SERI/TP-252-1869
UC Category: 59b
Preprint

Long Duration Thermal Storage for Solar Thermal High Pressure Steam IPH

R. J. Copeland (SERI)
C. Stern (University of California at Berkeley)
J. W. Leach (North Carolina State University)

December 1982

To Be Presented at the
Sixth Annual ASME Technical Conference
Orlando, Florida
19-21 April 1983

Prepared Under Task No. 1300.11
WPA No. 348-82

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401

Prepared for the
U.S. Department of Energy
Contract No. EG-77-C-01-4042

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 $3.00
Printed Copy $4.00

ABSTRACT

Solar thermal central receiver systems are cost effective for electric power and industrial process heat applications. Systems employing molten nitrate salt as both receiver working fluid and storage have previously been evaluated for diurnal thermal storage. This study evaluates the potential of employing a molten salt receiver for a baseload industrial process plant requiring saturated steam at 68 atm (1000 psi). Two types of thermal storage are evaluated: molten salt, and air and rock. When thermal storage of six hours or less is used, molten nitrate salt alone is the optimum storage. For more than six hours, the optimum storage is a combination of molten salt and air and rock. The air and rock system uses a molten-salt-to-air heat exchanger and a thermocline rock bed heated and cooled by the air. The economic potential of the system is determined. The results depend on the relative cost of fossil fuel and the solar thermal energy costs. The optimum quantity of storage is highly variable, and the range is from no storage to a long duration capacity--48 hours.

INTRODUCTION

Previous studies (1,2) indicate that a packed bed storage system using a crushed granite medium and air for transporting may be economically attractive for large, high-temperature solar thermal systems. This type of storage is not susceptible to chemical degradation at high temperatures and does not require pressure vessels for containment. The cost of the granite medium is extremely low when compared with that of liquids for sensible heat storage at high temperature or with phase change materials, and, since small air leaks are of little consequence, the containment vessel can be constructed from earth and concrete. However, air is a relatively poor heat transfer medium, and the interface between the storage medium and the primary transport loop of the solar thermal plant is a problem area. The cost of pumps for circulating air and heat exchangers at the interface can quickly overshadow the other inherent advantages of air and rock storage and, therefore, must be dealt with if this type of storage is to be cost effective.

This paper describes the conceptual design and optimization of a combined storage system that minimizes the problems at the interface and significantly reduces the overall cost of storage. This system uses sensible heat storage in a molten salt in addition to air and rock storage to moderate the required rate of heat transfer into the rock. There is an optimum combination of the two storage types that minimizes the cost of the energy delivered by the system taking account of the pumping power and the capital cost of storage and heat exchangers. This combination depends on how the process heat load varies with time, the averaged local daily variations in insolation, the fraction of the total process heat load met by solar energy, and the relative cost of the system components.

In this work, a process heat load of 300 MW_t is considered. Saturated steam at 288°C (550°F) is produced continuously 24 h/day, 7 days/week. The plant is assumed to be located in the southwestern United States. This is an appropriate test case for evaluating the rock bed storage because of the system size and the temperature required. It is also typical of actual process heat plants in the United States. Iannucci (3) shows that approximately 50% of the process heat produced in this country is consumed in plants of approximately this capacity and that the temperature is suitable for the vast majority of the processes involved. Also, the economics of solar IPH are much more favorable in the Southwest than in other parts of the country.

SYSTEM DESCRIPTION

Figure 1 is a simplified flow schematic of the system considered. A central receiver with a molten salt transport fluid is shown, since it should be the most appropriate choice for the temperatures and heat loads of this application. Thermal energy is stored either by pumping the molten salt from a cold storage tank, heating it in the collector, and then storing it in a hot tank; or by causing the heated salt to flow through a salt-to-air heat exchanger where it transfers heat to circulating air for storage in a rock medium. Energy is withdrawn from storage either by pumping the heated salt from the hot tank, cooling it at the load heat exchanger, and returning it to the cold tank; or by reversing the flow of the air and salt to cause heat to flow from the rock to the load. (For simplicity, Fig. 1 does not show the valving.)

The inlet water temperature must be kept above a prescribed minimum value to prevent it from cooling the molten salt below the salt's freezing point. This is done by a mixing valve that preheats the water with steam and by a heat exchanger that withdraws energy from the rock storage. The two methods for preheating are interchanged, depending on the operating conditions, to minimize parasitic losses.

Figure 2 details the air and rock storage subsystem. Heat is stored in the active bed as heated air enters through a series of hot ducts from above, flows through the active bed where it is cooled, and then returns through the cold ducts to the salt and air heat exchanger. Reversible fans located in vertical shafts distributed throughout the bed approximately every 15 m (50 ft) circulates the air through the system.

Because of the pumping power requirements, it is not practical to fully heat the rock near the bottom of the active bed. To do this the temperature of the air leaving the active bed would have to be high leaving little energy in the rock. Therefore, large quantities of air would have to be circulated to heat the rock near the exit. Similarly, when the air flow is reversed to withdraw energy from storage, it is not

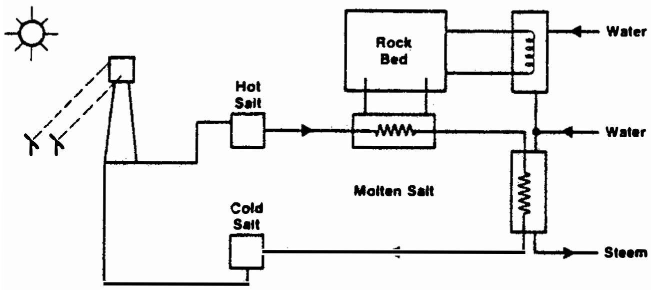

Fig. 1 300 MW_t Solar IPH System Schematic

practical to cool the rock near the top of the active bed. Thus, since the active bed cannot be fully charged nor fully discharged, only a fraction of its storage capacity is actually available. To be conservative we assume that the active rock bed is used only 50% of the time. Thus, the storage system size and cost and the pumping power are figured for an actual active rock bed mass twice the theoretical minimum value.

OPTIMIZATION ANALYSIS

This section describes how the storage system components were sized to minimize the cost of delivered solar energy. In the analyses, the temperatures of the salt flowing to and from the solar receiver were assumed to be fixed since the determination of these values depends on the design of the receiver itself, and since the objectives of the study, which is to evaluate the potential of the mixed storage, could be accomplished without precise values of the salt temperatures. The temperature of the salt flowing to the receiver is assumed to be fixed at 288°C (550°F), and the returning temperature is assumed to be 565°C (1050°F). These values are believed to represent the true optimum temperatures for the 288°C process heat application.

Cost data for the storage materials and for the heat exchangers were taken from Dubberly et al. (1). Data for the cost of collectors, land, buildings, and other miscellaneous equipment were taken from Battleson et al. (4). The storage subsystem was designed to minimize the present worth of revenues required (PWRR), which is computed by following procedures outlined in the EPRI Technical Assessment Guide (5). PWRR is essentially the amount of money that if invested at the beginning of plant operation would repay the initial capital cost and also pay operating cost for the expected life of the plant. In this analysis PWRR is computed from both capital investment and variable cost. Capital investment includes equipment, media, installation costs, engineering, interest paid during construction, and other costs attributed to the construction of the plant. Variable costs account for pumping power, operation and maintenance, and other miscellaneous expenditures required to keep the plant operating.

The size of the salt and air heat exchanger and the air and rock storage system are interdependent. When the heat exchanger is very large, the log-mean temperature difference (LMTD) is small, and the air entering the heat exchanger can be heated almost to the temperature of the salt returning from the solar receiver or cooled to the temperature of the salt at the load heat exchanger if the flow is reversed. This wide swing in temperature permits large amounts of energy to be stored in the rock and minimizes the storage mass. If the heat exchanger is made smaller to lower its cost, the storage mass must increase in inverse proportion to the difference between the maximum and minimum air temperature.

Figure 3 shows that an optimum heat exchanger size exists for which the combined cost of the heat exchanger and rock storage is at a minimum. The charging multiplier (CM)* in Fig. 3 is the rate that heat is transferred to the air at the heat exchanger in units of the process heat load (300 MW_t). Storage is measured as the time that energy can be continuously withdrawn from storage at a discharge rate of 300 MW_t. In Fig. 3, the curve for total cost is relatively flat over a wide band centered at the minimum point corresponding to an LMTD of approximately 52°C (125°F). This behavior is similar for other storage capacities and charging rates, but the optimum LMTD varies from case to case.

Determining the best combination of molten salt and air and rock storage also involves the salt and air heat exchanger. Heat is stored when solar energy is collected at a rate that exceeds the process load requirements and is withdrawn later at a rate that may equal the process demand. The storage charging rates during the hours around noon may exceed the maximum discharge rate. In this case, the salt-to-air heat exchanger must be oversized to accommodate the high heat flux, or collected solar energy must be stored elsewhere to avoid dumping or overheating. The question then arises as to whether it is more cost effective to provide an additional heat exchanger area or auxiliary storage. Auxiliary storage may also be bene-

*A-R charging multiplier = CM
Charging rate = CM × discharge rate.

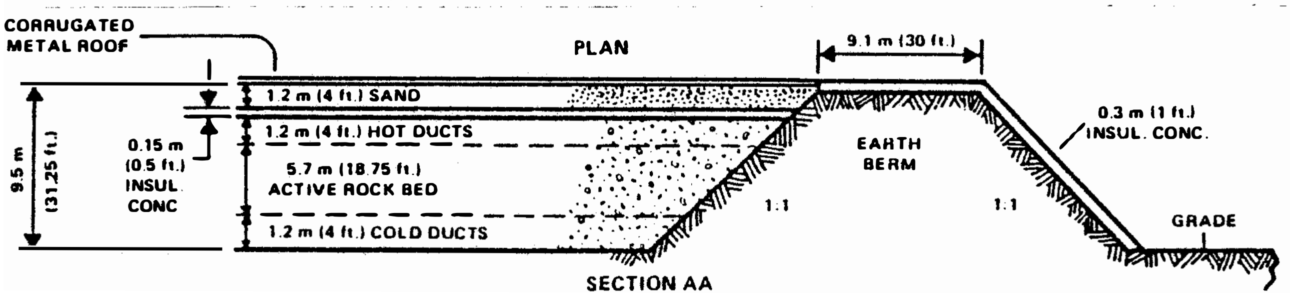

Fig. 2 Cross Section of Rock Bed Storage

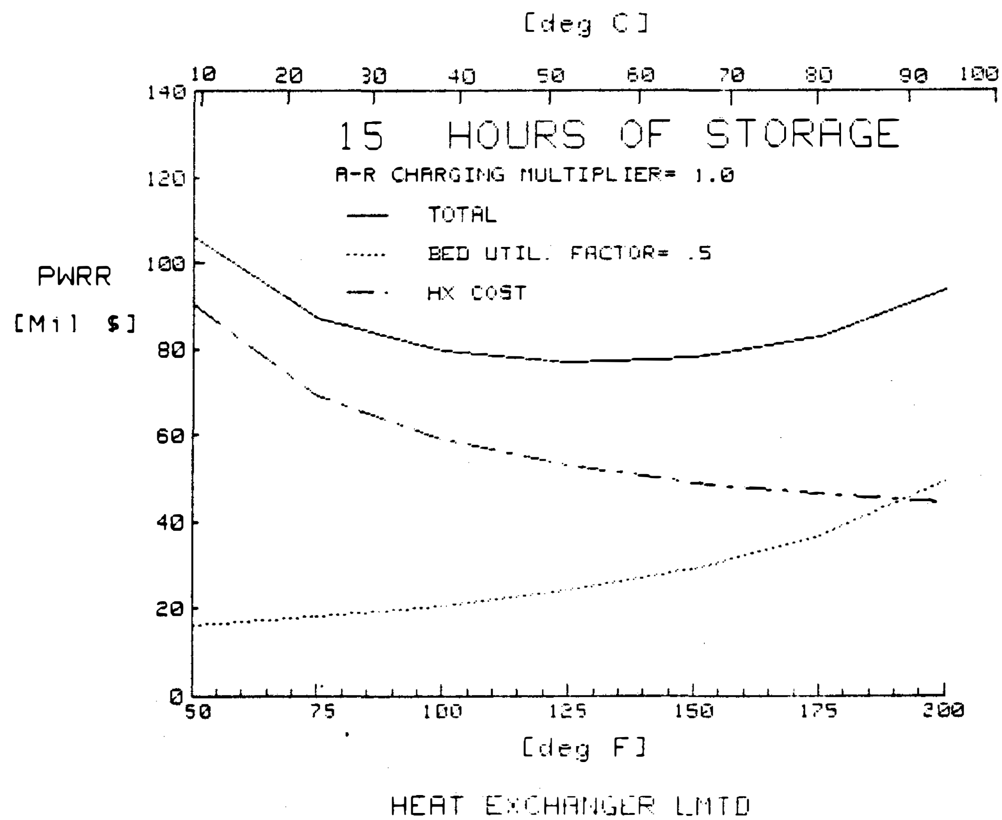

Fig. 3 Optimization of Heat Exchanger

ficial when the discharge rate is higher than the peak charging rate since it permits the heat exchanger to be sized smaller than would be necessary if the rock storage provided all of the process load.

Analyses by Dubberly et al. (1) and Battleson et al. (4) have shown that molten salt is one of the lowest cost media for small storage durations at the temperature of this application. Therefore, computations were made to determine whether cost savings are possible when this type of storage is used to reduce the required area of the salt-to-air heat exchanger. Figure 4 illustrates how the required size of the salt storage subsystem depends on the maximum charging heat flux. Solar energy collected during the period of peak insolation that cannot be delivered to the process load or to the rock storage through the air and salt heat exchanger is stored in the molten salt. If the heat exchanger is made larger so that the charging rate can be increased, the required mass of molten salt, which is proportional to the cross sectioned area at the dome of the insolation curve in Fig. 4, decreases. The charging rate that minimizes the total storage system cost is determined by parametric analyses. For each trial value of the charging rate the optimum heat exchanger LMTD is computed to minimize the combined cost of the heat exchanger and rock storage, and the required salt mass is computed from the insolation curve for the worst case day of the year.

Figure 5, which gives results for a fixed total storage mass, shows that the optimum rock charging rate is approximately the same as the discharge rate. The value of the best charging-discharging ratio depends primarily on the relative costs of the salt and heat exchanger and is not a strong function of the total storage mass.

Since the optimum charging rate is essentially the same as the discharge rate, the salt mass must be sufficient to store the fraction of the solar energy that is collected at a rate in excess of twice the process load. This fraction depends on the collector area. When the collector area is increased, the peak heat rate in Fig. 4 increases in direct proportion, whereas the rate at which energy is delivered to the load and to the rock storage does not change. Thus, more energy must be stored in the salt when the collector area is large. For large collector areas, the rock storage mass should also be increased since the rock bed may not completely discharge overnight during the summer months and may have to store energy collected over a period of several days. If the additional rock storage is not provided, the solar energy would eventually have to be dumped to avoid overheating the system.

Hour by hour computations for a typical meteorological year were made to determine how much solar energy is delivered to the process load as a function of collector area and total storage mass. This information was combined with the optimized storage system cost data of this work and the collector cost data of Battleson et al. (4) to establish how the cost of delivered solar energy depends on collector area and storage mass. The optimum storage system designs were determined for the minimum cost conditions. For a given total storage mass, the collector area was selected to give the minimum installed cost of solar energy delivered. Given this collector area and total storage mass the best combinations of the two storage types were then determined by means of the parametric analysis just described. Table 1 summarizes the system designs obtained in this manner. The analysis showed that salt storage is most economical when the storage capacity is less than about six hours, but that rock bed storage is economical in increasing proportions for larger storage capacities.

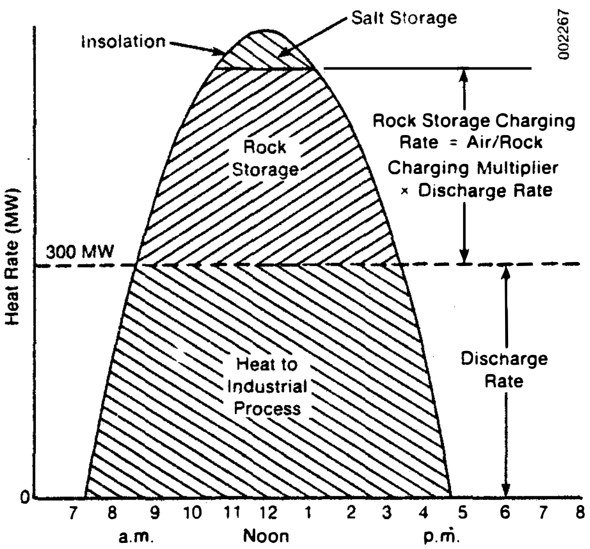

Fig. 4 Daily Storage Cycle

Table 1. Data for Optimum Design

	Total Storage Capacity (h)			
	6	15	48	100
Salt Storage (h)	6	3.6	8.3	12.0
Rock Storage (h)	0	11.4	39.7	38.0
Hx LMTD (°C)	-	52	38	24
ΔT of Rock (°C)	-	163.6	191.4	219.3
Fan Power (MW)	-	3.57	3.50	3.43

The final selection of the total storage mass depends on the cost of solar energy relative to that of energy from other possible sources. If solar energy collected without storage is relatively inexpensive, then storage can be justified to allow solar energy collected during the day to be used at night. However, solar energy becomes more expensive when storage is added and will eventually exceed the cost of the alternative fuel. One can determine the optimum storage mass by computing the total cost of energy delivered from solar energy and from the alternative source as a function of the fraction of the total load that solar energy provides. Figure 6 gives results for several values of the ratio of cost of solar energy without storage to cost of alternative energy. The results show that approximately 15 hours of the combined storage is optimum when the cost ratio is 0.9 and that approximately 48 hours of storage can be justified when the ratio is 0.5.

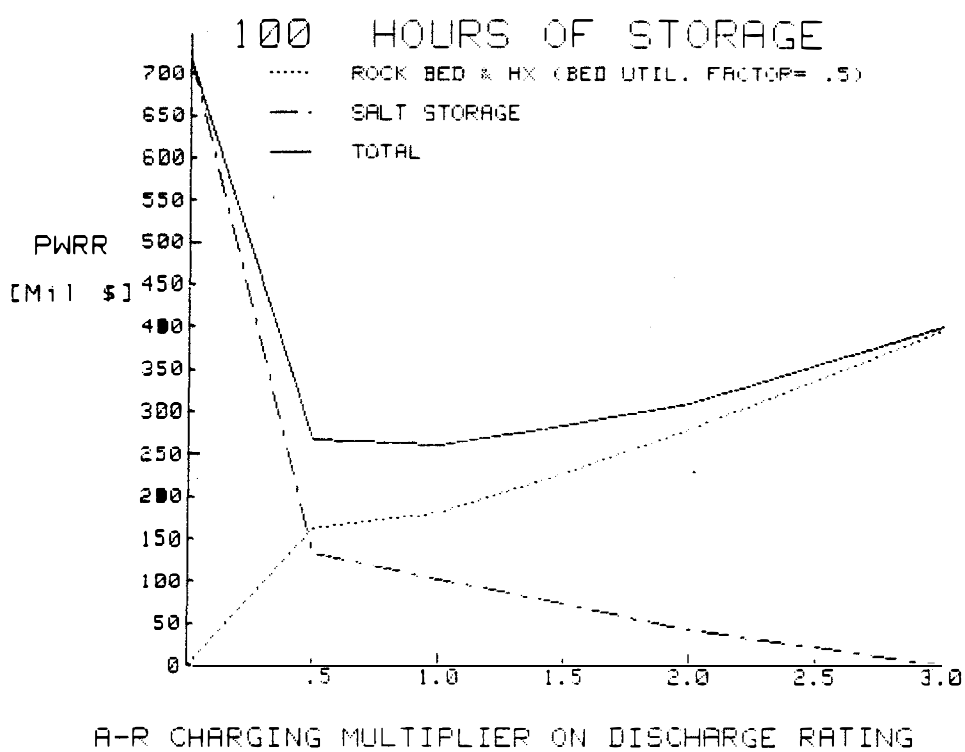

Fig. 5 Optimization of Rock Charging Rate for Fixed Collector Area

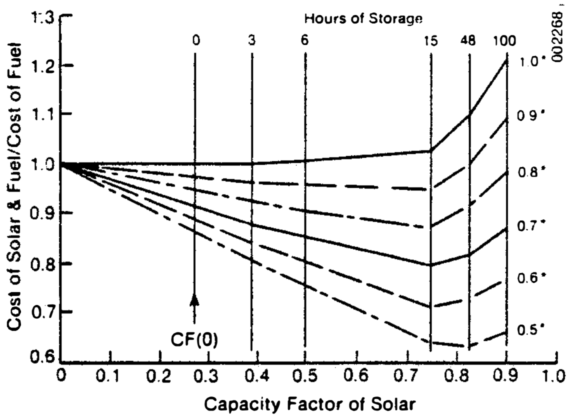

Fig. 6 Energy Costs for a Baseload IPH Plant

CONCLUSIONS

The analyses show that relatively large quantities of combined air and rock, and molten salt storage can be economically attractive in high pressure steam IPH plants. The optimum quantity of storage depends on the relationship between the type of solar energy and alternative fuels. The optimum quantity of storage may range from zero to as much as 48 hours. For most price relationships, 15 hours is the optimum quantity. This surprising result stems from the fact that large quantities of this type of storage can be provided at low cost.

The data demonstrate that a dual storage subsystem can be economical; i.e., one that includes molten salt and air and rock thermal storage. The optimum quantity of each medium depends on the quantity of storage desired. Research and development on the dual storage is recommended because this potential technology has the potential to save significant quantities of fossil fuel.

REFERENCES

1. Dubberly, L. J. et al., Cost and Performance of Thermal Storage Concepts in Solar Thermal Systems, Phase 2, Liquid Metal Receiver. SERI/TR-XP-9001-1-1-3, by Stearns-Roger Services Inc., Dec. 1981.

2. Davidson, W. S. et al., Closed Brayton Cycle Advanced Receiver Solar Electric Power System, SAN/1726-1, Boeing Engineering and Construction Company, Nov. 1978.

3. Iannucci, J. J., Survey of U.S. Industrial Process Heat Usage Distributions. SAND80-8234, Sandia Laboratories Energy Report, Jan. 1981.

4. Battleson, K. W., DeLaquil, P., Fish, J. D., Norris, H. F., and Iannucci, J. J., 1980 Solar Central Receiver Technology Evaluation, SAND80-8235, Sandia Laboratories Energy Report, Oct. 1980.

5. Technical Assessment Guide, PS-1201-SR. Prepared by the Technical Assessment Group of the Electric Power Research Institute, Inc. (EPRI), Palo Alto, California, July 1979.