5 MW) was specified. The quantity of lithium-potassium-sodium eutectic required for this capacity is about 7.5×10^6 kg (8.2×10^3 tons). The volume of the medium is about 3.6×10^3 m^3, requiring tank dimensions of about 8 m in depth and 24 m in diameter, for a cylindrical storage vessel.

Eight initial designs divided into three categories (single tank with raft thermocline, single tank with two-media, and two-tank systems), are presented in this section. Thermal insulation is the major consideration. Although the load-bearing structural elements are also given as part of the storage tank design, they are subject to change in Section 5.0 when detailed structural analysis is performed.

2.2 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, where the density difference between the hot and cold fluids inhibits convective mixing and heat transfer. Thermocline storage has been proven technically feasible for lower temperature systems [5], but a unique problem occurs with thermoclines at higher temperatures because radiant heat transfer becomes significant since a natural thermocline of a liquid transparent in infrared wavelength 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 two-media system consisting of a packed bed of solid particles opaque to infrared radiation and a 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 [6], and as phase change thermal storage at temperatures up to 500°C [7], and in many applications at lower temperatures. The raft concept has been demonstrated only at near-ambient temperature conditions [5].

Figure 2-1 shows a sketch of the general features of a raft-thermocline, molten-salt system. The floor, foundation, and water-cooled layer could be about the same for each concept, as 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 strength of the materials at operating temperatures, corrosion resistance, and cost are the key factors. There have been some preliminary corrosion studies at 900°C [8], but more corrosion information is required. A summary of the corrosion test results is shown in Section 3.0.

2.2.1 Single-Tank Raft Thermocline System

The general features of a single-tank, raft thermocline, system are shown in Figure 2-1. Two particular designs are proposed for the raft thermocline concept.

The first features the use of multiple-layered insulation, as shown in Figure 2-2. The high-purity ceramic bricks with internal slots are piled to form the inner insulation layer. The detailed design of the slotted brick is

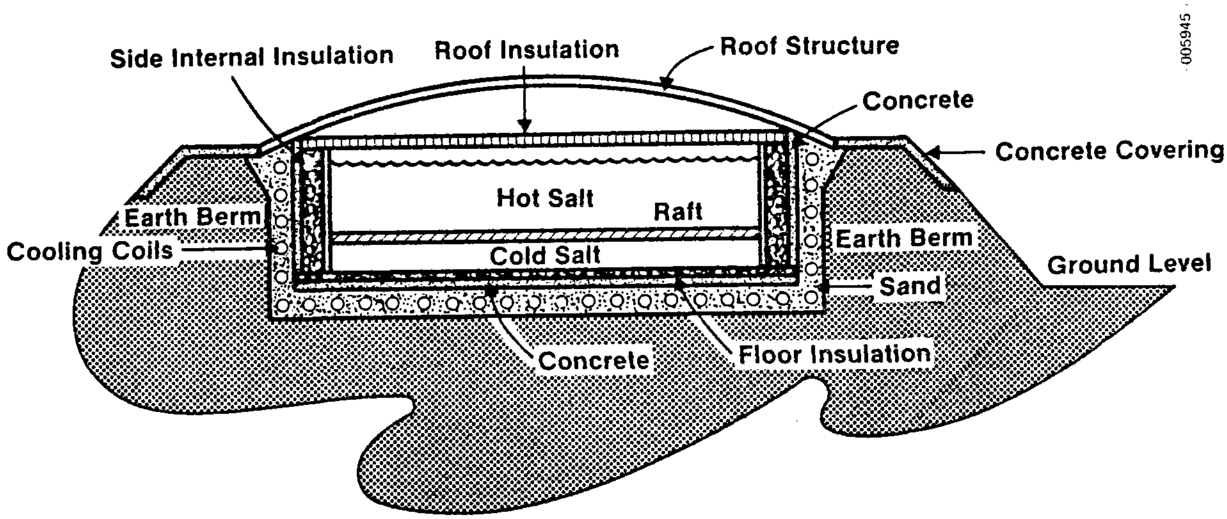

Figure 2-1. Single-Tank Raft Thermocline Storage Concept

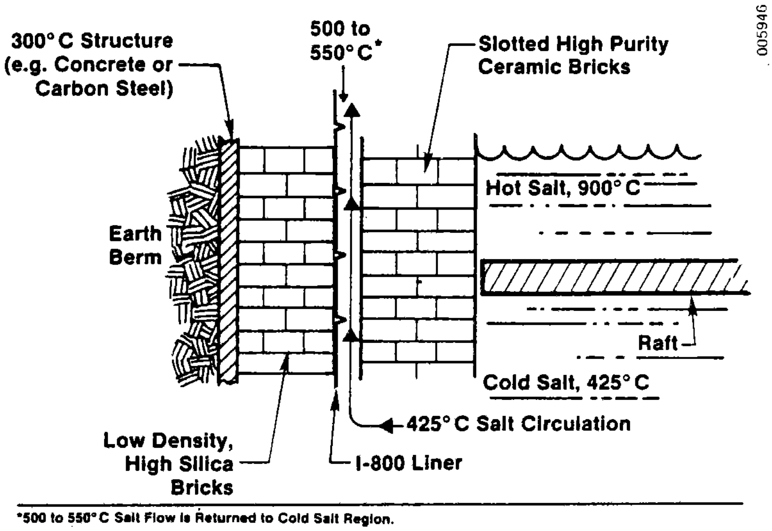

Figure 2-2. Single-Tank Raft Thermocline System with Alumina and Silica Bricks

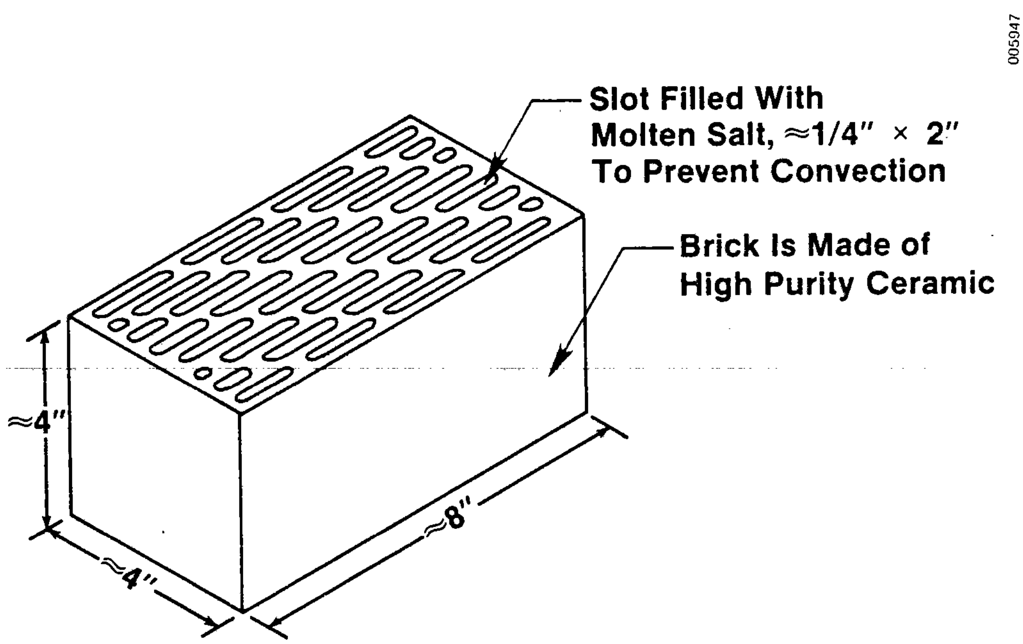

Figure 2-3. Slotted High-Purity Alumina Brick

given in Figure 2-3. The purpose of the slots is to reduce expensive alumina material requirement and also avoid possible salt circulation, which would enhance convective heat transfer. An Incoloy 800 waffled liner prohibits the salt from penetrating through to the outer insulation of inexpensive low-density, high-silica bricks. A regenerative cooling system, using circulating cold salt at about 425°C will reduce the amount of insulation material required, and increase the temperature of the cold salt. An economic optimal condition should be established between the amount of insulation material saved and the cooling pipes required and the extra storage volume needed. The total load of the structure is taken by concrete or carbon steel constituting the outer shell.

Another design for the raft thermocline concept is illustrated in Figure 2-4. This sidewall has an inner layer of high-purity, fused-cast-alumina bricks that can withstand 900°C molten carbonate salts, but it is very expensive. The salt penetrates the porous section of the bricks, and its temperature drops to about 858°C, the melting point of sodium carbonate, which is a component of the insulation layer. The diffusion barrier consists of overlapping sheets of Inconel that are not joined, but allow thermal expansion. The detailed design for the barrier is given in Figure 2-5. These sheets will inhibit, but not entirely prevent, movement of the molten salt into the next insulation layer of pelleted magnesia surrounded by Na_2CO_3 powder. The vertical Inconel sheets are held in place by horizontal bars anchored in the outer structural wall. As molten salt penetrates through

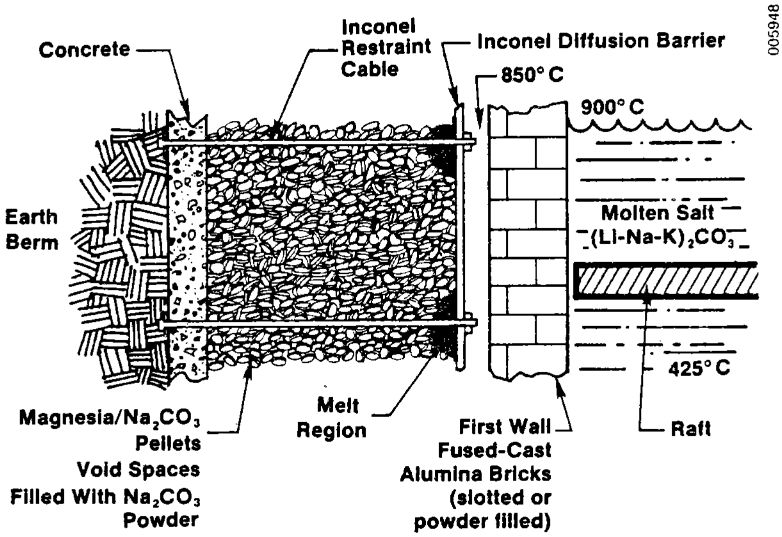

Figure 2-4. Single-Tank Raft Thermocline System with Alumina Bricks and Pellet Insulation

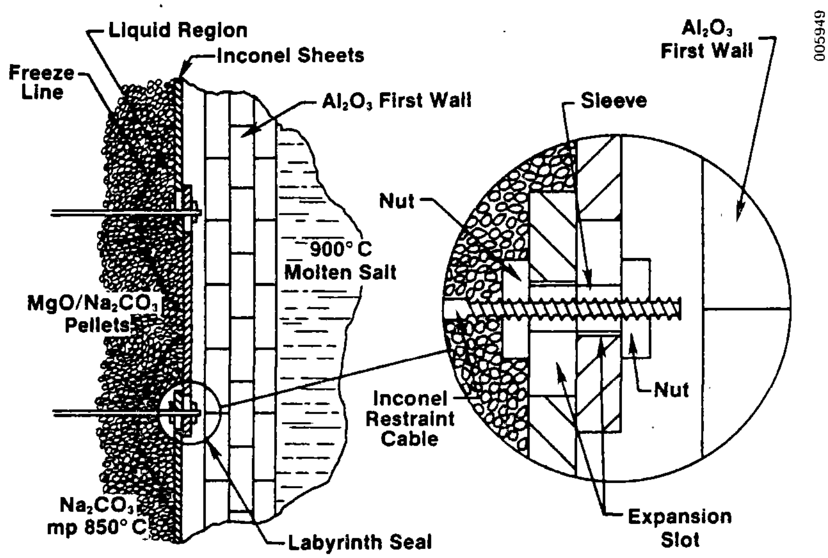

Figure 2-5. Details of Diffusion Barrier Shown in Figure 2-4

the diffusion barrier into the magnesia/Na_2CO_3 layer, it cools and dissolves Na_2CO_3 and 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 thought to be similar in design to the sidewall but ballasted to float at the thermocline.

2.2.2 Single-Tank Two-Media System

In a two-media system, a solid packing is used as a second storage medium with a liquid in the space between the solid particles. This approach is used in the Solar One power plant in Barstow, Calif., and is a proven concept for maintaining a thermocline and suppressing radiant transfer as long as the solid is opaque to infrared radiation [6]. The solid is often cheaper than the fluid medium (per unit of energy stored) and may offer a cost advantage as well. On the other hand, a solid must be found that can withstand the molten salt at high 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 and large temperature changes and large gradients as the thermocline moves up and down during the daily operation.

The general features of the two-media single-tank system are similar to those shown in Figures 2-1 and 2-6 but no raft is used. The invisible thermocline moves up and down in the media composed of molten salt and solid elements. Two potential designs for the two media concept are shown in Figures 2-7 and 2-8. Brief descriptions that highlight each design concept are given below.

The first concept uses Inconel sheets hung from the top of the storage tank to prevent bulk salt flow into the inner insulation layer that consists of magnesia pellets. The gaps between the Inconel sheets allow the molten salts to penetrate and fill void spaces between pellets, but liquid convection is minimized by the pellets. The temperature is reduced to about 550°C through this inner layer. The outer layer is composed of low-cost, low-density silica bricks, and is separated from the inner layer by an Incoloy 800 liner that is waffled to allow for thermal expansion. Since the bricks are separated from the molten salt and remain dry during operation, efficient insulation can be expected. The solid packing in the bed is also magnesia pellets, or other suitable material such as alumina. The pellets have been fabricated and used at temperatures up to 800°C [5].

Figure 2-8 illustrates another two-media concept. The container has the shape of the frustrum of a cone and is located in the ground using the 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 makes salt temperature drop drastically and thus a stainless steel shell can be used between the powder and the outer sand layers. The advantage of the sloped-wall tank design is that thermal expansion of the side walls may take place along the conical longitude.

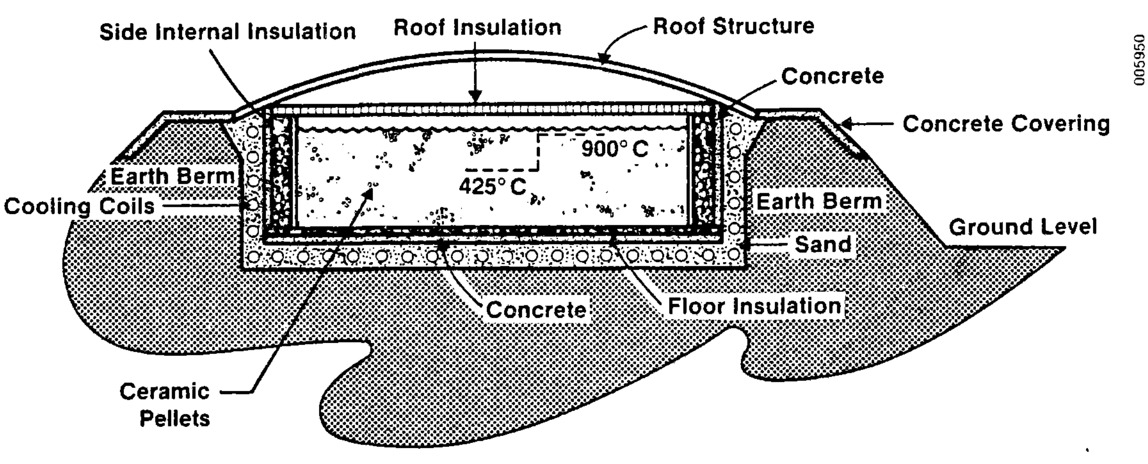

Figure 2-6. Single-Tank, Two-Media, Thermocline Storage Concept

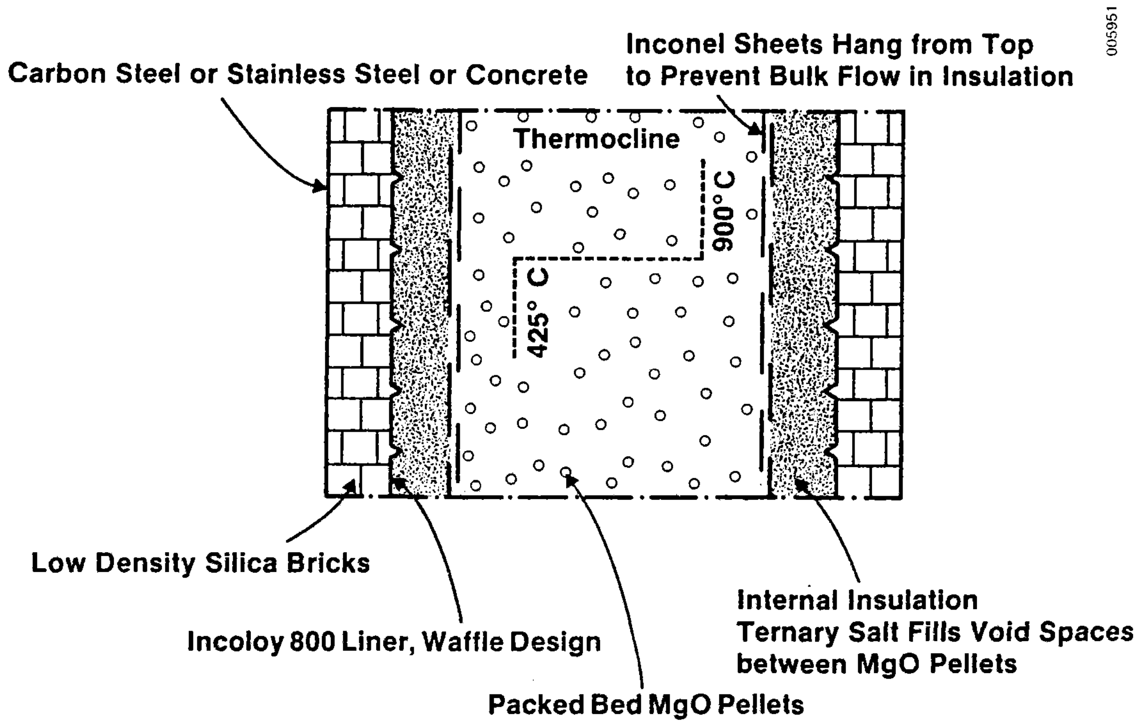

Figure 2-7. Single-Tank, Two-Media, Thermocline System--Cylindrical Storage Tank

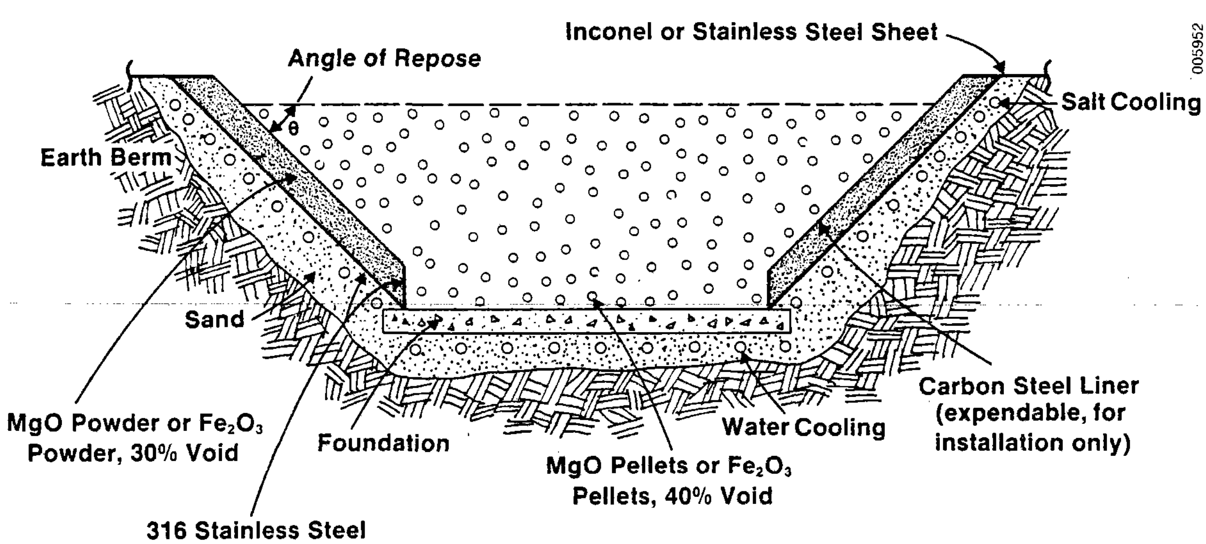

Figure 2-8. Single-Tank, Two-Media, Thermocline System--Conical Storage Tank

2.2.3 Two-Tank System

The two-tank system uses one tank for high-temperatures of 900°C, and uses the molten-salt storage and a second for low-temperature storage of 425°C. The major advantage over the single-tank system is the hot and cold fluids do not come in contact or exchange heat with each other. The disadvantages are that two separate tanks of equal volume are required, and 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 the thermocline concepts.

Since the cold tank is subject to temperatures up to 425°C, no technical problems with regard to corrosion, heat loss, or structure are expected. In fact, earlier work dealing with molten salt as high as 550°C has been demonstrated [9]. The potential technical risks for the two-tank system are associated with the hot tank, and therefore only the hot-tank designs will be presented in this section. The size of the cold tank will be almost identical to that of the hot tank, but there is no internal insulation required for the former. As indicated in Section 6.0, the hot tank dominates the total cost in the two-tank storage system.

The overall hot-tank design for a two-tank storage system is shown in Figure 2-9, which is in general similar to a single-tank system. Four design concepts are proposed and are illustrated in Figures 2-10 to 2-16.

Figure 2-10 shows the multiple-layered insulation concept for a hot tank. High purity ceramic bricks are stacked and filled with low-purity powder to form the inner insulation layer. The details of the bricks are depicted in Figure 2-10. The bricks do not serve as a load-bearing structural member, but as a barrier to prevent bulk salt motion. The salt penetrates through the cavity of the bricks and mixes with the low-cost powders. The ceramic bricks, shown in Figure 2-11, are expensive but are able to withstand corrosion at high temperatures. The Incoloy 800 pipes with the molten salt circulating inside are an option that could effectively reduce the insulation requirement. The waffled Incoloy 800 liner separates the first layer from the outer layer that consists of low-cost, low-density, and high-silica bricks. The packed sand on the outside of the load-bearing structures also provides insulation.

Two designs were derived from an "accordion wall" concept and are shown in Figures 2-12 and 2-13. The two are similar to each other except for the inner insulation layer. In Figure 2-12, a castable structure thick enough to withstand the corrosion for the lifetime of the storage tank (30 yrs) is assumed. The concept shown in Figure 2-13 features a fusion-cast-alumina structure (see Figures 2-14 and 2-15 for details) stacked on one side of a low-cost, water-based cast-alumina layer. The molten salt is allowed to penetrate through the castable structure for a short distance, but the corrosion product may limit further corrosive activity. The idea for the semi-circular sections on the periphery of the tank is to reduce the hoop stress by transmitting some stress through the supports to the foundation.

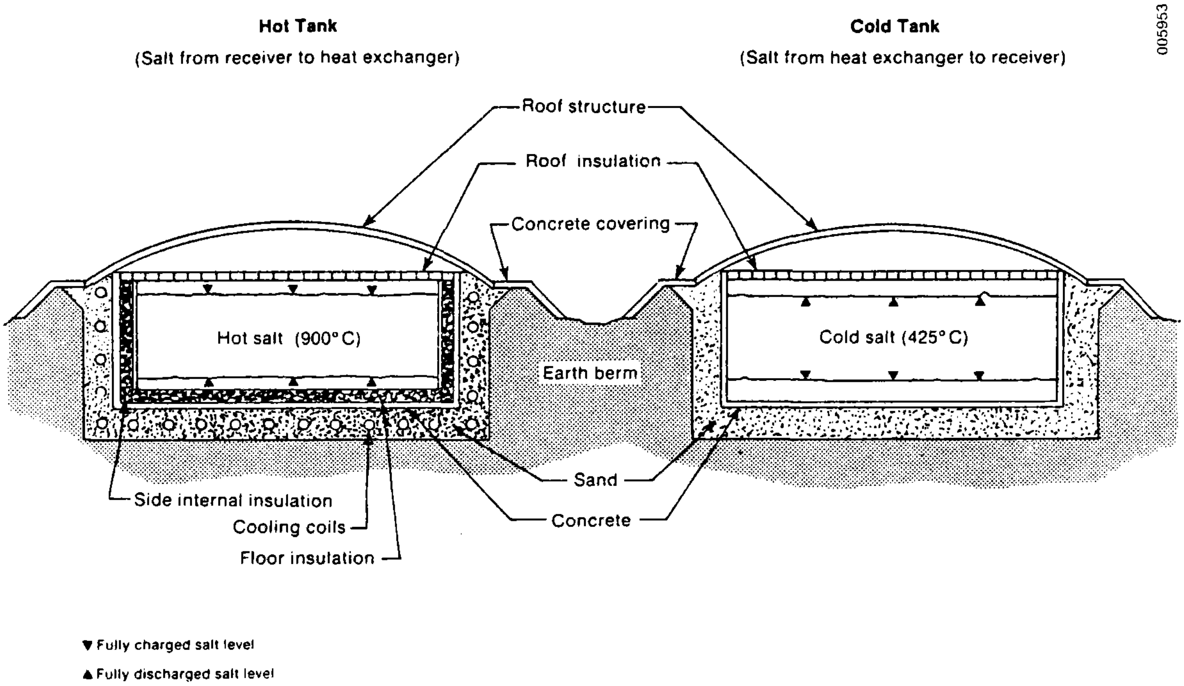

Figure 2-9. Two-Tank Storage Concept

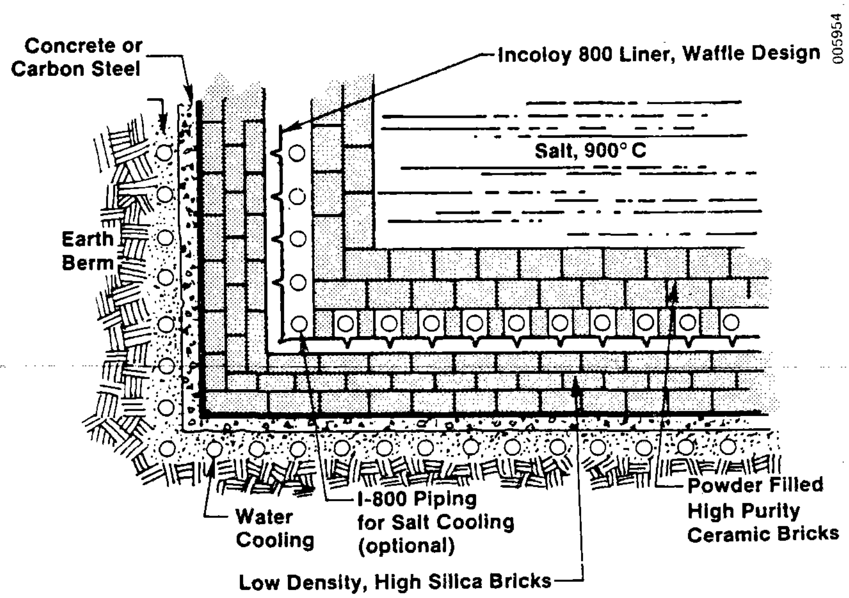

Figure 2-10. Two-Tank System with Multiple-Layered Insulation and Actively Cooled I-800 Liner Hot Tank

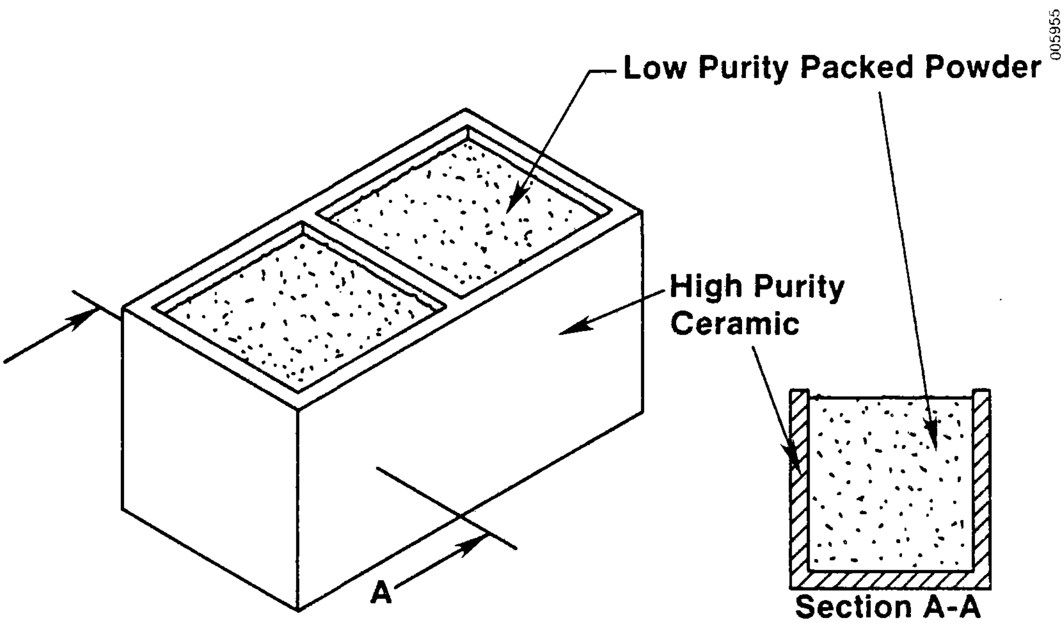

Figure 2-11. Powder-Filled, High-Purity Alumina Brick.

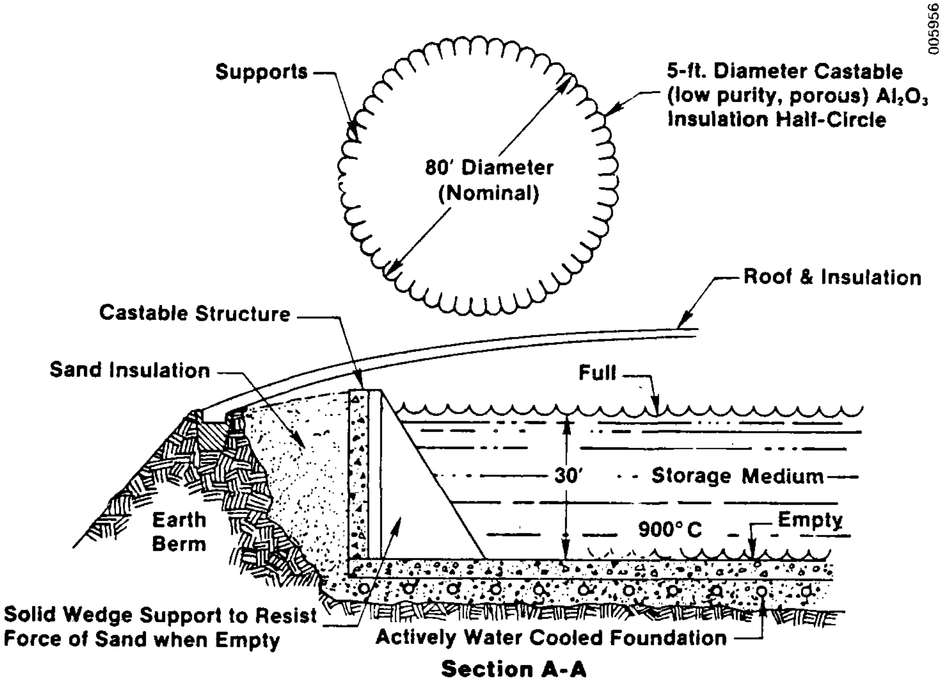

Figure 2-12. Two-Tank System with Unlined Castable Structure

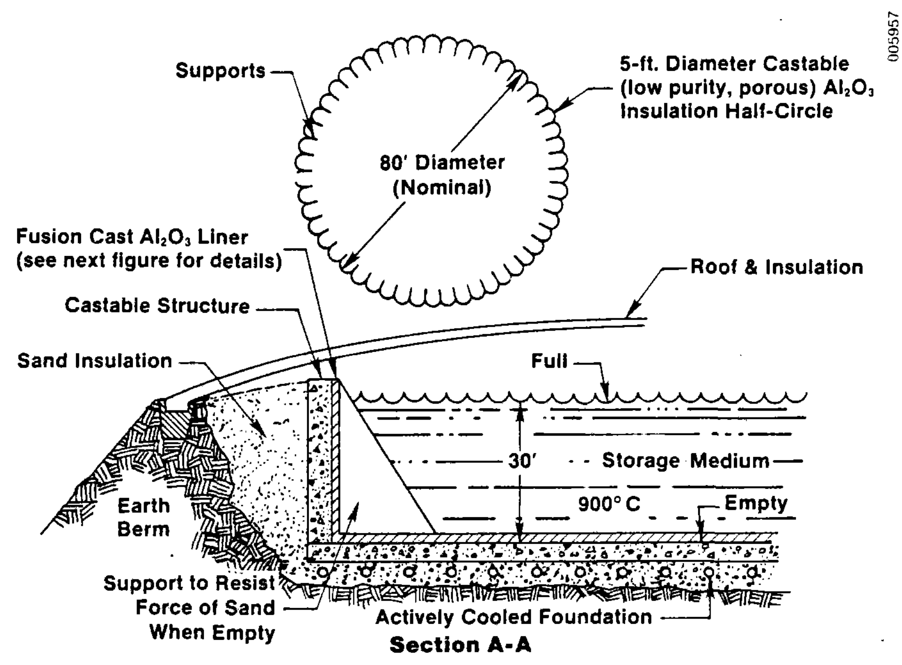

Figure 2-13. Two-Tank System with Lined Castable Structure

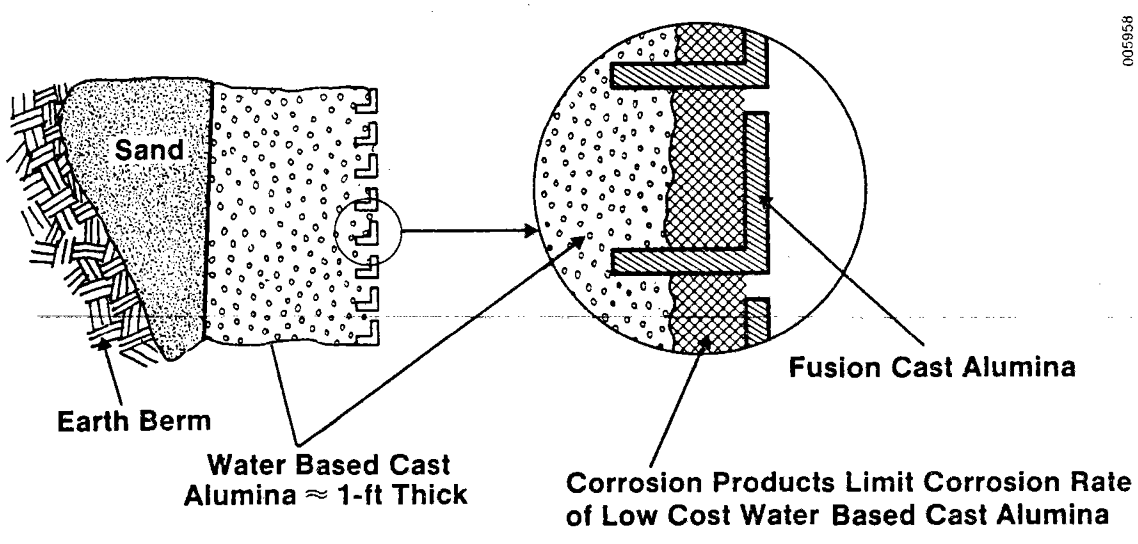

Figure 2-14. Liner Concept for the Castable Structure in Figure 2-12

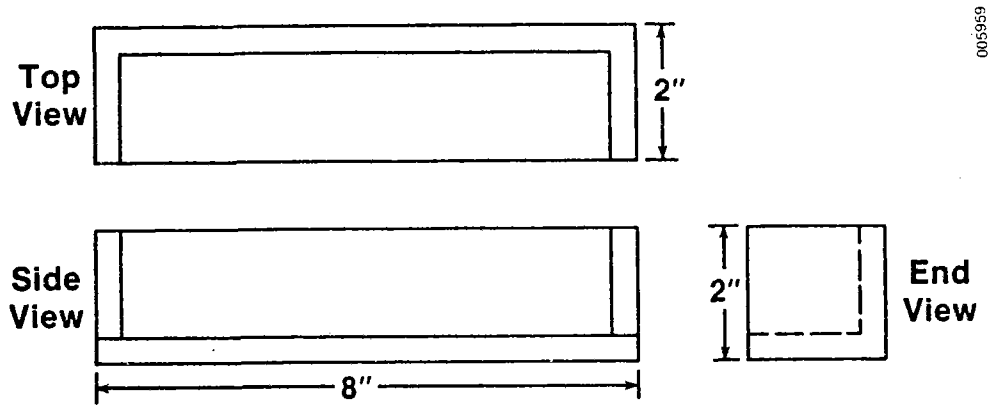

Figure 2-15. Liner Component of Fusion Cast Alumina for the Castable Structure in Figure 2-14

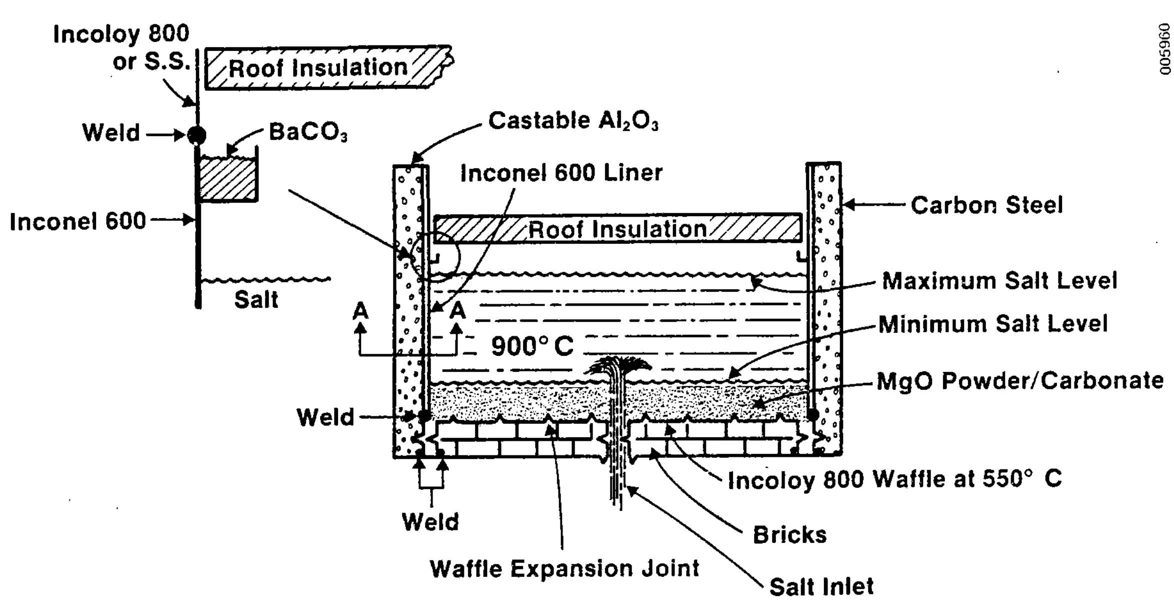

Figure 2-16. Two-Tank System with Inconel-Lined Hot Storage Tank

The design presented in Figure 2-16 utilizes the special properties of "creeping" and a $BaCO_3$ "seal". The surface of the inner insulation layer, i.e., the castable ceramic, facing toward the molten salt is specially curved with bumps and dips, as indicated in Figure 2-17. The Inconel liner, which has a circular periphery, is placed against the bumps of the wall before thermal expansion takes place, leaving air gaps between the two. When the tank is filled, thermal expansion of the metal liner fills in most of the gap. High temperature creep, occurring over time, eventually causes the liner to cover the ceramic surface firmly. The process is also illustrated in Figure 2-17. The load is transmitted to the carbon steel on the outside. However, lack of data regarding the creeping process makes this design rather risky technically. A ring-shaped container with $BaCO_3$ powder inside is placed above the maximum salt level. The purpose for this installation is that the liquid salt film rising along the tank wall due to capillary action will mix with the $BaCO_3$ powder, and the new product has a higher melting point and thus solidifies there. This eliminates the need to use the expensive Inconel liner above the powder container, and allows the use of less expensive Incoloy 800 or stainless steel liner.

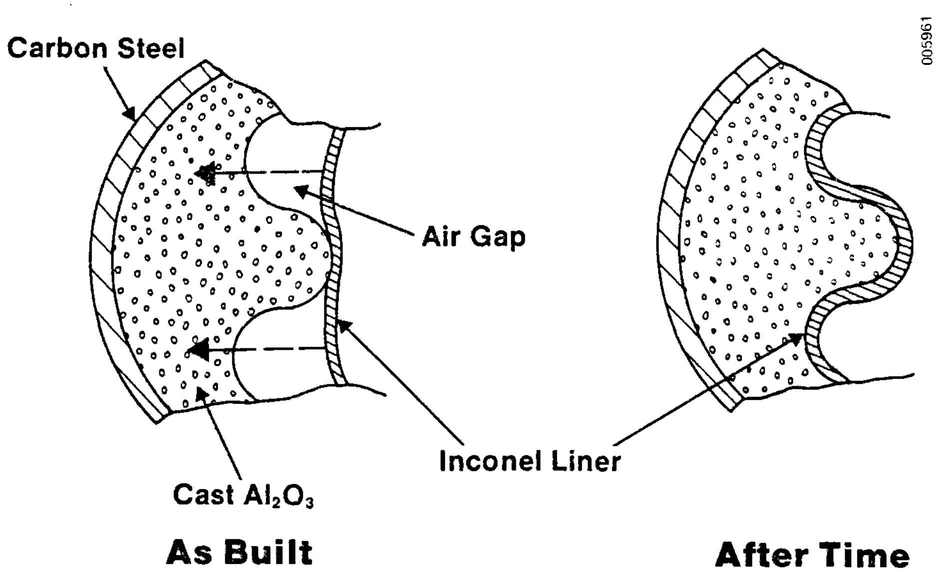

Figure 2-17. Detail of Inconel Liner for Two-Tank Storage Shown in Figure 2-16

SECTION 3.0

MATERIAL PROPERTIES

The material properties of the storage medium and insulation materials are essential to determine the sizes of the storage tank and its insulation layers. The mechnical strength of the load-bearing elements, such as concrete and steel, are also the prime factors in estimating the size of the foundation, roof, and side walls of the tank. These factors in turn affect the final cost of the entire storage system. To evaluate the feasibility of each concept given in Section 2.0, it is essential that the previous information be available. A summary is presented in this section concerning the findings of the property data. The data are given in the following order: the physical properties of molten salt, the material properties and price data of insulation and structural materials, and the exploratory corrosion test results. Sufficient references are given so that more information can be gathered if necessary.

3.1 MOLTEN SALT

Chloride, hydroxide, and carbonate-molten salts were proposed in the beginning as the working medium in the direct absorption receiver and thermal storage system (DARTS). However, further study has indicated that sodium hydroxide has the highest corrosion rate on containment materials, and in spite of its lowest price among the three, it is not suitable as the storage medium. Chlorides have low-corrosion rates on ceramics but high rates on metals. Thus, they are not good candidates as storage media because the resulting technical problems with piping can not be solved at this stage. Carbonates have low or modest corrosion rates on both metals and ceramics; the ternary eutectic of lithium, sodium, and potassium has been selected as the primary storage medium for DARTS [10].

The molecular composition of the carbonate salt being studied as the storage medium is 43.5% Li_2CO_3, 31.5% Na_2CO_3, and 25% K_2CO_3. The molecular weight is 100.1 g/mole, and the melting point of 397°C is much lower than the melting points of its individual components: 726°C, 858°C and 899°C, for Li_2CO_3, Na_2CO_3 and K_2CO_3, respectively. The following expressions give the density (ρ), viscosity (μ), heat capacity (C_p), and thermal conductivity (k) data in the appropriate temperature range [11, 12, 13]:

$$\rho\ (kg/m^3) = 2512.8 - 0.544 \times T\ (K),\ (680\text{-}1060\ K)$$

$$\mu\ (Pa.s) = 4.64 \times 10^{-6} \times \exp\ (5365/T(K)),\ (760\text{-}870\ K)$$

$$C_p\ (J/kg.K) = 1190 + 0.693 \times T(K),\ (680\text{-}1100\ K)$$

$$k\ (W/m{\cdot}K) = 4.28 \times 10^{-8} \times C_p\ (J/kg.K) \times \rho^{4/3}\ (kg/m^3)\ .$$

The above expressions give the physical properties of the molten salt necessary for making the thermal analysis of the system. Some other properties can be found in [11]. The numerical values of these properties are listed in Table 3-1. Extrapolation has been used for temperatures outside the range cited above.

3.2 INSULATION AND STRUCTURAL MATERIALS

The major physical properties necessary for calculating heat loss from the storage tank and the price data of each component are given in Table 3-2. The unit price should be viewed on a relative basis. A literature search was attempted first to collect those data, and when necessary, an individual manufacturer was contacted to confirm the information.

3.3 PRICE ADJUSTMENTS

The prices given in Table 3-2 were taken from the references indicated. Where prices are for a date other than mid-1984, they are updated to mid-1984 using the Gross National Product (GNP) Implicit Price Deflator. For example, this value was 222.4 for the 2nd quarter 1984 and 178.4 for 1980 [37]. The 1980 prices were adjusted [222.4/178.4 = 1.246] to update them to mid-1984. Other factors, such as the Marshall and Swift Index were considered, but they tend to be specific for equipment or plant and are not greatly different from the GNP-Deflator. The latter was chosen as more general.

3.4 CORROSION TEST

The carbonate, chloride, and hydroxide molten salts were chosen as the materials for the working medium of the solar energy storage system because they are inexpensive and have suitable stability and physical properties [2]. Experiments were performed at SERI to measure the corrosion rates of the various alloys and ceramics in the molten salt at 900°C over a period of up to 62 days. The research produced preliminary conclusions that helped eliminate unqualified candidates. A brief discussion is given below but the details are available in [15,24,25].

Results of the corrosion of alloys in molten-sodium hydroxide show that all of the alloys exhibit cracking, which is considered unacceptable. The test also indicated that all the alloy samples disintegrated after 19 days in chloride. Furthermore, the chlorides generate toxic and corrosive fumes. The carbonates indicate low-corrosion rates for both alloys and ceramics and are considered as the promising candidates for storage medium.

Table 3-3 gives a summary of the corrosion test results of several alloys in the ternary eutectic lithium-sodium-potassium carbonate [24,25]. The calculated corrosion rate was based on the sample weight change during the test period. Although there are reservations with regard to predicting the long term (30 years) corrosion rate from the relatively short term test results, the data at least provide the opportunity for comparison. The Hastelloy N, (71% Ni, 17% Mo, 7% Cr, 5% Fe) which was excellent in the previous corrosion test in the binary eutectic sodium-potassium carbonate [15], did not perform as well in the ternary eutectic carbonate. Although its apparent corrosion rate is low, delamination from the surface occurred and was judged unacceptable. One explanation for the discrepancy is that the 21-day test period

Table 3-1. Physical Properties of the Eutectic Lithium-Sodium-Potassium Carbonate Molten Salt

Temperature (°C)	(K)	Density[11] ρ (kg/m^3)	Viscosity [11] μ (Pa.s)	Heat Capacity[11] C_p (J/Kg.K)	Thermal Conductivity[12] k (W/m•K)
397	670	--	--	--	2.025[13]
407	680	2142.8	12.39×10^{-3}	1660	1.962
427	700	2132.0	9.89×10^{-3}	1670	1.965
477	750	2104.8	5.93×10^{-3}	1710	1.971
527	800	2077.6	3.80×10^{-3}	1740	1.977
577	850	2050.4	2.56×10^{-3}	1780	1.981
627	900	2023.2	1.80×10^{-3}	1810	1.984
677	950	1996.0	1.32×10^{-3}	1850	1.986
727	1000	1968.8	0.99×10^{-3}	1880	1.986
777	1050	1941.5	0.77×10^{-3}	1920	1.986
827	1100	1914.3	0.61×10^{-3}	1950	1.984
927	1200	1859.9	0.41×10^{-3}	2020	1.977
1027	1300	1805.5	0.29×10^{-3}	2090	1.965
1127	1400	1751.1	0.21×10^{-3}	2160	1.949

conducted previously in the binary carbonate may not be long enough to identify the delamination phenomenon. As Table 3-3 suggests, Inconel 600 (71% Ni, 15.5% Cr, 8% Fe) and pure Ni (99.99%) are the most promising. The problem with Ni is the material does not have sufficient strength to take external loads. Inconel 600 is currently the leading candidate for the liner material. Another possibility is the composite material taking advantage of Ni for corrosion protection and Inconel 600 for both corrosion protection and strength requirement.

Table 3-2. Properties of Materials for Molten Carbonate Salt Storage

Material	Density, ρ kg/m^3	Thermal Conductivity k,[a] (W/m•K)	Heat Capacity Cp,[b] kJ/kg•K)	Price \$/kg (Mid-1984 basis)	Comments and Sources
Refractories					
High Purity Alumina (99.8%)	3.8×10^3	12.1 @ 400°C 6.3 @ 800°C	1.2	5.5	Properties from Coors Porcelain [14]. Cost estimated based on discussion with Coors. Coors does not fabricate this material in shapes as large as we are interested in. Material has good resistance to molten carbonates [15].
High Purity Alumina Bricks, filled with MgO powder	2.9×10^3	4.1 (dry) (wetted 4.4 with carbonate)	--	3.5 (\$10,000/m^3)	Properties and price estimated based on hollowed block with 1/2-in. thick walls [16] filled with MgO.
Alumina Bricks (95.1%)	3.0×10^3	1.7	--	2.0	Density [17] conduction [18], price [19].
Magnesia (95.5)					
Bricks	2.6×10^3	2.3	1.25	1.4	Magnesia properties were obtained from several sources and were rather inconsistent. Values presented are from [20] price of bricks from [19] powder and pellets from [36].
Powder	2.3×10^3 (bulk)	2.0	1.25	0.43	
Pellets	2.1×10^3 (bulk)	1.8	1.25	0.76	
Concrete					
Ordinary structural concrete	1.9×10^3	1.4	--	0.090 (\$135/m^3)	k,ρ from [20], price from [19]
Ordinary insulating concrete	0.8×10^3	0.33	--	0.45 (\$360/m^3)	k,ρ from [21], price from [11]
Castable Refractory	1.2×10^3	0.27	--	0.59 (\$680/m^3)	From [22], properties of Kaolite 2200-HS castable.
Salt					
$(Na\text{-}K\text{-}Li)_2\ CO_3$ Eutectic	--	--	--	1.50	From [3]. See Table 3-1 for properties.
Insulations					
Mineral Fiber					Insulation properties from [23] prices from [19], thickness in parens
Blanket (200°C max.)	--	0.051 (100°C)	--	\$12./m^2 (0.1m)	
Board (980°C max.)	--	0.116 (400°C)	--	\$31./m^2×(0.1m)	
Calcium Silicate Board (650°C max.)	$.58 \times 10^3$	0.126 (200°C)	--	\$56./m^2×(0.1m)	
Diatomaceous Earth (1000°C max.)	--	0.13 (540°C)	--	\$5.4/m2(0.1m)	

[a]@900°C unless noted

[b]Mean, 400-900°C.

Table 3-3. Corrosion Test Summary, $(Na, K, Li)_2 CO_3$ at 900^oC*

Metal Alloy	Maximum Exposure Time (Days)	Calculated Corrosion Rate µm/day	Comments
Hastelloy N	60	0.68	High oxidation potential of salt [25]
Ni_3Al	10	Above 30	Nonprotective powdery scale formed
Haynes 556	6	-	Delamination
Inconel 600	62	0.47 1.6	High oxidation potential of salt [25] Black scale formed, may be protective
Cabot 201	60	1.37	High oxidation potential of salt [25]
Cabot 214	55	-	Swelling and cracking
Ni, 99.99%	14	0.6	Promising no protecive coating
Incoloy 800	14	-	Swelling

*Refer to [24], except where noted.

SECTION 4.0

THERMAL ANALYSIS

4.1 GENERAL CONSIDERATION

Storage-tank sizing is based on a capacity of 1800 MWh(th) and a loss rate of 2%/day (1.5 MW) average. A high temperature of 900°C and a low temperature of 425°C are used. The objective is to size the storage tank to supply the capacity, and to reach particular temperatures at certain boundaries. These depend upon the design concept that are generally 550°C at an Incoloy liner and 65°C at a concrete skin or 300°C at a carbon-steel skin. An analysis was done of the heat loss and the temperature distribution at the bottom of the tank regarding the need for active water cooling for foundation and soil protection. A study was conducted of the efficacy of wall cooling with 425°C molten salt.

Raft-thermocline and two-tank storage use molten salt as the only storage medium. The minimum volume of salt required is the total energy stored, 1800 MW(th) (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. These properties are available from Table 3-1. Two percent extra salt was included to compensate for a two percent maximum rate of heat loss per day. An additional amount of the medium is required because the thermocline takes space and to keep the 425°C salt at the bottom of a thermocline tank at all times, or to keep some 900°C salt in the high temperature tank of a two-tank system. Four percent extra volume was allowed for these factors. Three percent additional medium was allowed, as discussed later, when regenerative cooling was employed. Two-media storage requires that the heat capacity and density of the solid pellets plus eutectic salt in the bed be used. These were calculated using an estimated void fraction for the pellets and a volume averaged value 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.

The ideal assumption of no temperature gradients, hence a step thermocline, has been made, but 4% extra tank volume was allowed. No heat transfer across the thermocline has been included. These are optimistic assumptions made for design purposes. No transient heat balances have been made. The heat-loss rate of 2%/day is an average design value. In general, the storage tank would be filled with 900°C liquid for less than 12 h/day. A thermocline tank would average half or more of 425°C liquid. The hot tank of a two-tank system would always contain some hot liquid, but it would always be partially empty. The basis for our heat-loss calculations (insulation sizing) is a steady-state rate with the tank full at 900°C for 12 h/day, and a steady-state rate with the tank full at 425°C for the other 12 h; the daily average heat-loss rate is equal to 1.5 MW. The actual situation is much more complex because of the transient nature of the conduction and the thermal capacity, but since the above procedure is conservative, (i.e., it overestimates the insulation thickness required), it is satisfactory for the design purposes.

The insulation design procedure fixes a required temperature difference (e.g., 900° to 550°C) and the heat-loss rate at that difference. It then calculates the insulation thickness required using the steady-state conduction equation. Only heat conduction was considered at this point. This approach is discussed later.

Properties of insulations are taken from the open literature or manufacturers' publications. It was frequently found that literature values were inconsistent and in a few cases incorrect. In these cases, values were selected that were among the most frequently found and most reasonable relative to similar data. Values used are given in Tables 3-1 and 3-2. When property values were needed and available over a range of temperatures, mean values were used. Properties of wetted insulation were taken as the volume average of solid and liquid, except when the thermal conductivity of an "insulation" exceeded that of the liquid, the solid's property was used. The thermal conductivity of ceramics such as alumina and magnesia are strongly dependent on their purity, so we have estimated the composition to be used and generally the more pessimistic property values are used.

4.2 REGENERATIVE COOLING

Internal-insulation materials are expensive, and anything that can reduce the cost is desirable. Cooling with 425°C molten salt and returning this heated salt to colder storage is a possibility, (it is called regenerative cooling). The energy absorbed by the salt is not lost from the system because 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 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. A general analysis was conducted to indicate when regenerative cooling might be useful.

The key factors in the regenerative cooling analysis are:

- Average, steady-state, heat-loss flux of 1800 W/m^2 (use tank area based upon preliminary design, assume same flux through all surfaces),
- All heat-transfer resistance through pipe walls and fluid inside pipes is assumed to be negligible,
- Cooling pipes surrounded by an environment at 550°C are either Incoloy 800 pipes immersed in molten salt with natural convection heat transfer to the pipes, or steel pipes imbedded in castable refractory with conduction heat transfer,
- Only inner insulation, pipes, and heat costs are considered. Materials outside the 900° to 550°C zone are unaffected by regenerative cooling,
- Pumping costs were not included.

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 through a smaller temperature difference by the solar receiver. There is a loss of energy stored at high temperature as heat is transferred to the lower temperature. In order to recover a given amount of energy from the storage at high temperatures, the storage tank must be larger in the regenerative-cooling case than without it. Although there is no additional energy loss from the system, more storage medium is necessary. More capital is required because of the larger storage tank and the piping system for molten salt circulation, while the investment is reduced because less internal insulation is needed. The extra capital investment for the tank and medium was estimated from:

Extra Investment

= (quantity of heat transferred to regenerative cooling per day)
÷ (Design storage capacity, 1800 MWh)
× (capital cost of storage tank + capital cost of storage medium)

The capital costs of the storage tank and the medium were taken from preliminary storage investment estimates. The total capital cost of the pipe, the internal insulation, and the extra tank volume and medium was minimized. Regenerative cooling is cost effective when high-purity alumina brick insulation is used, but not for the other design concepts.

4.3 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 used as a guideline in deciding whether an extra active cooling system in the foundation be used.

The foundation is assumed to be a semi-infinite domain, and the bottom of tank insulation where the heat loss to the ground occurs is taken as a "disk" heat source at a specified temperature. 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 a lower temperature where the insulation meets the ground. The tank is assumed to have a diameter of 24 m. A conservative estimate used 0.2 W/m•K and 2 W/m•K as the thermal conductivities of the insulation and foundation, respectively.

Very little is known about soil or concrete properties at elevated temperatures; soil moisture trapped under the foundation may boil and produce unpredictable results. Thus, the bottom of the insulation layer should be kept below 100°C for the sake of safety. Calculations indicate that an insulated thickness over 3 m will be necessary. It is concluded that an additional active cooling system should be supplemented to the floor solid insulation in a two-tank storage system. Even in the case of a single-tank system, where the bottom of the tank is about 425°C at all times, the floor insulation thickness will still be over 1 m in order to keep boiling from occurring in the foundation. Therefore, an active cooling system should be employed for the foundation in all the tank systems.

4.4 THERMOCLINE STABILITY

In estimating the volume required to store the specified amount of heat it was assumed that the actual thermocline would occupy approximately less than 4% of the volume of a tank with a sharp temperature difference. To verify this assumption, calculations on the size of the thermocline were performed using the code developed by Sandia National Laboratories, Livermore (SNLL) for the design of the two media storage system [26]. For Solar One the working fluid is Caloria HT-43 heat transfer fluid and the solid medium is rock and sand [6]. The calculations for our design used the same procedure employed for the two-media storage system installed at Solar One with the best available properties for the carbonate salt working fluid and magnesia pellets. The results of this calculation are displayed in Figure 4-1 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. The thermocline in the 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. 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 a 6% 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 4% of the

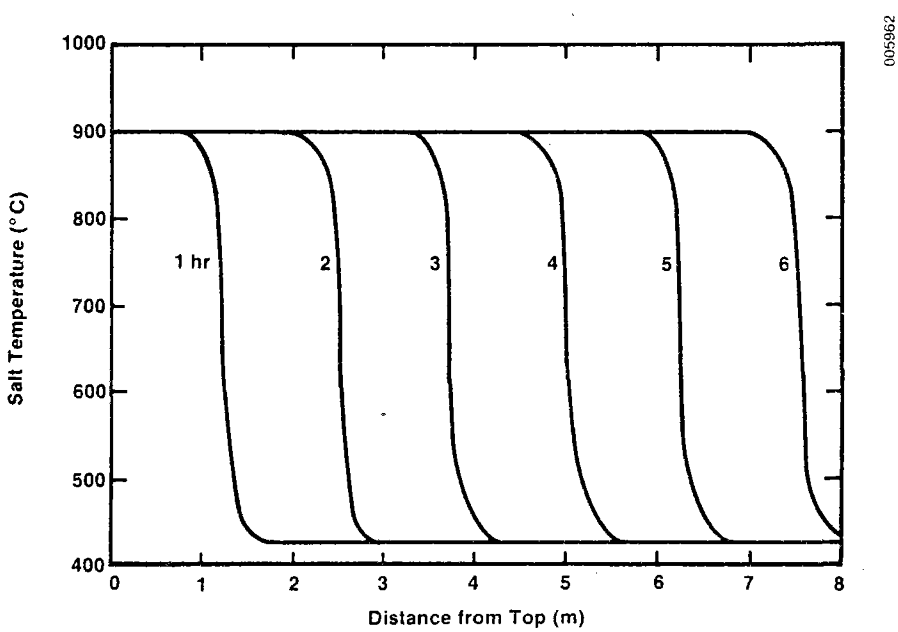

Figure 4-1. Molten Salt Temperature Distribution In A Packed Magnesia-Pellet Bed. Void Fraction = 30%, Pellet Diameter = 2.54 cm., Fluid Superficial Velocity = 0.03 cm/sec.

volume appears to be reasonable. It should be pointed out however, that the design code used for the above calculations neglected the affect of conductivity in the vertical direction. Hence, we recommend that a study be undertaken to investigate the affects of conduction on the size of the thickness of the thermocline. However, operation at Solar One also indicates that the thermocline may stretch out after 30 cycles and the liquid in the tank may have to be absorbed occasionally. This is a complicated phenomenon and more research work is expected [27].

In a qualitative manner the affect 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 [28] indicates that the equivalent radiative conductivity in the two-media zone 1 m in height and with a 475°C temperature difference (between 900°C and 425°C) is about 2 W/m•K. This is about the same as the solid conductivity through the media. To a first order approximation, both conduction and radiation can be neglected as compared to convective heat transfer. Further investigation of the affects of conduction and radiation should be included in the next phase of study for the development of a viable two-medium thermal storage system. It should also be pointed out that the above calculations have been made for a cylindrical tank. In future investigations it is recommended that the affect of sloping the sidewalls be studied and the affect of the slope on the size of the thermocline and the temperature distribution be investigated.

SERI

SECTION 5.0

STRUCTURAL CONSIDERATIONS

Molten salt containment design concepts are reviewed for structural considerations. They are, in order of discussion;

1. Single-tank, two-media, cylindrical tank storage (Figure 2-7)

2. Single-tank, two-media, sloped-wall tank (Figure 2-8)

3. Two-tank with multiple-layered insulation actively cooled hot tank (Figure 2-10)

Designs 1 and 2 are single-tank concepts combining the hot and cold molten salts through the use of thermoclines. Design 3 is a two-tank system consisting of hot and cold tanks.

For each design concept, when it is possible, both steel and reinforced concrete containment tanks are considered. Preliminary design drawings and structural design data are provided for the discussion of design merits and shortfalls. The liner thickness (allowing for corrosion loss) and various insulation thicknesses are estimated from a heat transfer consideration. The physical and material properties of the liners are summarized in Table 5-1.

5.1 SINGLE-TANK, TWO-MEDIA, CYLINDRICAL TANK

In the single-tank two-media thermocline system a cylindrical tank packed with MgO pellets is filled with molten salt. Figure 5-1 represents the design concept. A thermocline divides the tank into an upper hot zone of 900°C and a lower cold zone of 425°C. A ring-shaped vertical nonload-bearing barrier is introduced near the cylinder wall to prevent bulk flow; the outer layer of packed MgO bed acts as an internal insulation. The Incoloy 800H liner is backed by a four-inch lightweight insulating refractory concrete, and this is supported by either a structural steel or a reinforced concrete load-bearing cylindrical shell.

One inch thick (2.5 cm) Inconel 600 sheet piles are proposed for the barrier (see Figure 5-2). The bearing stress at the base of sheet piles is 92 psi (634 kPa), which is well below the creep-rupture strength of 1.5 ksi (10.4 MPa) [29]. Although there appears to be a safety factor of about 16., considering the uncertainty in the corrosion rate of Inconel to the salt, this large factor is necessary. A base plate ring is provided to support the sheet piles shown in Figure 5-3. Waffle-design, 1/2 in. (1.2 cm) Incoloy 800H, and liquid-tight liner is designed for the operating temperature of 550°C and thermal expansion. Beyond this liner a layer of 4 in. (10 cm) lightweight insulating refractory concrete, Kaolite 2200-HS (1.19 kg/m^3), or lightweight 1800 F (0.80 kg/m^3) is used. This reduces the temperature to 300°C.

Table 5-1. Physical and Mechanical Properties of Inconel 600, Incoloy 800, and Incoloy 800H

Temp.	Density	Thermal Expansion	Thermal Conductivity	Young's Modulus	Poisson's Ratio	Yield Strength	Fatigue Strength at 10^8 Cycles	Creep Ruptures Strength at 11.4 yr	ASME Allowable Tensile Stress
			k	E	--	Fy	Ff	Fcr	Fe
	Mg/m^3	$10^{-6}\ {}^oC^{-1}$	W/m^oC	GPa	--	MPa	MPa	MPa	MPa
			Inconel 600 (ASTM B168 Plate, Sheet, and Strip)						
300^oC	8.43	14.3	17.4	191	--	293	320.9	>110.3	>144.8
900^oC	8.43	16.4	28.7	149	--	93[a]	53.1	1.5	--
			Incoloy 800						
300^oC	7.95	16.2	16.3	178.3	3.57	260	--	280	113.1
900^oC	7.95	18.6	27.1	132.5	0.413	60[b]	--	--	--
			Incoloy 800H						
300^oC	Basically the same as Incoloy 800; Corrosion behavior of Incoloy 800 and 800H are the same		--	--	--	--	--	--	--
900^oD			--	--	--	--	--	12.5	--

(a)High-Temperature of annealed (899^oC/1 h) hot-rolled plate
(b)Hot-Rolled rod

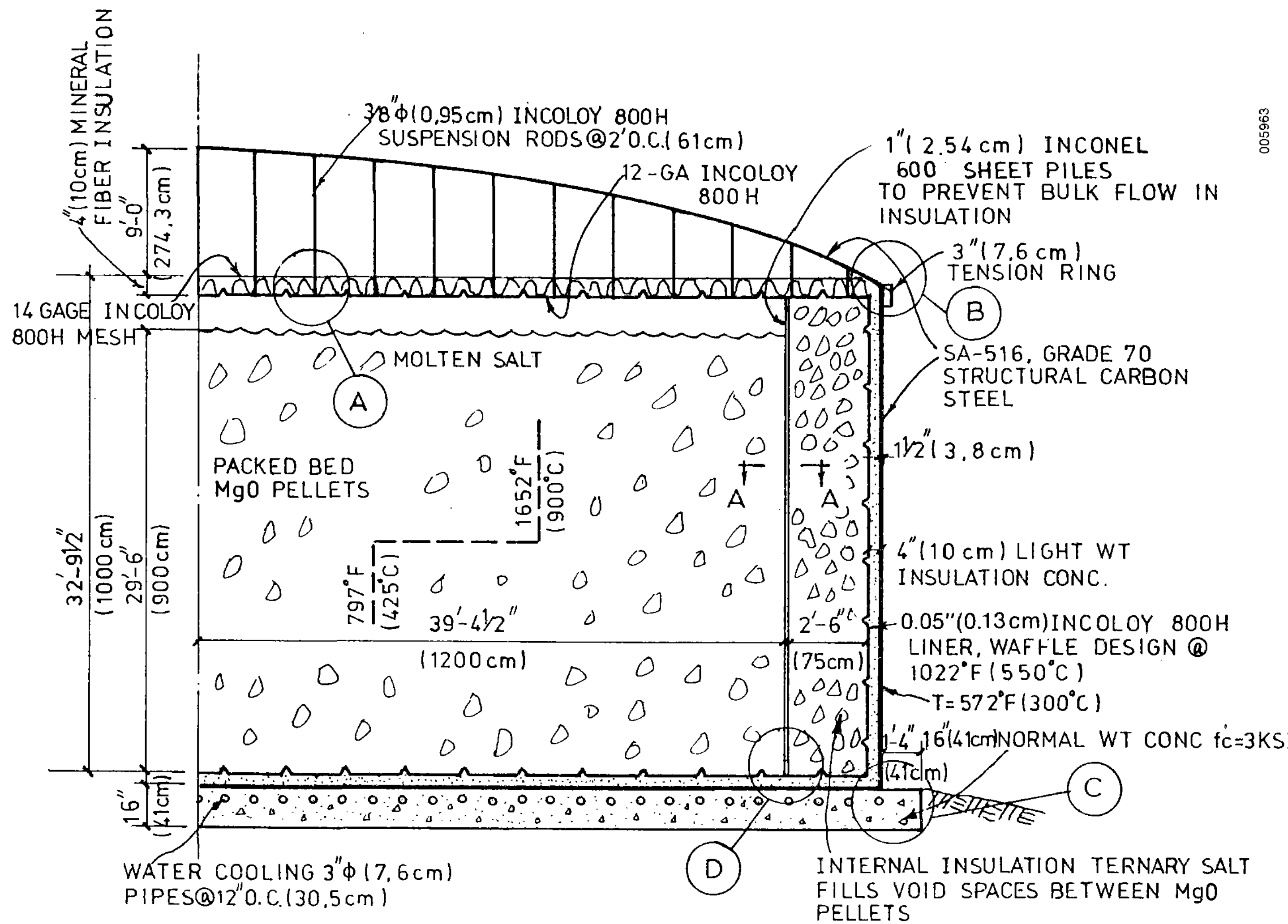

Figure 5-1. Details of Single-Tank, Two-Media Cylindrical Tank (Steel Tank).
Also refer to Figure 2-7.

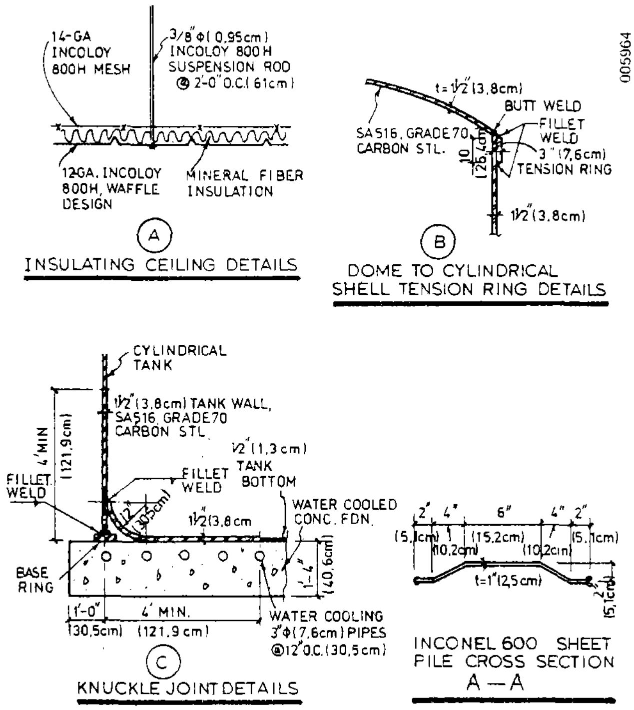

Figure 5-2. Details of Several Cross Sections in Figure 5-1.

Structural steel or reinforced concrete can be used as a load-bearing containment tank. A steel tank made of 1.5 in. (3.75 cm) SA-516, Grade 70 structural carbon steel plates is proposed for an above-grade tank design. At the service temperature of 300°C, the allowable design stress of SA-516 Grade 70 is 18.7 ksi (129.9 MPa) [30], hence the 1.5 in. (3.75 cm) steel skin is adequate in resisting the tank hoop stress and bending moment (Figure 5-4) due to hydrostatic load. A knuckle-joint connection shown in Figure 5-2 is designed to reduce thermal stress. The circular dome is designed for 120 lb/ft^2 (5.74 kPa) total downward load and is connected to the cylindrical tank by the 3 in.× 10 in. (7.5 cm × 25 cm) tension ring (Figure 5-2). A circular reinforced concrete water-cooled foundation is estimated to be 16-in. (40 cm) thick. The use of water cooling is necessary to meet the ACI 349-80 requirements [31] that limit the long term operation temperature to concrete below 65°C, except for local areas such as around pipe penetrations. Increased concrete temperatures less than 93°C are allowed near the cooling pipes.

If the tank is to be placed below the grade, a reinforced concrete tank is preferable (see Figure 5-5). A dry sand outer layer together with an enlarged concrete tension ring 4 ft × 6 ft (1.25 m × 1.82 m) is used to counteract some of the outward hydrostatic pressure. The sand and concrete are used to reduce the high bending moment at the tank wall-foundation junction. One advantage of using concrete (lightweight or normal weight insulating concrete) is that the net thermal expansion is rather small because of the nullifying effect of expansion and shrinkage [32] as shown in Figure 5-6. A few thermal cracks after the first heating and drying are expected and will not adversely affect the service performance of the concrete [32].

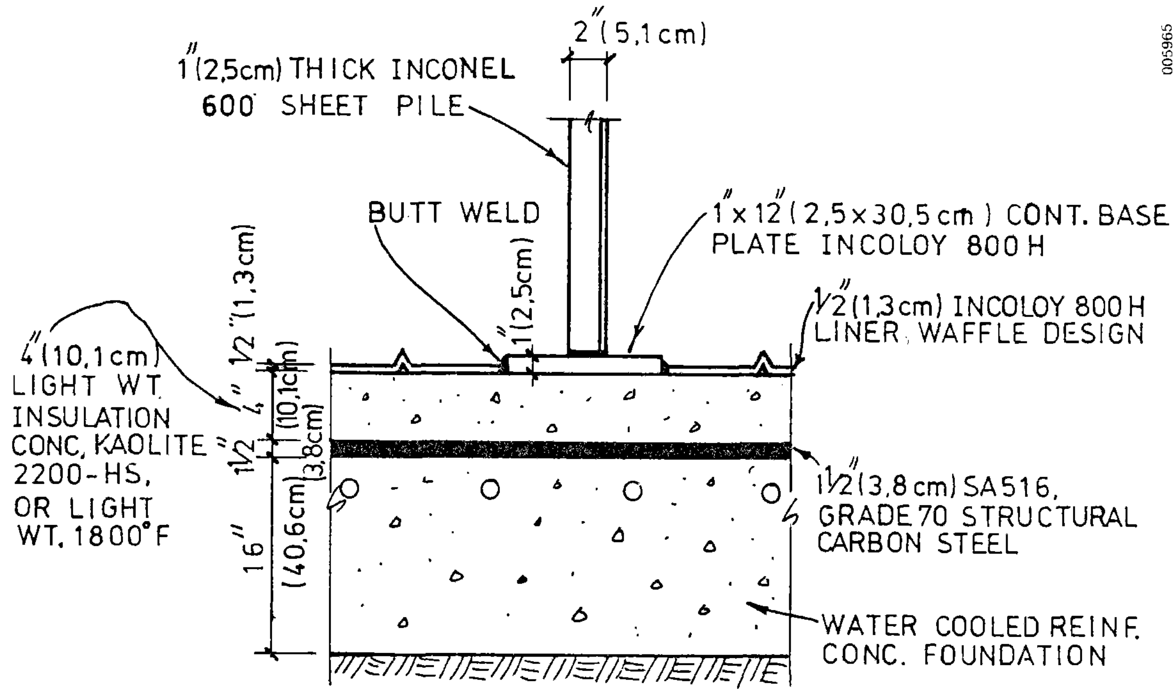

Figure 5-3. Details of Sheet Pile in Figure 5-1

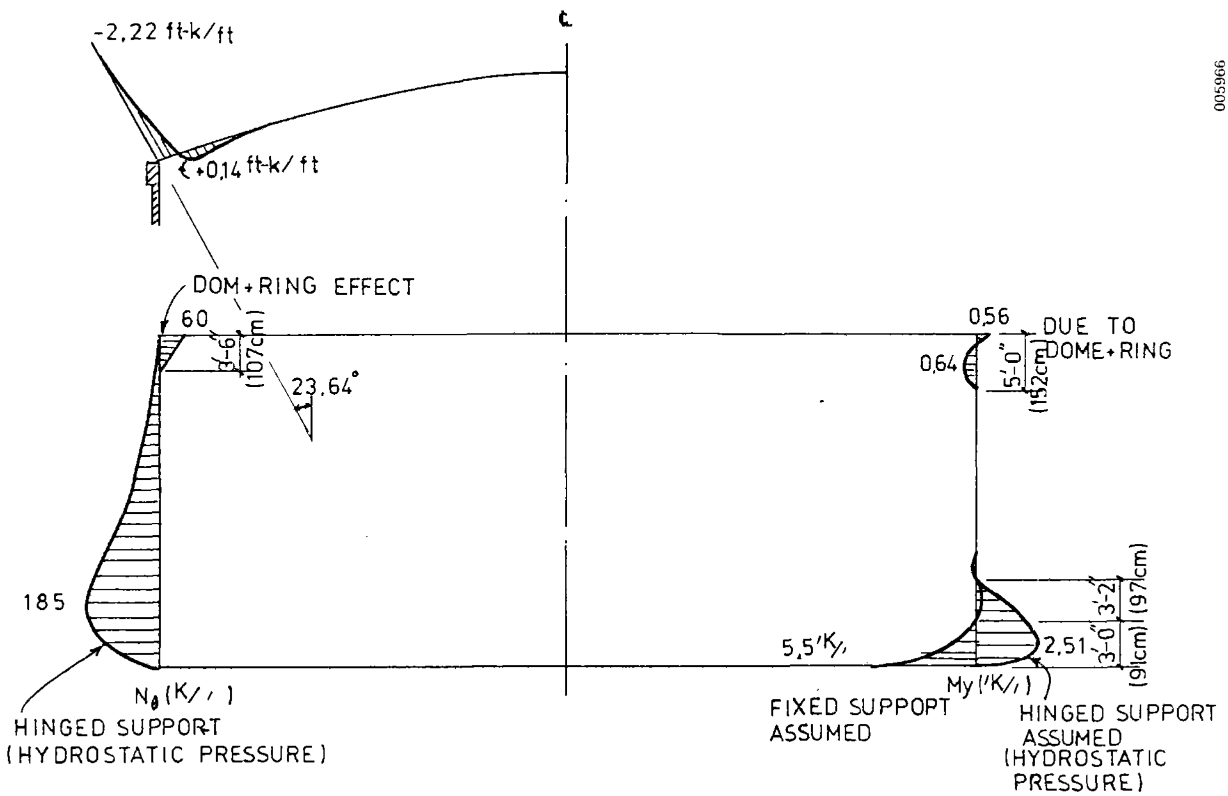

Figure 5-4. Hoop Force and Bending Moment Distribution

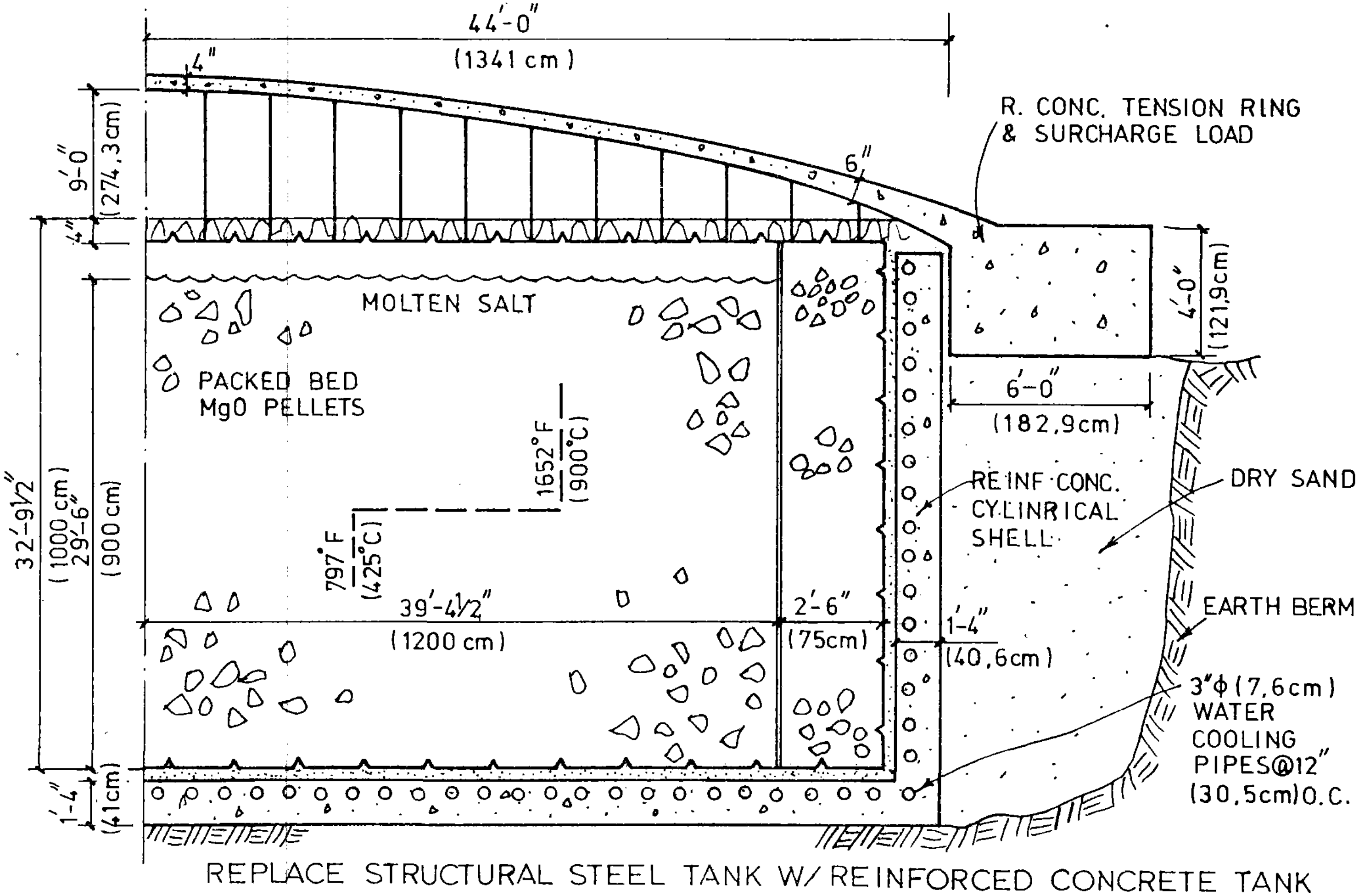

Figure 5-5. Details of Single-Tank, Two-Media, Cylindrical Tank (Reinforced Concrete Tank). Also refer to Figure 2-7

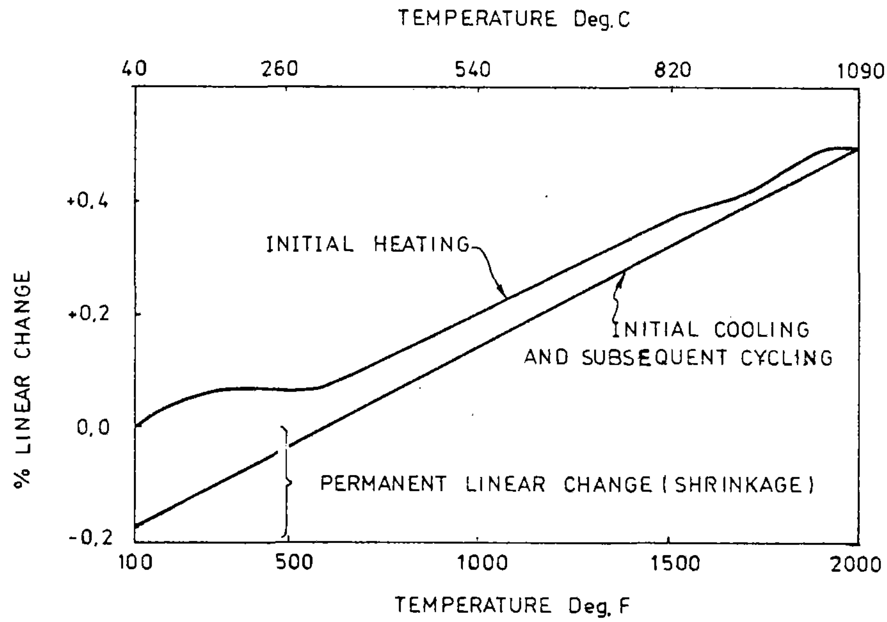

Figure 5-6. Net Thermal Expansion of a Typical Refractory Concrete

Under the dome a ceiling assemblage consisting of a 12-gauge Incoloy 800H, orthogonally corrugated sheets, 4 in. (10-cm) mineral fiber blanket, Incoloy 800H 14-gauge mesh, and 3/8-in. diameter (0.93 cm) Incoloy 800H suspension rods, is used. On the exterior of the dome another layer of 4 in. (10 cm) mineral-fiber insulation with water-proof metallic sheathing is required. The bill of materials for the single-tank, two-media cylindrical tank is shown in Table 5-2.

5.2 SINGLE-TANK TWO-MEDIA SLOPED-WALL TANK

In this design the molten salt with a thermocline is contained by a layer of MgO powder (30% void) that is inclined at a 45° angle of repose of the powder material. As shown in Figure 5-7, a temporary and expendable carbon-steel sheet is used for the installation of the 2 ft - 8 in. (0.81 m) inclined MgO powder insulation bed. Through this wet internal insulation the temperature drops from 900°C to a more manageable temperature of 350°C at the 1/4-in. (0.6-cm) 316 stainless steel, liquid-tight liner. For this service temperature the stainless steel possesses a yield stress of 18 ksi (124 MPa) [33], and the 1/4-in. (0.6-cm) thick liner is determined to perform adequately. To accommodate thermal expansion the liner is placed on a slip plane made of a 1/4-in. (0.6-cm) ceramic fiber blanket and a knuckle joint at the wall-foundation junction (see Figure 5-8).

The outer layer of this tank consists of 2-in. (5-cm) lightweight insulating concrete (lightweight 1800°F) that is supported by 1 ft - 4 in. (41 cm) of reinforced concrete, truncated, and inverted conical shell. Again these

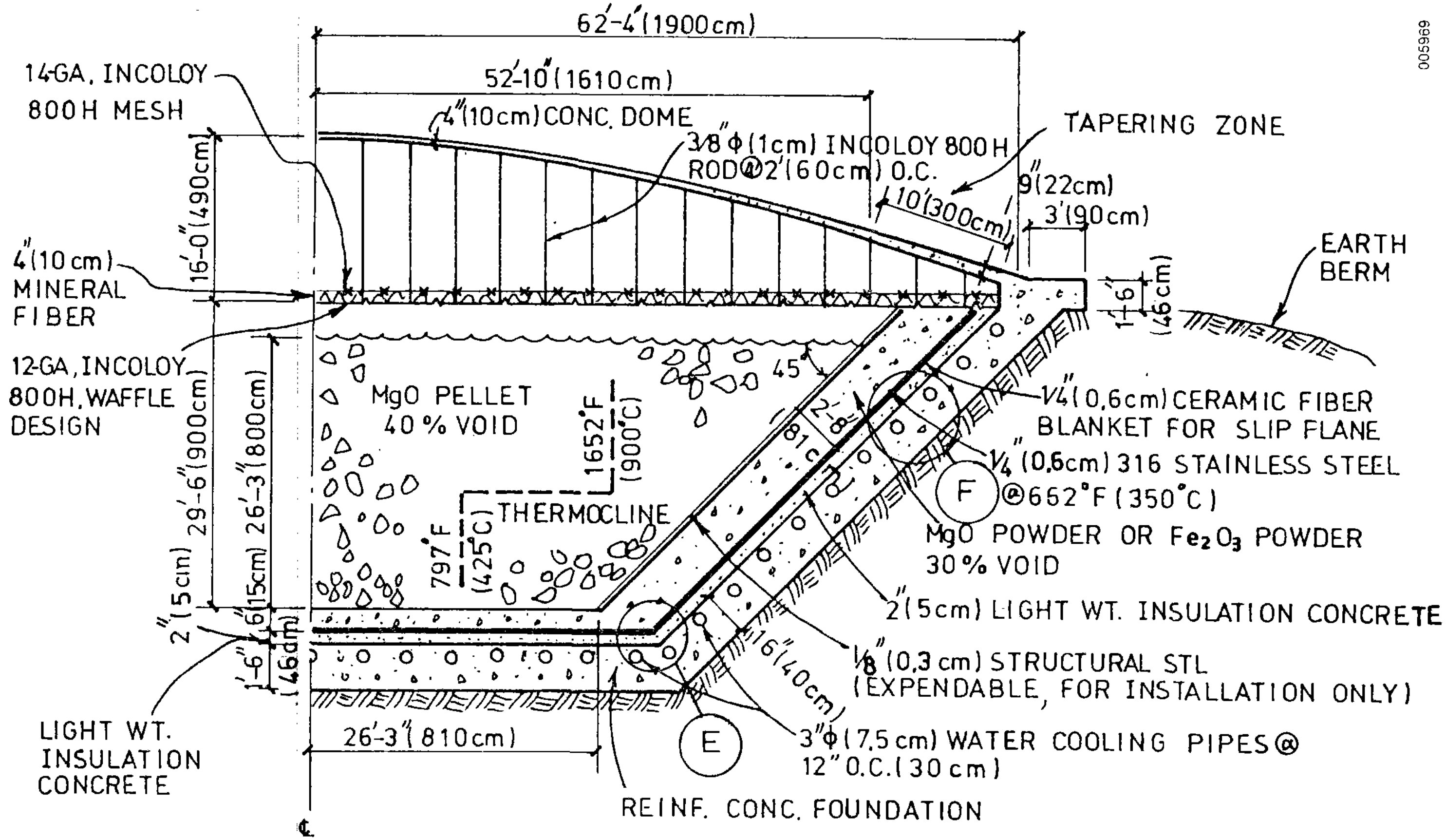

Figure 5-7. Details of Single-Tank, Two-Media, Sloped-Wall Tank (Reinforced Concrete Tank). Also refer to Figure 2-8

Table 5-2. Bill of Materials for a Single-Tank, Two-Media, Cylindrical Tank

Item	Quantity	
Steel Tank (Figure 5-1)		
Steel tank (SA516-Grade 70)	1,088,019 lb	493,600 kg
Mesh (Incoloy 800H)	1,173 lb	533 kg
Suspension rods (Incoloy 800H)	3,200 lb	1,447 kg
Liner (Incoloy 800H)	315,890 lb	143,282 kg
Sheet piles (Inconel 600)	353,013 lb	160,000 kg
Light wt. refractory concrete	177 yd^3	135 m^3
Reinforced concrete fc = 3 ksi	300 yd^3	230 m^3
Cooling pipes (structural steel)	46,045 lb	20,888 kg
Base plate (Incoloy 800H)	10,247 lb	4,647 kg
Concrete Tank (Figure 5-5)		
Mesh (Incoloy 800H)	1,173 lb	533 kg
Suspension rods (Incoloy 800H)	3,200 lb	1,447 kg
Liner (Incoloy 800H)	31,589 lb	14,328 kg
Sheet piles (Inconel 600)	353,013 lb	160,000 kg
Light wt. refractory concrete	177 yd^3	135 m^3
Reinforced concrete fc = 3 ksi	1,095 yd^3	840 m^3
Cooling pipes (structural steel)	175,787 lb	79,745 kg
Base plate (Incoloy 800H)	10,247 lb	4647 kg

concrete layers have excellent thermal expansion properties; the net concrete thermal expansion at the above service temperatures is about 0.06% - 0.08% linear change [32] (see Figure 5-6). For comparison, in the same condition a metal liner can easily expand as much as 10 times that of concrete.

The bottom of the truncated cone requires a thicker concrete foundation pad. It is estimated that a 1 ft - 6 in. (45 cm) thick, reinforced, and water-cooled concrete pad will meet all the requirements. The 2-in. (5 cm) lightweight refractory concrete is employed to maintain and limit the maximum concrete service temperature at 93°C.

S=RI

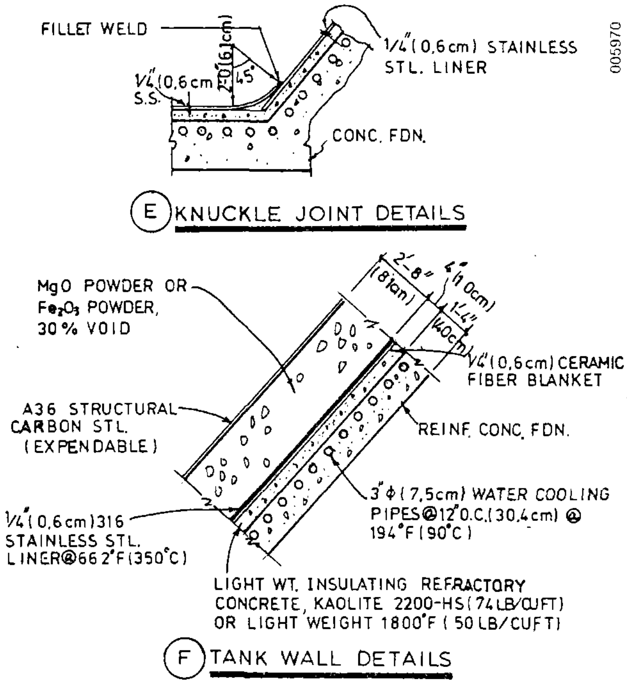

Figure 5-8. Details of Several Cross-Sections in Figure 5-7

Because of the truncated conical tank design, the dome span has increased considerably. At the span of 125 ft (38 m) and a load of 120 lb/ft^2 (5.74 KPa), a steel dome fabricated from welded-steel plates would require a 2.5 in. (6.25 cm) thickness, which can not be constructed without a special heat treatment of welds. Another form of the steel dome could be constructed with a steel stiffener rib and covered with 0.5 in. (1.25 cm) steel plates. But this would drive up the fabrication as well as construction costs. Only the concrete dome is presented in Figure 5-7. The reinforced concrete dome is basically 4 in. (10 cm) thick and tapers to 9 in. (22.5 cm) at the 1 ft - 6 in. × 3 ft (0.45 m x 0.91 m) tension ring along the periphery. It can be either constructed monolithic with the concrete conical shell or separately supported by ground foundation. The latter scheme allows lifting of dome for easy access to the tank interior for either routine maintenance or repair work.

The ceiling insulation consists of 12-gage Incoloy 800H sheets, a waffle design to support a layer of 4 in. (10 cm) mineral fiber insulation, and a 14-gauge Incoloy 800H mesh. The ceiling assemblage is suspended from the concrete dome by a series of 3/8 in. diameter (0.93 cm) Incoloy 800H rods spaced at 2 ft (61 cm) of centers. A layer of mineral-fiber blanket insulation 4 in. (10 cm) thick with a thin aluminum or galvanized steel (14-gauge) sheathing may be necessary at the dome exterior to reduce thermal shock during heavy rain falls and for safety considerations.

The practical size of the tank is only limited by the concrete dome span that can be as large as 200 ft to 250 ft (61 m to 76 m) without requiring a special and costly design. An earth berm should be constructed as shown in Figure 5-7, and its surface should be properly covered with a water-tight concrete skirt to drain surface run-off away from the tank. The bill of materials for this design is shown in Table 5-3.

5.3 TWO-TANK WITH MULTIPLE-LAYERED INSULATION ACTIVELY COOLED HOT TANK

In this design concept a two-tank system is proposed. The hot tank consists of multiple-layered insulation in the form of MgO powder filled, hollow, and high-purity-alumina ceramic bricks, resembling ordinary concrete blocks in shape, waffle design Incoloy 800H liner, and solid low-density high-silica firebricks. Figure 5-9 represents a schematic drawing of this design.

For the corrosion resisting high-purity-alumina ceramic brick, its ultimate compressive stress is about 100 ksi (689 MPa) [34] at 900°C. By taking 15% of this stress as its ultimate tensile stress and applying a factor of safety of 4, one has an allowable tensile stress of 3.75 ksi (25.8 MPa). On this basis, it is determined that the brick wall shall be at least 3/8 in (0.93 cm) thick for the design height of about 29 ft (9 m) as shown in Figures 5-9 and 5-10.

To effect a better containment of MgO powder inside the brick, a grooved wall design is proposed as shown in Figure 5-10. A layer of molten-salt saturated brick powder together with salt cooling pipes forms the first layer of insulation, reducing the temperature down to 550°C from 900°C.

Behind this brick layer a waffle design of a 0.05 in. (0.125 cm) Incoloy 800H liner is employed. The orthogonal corrugations in this liner are to accommodate thermal expansion. However, this approach may prove to be impractical because the protruding corrugations, sandwiched between two brick layers, may easily be crushed and cracked mainly because of the weight of materials above and hydrostatic pressures. A special set of grooves should be provided in the

Table 5-3. Bill of Materials for a Single-Tank, Two-Media, Sloped-Wall

Item	Quantity	
Reinforced concrete, fc = 3 ksi	1,039 yd^3	797 m^3
Light wt. refractory concrete	86 yd^3	66 m^3
Liner (316 stainless steel)	143,327 lb	64,792 kg
Cooling pipes (structural steel)	208,295 lb	94,161 kg
Suspension rods (Incoloy 800H)	10,237 lb	4,623 kg
Ceiling liner (Incoloy 800H)	54,058 lb	24,437 kg
Mesh (Incoloy 800H)	2,510 lb	1,135 kg
Expendable structural steel for installation only	12,399 lb	5,605 kg

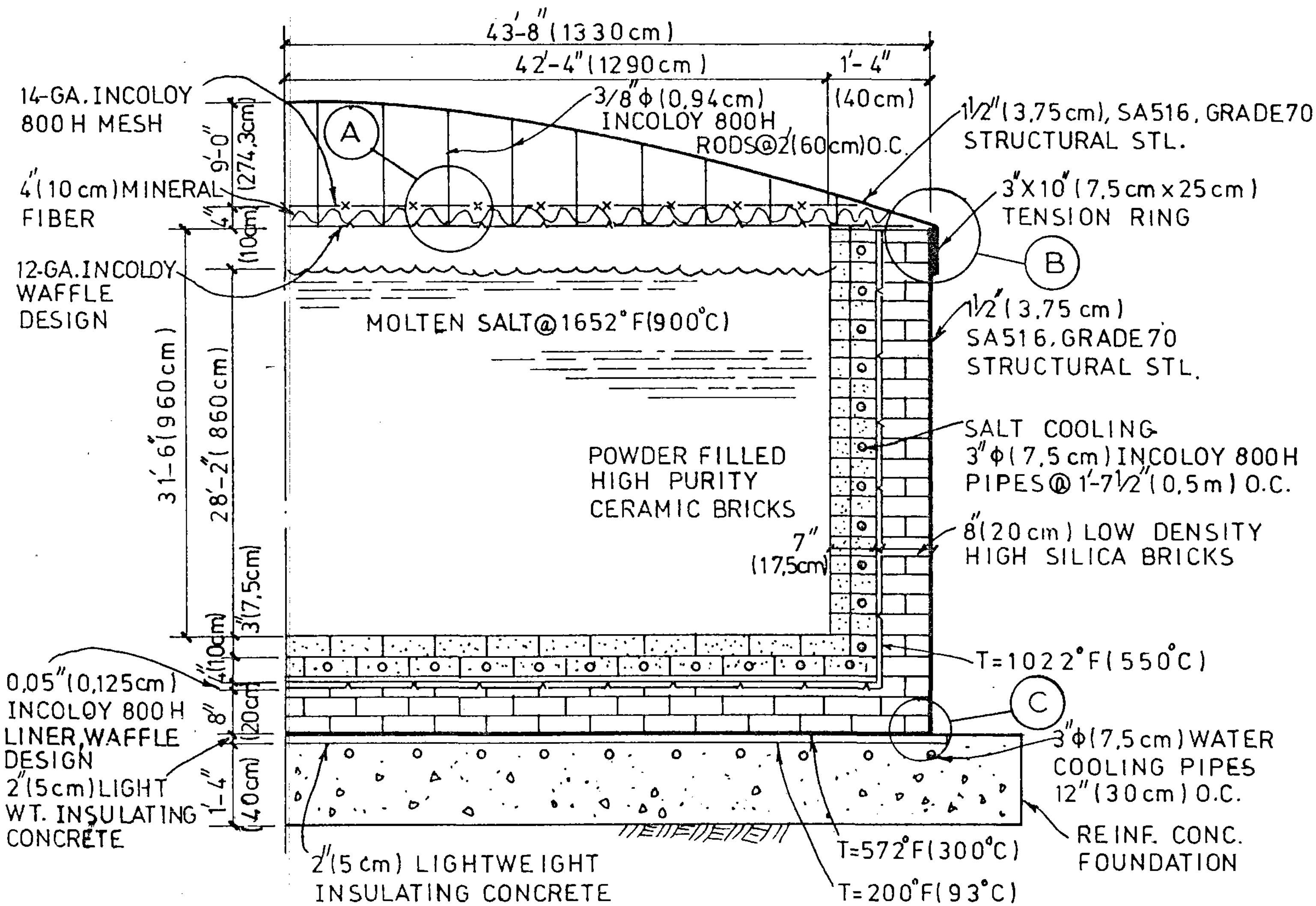

Figure 5-9. Details of Two-Tank System with Multiple-Layered Insulation and Actively Cooled Hot Tank (Steel Tank). Also refer to Figure 2-10

brick floor and wall to free the liner corrugations from any bearing stresses. One such scheme is shown in Figure 5-11.

The second layer of insulation provided are 8 in (20 cm) thick low-density high-silica solid bricks. They transfer bearing pressures from the Incoloy 800H liner to the outer structural wall and foundation. Through this layer the temperature drops further to 300°C. Another layer of 2 in (5 cm) lightweight refactory concrete will keep the temperature below 93°C, and allows for the design of the water cooled concrete foundation beneath it.

The use of regenerative cooling to minimize heat loss is a good idea, from the structural point of view. The large quantity and length of pipes tend to produce undesirable brick movements that are caused by the thermal expansion incompatibility of the two materials, if the pipes are tightly embedded in the bricks. The bricks are laid with no binding agent between them and are especially vulnerable to disturbing forces.

The outer structural containment vessel can be either structural steel or reinforced concrete shells. Figure 5-9 shows an above-grade design with 1.5 in. (3.75 cm) SA 516 Grade 70 structural carbon-steel cylindrical shell with a circular dome. A below-grade reinforced concrete design is given in Figure 5-12, where the outer sand layer and large concrete tension ring are provided to counteract internal hydrostatic pressure so the tank wall will not

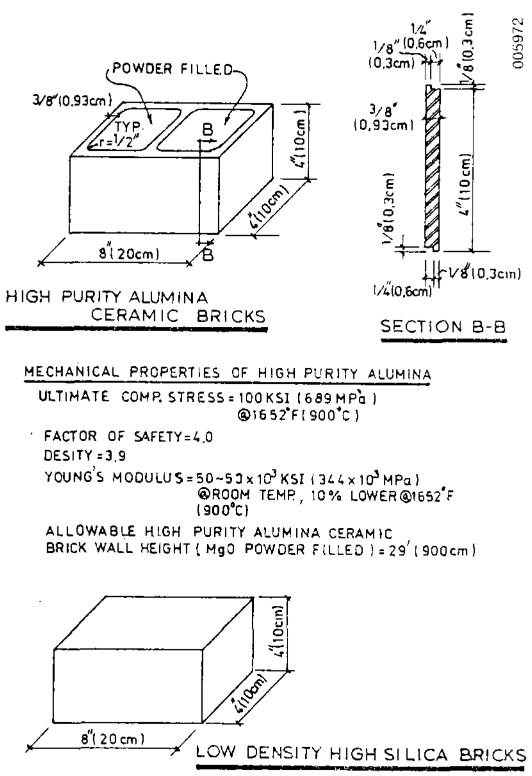

Figure 5-10. Details of Ceramic Bricks Used in Figure 5-7

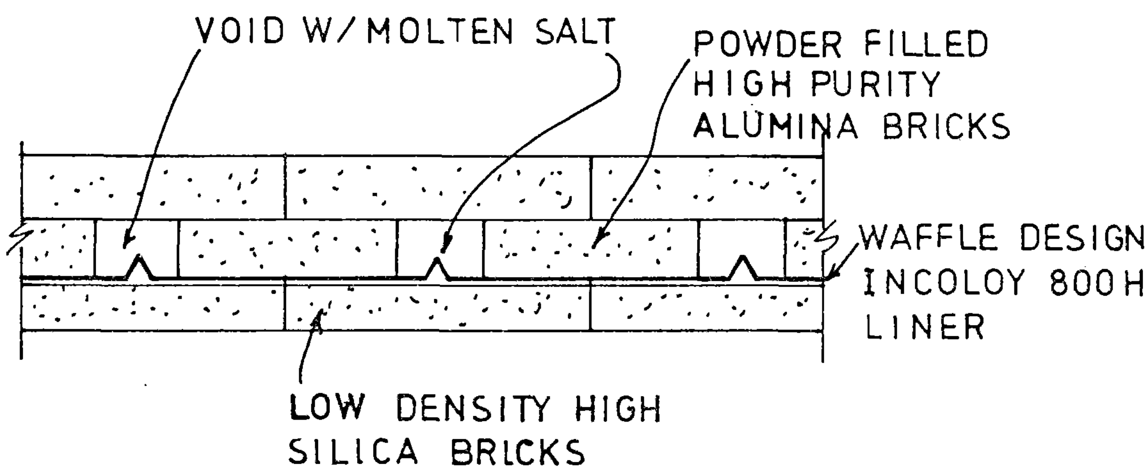

Figure 5-11. A Special Brick Arrangement for Figure 5-9

be excessively thick. Ceiling insulation and exterior dome insulation are similar to those in the previous design concepts.

The principal advantage of this design concept is in its use of highly corrosion resisting, high-purity-alumina bricks. However, the main complications come from the same source. Many unknowns exist with the application of unbound brick liner. The stability of the brick wall under the given environment is unpredictable, especially with a sandwiched metal liner and cooling pipes. To achieve a practical design, the cylinder wall may have to be tilted 5^{o} outward to increase the brick wall stability. The bill of materials for this design is shown in Table 5-4.

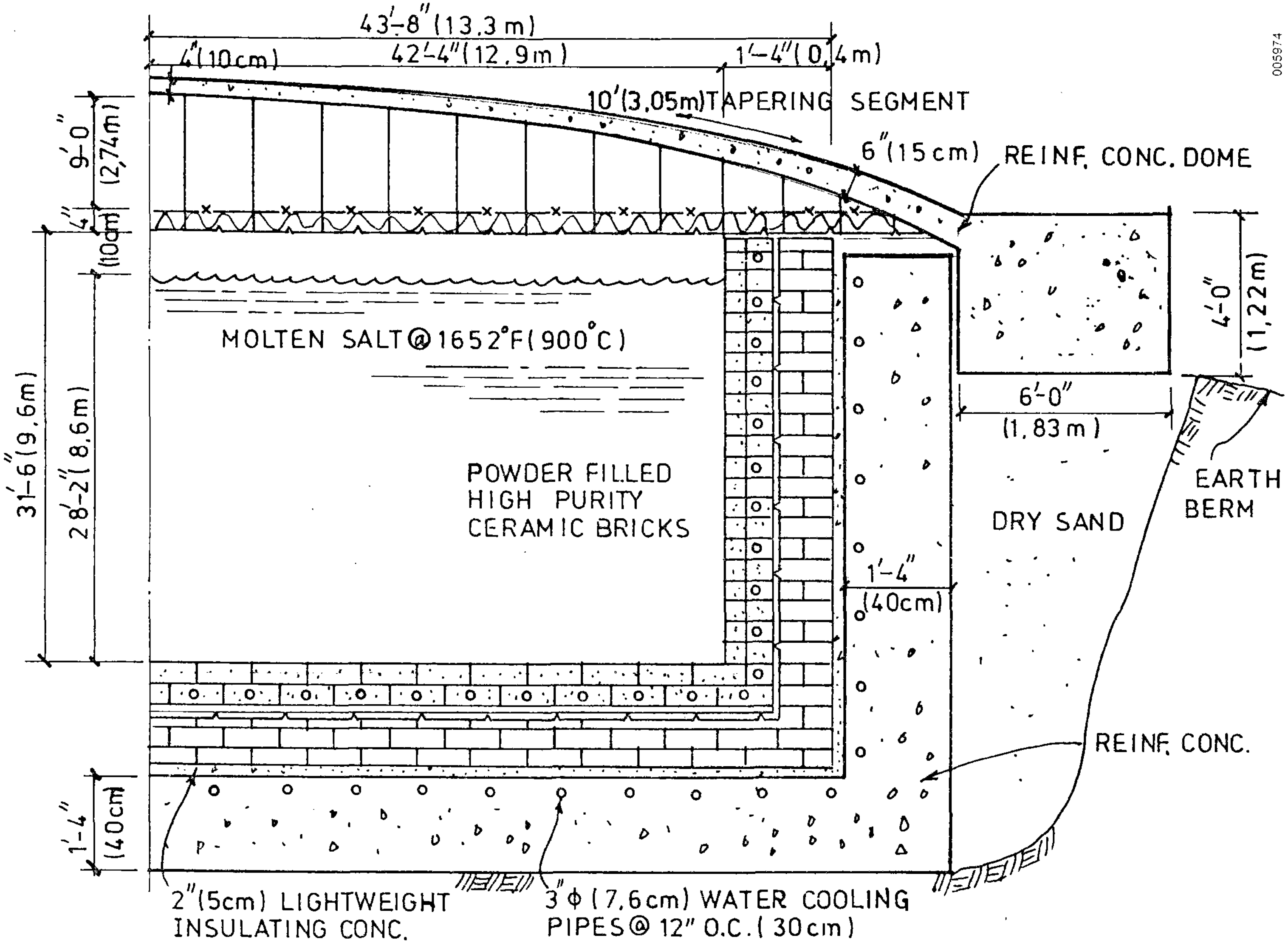

Figure 5-12. Details of Two-Tank System with Multiple-Layered Insulation and Actively Cooled Hot Tank (Reinforced Concrete Tank). Also refer to Figure 2-10

Table 5-4. Bill of Materials for a Two-Tank with Multiple-Layered Insulation, Actively Cooled Hot Tank

Item	Quantity	
Structural Steel Tank (Figure 5-9)		
Steel tank (SA516-Grade 70)	1,342,158 lb	608,793 kg
Mesh (Inoloy 800H)	1,173 lb	533 kg
Suspension rods (Incoloy 800H)	3,200 lb	1,447 kg
Liner (Incoloy 800H)	56,777 lb	25,770 kg
Cooling pipes (structural steel)	46,045 lb	20,888 kg
Cooling pipes (Incoloy 800H)	129,349 lb	58,721 kg
High purity ceramics bricks	1,394,000 lb	632,713 kg
Low density high silica bricks	1,516,554 lb	688,388 kg
Reinforced concrete fc = 3 ksi	315 yd^3	242 m^3
Reinforced Concrete Tank (Figure 5-12)		
Mesh (Incoloy 800H)	1,173 lb	533 kg
Suspension rods (Incoloy 800H)	3,200 lb	1,447 kg
Liner (Incoloy 800H)	56,777 lb	25,770 kg
Cooling pipes (Structural Steel)	175,394 lb	79,566 kg
Cooling pipes (Incoloy 800H)	129,349 lb	58,721 kg
High purity ceramics bricks	1,394,000 lb	632,713 kg
Low density high silica bricks	1,516,554 lb	688,388 kg
Reinforced concrete fc = 3 ksi	1,133 yd^3	869 m^3

SECTION 6.0

COST ESTIMATES

In this section comparisons are made of the expected investment cost of several of the suggested storage concepts. Emphasis is primarily on differences between concepts and on the more expensive components. Hence common and relatively inexpensive features, such as an earth berm and process piping, are not included in the cost analysis. An initial analysis was done of some concepts to get an indication of the more expensive components. In this initial analysis we tended to be pessimistic (i.e., chose the more costly values) with respect to physical properties and unit prices of materials and the design of certain components such as roof and foundation. In later calculations we tended to be more optimistic, but generally we believe these later values to be more realistic also. The cost estimates are all made using reinforced concrete external structure, as rough estimates showed this construction to be less expensive than to use structural steel vessels. All the cost estimations were done with the same approach and same basic data, so that relative values are more dependable than absolute values.

The general approach is to estimate the material quantity requirements based on thermal design specifications, and then multiply the quantities by the individual materials' unit price (see Table 3-2 and Table 6-1 for prices used). The material unit prices are updated as necessary to mid-1984 using the GNP Implicit Price Deflator [37]. The materials' costs are multiplied by 1.8 (direct field cost factor) and by 1.95 (total investment factor) [19]. The cost of the storage medium is multiplied by the 1.95 investment factor only, as no installation is required [19]. This is a common type of investment estimation procedure and, while it is not precise, it is useful for comparative, screening purposes. Some independent checks are made to verify that estimated investment costs were reasonable.

The unit prices for materials could be estimated only roughly in some key cases, in particular for magnesia and alumina components used in direct contact with molten salt. The reason is that the specifications--purity required

Table 6-1. Price Data for Metal Liners

Metal	Price $/kg Mid-1984 Basis	Ref.
Carbon steel	1.75	19
Stainless steel-304	6.85	19
Stainless steel-316	11.00	19
Incoloy 800 or 800h sheet	13.70	19
Incoloy 800 waffle	$238/m^2	9
Inconel 600	26.0	35

part size, shape and porosity, and lot size for fabricated parts--are not sufficiently estiblished. Thus, the prices used for these materials have a high degree of uncertainty. Yet, they are major cost contributors in certain designs, which leads to considerable uncertainty in the investment estimates for those designs.

Results and discussion of the cost estimates are presented below. Many assumptions are made in the cost estimate calculations. Certain key assumptions are listed here.

- Corrosion rate of Inconel 600 in contact with molten salt at 900°C is 2 μm/day, which converts to 0.86 in. (2.2 cm) in 30 years. Cost based on 1-in. (2.54 cm) thickness
- Commercially fabricated Incoloy "waffle" liner could be used at 550°C
- Corrosion suppression could allow the use of Incoloy 800 at 900°C, 0.48 cm in thickness (optimistic) or 0.95 cm in thickness (pessimistic)
- Magnesia and alumina components of sufficient purity to withstand the molten-salt atmosphere could be fabricated.

No attempt has been made to optimize the design parameters in this study. For example, the tank height-to-diameter ratio was fixed at 1-to-3 [9], but it could be optimized. Not every one of the concepts introduced above were subjected to cost estimation. In particular, two of the two-tank systems (Figures 2-12 and 2-13) utilizing the castable-refractory wall were not done, nor was the raft-thermocline, alumina brick, Incoloy 800 liner (Figure 2-2) concept estimated. The two-tank castable refractory designs were not done for several reasons based upon our preliminary analysis, including these: there was considerable doubt as to the structural soundness of these designs; it was doubted that unlined castable refractory could withstand the corrosion conditions; the alumina-lined concept appeared too expensive. The Incoloy-liner raft thermocline was not estimated because it did not appear to be advantageous compared to the Inconel-diffusion-barrier case (Figure 2-3) which was estimated.

Table 6-2 shows investment-cost results for the diffusion-barrier-raft-thermocline system (see Figure 2-4). The principal differences between the optimistic and pessimistic alternatives are: we used a price of $5.50/kg compared to $26/kg for the high-purity alumina; and the tank top and bottom were estimated as being similar in design to the sidewalls in the pessimistic case, but were based upon a separate design analysis in the optimistic case. The estimated investment for this design, ranging from 43.1 to 61.4 million dollars, is substantially higher than for the other designs considered. This is due to the use of Inconel 600 and high-purity alumina, both very expensive materials, in this concept.

Table 6-3 gives the results for a two-media (molten carbonate eutectic salt plus magnesia pellets) system in a cylindrical tank with Inconel sheets as inner liner (Figure 2-7). After the media, the Inconel sheets and the Incoloy liner are the principal cost items. The main differences between the pessimistic and optimistic cases are the top, bottom, and sidewall designs and

Table 6-2. Materials-Based Cost Summary for Diffusion-Barrier Raft Thermocline System (Figure 2-4)

Item	Investment (10^6\$)	(\$/kWh)	Investment Percentage of Total
A. Optimistic			
Sidewall	13.0		30
Raft	4.3		10
Top	1.6		4
Bottom	0.5		1
Medium	23.7		55
Total	43.1	(24.0)	100
B. Pessimistic			
Sidewall	21.1		34
Raft	10.6		17
Top	4.0		7
Bottom	2.0		3
Medium	23.7		39
Total	61.4	(34.0)	100

Table 6-3. Materials-Based Cost Summary for Cylindrical Two-Media System (Figure 2-7)

Item	Investment (10^6\$)	(\$/kWh)	Percentage of Total
A. Optimistic			
Sidewall	10.2		32
Top	1.6		5
Bottom	0.5		2
Media	19.5		61
Total	31.8	(17.7)	100
B. Pessimistic			
Sidewall	17.3		40
top	4.0		9
Bottom	2.0		5
Media	19.5		46
Total	42.8	(23.7)	100

costs and a lower cost for the Incoloy waffle in the latter case. The cost for the media is less for the two-media concept than for salt alone, because of the (estimated) lower cost of the magnesia pellets. The results of the two-media, sloped, powder-insulated wall concept (Figure 2-8) are shown in Table 6-4. A 45° angle of repose was used, based upon initial laboratory tests. 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 ($0.43/kg for powder and $0.76/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. We also considered use of high-purity-alumina solid packing in high-void shapes, e.g., thin-wall cylinders. This gave media costs which started at about the same as the pessimistic case in Table 6-4 and ranged upward. We cannot eliminate the high uncertainty associated with the solid medium cost at this time.

Results for the multilayered insulation, regeneratively cooled with salt, two-tank system (see Figure 2-10) are shown in Table 6-5. Only an "optimistic" estimate has been made for this case. The major cost factor in this design (other than the medium) is the powder-filled alumina brick (about 60% of the sidewall cost) even though an optimistic unit price and regenerative cooling are used.

Table 6-6 shows the results of a pessimistic analysis of a two-tank system with an Inconel liner over castable refractory (Figure 2-16). The Inconel

Table 6-4. Material-Based Cost Summary for Sloped-Wall Two-Media System (Figure 2-8)

Item	Investment (10^6\$)	(\$/kWh)	Percentage of Total
A. Optimistic			
Sidewall	5.2		19
Top	1.9		7
Bottom	0.5		2
Media	19.5		72
Total	27.1	(15.1)	100
B. Pessimistic			
Sidewall	7.8		19
Top	1.9		5
Bottom	0.5		1
Media	30.8		75
Total	41.0	(22.8)	100

Table 6-5. Material-Based Cost Summary for Cylindrical Two-Tank System (Figure 2-10) (optimistic design only)

Item	Investment (10^6\$)	(\$/kWh)	Percentage of Total
Hot Tank			
Sidewall	8.6		22
Top	1.6		4
Bottom	0.5		1
Medium	26.0		67
Cold Tank	2.5		6
Total	39.2	(21.8)	100

Table 6-6. Material-Based Cost Summary for Inconel Lined, Castable Refractory, Two-Tank System (Figure 2-16) (pessimistic design only)

Item	Investment (10^6\$)	(\$/kWh)	Percentage of Total
Hot Tank			
Sidewall	11.1		25
Top	4.0		9
Bottom	2.0		5
Medium	24.5		55
Cold Tank	2.5		6
Total	44.1	(24.6)	100

liner is the dominant cost factor. The top, bottom and cold-tank costs are high, for they were estimated based on a design similar to the sidewall. A more "optimistic" (and realistic) estimate would be $4.5 million vs. $8.5 million total for the top, bottom and cold tank. Thus, an optimistic total system estimate would be $40.1 million (vs. $44.1 million), which is still quite high.

As one reviews the results of all these cost estimates, several observations occur, including:

- Pessimistic investment estimates are about 1.5 times the optimistic ones for the tank plus media. Considering the tank alone (excluding the media), pessimistic estimates are about twice the optimistic ones. This factor-of-two range is probably a reasonable reflection of the uncertainties in these designs.
- The cost of the media is a significant portion, typically half to three quarters, of the total investment.
- The raft-thermocline, Table 6-2, appears to be significantly more expensive than the other concepts considered.
- The estimated costs of the two-media systems, Table 6-3 and 6-4, are less than those of the systems examined. The sloped wall, two-media system shows the least cost. However the differences are only marginally significant given the uncertainty of the estimates.
- The operating costs for each design are not considered at this point. However, the difference between designs should not be a significant factor when it is compared to the construction.

SECTION 7.0

DISCUSSION OF TECHNICAL RISKS

7.1 RISK ASSESSMENT

Table 7-1 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.

7.2 SINGLE-TANK RAFT SYSTEM

The single tank raft concept (see Figures 2-2 and 2-4 for this concept) was proposed in order to eliminate the effects of radiation in a thermocline system. Radiant heat transfer could result in significant heat losses and could destabilize the thermocline at the high-temperatures considered. However, the raft concept turned out to be higher in cost than two media or two-tank storage systems. Moreover, the stability of the raft has not been studied at higher temperatures or in the large diameter (order 24 m) required. In view of the fact that there exist still technical uncertainties with the raft system and the system appears to have no cost advantages, this particular idea does not appear to be promising.

7.3 SINGLE-TANK TWO-MEDIA SYSTEM

The two media single tank concept has two subdivisions: one with a cylindrical container, Figure 2-7, and the other with a sloped-wall design as shown in Figure 2-8. A major technical risk in this concept, the integrity of the solid pellets in molten salts at 900°C, has not been demonstrated. In addition, there are also questions on thermocline stability which have been mentioned previously in this report. The sloped wall concept has potentially a lower cost, because an expensive metal or ceramic liner is not required. In both designs, however, there 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 circulation currents being 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. This concept is the least expensive of those considered.

7.4 TWO-TANK SYSTEM

The various two-tank design concepts are displayed in Figures 2-10 through 2-16. The concepts in 2-12 and 2-13 show an "accordion" wall. Initially it was believed that the accordian design offers an advantage because much of the compressive load on the wall is transmitted to the foundation via buttresses. However, further detailed study of this concept revealed that the accordion design does not have any significant structural advantage and it is therefore not recommended to pursue the accordion wall any further. The

Table 7-1. Summary of Storage Tank Designs

Design Figure	Storage System	Design Features	Technical Risks or Disadvantages	Remarks	Investment Estimates low (10^6 $)	high (10^6 $)	low ($/kWh)	high ($/kWh)
2-2	Single Tank Raft	Multiple layered insulation (ceramic and silica bricks)	Very high cost in ceramic bricks Technical uncertainty about raft stability	Not pursued				
2-4	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	43.1	61.4	24.0	34.0
2-7	Single Tank Two-Media	MgO Pellet in bed. Inconel sheet to present bulk salt flow in (MgO pellet) inner insulation	Integrity of solid pellets is a key question	Modified as Figure 5-1 (Steel tank)				
				Figure 5-5 (Concrete Tank)	31.8	42.8	17.7	23.7
2-8	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	Modified as Figure 5-7	27.1	41.0	15.1	22.8
2-10*	Two-Tank	Multiple layered insulation (ceramic and silica bricks)	Very high cost in ceramic bricks	Modified as Figure 5-9 (Steel tank)				
				Figure 5-12 (concrete tank)	39.2		21.8	
2-12*	Two-Tank	Unlined castable structure, accordion wall.	Accordion wall design does not offer hoop stress advantage	Not pursued				
2-13*	Two-Tank	Lined castable structure, accordion wall	Accordion wall design does not offer hoop stress advantage	Not pursued				
2-16*	Two-Tank	Castable alumina wall, Inconel liner creeped into position, use $BaCO_3$ powder to solidify salt	No reliable data on creeping process	Not recommended	44.1		24.6	

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

designs in Figures 2-10 and 2-16 are geometrically similar. However, the design shown in Figure 2-10 uses multilayered insulation with ceramic bricks, which are very expensive. As a result, this design can be expected to have an excessive cost and it is not recommended to be pursued. The design in Figure 2-16 uses a castable alumina wall with an Inconel liner creeped into position. However, there are no reliable data on the creep process and there is no an adequate basis to design a tank for this concept. Consequently, the technical risk of this proposed design is unacceptably high until this question is resolved and, at this time, pursuing the design shown in Figure 2-16 is not recommended.

SECTION 8.0

CONCLUSIONS AND RECOMMENDTIONS

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

- Regenerative cooling is worthwhile when high-cost, high-purity alumina brick insulation is used, but not for the other design concepts.
- Active cooling under the tank is necessary to reduce the need for solid insulation and prevent boiling in the ground in all concepts.
- A thermocline is stable in a two-media system according to an analysis that considers convective heat transfer only.
- The single-tank raft system concept has technical uncertainties and the highest cost of the three systems.
- The use of high-purity ceramic brick internal insulation results in excessive cost.
- The two-media single tank with sloped walls, shown in Figure 2-8, has the potential of being the lowest cost system.

The following questions should be answered to remove technical uncertainties:

- The compatability of the sensible heat storage solids with the molten salt in a two-media hot tank should be studied more thoroughly.
- 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°C, but very little is known about its stability, especially in a molten salt at elevated temperatures.
- The wet insulation layers must be designed in such a way that natural convective heat loss, due to circulation inside the insulation, and heat conduction through the insulation from above to below the thermocline can be suppressed. Experimental study to provide design guidelines under high temperature conditions are recommended.
- The effect of conduction and radiation on the stability of thermocline should be analyzed rigorously. Also, the effect of sloped walls on the shape and the temperature distribution of thermoclines should be investigated.

SECTION 9.0

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Document Control Page	1. SERI Report No. SERI/TR-252-2490	2. NTIS Accession No.	3. Recipient's Accession No.

4. Title and Subtitle High Temperature Molten Salt Containment	5. Publication Date May 1985 6.
7. Author(s) K. Y. Wang, R. E. West, F. Kreith, P. P. Lynn	8. Performing Organization Rept. No.
9. Performing Organization Name and Address Solar Energy Research Institute 1617 Cole Boulevard Golden, Colorado 80401	10. Project/Task/Work Unit No. 4253.11 11. Contract (C) or Grant (G) No. (C) (G)
12. Sponsoring Organization Name and Address	13. Type of Report & Period Covered Technical Report 14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

The feasibility of several design options for high-temperature, sensible heat storage containment is examined. The major concerns for a successful containment design include heat loss, corrosive tolerance, structural integrity, and cost. This study is aimed at identifying the most promising high-temperature storage tank among eight designs initially proposed. The study is based on the heat transfer calculations and the structure study of the tank wall and the tank foundation and the overall cost analyses. The results indicate that the single-tank, two-media sloped wall tank has the potential of being lowest in cost. Several relevant technical uncertainties that warrant further research efforts are also identified.

17. Document Analysis

a. Descriptors Alkali Metal Compounds ; Building Materials ; Central Receivers ; Corrosion ; Energy Storage ; High Temperature ; Molten Salts ; Solar Receivers ; Tanks ; Thermal Insulation ; Very High Temperature

b. Identifiers/Open-Ended Terms

c. UC Categories

18. Availability Statement National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, Virginia 22161	19. No. of Pages 64 20. Price A04

Form No. 0069 (3-25-82)