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ABSTRACT

A major constraint to the evolution of solar thermal power systems is the need to provide continuous operation during periods of solar outage. A number of high temperature thermal energy storage technologies which have the potential to meet this need are currently under development. The development status is reviewed of some thermal energy storage technologies specifically oriented towards providing diurnal heat storage for solar central power systems and solar total energy systems. These technologies include sensible heat storage in caverns and latent heat storage using both active and passive heat exchange processes. In addition, selected thermal storage concepts which appear promising to a variety of advanced solar thermal system applications are discussed.

THE DEGREE OF PENETRATION and future impact of solar thermal power systems depend on the successful development and integration of thermal storage subsystems. Currently available technologies for storage subsystem development are limited to relatively few sensible heat concepts capable of delivering steam (or an organic working fluid) to a turbine at temperatures up to approximately 399°C (750°F). More advanced solar thermal power systems, on the other hand, will require storage subsystems capable of delivering steam at temperatures of 538°-649°C (1000-1200°F), and gases at temperatures of 704°-1093°C (1300-2000°F), to respective heat engines.

The DOE Division of Energy Storage Systems (DOE/STOR) is responsible for formulating and managing research and development in energy storage technologies in response to these requirements. As part of DOE's Thermal Energy Storage and Transport Program, the NASA Lewis Research Center (LeRC) was given the primary responsibility for the development of high temperature sensible and latent heat storage technology. Structure and key areas of development of the NASA-LeRC project organized to implement the development of these technologies are presented in Fig. 1

The following discussion relates to the development of some of the storage technologies that have potential for meeting both solar central (10-100's MWe) power and dispersed (10 KWe-10 MWe) power system requirements. While limited to sensible and latent heat technologies, it should be mentioned that thermochemical storage technologies have unique characteristics which offer several significant advantages not available from the other types of thermal storage. These advantages appear particularly attractive for solar thermal power systems requiring thermal transport and/or long-term storage capability. Thermochemical storage and transport technologies are being developed for DOE/STOR by Sandia Laboratories at Livermore. (1)*

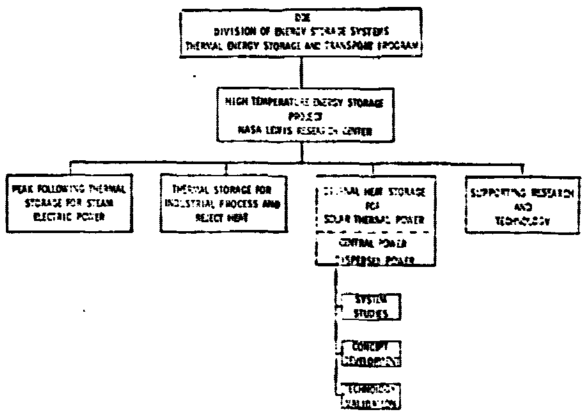


Fig. 1 - Project structure

HIGH TEMPERATURE STORAGE TECHNOLOGIES

Storage technologies can be classified by elements as presented in Figs. 2-3. They cannot just include sensible and latent media. Instead, the technologies must be "systems" oriented and include containment and heat exchange as well. As is readily apparent, a large, multiple combination matrix can easily result. A similar classification of available energy storage system technologies for conventional utility application resulted in 50+ technologies for consideration. Because of system similarities with central and dispersed power applications, one can realistically anticipate a similar number of technologies for consideration.

*Numbers in parentheses designate References at end of paper

(MHG/JEC)

MEDIA

SENSIBLE HEAT

LIQUIDS

- o HIGH TEMPERATURE WATER
- o ORGANIC COMPOUNDS (OILS, SILICONES)
- o INORGANIC COMPOUNDS (SALTS, SULFUR, METALS)

SOLIDS

- o METALS (IRON/STEEL)
- o MINERALS (SILICATE, GRANITE)
- o CERAMICS (ALUMINA, MAGNESIA)

LATENT HEAT

SOLID/LIQUID

- o NITRATES
- o NITRITES
- o HYDROXIDES
- o CHLORIDES
- o CARBONATES
- o FLUORIDES
- o FUSIBLE METAL ALLOYS

SOLID/SOLID

- o SODIUM SULPHATE
- o SODIUM HYDROXIDE

Fig. 2 - Storage technologies

CONTAINMENT

ABOVE GROUND

- o HIGH PRESSURE TANKS (WELDED STEEL, PRESTRESSED CAST IRON, PRESTRESSED CONCRETE)
- o LOW PRESSURE TANKS - SENSIBLE (THERMOCLINE, PACKED BEDS)
- o LOW PRESSURE TANKS - LATENT (PCM)

UNDERGROUND

- o STEEL LINED (AIR/CONCRETE SUPPORT)
- o UNLINED NATURAL (AQUIFERS, SALT DOMES EXCAVATED)

HEAT EXCHANGE

ACTIVE

- o SALT REMOVAL FROM SURFACE

PASSIVE

- o CONVENTIONAL TUBE/SHELL

Fig. 3 - Storage technologies

MEDIA-When considering storage subsystems, this element is of primary significance. The thermal energy may be stored as the heat required to induce a temperature change, a phase change, or a chemical change in a storage material. There are a variety of media for selection dependent upon the applicable end-use of the stored energy. For solar thermal power generation applications, much of the initial effort of the storage technology program has been directed towards providing heat input to organic working fluids in the temperature range of 260°-427°C (500-800°F) and to steam in the temperature range of 371°-538°C (700-1000°F).

A promising candidate for thermal energy storage at high temperatures is the utilization of the heat of fusion of molten salts. Many salts are attractive because of their high mass and volumetric heat storage capabilities, their abundance in nature and as a result of industrial processes, and their low cost per unit storage capability. By utilizing the heat of fusion (liquid-solid transition) of various salts, large amounts of thermal energy can be stored and subsequently released at nearly constant temperature.

In a recent study (2) conducted by the Institute of Gas Technology (IGT), mixtures of 31 salts were considered for storage subsystem integration with a steam Rankine cycle. These salts were selected for consideration because their melting points fell in or near the 454°-538°C (850-1000°F) range and they did not display any particular difficulties in handling, containment, stability or availability. Because of the importance of salt cost in determining the economic viability of the entire storage subsystem, cost envelopes of these salts, \$/kwh (\$/10^6 BTU), were made as a function of volume, m^3/mwh (ft^3/10^6 BTU), of the salts. This is presented in Fig. 4. The highest cost salts are composed of bromides, fluorides, and hydroxides. The lowest cost salts are composed of mixtures of alkali and alkaline earth chloride salts, whereas moderate-to-high cost salts are composed of carbonate salt mixtures and some chloride and fluoride salts. However, several of these low-to-moderate cost salts emit highly toxic fumes when heated, presenting potential safety hazards that could restrict their use and increase cost of containment to prevent leakage.

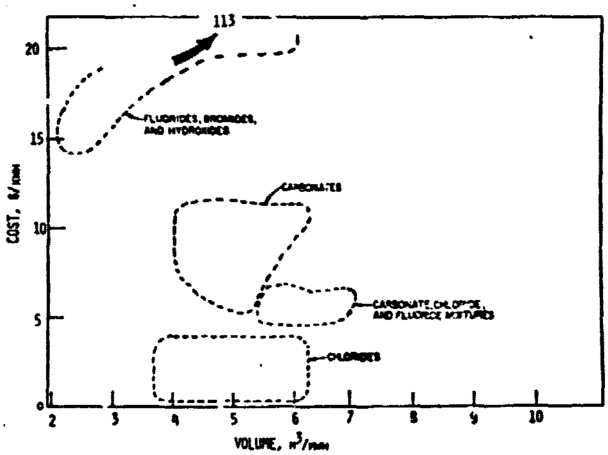


Fig. 4 - Latent heat salts cost comparison

In the same IGT study, laboratory sized modules as shown in Fig. 5 were designed, tested and analyzed to confirm the capabilities of the carbonate salts for meeting solar thermal energy storage requirements. A 35 weight percent Li_2CO_3-65 weight percent K_2CO_3 salt mixture was selected for experimental work. This is a congruently melting mixture that forms an intermediate compound $LiKCO_3$.

(LHG/JEC)

Use of these laboratory test modules to verify the ability to predict and/or extrapolate characteristics of storage media is shown in Fig. 6. Modeling of this type is necessary for determining key design parameters for large scale systems. A modification of Megerlin's solutions (3) forms the basis for the agreement between the predicted and observed interfacial location upon cooling of a salt.

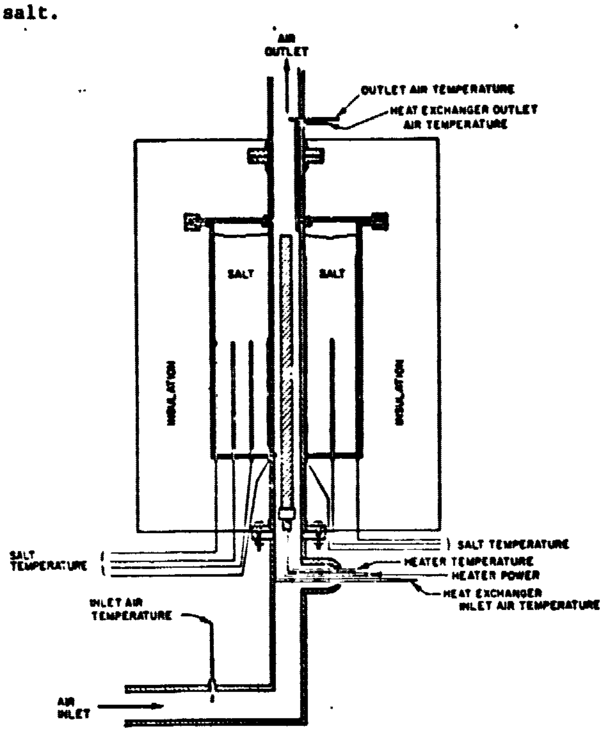
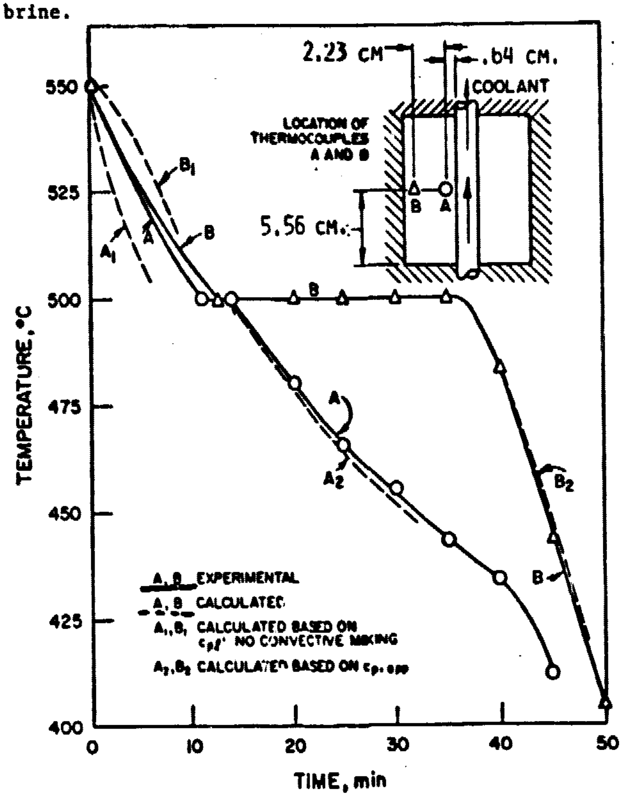


Fig. 5 - Engineering-scale unit mounted in testing station

Latent heat storage system concepts which utilize the heat of fusion from a solid-solid phase transition are particularly enticing. The technical problems associated with these systems, such as volume change, are generally less imposing than those associated with the liquid-solid phase change latent heat system concepts. This concept is being evaluated as part of the NASA-LeRC in-house experimental efforts with potential applications existing in solar total energy systems to provide space heating. Calmac Inc. has designed and fabricated a sodium sulfate, solid-solid phase change, thermal energy storage module. The module consists of three interchangeable packed bed configurations to provide the capability of determining the best design to minimize solid particle breakup in a heat transfer fluid. Thermal storage capacity is approximately 58.6 kwh (200,000 BTU).

CONTAINMENT-Upon selection of the storage media, attention can be focused on containment. Obviously temperature, pressure, and material compatibility play a dominant role in the selection of the storage container. Consideration is being given to both underground and above ground storage containment. One potential candidate for underground storage being explored by the University of Houston and Subsurface Inc. (4) is a deep cavern storage of hot oil utilizing solution caverns in massive salt deposits. The essential geologic requirements are known and easily satisfied as evidenced by the many salt domes of the Gulf region of the United States. Fig. 7 shows the extent of these deposits in this area, as well as rock salt formations throughout the United States. The cavern construction, as shown in Fig. 8, requires an adequate supply of fresh water which is injected into the well and circulated causing dissolution of the salt to form brine.



$$c_{p,\ app} = c_{ps}\left[1 + \frac{\Delta H_f}{c_{ps}\,(t_m - t_a)}\right]$$

Fig. 6 - Cooling rates in a lab-scale thermal energy storage unit

Several technical and economic issues related to a proposed storage temperature of 342°C (648°F) are being addressed in the current study. Some of the technical issues are high thermal stresses in the well on the cement to casing and formation bonds, cavern constructions designed to minimize heat losses, and a potential problem of plastic flow in the containing salt formation. Economically, the major issue involves the capability to deliver power cycle working fluids at required qualities. Ultimately, the future development of this technology for solar thermal power system application depends on a system definition matching system requirements to storage subsystem capabilities.

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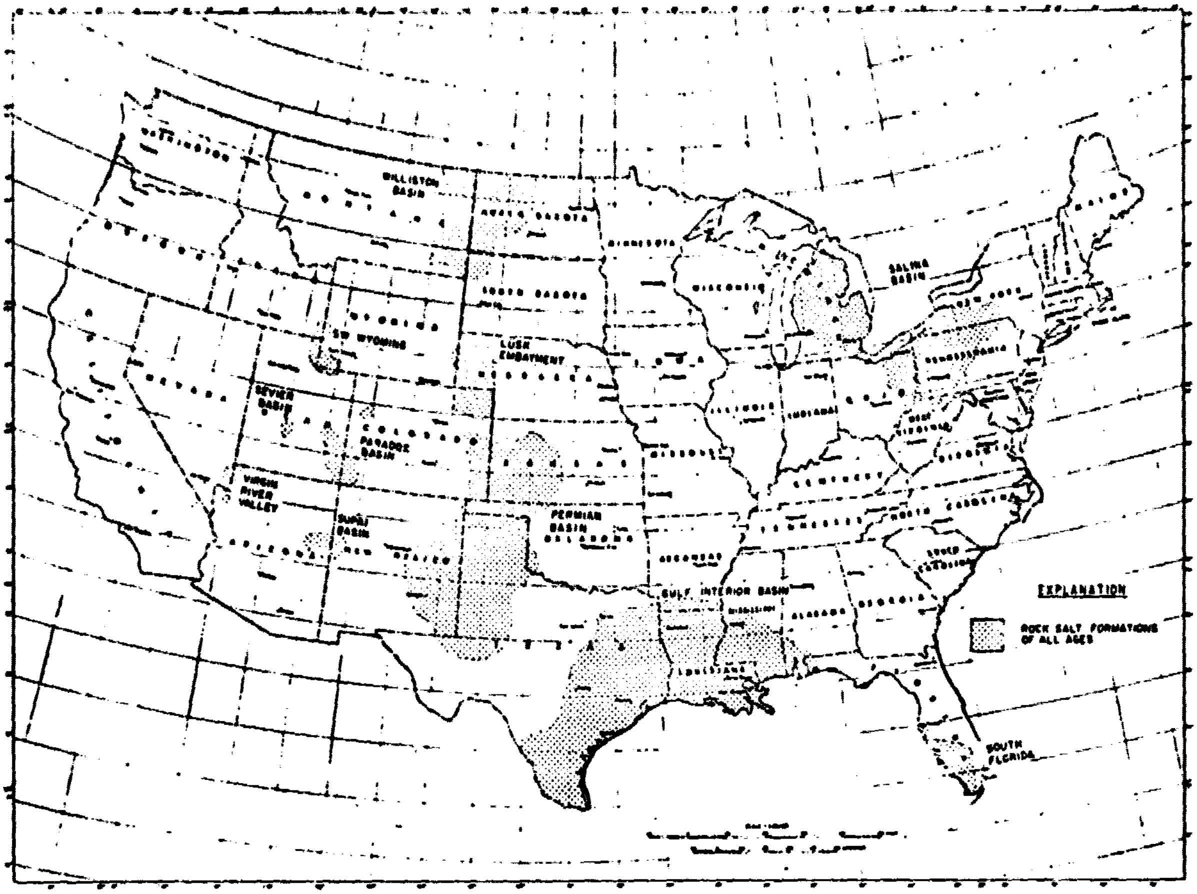

Fig. 7-Salt deposits of the United States

An alternative containment for a variety of above ground storage applications makes use of prestressed cast iron vessels (PCIV). As background, various sensible, latent and thermochemical storage concepts were examined by Boeing Engineering and Construction (BEC) in relation to a reference solar central power system which used a closed cycle Brayton power conversion system (5). The reference solar system had a six hour requirement for extended operation. A storage subsystem consisting of MgO brick checkerwork in a welded steel pressure vessel was chosen by B.E.C. as the benchmark subsystem; (i.e. requiring little or no technology advancement). As part of the same study, Professor Gilli of the University of Graz, Austria esitmated that a PCIV would reduce the containment cost of the sensible heat scheme by some 50 percent. As shown in Fig. 9, this would result in about a 33 percent reduction of storage subsystem costs. Further evidenced in this figure are potential cost benefits associated with the advancement of both thermochemical and latent heat storage technologies.

The PCIV construction is shown in Figs. 10 and 11. Basically, the containment consists of cylindrical cast iron blocks stacked to the desired height. These segments are placed in compression by axial and tangential tendons. A liner and pressurized insulation as well as the necessary fill/drain posts must also be provided as dictated by the respective storage media. A reference PCIV, for application to storage of high pressure, high temperature water (6) of 8000 m^3 (282,517 ft^3), 275°C (527°F) was developed, designed, and stress-analyzed. A parametric study showed that pressures between 4 and 8 MPa (580 and 1160 psi) and L/D ratios larger than 4 should be optimal. Cost of the reference vessel is about $10M or 33 to 50 $/kwh electric energy stored.

HEAT EXCHANGE-Another area of concern in an energy storage subsystem is often the most important factor affecting system performance and cost. A recently completed study by Grumman Aerospace Corp. (7) with Burns and Roe as a subcontractor, addressed the importance of the heat exchanger as it impacted the consideration of latent heat storage concepts for conventional electric utility power plant applications. The results of this study indicate that latent heat thermal energy storage systems using conventional tube and shell heat exchangers are economically competitive with enlarging a plant to provide peaking capacity. Thus, if heat exchange can be improved, latent heat storage concepts would be more attractive.

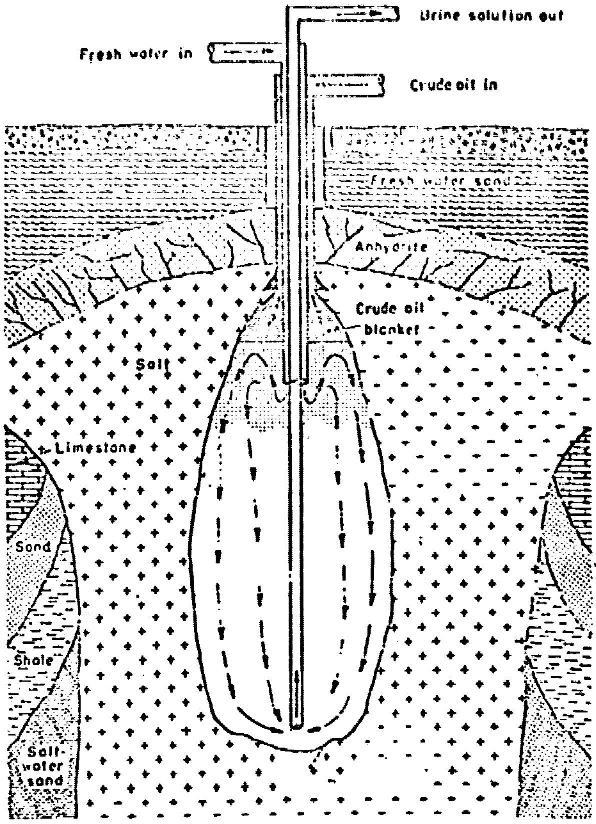

Fig. 8-Schematic of a salt cavern leaching operation

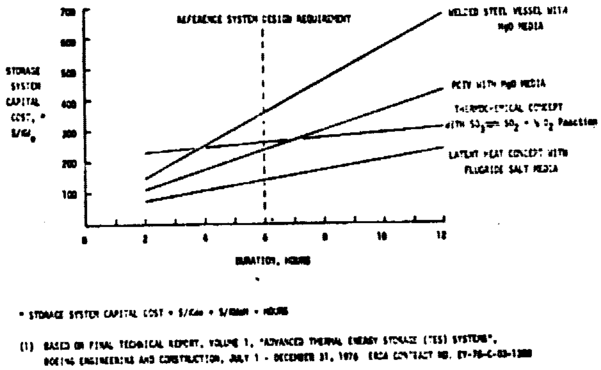

Fig. 9-Storage system cost comparison

A typical passive type heat exchanger currently being considered for Solar Total Energy Systems is coiled tubes immersed in sodium hydroxide. The heat transfer media is Therminol-66 This concept is described in another conference paper by Comstock and Wescott (8).

Two concepts of advanced heat exchangers are also under development by the High Temperature Energy Storage Project Office. The first concept (9), being constructed and tested by the Naval Research Laboratory (NRL), is shown schematically in Fig. 12. To charge the storage unit, input heat

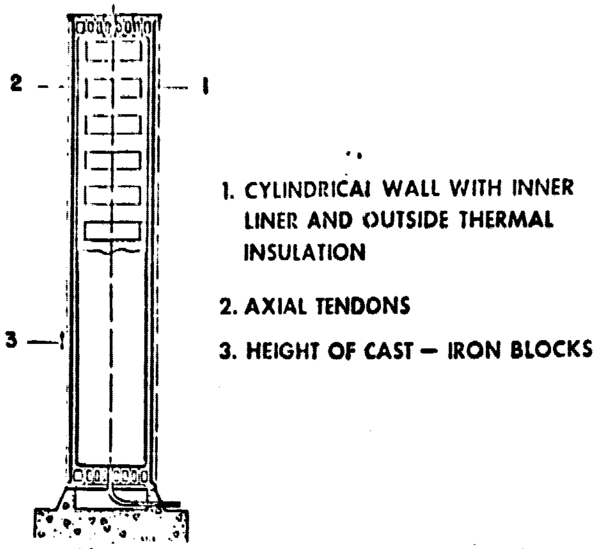

Fig. 10-Prestressed cast-iron pressure vessel

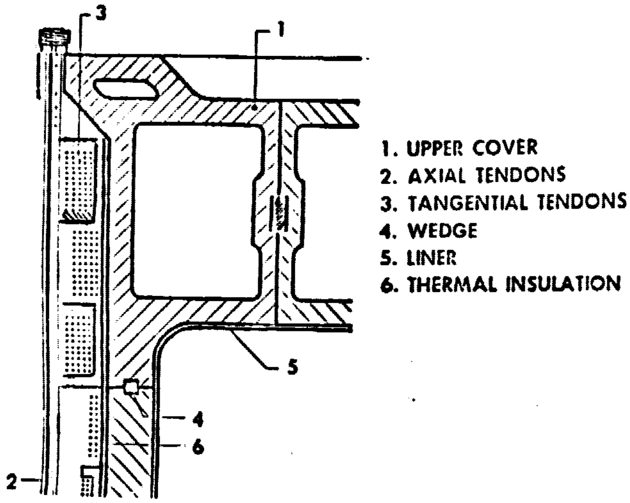

Fig. 11-Detail of prestressed cast-iron pressure vessel

is transferred to a heat pipe fluid which evaporates and produces an increase in the pressure of the heat pipe vapor in the tank. The heat is delivered to an eutectic salt mixture stacked in many individual containers by condensation of the vapor on the container surfaces, thereby melting the salt.

Energy withdrawal is also accomplished by heat pipe techniques. Near the top of the tank is another pipe network. Heat pipe fluid is sprayed onto the salt cans and evaporated. Water is flowed through the upper piping, the heat pipe fluid condenses on these pipes and produces steam in direct response to feedwater flow. NRL has projected costs for a storage subsystem, as described, and utilizing a chloride salt, eutectic mixture with m-terphenyl as the heat pipe fluid at less than $\$5/kwh_t$, approximately. This cost does not include heat exchangers required for charging and heat withdrawal.

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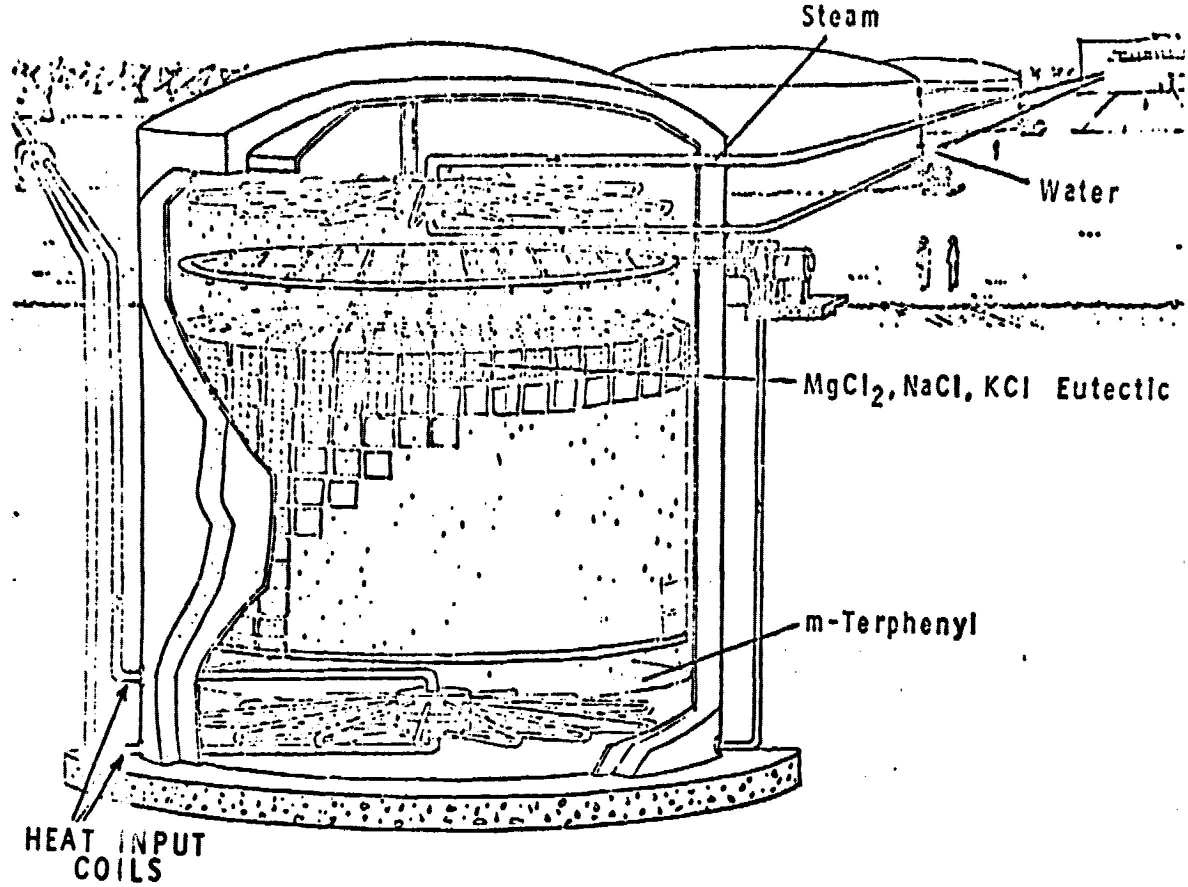

Fig. 12-Energy storage/boiler tank concept

Another means of minimizing a potentially large capital investment in required heat exchangers is to actively inhibit or remove the formation of salt depositions on the discharge tube surfaces. Fig. 13 is a partial list of candidate active heat exchange concepts which will be technically and economically assessed by the Grumman Aerospace Corporation and Honeywell. Potential application to solar thermal steam-Rankine power conversion systems will be emphasized.

- TUBE AND SHELL WITH TRANSLATING, MULTITUBE SCRAPER
- ROTATING SCRAPERS
- ROTATING DRUM WITH FIXED SCRAPERS
- MECHANICAL VIBRATORS
- ULTRASONIC LIQUID BATH
- FLEXIBLE TUBES WITH PRESSURE PULSATIONS
- PCM SPRAY WITH INTERMEDIATE LIQUID METAL LOOP

Fig. 13-Active heat exchange concepts

With the successful identification, design, fabrication, and testing of several active heat exchanger concepts, the potential cost savings to a storage subsystem is significant. The previously referenced Grumman study indicated that the heat exchanger (passive type) of a typical storage subsystem is approximately 50% of the total subsystem cost. With 50% heat exchange component cost reduction resulting from active heat exchange components, the overall storage subsystem costs can be reduced by 25%. Results from these active heat exchange efforts will be available in early CY 79.

A third class of technologies that may reduce overall storage subsystem cost (10) utilizes the heat of fusion of metal alloys. The predominant advantage of metal alloys for thermal energy storage lies in their high values of thermal conductivity. Consequently, heat exchanger, size-limited by the solid media thermal resistance, can be made smaller (lower costs) than a corresponding heat exchanger utilizing the heat of fusion of an inorganic salt mixture.

The current effort in metal alloys (11) spans a phase change temperature range of 477-1127°C (890-2060°F), which covers a broad range of potential system applications. This effort is aimed at identifying promising media and measuring heats of reaction, specific heats and density changes. For those system applications which require a long lifetime (20-30 years), future development activities

(LHG/JEC)

will be directed towards potential media/containment material compatibility problems.

CONCLUDING REMARKS

In conclusion, it is important to recognize that results of all of the current storage technology developments which directly or indirectly support solar thermal power system applications cannot be presented within the limited scope of this paper. Nor does the current DOE/STOR technology development program encompass all of the system applications within the solar thermal program. Consequently, planning activities are now underway to augment the storage program in support of all solar thermal central and dispersed power system applications. Storage subsystem development in the FY 80-85 time period will emphasize interfacing with advanced thermodynamic cycles.

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