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ADVANCED THERMAL-ENERGY-STORAGE CONCEPT DEFINITION STUDY
FOR SOLAR BRAYTON POWER PLANTS

System Requirements Data Book
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1.0 INTRODUCTION

This data book contains a description of the design and operating criteria to be used in the Advanced Thermal Energy Storage Study, E(04-3)-1300. The principal data source used in the development of the criteria is the results of EPRI contracts RP377-1 (Closed Cycle, High Temperature Central Receiver for Solar Electric Power) and RP788-1 (Advanced Thermal Energy Storage).

The preferred storage media selection rationale is reported in depth in the final technical report to RP788-1. Section 2.0 of this data book contains an outline of the storage system operating requirements and design standards, and Section 3.0 outlines the corresponding power plant interface requirements. A summary technical description of each of the three alternative high temperature TES systems is presented in Section 4.0. These technical descriptions represent the cumulative results of the two previous EPRI studies and are presented here as background information and to clearly define the starting point of the current ERDA-sponsored study. The approach and criteria to be used in developing energy cost numbers are described in Section 5.0, and Section 6.0 summarizes the systems requirements data and the requirements perturbations to be used in the Task II trade studies.

All of the requirements data to be used in the Task II thru Task V work are compiled in this data book. This data book is a complete revision of an earlier report released March 15, 1976, as a part of the EPRI Research Project 788-1. During the course of the E(04-3)-1300 study, these requirements will be updated as necessary, and the resultant data book will serve as a central point for the definition of all system requirements.

2.0 STORAGE OPERATING REQUIREMENTS AND DESIGN STANDARDS

Sections 2.1 through 2.5 contain preliminary operational requirements to be used in the E(04-3)-1300 study. Section 2.6 presents the storage system design standards. The operating requirements stated here are baseline requirements. The perturbation studies described in Section 6.0 include a sensitivity analysis of several of the baseline operating requirements.

2.1 THERMAL PERFORMANCE

The thermal performance requirements for the storage system include the following:

- o The storage system is required to accept hot helium at the design system operating temperature 816°C (1500°F) for charging.
- o The storage system is required to accept cold helium at the cold side recuperator discharge temperature during storage system discharge.
- o The helium discharge temperature from storage during charging must be less than the inlet helium temperature by at least 111°C (200°F) at the full charge rate and fully charged condition.
- o The helium discharge temperature from storage during discharge must be greater than 593°C at the full discharge rate and the fully discharged condition.

2.2 PRESSURE LOSSES

Pressure losses in the primary working fluid heat exchanger shall not exceed 4% of the system operating pressure in the worst case.

2.3 ENERGY STORAGE REQUIREMENT

The thermal storage system must be capable of providing sufficient heat energy to the turbogenerator to allow six hours of operation at 100% generator output (50 MW_e).

2.4 STORAGE SYSTEM DISCHARGE CAPACITY REQUIREMENT

The thermal storage system must provide sufficient discharge capacity to operate the turbogenerator at 100% output (50 MW_e) at the minimum

turbine inlet temperature (consistent with the storage system thermal performance).

2.5 STORAGE SYSTEM CHARGE CAPACITY REQUIREMENT

The thermal storage system must be capable of accepting charging rates consistent with the power plant operation. The expected range of charging rates is 60-90% of the maximum discharge capacity. The storage system must furthermore be capable of full operation within the power plant operating conditions as described in Section 3.0.

2.6 STORAGE SYSTEM DESIGN STANDARDS

The following design standards will be used in the RP788-1 study:

- o Minimum temperature* of any part of TES system = 427°C.
- o Maximum temperature* of any part of TES system = 816°C.
- o System operating pressure = $3.45 \times 10^6 \text{ N/m}^2$ (500 psi).
- o Service life = 30 years.
- o Heat loss through container vessel walls and circulation lines = 2% of thermal energy input to system.
- o Container vessel safety factors will be designed in accordance with the 1974 ASME Boiler and Pressure Vessel Code, Section VIII Rules for Construction of Pressure Vessels.

*The difference 816° - 427°C is not to be interpreted as the temperature swing of the TES media. The actual temperature swing experienced is a function of integration into the entire plant operation and cannot be specified as a standard.

3.0 POWER PLANT OPERATING CONDITIONS

The following are baseline power plant operating conditions to be used in the E(04-3)-1300 study.

3.1 INSOLATION DATA

The insolation data to be used in this study are based on clear day specular insolation data taken at Inyokern, California, in 1963. The seasonal data are shown in Figure 1.

3.2 HELIOSTAT FIELD PERFORMANCE

The heliostat field efficiency, η_F , is made up of the product of the tracking efficiency, η_T , the mirror reflectivity, η_M , and the receiver intercept efficiency, η_I . The tracking efficiency includes projected area losses and shadowing and blocking losses. The tracking efficiency data used in this study are from RP377-1 and are shown in Figure 2. The value of mirror reflectivity to be used is $\eta_M = 0.88$. The receiver intercept efficiency is the fraction of energy reflected from the heliostat field that

Figure 1. Clear Day Specular Insolation (Inyokern, California 1963)

Figure 2. Mirror Field Tracking Efficiency

enters the receiver aperture. The value of η_I to be used is $\eta_I = 0.90$. The total receiver input heat rate is given by the product of the insolation times the collector area times η_F where $\eta_F = \eta_T \times \eta_M \times \eta_I$. The total receiver input heat rate is shown in Figure 3.

3.3 RECEIVER OPERATING PERFORMANCE

The receiver performance is parameterized by defining the cavity thermal efficiency, η_{TC} , as the ratio of the heat rate transferred to the helium circuit to the solar heat rate transferred into the cavity. The cavity thermal efficiency to be used in this study is given in Figure 4.

The cavity thermal efficiency data presented in Figure 4 represent the results of a thermal scaling analysis for a well-defined design point for a gas-cooled receiver. The loss mechanisms assumed in the analysis are:

- o Reflective Losses - includes fraction of incident solar energy reflected from receiver.

Figure 3. Receiver Heat Input

Figure 4. Receiver Thermal Efficiency at Part-Load Conditions

- o Convective Losses - includes energy convected away by air from inside receiver cavity.
- o Reradiation Losses - includes energy re-emitted by cavity walls and tubing that escapes out aperture.
- o Conduction Losses - includes energy conducted through insulation.

3.4 TURBINE OPERATING PERFORMANCE

The turbogenerator thermal cycle efficiency, η_{TC} , and recuperator outlet temperature are functions of the turbine inlet temperature. The variations of η_{TC} and recuperator outlet temperature to be used in this study are shown in Figure 5.

Plant output power would normally decrease with decreasing turbine inlet temperature which could be caused by reduced solar input or operation from the storage system. However, by increasing the pressure level (i.e., mass flow) of the system to compensate for the reduced thermal efficiency, the electrical output can be maintained at the desired level. The pressure level/mass flow ratio variation with turbine inlet temperature to be used in this study is shown in Figure 6.

Figure 5. Thermal Cycle Efficiency and Recuperator Outlet Temperature Versus Turbine Inlet Temperature

The turbine will also be operated to produce power to meet the instantaneous demand. This is accomplished by maintaining a fixed turbine inlet temperature while changing pressure level and mass flow to follow the demand level. This also assumes that the turbogenerator thermal cycle efficiency is a function mainly of the turbine inlet temperature which will remain constant with varying electrical output.

3.5 PLANT OPERATION GUIDELINES

The following are general power plant operation guidelines to be used in this study:

- o Generator will be on-line at 0800.
- o Storage system will be charged with early morning insolation.
- o Storage system will be charged in parallel with the receiver (see Figure 7).
- o Storage system will be discharged in series with the receiver (see Figure 7).
- o Turbine will supply all power required including parasitic power required by storage system.
- o Helium mass flow rate and system pressure will be adjusted to exactly meet demand ($50 \text{ MW}_e + \text{MW}_{\text{parasitic}}$).

A schematic of the plant control algorithm is shown in Figure 8. This schematic serves as the specification for the basic plant operation when combined with the operation guidelines listed above.

Figure 6. Pressure Level/Mass Flow Ratio Versus Turbine Inlet Temperature

Figure 7. Storage Charge and Discharge Cycles

3.6 BASELINE OPERATION DATA

The sensible heat storage concept described in Section 4.3 is to be used throughout the study as an overall benchmark. The baseline thermal cycle to be used is shown in Figure 9. The baseline daily plant performance with the sensible heat TES systems is given in Figure 10. A summary of the baseline system performance on four representative days of the year is shown in Figure 11.

Baseline:

T_4	~	Turbine inlet temperature	1,500°F (816°C)
T_1	~	Compressor inlet temperature	120°F (49°C)
T_0	~	Ambient temperature	80°F (27°C)
P_4/P_5	~	Pressure ratio	1.9
P_2	~	Maximum pressure	500 psi ($3.45 \times 10^6 \text{ N/m}^2$)

Figure 9. Baseline Thermal Cycle

Figure 10. Daily Plant Performance Closed Cycle Helium

Season	Plant operation (hours)	*Plant efficiency η_p	Max-min generator capacity (MW _E)	Max receiver mass flow (kgm/sec)	Max turbine mass flow (kgm/sec)	Max syorage mass flow (kgm/sec)	Charge to discharge ratio	Round trip storage efficiency	Daily storage (hours)
Winter	11.7	29.6, 14.9	63-50	196	195	195	0.49	0.60	3.1
Spring	16.3	29.1, 16.3	70-50	256	195	195	0.72	0.64	6.0
Summer	16.8	28.6, 16.5	71-50	259	195	195	0.72	0.62	6.0
Fall	14.3	29.1, 16.5	67-50	233	195	195	0.63	0.64	5.3

*Plant efficiency definition

$$\eta_p = \frac{\text{Net generator energy}}{\text{Heat energy input to receiver}} \quad , \quad \frac{\text{Net generator energy}}{\text{Specular insolation energy}}$$

Figure 11. Four-Day Performance Summary (Phase Change TES System)

4.0 BASELINE SYSTEM DESCRIPTION

Based on the RP788-1 study, baseline conceptual designs of three thermal energy storage types were identified. Two advanced conceptual designs included phase change and thermochemical energy storage. A current technology sensible heat TES system conceptual design was developed as an overall benchmark.

This section presents a summary of the baseline conceptual design for each of the three storage types. Included for each system type is a design description, a preliminary evolution of materials compatibility and availability, the basis for systems costs, a description of remaining critical technical problems, and considerations of safety, ecology, and maintenance. The baseline conceptual designs serve as starting points for the present study and will be embellished and/or revised as required under the present study.

4.1 PHASE CHANGE CONCEPT

The phase change concept is the first of two advanced thermal energy storage concepts identified for study. The phase change concept utilizes the thermal energy stored in the latent heat of fusion of inorganic salts. This concept offers high energy densities relative to sensible heat thermal energy storage systems. The high energy density implies more compact and less expensive containment vessels.

This subsection contains a baseline system description of the phase change TES device developed under the RP788-1 study.

Design Description

The conceptual design is based on the operating requirements listed in Section 2.0. The phase change TES system designed to meet these operating requirements is summarized in Figures 12 and 13 and in Table 1. The phase change material and heat exchanger is contained in a reinforced concrete, insulated cubic vessel (12.3 m x 12.3 m x 12.1 m height). The helium flow

- FUSIBLE FLUORIDE SALT BATH
- TEMPERATURE SWING 246°C (443°F)
- KEY THERMOPHYSICAL DATA
 - $T_{\text{MELT}} = 640^{\circ}\text{C}$ (1183°F)
 - $\rho C_p = 0.672 \text{ cal/cm}^3\text{--}^{\circ}\text{C}$
 - $h_f = 143 \text{ cal/g}$
 - $k = 0.0103 \text{ cal/sec--cm--}^{\circ}\text{C}$
 - $\text{COST} = 0.97 \text{ \$/kg}$
- CRITICAL TECHNICAL PROBLEMS
MATERIAL COMPATIBILITY

Figure 12. Phase Change TES

Account	Quantity	Unit cost	Total cost (M \$)
Salt (fluoride eutectic)	$4.2 \times 10^6 \text{ kg}$	0.97 \$/kg	3.9
Storage container (square, 12.3 m x 12.3 m x 12.1 m)	722 m ³	970 \$/m ³	0.7
Insulation	135 m ³	741 \$/m ³	0.1
Heat exchanger (0.96 cm O.D. x 12.1 m) tubes	33,600 tubes	51.8 \$/tube	1.7
welds	33,000 welds	12.0 \$/weld	0.4
Manifold allowance (20%)			0.5
Helium circulation system	24.38 MW (pumping capacity)	53,500 \$/MW	1.3
Total			8.6

Figure 13. Phase Change TES Cost Summary

Table 1. Phase Change TES Conceptual Design Summary

Vessel cross section shape	Square
Tube spacing pattern	Square
Vessel width, D	12.30 m
Vessel height, H	12.08 m
H/D	0.98
Tube number	33,580
Tube outer diameter	0.96 cm
Centerline to centerline intertube spacing	6.64 cm
Tube wall thickness	0.065 cm
Heat exchanger NTU-value	5.7
Unit thermal conductance	477 watt/m ² -°K
Required TES media mass	4.197 x 10 ⁶ kg
Material choices:	
TES media	63 NaF/37 ZnF ₂ Eutectic salt
Tubing metal	Inconel 617
Vessel outer wall	Reinforced concrete
Insulation	Refractory brick
Liner metal	Hastelloy-N

is dispersed and collected by manifolds into 33,600 tubes (0.96 cm diameter x 0.065 cm wall) placed vertically on a square spacing pattern (centerline to centerline tube spacing - 6.64 cm). The phase change salt is contained as a bath immersing the helium tubes. The vertical flow arrangement with the hot helium entering the top manifold during charging and the cold helium entering the bottom manifold during discharging will maintain the solidified salt below the liquified portion. This arrangement will assure that the salt will remain in intimate contact with the helium tubes by avoiding the formation of voids during salt solidification.

Inconel 617 is the present choice for the tubing metal because of demonstrated stress rupture life and because it is also the choice for the receiver heat exchanger system⁽¹⁾. The phase change salt is 63 NaF/37 ZnF₂. Thermophysical data on the fluoride eutectic is given in Figure 12. Fluoride salts were chosen because of their acceptable economics combined with their well defined and reasonably benign corrosion characteristics. Preliminary evaluation of the candidate fluoride eutectic salts led to the selection of the 63 NaF/37 ZnF₂ eutectic as a result of cost and melt temperature. The container vessel wall has an inner liner of Hastelloy-N, a middle insulating layer of refractory brick, and an outer layer of reinforced concrete. The helium circulation system consists of a compressor sized to recoup the 7% pressure drop through the receiver and the TES system while maintaining the design mass flow rate.

MATERIALS COMPATIBILITY AND AVAILABILITY

The primary material compatibility concern is with the corrosion of tubing metal and vessel wall by the fluoride salts. The corrosion mechanism is basically a chromium mass transport reaction. The corrosive attack on chromium has been shown to be controlled by the addition of small quantities of aluminum to the salt mixture. ^(2,3) The present tubing metal choice, Inconel 617, is being employed in other fluoride eutectic designs. ^(3,4) An alternative choice for tubing metal is Hastelloy-N. This alloy was specially developed by the Atomic Energy Commission for use with high temperature fluoride eutectics in their Molten Salt Reactor program. ^(5,6) During corrosion tests conducted by AEC, the low chromium alloy exhibited excellent corrosion resistance after lengthy exposure to molten fluoride eutectics. It is known that the fluorides will attack the silicates and oxides found in refractory bricks. A thin metal liner made of Hastelloy-N will alleviate this problem. An alternative design will employ graphite as the liner material. Based on testing done by AEC, ⁽⁷⁾ it was found that graphite and fluoride eutectics do not react with each other. Carburization of the heat exchanger tubing with this material combination is an area requiring further experimental investigation.

The availability of the fluoride salts seems certain. Based on conversations with the Pennwalt Corporation, ⁽⁸⁾ the constituent salts NaF and ZnF_2 can be supplied in the volumes envisioned. The availability of the Inconel 617 is also not of great concern, although a certain amount of lead time will be required to produce the quantity needed. The availability of the liner metal and refractory brick is also certain.

SYSTEMS COSTS

The systems costs are presented in Figure 13. The fluoride salt cost is based on estimates of 1981 fluoride prices delivered to Inyokern, California in quantities of 725 metric tons (800 tons) ⁽⁸⁾ The metal costs were based on $99,000\$/\text{meter}^3$ ($2800\$/\text{foot}^3$) of base metal cost + $4.92\$/\text{meter}$ ($1.50\$/\text{foot}$) fabricating costs. This relationship was derived from cost estimates given by Huntington Alloys. ⁽⁹⁾ The helium circulation system costs were estimated by scaling by existing compressor costs to the power rating required. ⁽¹⁰⁾ The cost estimates for the container vessel

and insulation are based on a metal inner liner, refractory middle, and concrete outer shell. The estimate accounts for materials and construction costs. It is expected that a graphite inner liner will lower these costs.

CRITICAL TECHNICAL PROBLEMS

The main critical technical problem that remains is in extrapolation of the corrosion data now available for the selected material combinations to the temperature ranges for the proposed design. It is anticipated that experimental investigations will be necessary to validate the concepts. Also, the long-term resistance of graphite to cracking caused by thermal cycling stresses is an area of concern. The details of the manifolds require additional work.

Another remaining technical concern is the effects of salt melt face propagation, i.e., the "skinning over" effect, on the thermal performance of the phase change TES device. At present, the device is sized assuming an "averaged" thermal conductivity for the salt. If the salt melt face propagation effects are significant, the device sizing will have to be modified to account for these effects. Mathematical tools are being developed as a part of this study contract to assist in evaluation of the magnitude of these effects.

SAFETY, ECOLOGICAL AND MAINTENANCE CONSIDERATIONS

Other areas that require consideration in the TES design have been identified. The chief safety concern is the containment of the molten salt. The high chemical stability of the fluorides indicates that it is unlikely that reducing reactions would take place if the fluorides were released accidentally. However, because of its high temperature, a leak in the molten salt would pose a fire hazard to any flammable substance it contacts. This will require the use of non-flammable insulation materials. It should be noted that a leak of the salt is "self-healing"; that is, the leaking salt will solidify and tend to plug any leak. Release of large quantities of salt will require a massive structural failure. Again, because of the fluoride salts' chemical stability, it is unlikely that a release of the salts will pose a hazard to the environment. A number of fluoride salts occur naturally in

the environment; e.g., NaF (villiaumite), CaF_2 (fluorite), MgF_2 (sellaite), Na_3AlF_6 (cryolite), $\text{Al}_2(\text{F,OH})_2\text{SiO}_4$ (Topaz), and $\text{Ca}_5(\text{PO}_4)_3\text{F}$ (fluorapatite). However, the specifics of a particular location and a particular system design must be considered before a definitive statement on the ecological impact of a phase change TES system can be made.

In the area of maintenance, continuous monitoring of the system performance will be required. Also, periodic inspection for leaks or possible failures is needed. A means of sampling the salt at various levels will allow determination of any corrosion or sedimentation occurring. The helium stream must be constantly monitored to insure that leaks into the helium flow will not foul the helium circulation system.

4.2 THERMOCHEMICAL CONCEPT

The thermochemical energy storage concept (CES) is the second of two advanced thermal energy storage concepts identified for study. The thermochemical storage concept involves the storage of thermal energy in heat of decomposition and recombination of reversible chemical reactions. This concept is unique in that through proper chemical process design the helium outlet temperature can be controlled in both the charge and discharge mode of operation. This feature provides substantial operational flexibility and reduces the extent of the gas inventory control requirement in the solar power plant. The CES system offers the highest energy storage density potential and will also require the greatest advanced development commitment.

This subsection contains a baseline system description of the thermochemical energy storage device developed under the RP-788-1 study.

SYSTEM DESCRIPTION

The basic requirements for the CES system operation and interface with the STC power plant are presented in Section 2.0. The reversible thermochemical decomposition and recombination of sulfur trioxide (SO_3) has been selected as the preferred thermochemical reaction for the high temperature solar power plant application.

This particular reaction is highly controllable and most of the reaction constituents are stored at near ambient conditions as a liquid.

CES system schematics are shown in Figures 14 and 15. The bold lines shown in the schematics identify the active reaction constituent flow times during the heat generation cycle and the heat generation cycle.

During the heat generation cycle (see Figure 14) liquid SO_2 is withdrawn from storage and vaporized in the condenser at the top of the fractionation column. Oxygen is concurrently withdrawn from storage, heated in the same condenser and combined with the gaseous SO_2 . This mixture is then transported to the regenerative heat exchanger where it is heated by the reaction products to the operating temperature of the reactor.

The high temperature gaseous mixture then enters the reactor and in the presence of the catalysts undergoes the heat generating reaction. This reaction is currently designed to take place at 10 atmospheres and is more than 80% complete by the time the hot reactants leave the reactor.

After leaving the reactor, these hot reaction products give up their sensible heat to the unheated gas stream in the regenerative heat exchanger. The cool gaseous products are then transported to the fractionation column where they are separated by condensation. Most of the cooling load for condensation is derived from the SO_2 vaporizer and the oxygen warm up following its expansion from 150 to 10 atmospheres. Some additional cooling load will be provided by a dry cooling tower of approximately $30 \text{ MW}_{\text{th}}$ capacity.

The separated constituents are then transported for storage to their respective storage containers. SO_3 is stored as a liquid in joint SO_2/SO_3 storage tanks and the unreacted oxygen and SO_2 are re-introduced into the feed gas stream for transport back to the reactor.

The reactant generation mode is (see Figure 15) is simply the reverse procedure with high pressure oxygen and liquid SO_2 as the stored reaction products. In the reactant generation mode, however, the reactor operates under significantly different conditions. A low pressure and high temperature favors the SO_3 dissociation. Consequently, the reactant generation mode reactor operation is at 1 atmosphere

Figure 14. Chemical Energy Storage System -
Reactant Generation Cycle

Figure 15. Chemical Energy Storage System -
Heat Generation Cycle

and is only about 60% complete. A significant amount of parasitic power is then required to bring the reaction products back to 10 atmospheres which is required for proper operation of the fractionating column. At a charge rate of $110 \text{ MW}_{\text{th}}$ the parasitic pumping load is approximately 28 MW_e , 22 MW_e for the reaction products pump and 6 MW_e for the oxygen compressor.

The CES system requires two major chemical process systems which must be designed and developed for this specific application - the catalytic reactor and the fractionation column. The fractionation column separates the dissociation or reaction products so that the undissociated or unreacted species can be returned to the reactor. The fractionation column operates both in the reactant generation and in the heat generation cycle. A large number of different designs of fractionating columns are in use. The objective of all designs is to achieve intimate interaction of the rising vapors and the countercurrent condensing liquid. This is achieved by filling the column with large surface area geometrical shapes (Rasching rings, Berl saddles) of glass, ceramic or steel or by bubbling the vapor through a stack of trays. A typical example of a distillation column is shown in Figure 16.

Figure 16. Cutaway Sketch of Distillation Column

The product to be separated is generally fed to a position approximately halfway up the column. Within a fractionation column there exists a temperature gradient from the hot bottom to the colder top. The column does not have to be perfectly insulated and some heat loss can be tolerated or may be desirable. The top of the column carries a condenser with a cooling coil. The cooling fluid has to be cold enough to allow condensation of the components to be separated (except oxygen which passes through as a gas).

The distillation column has been sized using first-order approximations for both the endothermic and exothermic mode of operation. Under these approximations and in order to limit the vapor velocity to 0.65 meters/second (2.14 feet/second), the column has to have a diameter of 3.4 meters (11.2 feet) and a packing height of 13.3 meters (43.8 feet). This packing is not in one single unit, but several spacers and flow equalizers have to be inserted between each 10-foot unit (approximately) of column packing. This increases the column height to approximately 15 meters (50 feet). The condenser section on top of this will be at least 4.5 meters (15 feet) in diameter and 6 meters (20 feet) tall.

There are numerous sulfur trioxide synthesis reactors in existence (even though none uses pure oxygen and sulfur dioxide nor do they operate at the temperatures and pressures envisioned here) to help in the exothermic reactor design; however, there are no sulfur trioxide dissociation reactors in existence after which the endothermic reactor could be patterned. With a charge-to-discharge power ratio of approximately one, a single reactor can be used for both endothermic and exothermic reactions. In this context, the dimensions of the reactor will be determined by the rate of SO_3 dissociation which can be achieved in the endothermic reaction.

A cutaway sketch of the reactor as currently conceived is shown in Figure 17. A 0.95 cm (0.375 in.) pellet, supported catalyst bed, an $L/D = 1.0$ and a pressure drop of 2% on the reaction side in a 15 m (50 feet) diameter reactor is currently envisioned. The conceptual reactor construction includes a ceramic lined superalloy shell covered by external insulation. The heat losses from the reactor are minimized by applying the high-temperature insulation both inside and outside the reactor.

shell. The inside coating could be flame-sprayed alumina or zirconia (Rockide-A or -Z). The coating has a low thermal conductivity and will also protect the metal from corrosion.

Figure 17. Cutaway View of Catalytic Reactor

A summary of the system design characteristics and the corresponding cost estimates are shown in Figure 18. A model of the CES system was built during the RP377-1 study. A picture of that model with explanatory notes and basic operating characteristics is shown in conjunction with a quarter section of the base of the tower in Figure 19.

Account	Quantity	Unit cost	Total cost (M \$)
Sulfur trioxide	2.3×10^6 kg	0.44 \$/kg	1.0
Storage containers			
Oxygen	10 (5.32 m ³)	29,000 \$/tank	0.3
SO ₂ /SO ₃ (10 atms)	6 (227 m ³)	32,000 \$/tank	0.2
Reactor			
Heat exchanger			
(1.37 cm OD) tubes (15.2 m)	11,000 tubes	125.00 \$/tube	1.4
welds (3/tube)	33,000 welds	12.00 \$/weld	0.4
Vessels (10 atms)	35.2×10^4 kg	23.59 \$/kg	8.3
(15.2 m x 15.2 m)			
Insulation	147 m ³	1836 \$/m ³	0.3
Catalyst	0.9×10^5 kg	2.20 \$/kg	0.2
Miscellaneous plant equipment			
O ₂ compressor	1 (10 MW)	2.5×10^6 \$/unit	2.5
SO ₂ /SO ₃ /O ₂ compressor	2 (15 MW)	3.7×10^6 \$/unit	7.4
Other			0.4
Helium circulation system	10 MW	115,000 \$/MW	1.2
Total system			23.6

Estimated system weight: 3.6×10^6 kg

Figure 18. Thermochemical Energy Storage System

Figure 19. Thermochemical Storage Concept

MATERIALS AND COMPONENTS SELECTION

The high temperature environment in the reactor and the corrosive action of sulfur oxides makes material selection for the CES system a very difficult task. From a standpoint of creep rupture resistance and desired 30 year service life, Haynes 188 and Inconel 617 have been identified as candidate materials for the solar receiver and other parts of the system. Materials compatibility evaluation in flowing $O_2/SO_2/SO_3$ at $816^{\circ}C$ ($1500^{\circ}F$) will be required. Weight change, tensile strength, microhardness and metallurgical investigation of cross-sections under the microscope will be required to document the compatibility data.

Another materials compatibility concern is the effect of the operating conditions on the lifetime of the catalysts. The vanadium type catalysts have not to date exhibited the long life potential required by the 30-year life for the TES system. Additional investigation is required in this area.

For the storage tanks, pumps, vaporizers, and distillation column, there exist sufficient data from the chemical processing industry to allow the selection of materials with long life capability. Sulfur dioxide and sulfur trioxide are common chemicals and are readily available, inexpensive and easily transported. Pumps, valves, regulators, pressure gauges, thermocouples, mass flowmeters, and fill level indicators for SO_2/SO_3 service are standard items and can be selected from stock of various equipment manufacturers.

SYSTEM COSTS

A preliminary system cost statement is presented in Figure 18. As much cost data as possible were assembled on the various components (i.e., valves, filters, pumps, compressors, air coolers, heat exchangers, distillation columns, and storage vessels) that constitute much of the system. The preliminary results of that work are summarized in Figure 18.

The reactor costs are based on the conceptual design data cited earlier. These cost data include materials and allowances for on-site construction. All cost data are based on 1975 dollars.

The cost for the catalyst will depend on the type of catalyst chosen for this task. For the purpose of these preliminary estimates, a vanadium catalyst currently selling for \$2.20/kg has been chosen as a baseline. This cost may be lower for an iron catalyst or higher for a composite bed approach using noble metal catalyst in the hottest section of the reactor.

SAFETY, ECOLOGICAL AND MAINTENANCE

SO_2 and in particular SO_3 are very hazardous chemicals, however, sufficient experience with handling large quantities has been accumulated to allow safe handling. Detailed safety and treatment procedures for handling spills and leaks will have to be established.

The operation of this TES system is not expected to result in significant environmental problems. Neither SO_2 or SO_3 are persistent contaminants and are readily absorbed by rain and soil.

The system will be designed to minimize the number of parts requiring maintenance. Maintenance experience with similar sulfuric acid plants indicates maintenance materials costs of 2% of capital investment and maintenance labor equal to operating labor. The replacement of spent catalyst is also a critical maintenance problem.

CRITICAL TECHNICAL PROBLEMS

Several areas of the CES design concept are beyond established technology and additional development work and subscale testing will be required before the full size plant can be designed with confidence. A large amount of experience of SO_2/SO_3 conversion exists with sulfuric acid and sulfur trioxide producers. However, all these reactors operate at lower temperatures and ambient pressure. The CES reactor constitutes a significant step beyond current state-of-the-art.

A major unknown is the lifetime of existing vanadium or platinum catalysts under CES reactor conditions. Most catalysts lose activity when heated to temperatures above their nominal operating conditions.

In addition to supported catalysts envisioned for the CES reactor, skeleton catalysts of the Raney-vanadium type should be evaluated.

The area of maximum heat flux in the reactor constitutes a high-risk area. Very little is known about compatibility of Haynes 188 or Inconel 617 with sulfur oxides at such high temperatures. Sulfur compounds are inherently corrosive and traces of sulfur (mostly sulfide) are sometimes sufficient to drastically alter mechanical properties of structural alloys, frequently resulting in material failures. Another potential problem area is the bearings and vanes in compressors exposed to sulfur oxides. As a general rule in engineering practice, the sulfur content in fuels for gas turbines, etc. is kept as low as possible. Special alloys may have to be developed to satisfy service requirements in such a corrosive environment. The reactor shell can be protected by a ceramic liner. This liner would reduce heat loss and protect the shell from corrosion, even though it will be very difficult to design a seamless liner. The area of ceramic liners requires additional evaluation.

4.3 SENSIBLE HEAT CONCEPT

The sensible heat thermal energy storage concept represents a current technology system. The concept utilizes the thermal energy contained as sensible heat in a storage media. The concept offers a system which will perform the task of high temperature thermal storage with materials and construction techniques within the present state-of-the-art.

This subsection contains a baseline system description of the sensible heat TES device developed under the RP788-1 study.

DESIGN DESCRIPTION

The conceptual design is based on the operating requirements listed in Section 2.0. The sensible heat TES system designed to meet the operating requirements is summarized in Figure 20. The refractory brick is contained in four horizontally placed, insulated cylindrical pressure vessels (6.2 meters inside diameter x 32.0 meter length). The helium flow is distributed and collected to each vessel by a piping system.

Diffuser plates in each vessel distribute the flow evenly to channels contained in the refractory brick checkerwork. A schematic of the vessel design is given in Figure 21. The refractory material is MgO. Thermophysical data on this refractory is given in Figure 20. Magnesia is selected as the preferred media because

Account	Quantity	Unit Cost	Total cost (M\$)
Brick (Mg O)	$8.2 \times 10^6 \text{ kg}$	0.26 \$/kg	2.1
Storage containers (4) (34 atms, 6.2 m x 32 m)	$1.8 \times 10^6 \text{ kg}$	6.20 \$/kg	11.2
Insulation	$4.4 \times 10^4 \text{ kg}$	11.30 \$/kg	0.5
Heat exchanger fabrication*	$1.7 \times 10^6 \text{ bricks}$	0.76 \$/brick	1.3
Helium circulation system	20 MW (pumping capacity)	87,000 \$/MW	1.7
Total system			16.8

Estimated system mass: $10 \times 10^6 \text{ kg}$

*Brick construction cost — 145 bricks per man-day/\$110 per man-day (1976, Means Cost Data Handbook)
4.8 kg/brick — $1.7 \times 10^6 \text{ bricks}$ @ 76¢/brick

Figure 20. Sensible Heat TES

Figure 21. Sensible Heat TES Tank Schematic

of its thermophysical properties and its high temperature structural characteristics. The surface of the bricks is smoothed to eliminate any loose material. The brick is surrounded with a layer of insulation. Kaowool^(R) block is used on the bottom third of each tank to support the brick checkerwork because of its load bearing characteristics. Because of its lower cost, mineral wool is used in the remaining areas where loading stresses are much smaller. The insulation thickness was sized to allow a 5% maximum heat loss and maintain the carbon steel vessel at 260°C (500°F). The vessel wall is made of 7.6 centimeter carbon steel (ASTM 516). The vessel is designed in accordance with the ASME Boiler and Pressure Vessel Code, Section VIII, Division II. The thickness of material is consistent with field shop welding practices. (11) The design wall thickness and vessel diameter allow the use of four vessels, each with a length to diameter ratio of about 5, to contain the required volume of solid thermal storage media.

The helium circulation system consists of a compressor sized to recoup the 7% pressure drop through the receiver plus the TES system while maintaining the design mass flowrate. Also included in the circulation system is a filter to remove any particles that may erode from the brick.

MATERIALS COMPATIBILITY

The main concern in the area of materials compatibility for the sensible heat TES conceptual design is the possibility of brick erosion and the subsequent contamination of the helium stream. By careful design of the manifold, it is expected that the helium flow velocity through each channel in the refractory will be low enough to minimize any brick erosion. The relatively high resistance to spalling exhibited by the MgO bricks minimizes this materials problem. Another materials problem could be introduced by thermal cycling stresses inherent in such a TES system. Again, the high strength of the MgO brick would alleviate this problem.

SYSTEMS COSTS

The systems costs are presented in Figure 20. The refractory brick material cost is based on manufacturers' estimates (see Section 2.1). The assembly costs of the bricks into a heat exchanger form are listed in a separate account.

The costs are based on data gained from 1976 Means Cost Data Handbook for fire-brick installation. The costs for the storage vessels are based on estimates given by Chicago Bridge and Iron for vessel dimensions of the design used. The helium circulation system costs were estimated by scaling up existing compressor costs to the power rating required. (10)

CRITICAL TECHNICAL PROBLEMS

The main technical problem involved with this conceptual design is to insure that the helium stream does not become contaminated with brick particles. The detailed design of the manifolds dictates a careful reduction of the inlet flow velocity to levels that will not induce brick erosion. A filter system may be necessary to insure particles do not enter and contaminate the compressor system.

SAFETY, MAINTENANCE, AND ECOLOGICAL CONSIDERATIONS

Other areas that require consideration in the sensible heat TES conceptual design have been identified. The chief safety concern is the design of a pressure vessel for use at the expected temperature levels. Strict adherence to pressure vessel construction codes will be required to avoid this problem. The high temperature levels require that non-flammable materials be used in the construction and insulation of the container vessel. By using a solid media for thermal storage, there are no ecological hazards that could be released in the event of a leak in the container vessel. However, the specifics of a particular location and a particular design must be considered before a definitive statement on the ecological impact of a sensible heat TES system can be made.

In the area of maintenance, continuous monitoring of the system performance will be required. Also, periodic inspections for leaks or possible failures are needed. Continuous monitoring of the helium flow will allow the detection of any contaminating brick particles. The modular tank approach allows the shut-down of a portion of the system for repair or refurbishment at selected times during the lifetime of the TES system, with only a nominal reduction in storage system capacity.

5.0 PLANT ECONOMICS

This section describes the approach and criteria to be used in developing energy cost estimates. This study will use, for its economic analysis, the levelized fixed charge method described in Aerospace Corporation Mission Analysis Report No. ATR-74(7417-16)-1, Vol. IX.

Section 5.1 summarizes the economic analysis method and Section 5.2 delineates the power plant system cost account structure. A minimum of two additional storage concepts will be included in the comparative economic assessment. The specific economic and operation parameters to be used will be established during the third month of the E(04-3)-1300 study and will be presented for ERDA approval in the October 1 progress letter.

5.1 BUSBAR ENERGY COSTS

The Busbar energy costs (BBEC) are a function of the fixed charge rate, capital costs, capacity factor, heat rate, fuel cost, and operation and maintenance cost (O&M). The formulation to be used in this study to relate these parameters is shown in Figure 22.

CAPITAL COSTS

Power plant costs will be established as described in Section 5.2.

FIXED CHARGE RATE

A fixed charge rate of 15% per year will be used throughout the study.

OPERATION AND MAINTENANCE

The operation and maintenance cost will be a constant 6 mills/kWh for all storage systems considered in this study.

CAPACITY FACTOR

The capacity factor will be computed as the available hours of operation of the

power plant expressed as a fraction of the 8,760 hours in the year with 30 days per year for planned maintenance.

HEAT RATE AND FUEL COSTS

Heat rate and fuel costs are not included in the baseline storage systems.

5.2 BASELINE SYSTEM COST ACCOUNTS

The cost account structure to be used in the economic portion of the study is shown in Figure 23. The values of each account for the baseline system are included with the account structure. These values are intended to be guideline parameters and will remain as fixed values in all cases with exception of the storage system, bailer plant and heliostats.

Generation cost

- Busbar energy cost = fixed charges + incr fuel cost + O&M

$$BBEC = \frac{CC \times FCR}{CF \times 8.76} + \frac{HR \times FC}{10^5} + O\&M$$

Where CC = Capital cost, \$/kW*

FCR = Fixed charge rate, %/year

CF = Capacity factor, %

HR = Heat rate, Btu/kWh

FC = Levelized fuel cost, ¢/million Btu

O&M = Level operating and maintenance cost, mills/kWh

Figure 22. Energy Costs

Collector area (km ²) – 2 modules	1.0
Storage time (hour)	6
Account	
Land	2
Structures and facilities	44
Heliostats*	600
Central receiver/tower/heat exch	209
Storage/tanks** (sensible heat)	180
Boiler plant	—
Turbine plant equipment	119
Electric plant equipment	20
Misc plant equipment	4
Allowance for cooling towers	15
Total direct cost	1,193
Contingency allowance (4%)	48
Spare parts allowance (1%)	12
Indirect costs (10%)	119
Total capital investment (1975)	1,372
Interest during construction (15%)	206
Total cost at year of commercial oper.	1,578

*Collector cost \$60/m² **Storage cost \$30/kWh

Figure 23. 100 MWe SOLAR POWER PLANT COST ACCOUNTS (\$/kW)

6.0 TRADE STUDY REQUIREMENTS

The conceptual design trade studies to be carried out as a part of the E(04-3)-1300 study include two major subtasks. The first is to conduct a point design study consistent with the Point Design Matrix. The other is to conduct conceptual design trade studies of the two advanced technology baseline TES systems. A summary description of the scope and objective of these trade studies is presented in this section with emphasis on the operating requirements and conditions to be penetrated during the studies.

6.1 POINT DESIGN MATRIX

Conceptual designs will be developed for each of the 13 (thirteen) design points identified in shading in the Point Design Matrix presented in Figure 24. Each conceptual design will include initial thermal sizing, preliminary mechanical design and system cost estimates; and will be developed with the support of the TES configuration synthesis computer programs and the solar power plant operation analysis computer program.

Each design point will be a straight forward extension of the baseline conceptual designs presented in Section 4.0. Power plant performance work will be undertaken to support these trade studies. The overall objective of these trade studies is to establish the sensitivity of each storage concept to:

- (1) Storage time in hours, and
- (2) Storage capacity in MW_e .

6.2 CONCEPTUAL DESIGN TRADES

Conceptual design trades will be performed based on the results of the preliminary trade studies performed under the EPRI RP-788-1 study. Under the ERDA study, the conceptual design trade studies will be expanded in depth to include identification and preliminary evaluation of containers, insulation, heat exchangers, and materials and exploration of design sensitivity to heat loss and pressure drop criteria.

The least cost container concept identified under the RP788-1 study for the phase change concept device was an underground, insulated, reinforced concrete

vessel. Additional trades will be performed on this concept to produce more detailed material selections, estimates of service life, repair, and material and construction costs. Similarly, the details of the sensible heat TES concept containment vessel and the reactor shell for the CES concept require additional investigation.

Additional trades are required to identify specific insulation materials for the various containment vessels. Firebrick insulation is used in the phase change concept design. The choice of the brick type will be influenced by both brick thermophysical and high temperature structural properties. Similarly, the insulation chosen for the interior of the reactor shell for the CES concept will require evaluation of the effects thermal conductivity, high temperature mechanical strength, and corrosion resistance to the SO_2/SO_3 reactions. Mineral wool block and Kaowool^(R) are used in the sensible heat TES concept design. The effects of helium permeation on thermal conductivity of these insulation materials needs investigation.

The phase change TES conceptual design identified INCONEL 617 as the preferred heat exchanger tubing metal with Hastelloy-N as an alternative. Additional corrosion and mechanical data on both metals will be gathered. This will allow a trade to be performed to determine which of the metals will be best suited for the phase change concept. A similar situation exists with the heat exchanger tubing metal for the CES reactor, especially with reference to the corrosion resistance of INCONEL 617 to the SO_2/SO_3 reactions.

For the phase change concept, thru a Hastelloy-N metal liner is identified to protect the refractory insulation from the molten salts. An alternative design would use a graphite layer as the liner material. Additional data on the graphites' thermophysical, structural corrosive resistance properties needs to be gathered. A series of design trades will then allow the solution of the most effective liner material.

The sensitivity of the conceptual designs to the pressure drop criteria will be explored. The conceptual designs were sized to a 4% pressure drop through the TES devices. The pressure loss value significantly affects the size of the helium circulation system. The component cost for the helium circulation systems for the various TES conceptual designs varies from 1.7M\$ for the sensible heat

system to 1.2M\$ for the CES system. By increasing the tube diameter, i.e., decreasing the pressure loss, heat exchanger costs will increase. However, these increases may not be as large as the cost decreases for the helium pump, the result being a reduction in overall system cost. A series of trades will be performed to determine what pressure loss criterion would be most suited for each TES concept.

The conceptual design sensitivity to the heat loss criterion will also be explored. Because of the large surface area of the sensible heat TES design, use of a 2% heat loss criterion may require prohibitive amounts of insulation material. On the other hand, the CES system may be able to more effectively operate at an even lower heat loss value. The effects of variations of heat loss criterion on each of the TES systems costs and performance will be investigated.

	1/2 HOUR THERMAL BUFFERING	3 HOUR STORAGE	6 HOUR STORAGE	24 HOUR STORAGE
50 MW _e PHASE CHANGE			EPRI EMPHASIS CONCEPT	
100 MW _e PHASE CHANGE				
5 MW _e PHASE CHANGE				
50 MW _e THERMO- CHEMICAL			EPRI EMPHASIS CONCEPT	
100 MW _e THERMO- CHEMICAL				
5 MW _e THERMO- CHEMICAL				

Figure 24. Point Design Matrix

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