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CENTRAL RECEIVER STEAM SYSTEMS FOR INDUSTRIAL PROCESS HEAT APPLICATIONS

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ABSTRACT

Various central receiver technologies for supplying 550°F and 350°F saturated steam for industrial process heat applications are compared. Conceptual designs of systems based on molten salt, water/steam, and oil receivers were derived, where possible, from earlier work within the Department of Energy Solar Thermal Program. Systems include either molten salt or oil/rock storage subsystems. Cost estimates of delivered energy over a capacity factor range from 0.27 to 0.67 are reported.

For conditions of little or no storage several different technologies can be used to supply saturated steam for industrial process heat applications at roughly equal costs. For systems with large amounts of storage, the results clearly demonstrate the advantages of collecting energy at temperatures higher than the application temperature.

A significant implication of this study is that process steam represents an additional market for the 1050°F molten salt receiver system currently receiving program emphasis for electrical power production. All of the work in support of that effort is directly applicable and timely for this industrial application.

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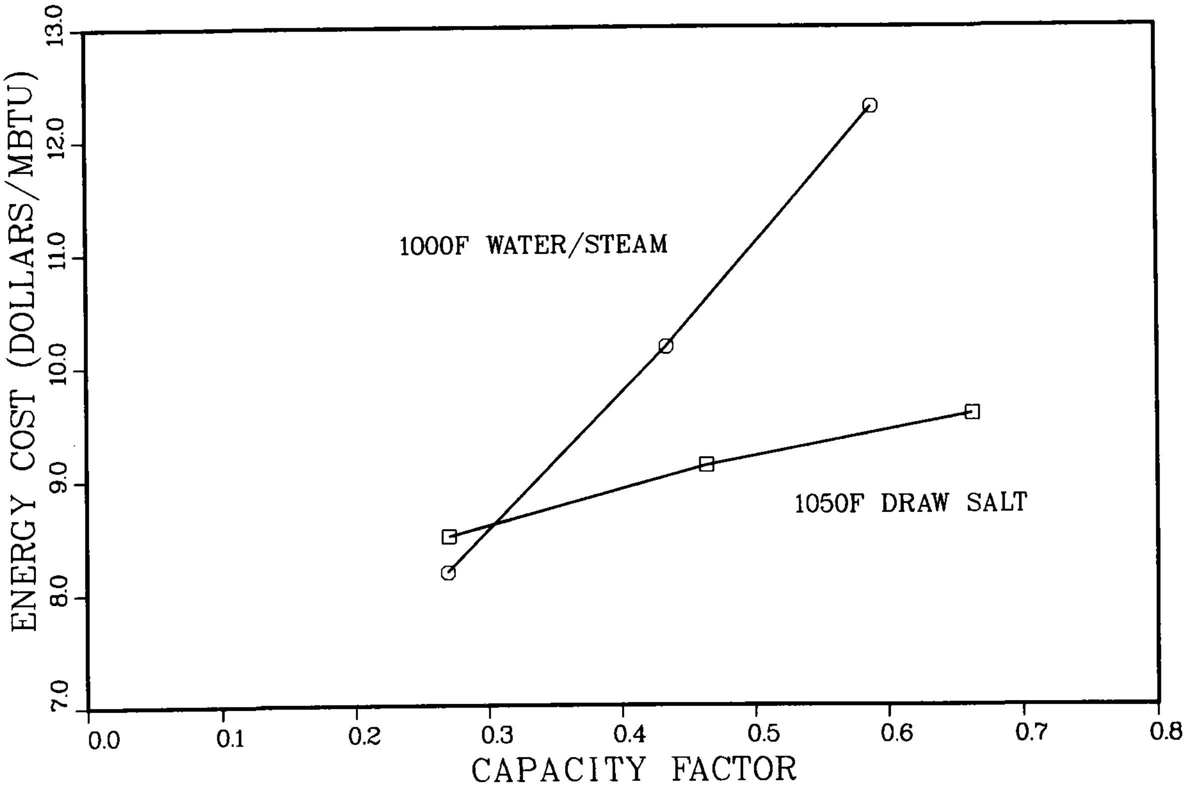


Figure 1. 550°F Saturated Steam System Costs

CENTRAL RECEIVER STEAM SYSTEMS FOR INDUSTRIAL PROCESS HEAT APPLICATIONS

I. Introduction and Summary

Production of steam for industrial process heating has been identified as a potentially significant market for near-term application of solar thermal technology [1]. Currently, energy used to generate saturated steam and hot water for process heating purposes accounts for 4 x 10^{15} Btu/yr, or five percent of the total U.S. energy consumption of 80 x 10^{15} Btu/yr.

Efforts carried out over the past few years under the Department of Energy Solar Central Receiver Program provide a technology base from which designs of systems for steam generation can be drawn. The data base includes site- and application-specific conceptual designs, detailed designs for electrical generating systems, and the fabrication and testing of key components [2].

This report documents a study in which central receiver systems based on a number of receiver and thermal storage options are compared. Two applications were considered: 550°F saturated steam and 350°F saturated steam.

Figure 1 summarizes the results for the 550°F application. With no storage,* the system based on a water/steam receiver is competitive with the nitrate salt receiver system. As salt storage is added to both systems, however, the salt system becomes more cost effective. The primary reason for this trend is that in the salt system the receiver heat transport fluid and the storage medium are the same. The water/steam system is more complicated and more costly as a result of the interface between the receiver and the storage subsystem. Furthermore, direct storage in the salt system provides for a larger temperature swing across storage and across the steam generators. These effects combine to give the salt system a clear advantage over the water steam system at higher capacity factors. Of particular importance, a salt system is capable of supplying energy for two shifts (capacity factor of 0.66) at a cost of energy only slightly higher than the cost for one shift.

*Corresponding to an annual capacity factor of 0.27 for a plant located at Barstow, CA.

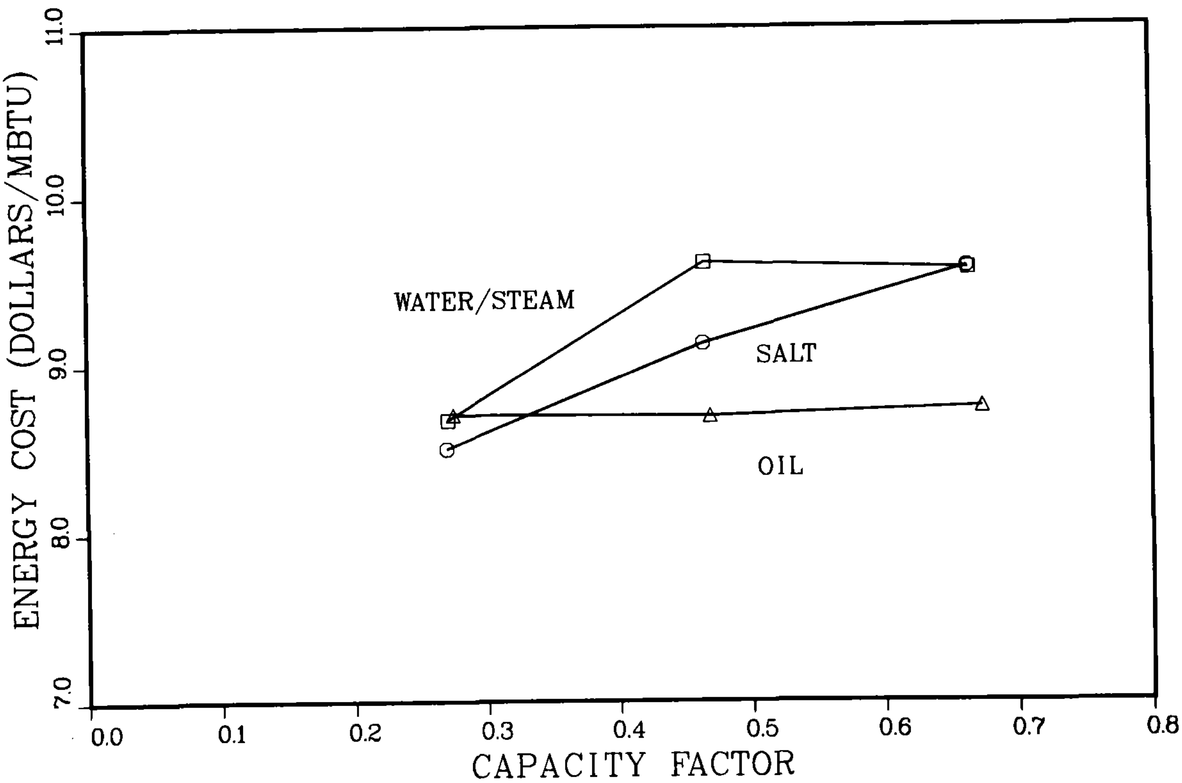


Figure 2. 350°F Saturated Steam System Costs

The results for the 350°F application are summarized in Figure 2. Systems based on three types of receivers were considered: water/steam, nitrate salt, and heat transfer oil. The water/steam system is now competitive with the salt system over the entire capacity factor range. Because of the lower application temperature in this case, the water/steam system can effectively use oil/rock storage which is considerably cheaper than nitrate salt storage. The reduced storage cost compensates for the increased system complexity. The oil system, with cheap direct storage, is more cost effective than either the water/steam or the nitrate salt system at higher capacity factors.

Details of the scope of the study and the approach taken are discussed in Section 2. Subsystem cost and performance estimates are covered in Section 3. Sections 4 and 5 provide detailed results for the 550°F and 350°F applications, respectively. Finally, Section 6 is a summary of the conclusions and their programmatic implications.

II. Scope and Approach

2.1 Applications

Two applications were chosen for investigation: 550°F saturated steam and 350°F saturated steam. These two cases are representative of the high pressure (1000-1500 psia) and the intermediate pressure (100 - 150 psia) steam headers of a typical industrial plant. The breakdown of industrial steam usage nationwide is 1 QUAD (10^{15} Btu/yr) below 212°F (hot water), 2 QUADS between 212°F and 350°F, and 1 QUAD between 350°F and 550°F. The pulp and paper industry and petroleum refineries are the two largest identified steam users, with the former accounting for over a QUAD and the latter for approximately half a QUAD. Other industries in which steam usage is large are food, textiles, chemical, and primary metals [1].

2.2 System Size

All of the systems were designed to deliver 300 MW thermal power to the industrial plant. This size is in the same range as the 100 MW_e central receiver power plants for which considerable information exists. For example, during the course of two studies [3,4] recently completed, costs for systems based on the various receiver/storage options were put on a common basis by an independent A&E firm. Our confidence, therefore, in relative costs of systems covered by these two studies is high. By looking at systems in the same size range, little scaling of components was required for the current study. Reasons for believing that the results would not change significantly for systems down to the 20-30 MW_t size range are presented in the final section.

2.3 Heat Transport and Storage Media

For the 550°F application, two receiver heat transport fluids were considered: nitrate salt and water/steam. Results of the 1980 Solar Central Receiver Technology Evaluation [3] showed that salt systems are more cost-effective than sodium systems in producing superheat steam for a power plant. The same cost differences would hold for systems generating saturated steam. Sodium systems, therefore, were not considered in this study.

Single-stage, dual-tank nitrate salt storage was used for both the water/steam and the salt systems. Air/rock storage may be a better option for the water/steam system, but was not considered here because neither the cost nor the performance of air/rock storage subsystems is well known. A maximum allowable temperature of less than 600°F on the oil and the desire to supply saturated steam combine to make oil/rock storage subsystems impractical for the 550°F application.

For the 350°F application, three receiver heat transport fluids were considered: nitrate salt, water/steam, and heat transfer oil. For both the water/steam and the oil systems, oil/rock thermocline storage is more cost-effective than salt storage. Both the medium and the containment materials are more expensive for the salt storage subsystems. Furthermore, temperature swing is not the constraint on oil/rock systems at this temperature as it is at 550°F.

Latent heat storage subsystems were not considered in this study due to lack of an engineering data base. As cost/performance information for latent heat systems becomes available, comparison with the results presented here should be straightforward.

2.4 Capacity Factor

Systems were designed with annual capacity factors ranging from ~0.25 to ~0.70, where capacity factor is defined as the ratio of the energy actually supplied by the solar plant and the energy it could supply if it were to operate 24 hours a day, 365 days a year at its peak rating. For the 550°F application, cost of energy increases with capacity factor over this range for all systems considered. Economies of scale do not compensate for the additional cost of storage. This situation is different than for solar electric plants in which cost of storage is traded against increased use of the turbine/generator set, which represents a large fixed cost. On the other hand, for the 350°F application, cost of energy is constant over a large range of capacity factors (see Figure 2). Oil/rock storage is sufficiently cheap that economies of scale are apparent.

2.5 System Optimization

A logic map of the approach taken is shown in Figure 3. With subsystem cost and performance relationships, the DELSOL code [5] designs the optical portion of the system: the heliostat field, the receiver, and the tower. The STEAEC code [6] is then used to get the detailed performance of this system with different amounts of storage. With cost of storage from the QDSTOR code [7], the optimum amount of storage, and thereby, the optimum system based on lowest cost of energy, is determined.

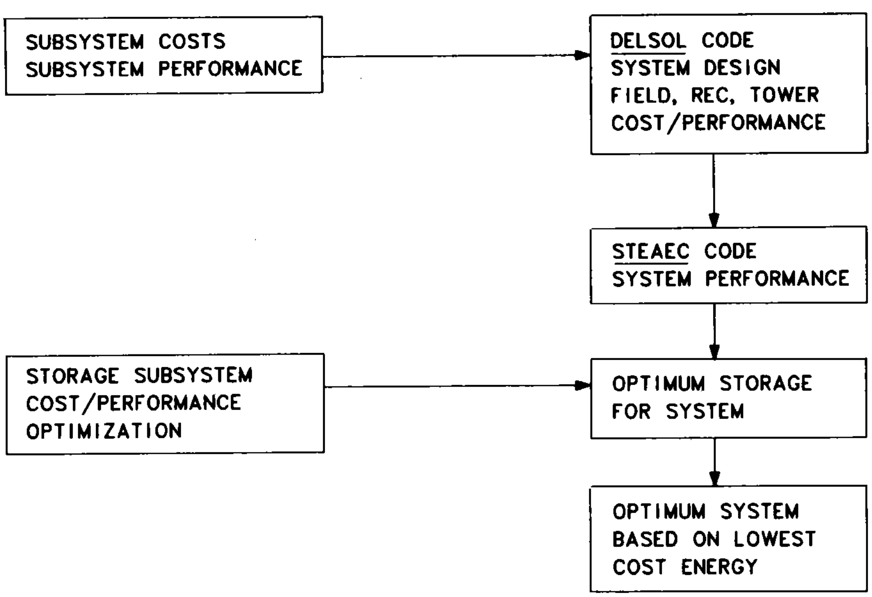


Figure 3. System Optimization Logic Map

System performance is based on a Barstow, CA location and 1976 weather data. Although absolute costs would change with location, relative costs of systems, and therefore, the conclusions of this study, are independent of location, within reason.

2.6 Depth of Study

This study is based on an understanding of central receiver technology as defined by the references and the experience they document. Areas of technology development currently underway could lead to systems more cost effective than those compared here. The two primary purposes of this study are 1) to indicate areas of technology development that appear at this time to have potential payoff, and 2) to provide a framework within which to make further comparisons and recommendations as additional technical data become available.

III. Subsystems

3.1 Receivers

Maximum receiver temperature and receiver efficiency are key parameters in determining cost of energy produced by a central receiver system. Receivers operating over a wide temperature range were considered in this study. Efficiencies for receivers for which designs did not exist were determined by scaling from receivers with known efficiencies. Convection and conduction losses were scaled with temperature; radiation losses were scaled with temperature to the fourth power; and receiver absorptivity was held constant at 98% for cavity receivers and at 96.5% for external receivers.

The five receivers considered for the 550°F application are listed in Table I. The 1050°F Draw Salt Cavity and the 1000°F Water/Steam Cavity receivers are both Martin Marietta designs [8,9]. The cost and the performance of these receivers were normalized as a part of the 1980 Evaluation [3]. The 900°F Draw Salt Cavity receiver is essentially the same as the 1050°F receiver. Operating at a lower temperature, however, its efficiency is higher. The third receiver is the same as the first two but in an external configuration, i.e., the cavity structure has been removed and the tubes rearranged. Due to reduced amounts of materials, the cost is less. Due to its external configuration, the efficiency is also less. The cost and the performance of the 550°F saturated Water/Steam receiver are drawn from the 1000°F design in an analogous manner. In this case, the loss of efficiency in going to an external configuration is less than the gain in efficiency as a result of reduced temperature. The costs are normalized to 300 MW_t and are direct costs for the receiver subsystem only.

The five receivers considered for the 350°F application are listed in Table II. The 1050°F Draw Salt receiver and the 550°F Saturated Water/Steam receiver are the same receivers considered for the 550°F application. The 620°F Saturated Water/Steam receiver is scaled from the 550°F receiver. The cost of the 620°F receiver is slightly higher due to higher flow rate required by the reduced enthalpy change at the higher pressure.

The oil receiver is based on a design by Northrup [10]. As a result of the significant degree of scaling required, there is less confidence in both the cost and the performance of this receiver than for the other receivers. The cost is probably a lower bound and the efficiency an upper bound. Implications of this uncertainty with respect to the interpretation of the results are discussed in Section 5.

TABLE I

RECEIVERS FOR 550°F APPLICATION

Temperature (°F)	Receiver	Cost ($$10^6$)	Efficiency
1050	Draw Salt Cav.	3.84	0.92
900	Draw Salt Cav.	3.84	0.93
900	Draw Salt Ext.	2.60	0.88
1000	W/S Cav.	8.45	0.92
550	Sat. W/S Ext.	7.55	0.93

Table II

RECEIVERS FOR 350°F APPLICATION

Temperature (°F)	Receiver	Cost ($$10^6$)	Efficiency
1050	Draw Salt Cav.	3.84	0.92
620	Sat. W/S Ext.	7.64	0.92
550	Sat. W/S Ext.	7.55	0.93
600	Oil Cav.	8.15	0.93
550	Oil Cav.	8.15	0.93

3.2 Piping

Receiver heat transport fluid and maximum receiver temperature are key parameters in determining costs for the riser, the downcomer, and the horizontal piping between the tower and the storage subsystem. The type of fluid and the upper temperature together determine the materials from which the pipes are fabricated. Fluid properties and temperatures across the receiver determine the flowrate through the piping subsystem, and thereby, the size of the pipes.

Piping materials, pipe sizes, and piping system costs were drawn from the same data base as the receiver designs [3,4,8,9,10]. Costs for installed, insulated, and heat-traced piping systems were scaled with diameter. This relationship corresponds to scaling with the square root of thermal power.

3.3 Heat Exchangers and Storage

The ten combinations of storage media, receiver fluids, and storage operating temperatures are listed in Table III. The storage subsystems fall into four categories discussed individually below: salt storage for salt receivers; salt storage for water/steam receivers; oil/rock storage for water/steam receivers; and oil/rock storage for oil receivers.

Storage subsystem component cost data and a detailed description of the methodology used to arrive at the minimum storage subsystem costs for each system are covered in Reference 4. Table VII of that reference is reproduced here as Table IV. The materials used for construction of the heat exchangers and tanks were determined by the operating temperature of the unit. A summary is presented in Table V.

TABLE III

STORAGE SUBSYSTEMS

Receiver Fluid	Storage Media	Temperature (°F) High	Low	ΔT
Salt†,*	Salt	1050	550	500
Salt†	Salt	900	550	350
Water/Steam†	Salt	885	560	325
Water/Steam†	Salt	700	554	146
Water/Steam†	Salt	679	551	128
Water/Steam†	Salt	670	552	118
Water/Steam*	Oil/Rock	600	318	282
Water/Steam*	Oil/Rock	540	328.5	211.5
Oil*	Oil/Rock	600	318	282
Oil*	Oil/Rock	550	327	223

†550°F application
*350°F application

TABLE IV

STORAGE SUBSYSTEM COMPONENT COST DATA

Storage Media	Caloria: \$.35/lb Draw Salt: \$.15/lb Hitec: \$.30/lb Crushed Granite: \$0.005/lb [\$10/ton] Taconite: \$.04/lb [\$80/ton]
Tanks	Carbon Steel Tank, Cylindrical: \$.5/lb Stainless Steel Tank, Spherical: \$4/lb Insulation: \$6/ft^3
Pumps	Pumps: $\$69.5*(\Delta p \cdot Q)^{0.43}$ [carbon steel] Pumps if Stainless Steel: multiply above by 1.64 where Δp = pressure head (psi), and Q = volumetric flow rate (ft^3/hr)
Heat Exchangers	Carbon Steel HX: \$17.7/ft^2 @ 10,000 ft^2 Chrome - Moly HX: \$21.2/ft^2 @ 10,000 ft^2 Stainless Steel HX: \$37.2/ft^2 @ 10,000 ft^2 Multiplier for Kettle Boiler or Condenser: 1.35 Multiplier for Shellside Pressure > 650 psia: 1.35 Economy of Scale Exponent: 1.05 $\$ = 17.7 \left(\frac{Area}{10000}\right)^{1.05} * 10000$
Balance of Plant	Fraction of the above costs: 0.32

TABLE V
STORAGE SUBSYSTEM MATERIALS SELECTION CRITERIA

Heat Exchangers

$T \leq 600°F$	:	Carbon Steel
$600°F < T \leq 800°F$	:	Chrome - Moly
$800°F < T$	:	Stainless Steel

Tankage

$T \leq 700°F$	:	Carbon Steel, Cylindrical
$700°F < T$	:	Stainless Steel, Spherical

3.3.1 Salt Storage--Salt Receivers

The configuration of the salt receiver systems is shown in Figure 4. Hot salt from the receiver flows through the hot tank, the evaporator, the preheater, the cold tank, and back to the receiver.

Temperature swings across storage are determined by the two receiver operating temperatures and the minimum salt temperature of 550°F. In addition to this safety margin of 90°F above the freezing point of the salt (460°F), a recirculation loop on the preheater raises the inlet water to 460°F and assures an adequately high film temperature on the salt side of the heat exchanger.

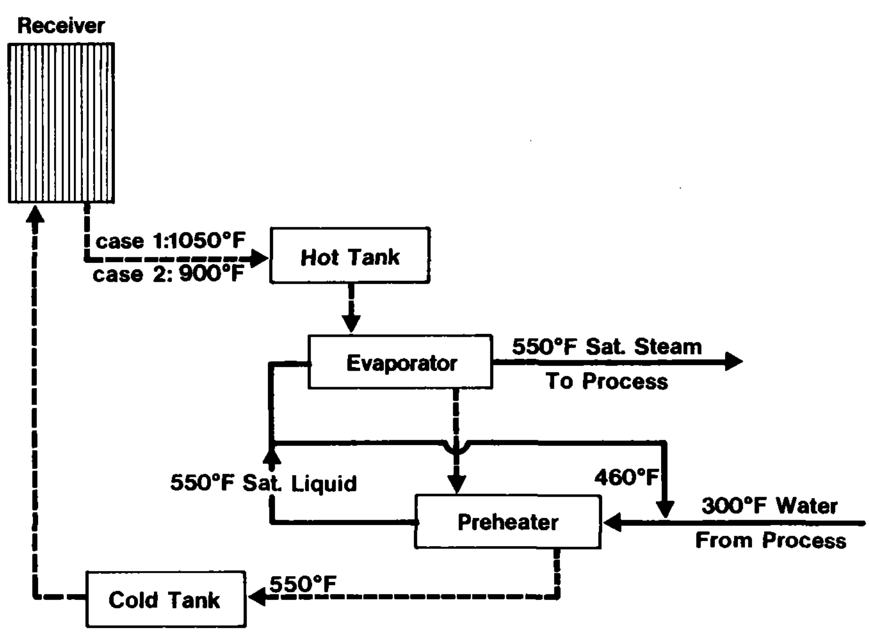


Figure 4. Salt Storage--Salt Receiver System Configuration

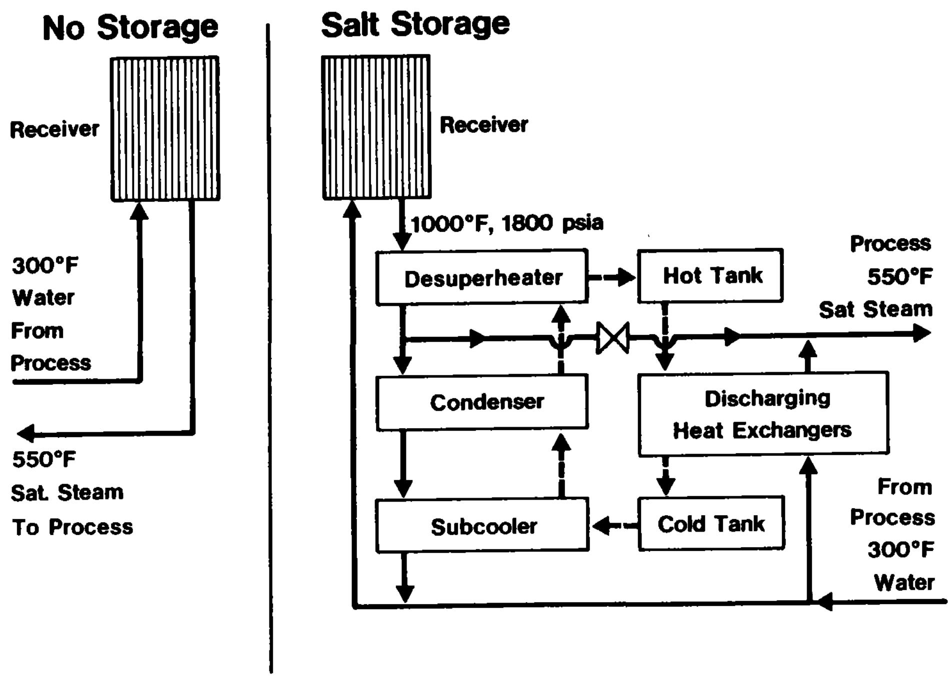


Figure 5. Water/Steam Receiver System Configurations

3.3.2 Salt Storage--Water/Steam Receivers

Configurations for the water/steam receiver systems, with and without storage, are shown in Figure 5. For a system without storage, steam is generated in the receiver and sent directly to the process. Adding storage to the system drastically increases complexity. In addition to the storage tanks and the discharging heat exchangers required in the salt systems (Figure 4), the water/steam systems require charging heat exchangers. Furthermore, due to thermodynamic and economic constraints, the receiver must produce higher temperature, superheated steam. The maximum reasonable pressure in water/steam receivers is approximately 12.4 MPa (1800 psia). This pressure corresponds to a saturation temperature of 327°C (620°F). The highest temperature swing across the storage subsystem, therefore, is only 70°F for a 550°F saturated steam application if the water/steam receiver is constrained to produce saturated steam. A storage subsystem designed to accommodate such a low temperature swing would be prohibitively expensive.

Utilizing a superheated steam receiver results in much larger temperature swings across storage (refer to Table III). The steam from the receiver is sent first to a desuperheater where it is cooled from 1000°F to 644°F by transferring heat to the salt storage medium. After the desuperheater, the steam required for the process is split off, throttled to 550°F saturated steam, and piped to the process. The excess superheated steam is sent to the condenser and subcooler heat exchangers where additional energy is transferred to the salt, preheating it before it is sent to the desuperheater. Finally, water from the subcooler is mixed with that returned from the process and sent back to the receiver.

Figure 6 shows temperatures in the storage subsystem as a function of percent energy transferred. Figure 6(a) is based on a system designed for three hours of storage. Figure 6(b) is for twelve hours of storage. Figure 6 clearly shows the phenomenon that controls the temperature swing in the storage media, and thereby, the cost, of the storage subsystem. For short storage times, most of the energy on the charging side is transferred in the desuperheater. The pinch point occurs near the left side of the diagram such that a large temperature swing can be accommodated. As the amount of storage increases, more energy is transferred to storage in the condenser and subcooler heat exchangers moving the saturated steam point to the right. Figures 6(a) and (b) correspond to the first and fourth salt--water/steam subsystems listed in Table III, respectively. The other two salt-water/steam subsystems are for six and nine hours of storage.

3.3.3 Oil/Rock Storage--Water/Steam Receivers

For the 350°F application, a superheated receiver is not required. Temperature swings for either 620°F or 550°F saturated steam receivers interfaced with oil/rock storage subsystems are sufficiently high that storage design is straightforward.

3.3.4 Oil/Rock Storage--Oil Receivers

The storage subsystems for oil receivers are the same as for the saturated water/steam receivers without the charging heat exchangers.

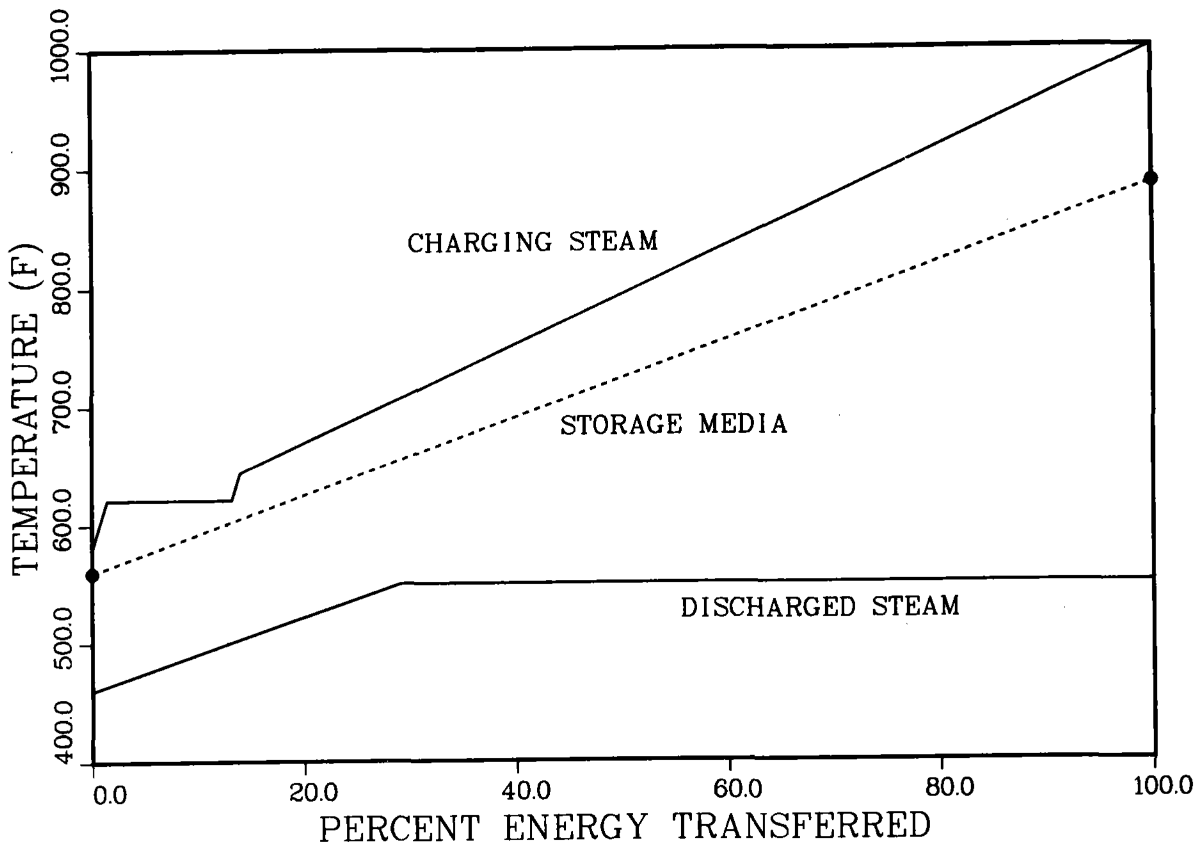
3.4 Land, Field, and Fixed Costs

A land cost of $2.09/m^2 and a heliostat cost of $78.6/m^2 were used in this study for all systems. With 15% indirects, the heliostat figure corresponds to $90/m^2, which represents the expected cost under mass production.

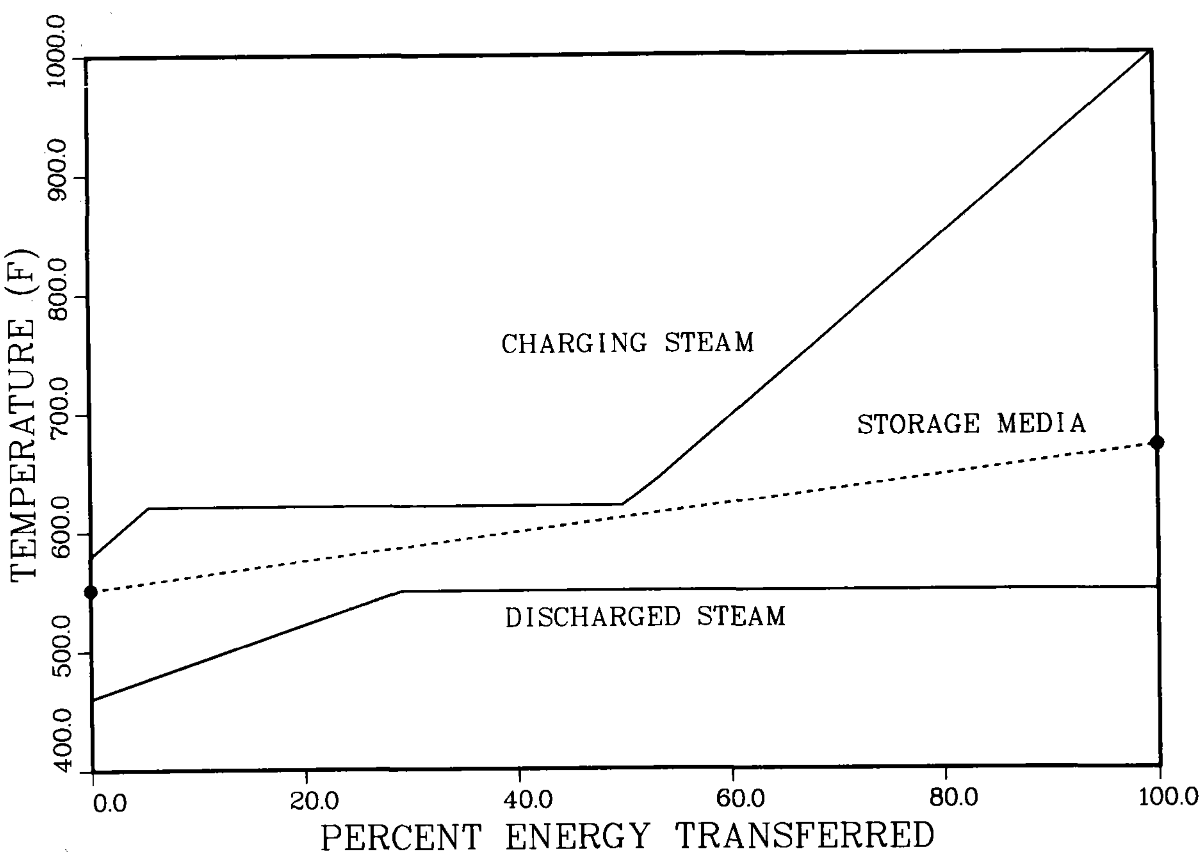
A fixed cost of $6 x 10^6 (independent of both system and capacity factor) was included to cover such items as master control, buildings, roads, landscaping, safety systems, and security devices.

3.5 Economic Parameters

Economic parameters used in this study are listed in Table VI. It is important to keep in mind that different economic assumptions could significantly change the absolute values of the various reported results without affecting the relative comparisons and the conclusions of the study.



(a)



(b)

Figure 6. Storage Heat Transfer Diagrams

TABLE VI

ECONOMIC PARAMETERS

1980 $'s
15% Indirects
8% Capital Escalation
8% Inflation
5 Years to Construction
25% Interest During Construction
18% Fixed Charged Rate
3.48% Levelized Operation and Maintenance

IV. 550°F Application Results

Five systems for the production of 550°F saturated steam were compared. The results are shown in Figures 7 and 8. For each system, storage capacity was optimized for each solar multiple.* Plotted points correspond to solar multiples of 1.0, 1.75, and 2.50. In Figure 8, only the upper portions of the bar charts representing the land, field, and fixed costs are shown with the base cost for each group of bars indicated.

Four systems are compared at all three solar multiples. The fifth system, based on a 550°F saturated water/steam receiver, could not produce 550°F saturated steam from storage and is considered only at a solar multiple of 1.0.

At the low end of the capacity range, corresponding to systems with no storage, all of the systems except for the one with the 900°F external salt receiver, deliver energy of approximately the same cost.

At all points, the energy costs for the 900°F external salt receiver system is 8 to 10 percent higher than for the 900°F cavity salt receiver system. The external receiver, being less efficient than the cavity receiver requires more heliostats for the same power to the process. A larger heliostat field implies 1) a larger receiver for the same spillage, and 2) a less efficient field for the same tower. The net effect is approximately two percent increase in energy cost for each one percent decrease in receiver efficiency. The savings in going to an external receiver are swamped by these added costs related to efficiency loss. This effect can be seen by comparing Bars B and C in Figure 8.

*Solar multiple is defined as the ratio of thermal power delivered to the base of the tower at the design point to the peak thermal power delivered to the process.

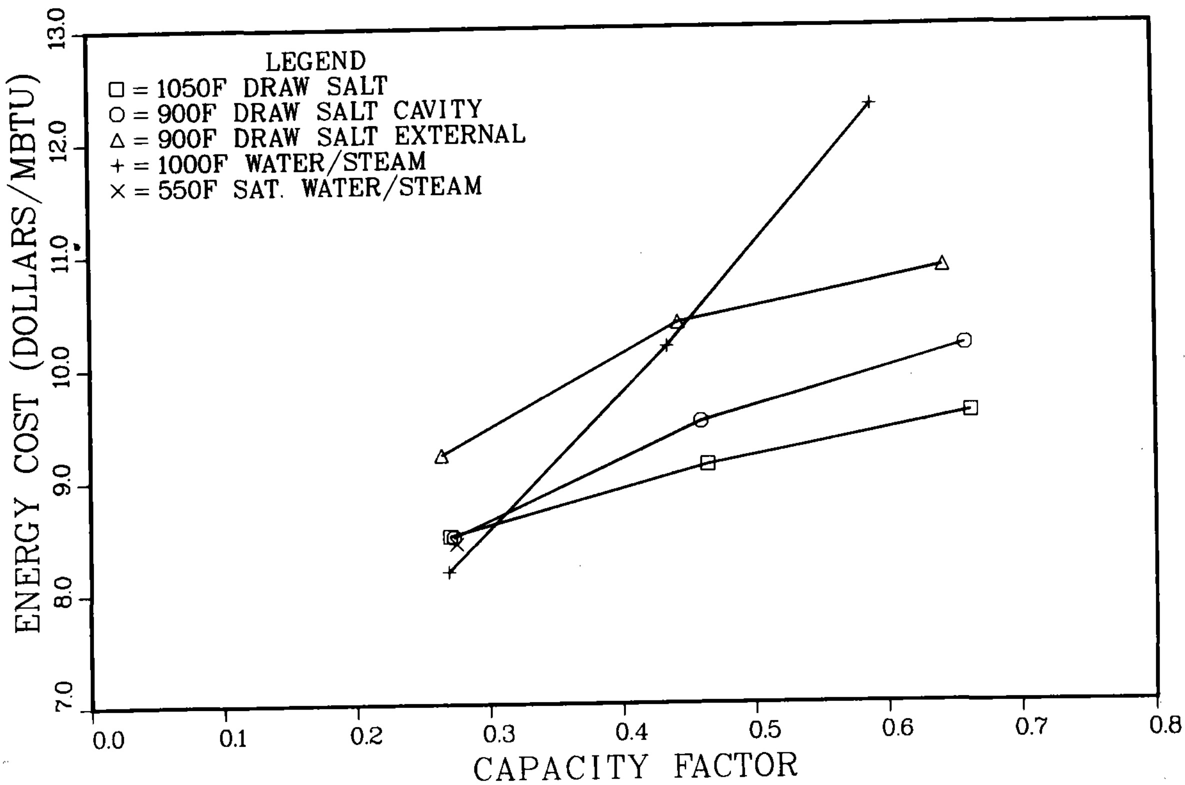


Figure 7. 550°F Saturated Steam System Costs

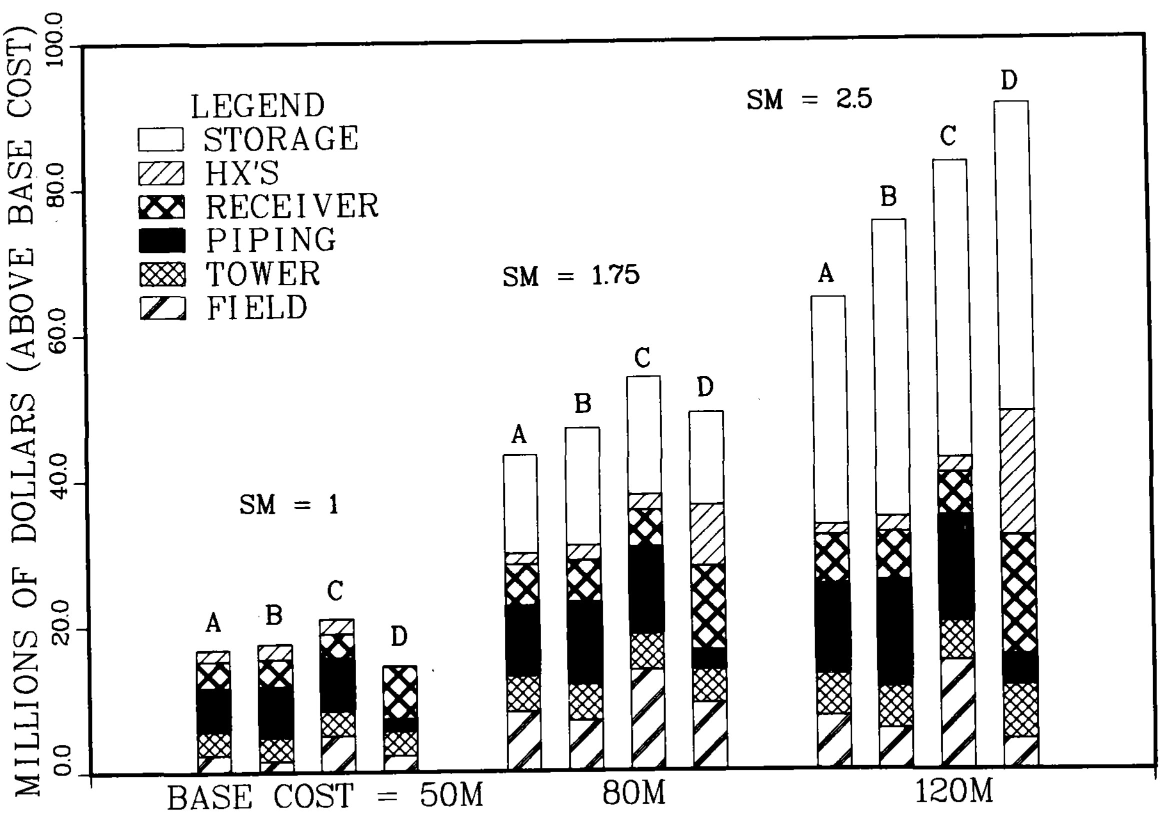


Figure 8. Cost Breakdown for 550°F Application; Receiver: (A) 1050°F Draw Salt Cavity, (B) 900°F Draw Salt Cavity (C) 900°F Draw Salt External, (D) 1000°F Water/Steam Cavity

Between the 1050°F cavity salt system and the 900°F cavity salt system, the primary difference is the cost of storage. As a result of the lower temperature swing in the 900°F system, more storage medium and larger tanks are required for the same thermal capacity. In addition, the reduced temperature swing across the receivers results in higher flowrate and larger, more costly piping. Increased receiver efficiency due to the lower operating temperature does not compensate for the increases in storage and piping costs.

Comparing systems with no storage, the water/steam system is the most cost-effective by a small amount. The higher pressure in the receiver makes it more expensive to fabricate. The water/steam piping system, however, is cheaper as a result of less expensive materials: 1 1/4 Chrome - 1/2 Moly for water/steam vs. 316 stainless for salt. Furthermore, with no storage, the water/steam system has no heat exchangers.

As storage is added to the systems, heat exchanger and storage costs quickly overwhelm all other differences between the water/steam system and the 1050°F salt system. The effect is even more exaggerated than indicated by Bars A and D in Figure 8. The optimum storage for the water/steam system at a solar multiple of 2.5 is 7 hours, corresponding to a capacity factor of 0.59. For the salt system at a solar multiple of 2.5, the optimum is at 11 hours of storage and a capacity factor of 0.66.

V. 350°F Application Results

The results for the five 350°F saturated steam systems are shown in Figure 9. Figure 10 shows the cost breakdown for (A) the salt system; (B) the more cost effective of the water/steam systems; and (C) the oil system with the lesser technical risk. There is much less spread in the results than for the 550°F application. The salt system is the same as used for the 550°F application. The two water/steam systems both have saturated water/steam receivers, one operating at 620°F, the other at 550°F. Storage for the water/steam systems is oil/rock thermocline. The energy costs for the water/steam systems do not take off in this case for two reasons: 1) oil/rock storage is much cheaper than salt storage (by a factor of 4 or 5); and 2) adequate temperature swings are possible for this application temperature with the saturated water/steam receivers. The oil systems with direct storage are cheaper than the more complex water/steam systems, but only by approximately 9%.

The oil systems are based on Caloria HT43 manufactured by Exxon Corporation. Degradation of this material at 600°F is prohibitive, on the order of 30% per year. At 550°F, degradation drops to ~4%. [11]. Both temperatures were considered in this study to see if a program to reduce degradation at 600°F is warranted. Based on the results shown in Figure 9, it is not. Energy costs for the 550°F system are only 3% higher than for the 600°F system.

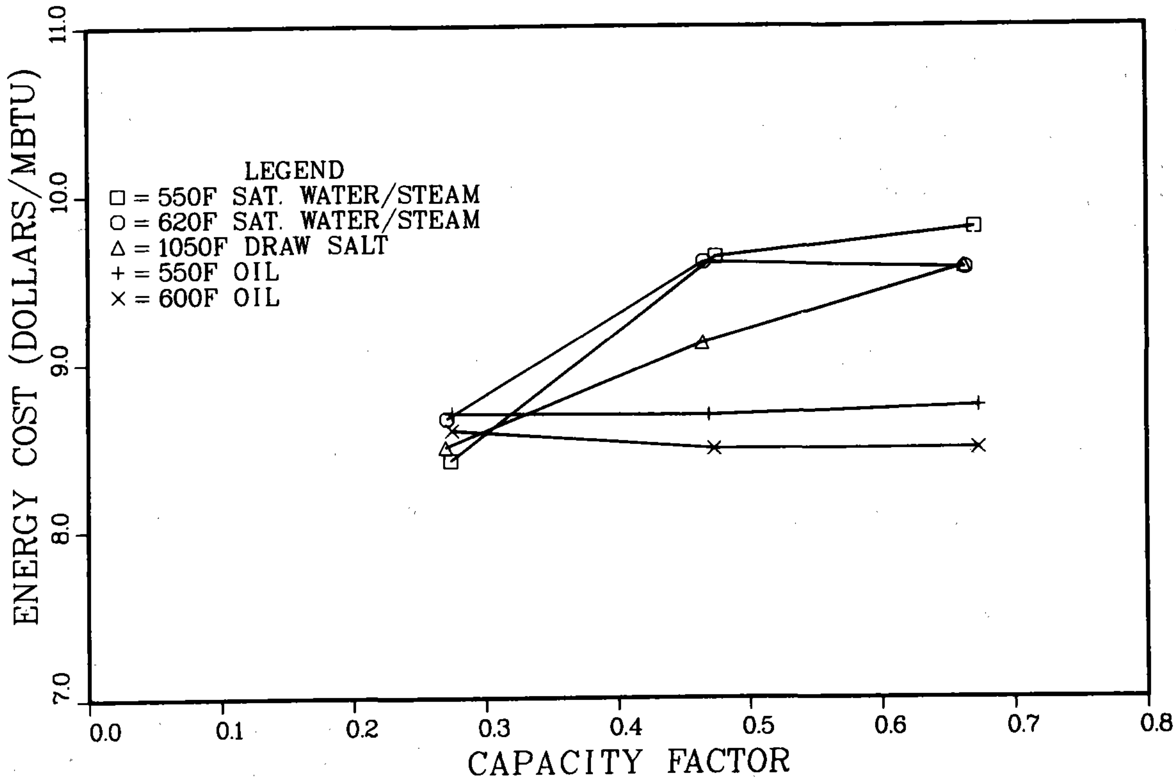


Figure 9. 350°F Saturated Steam System Costs

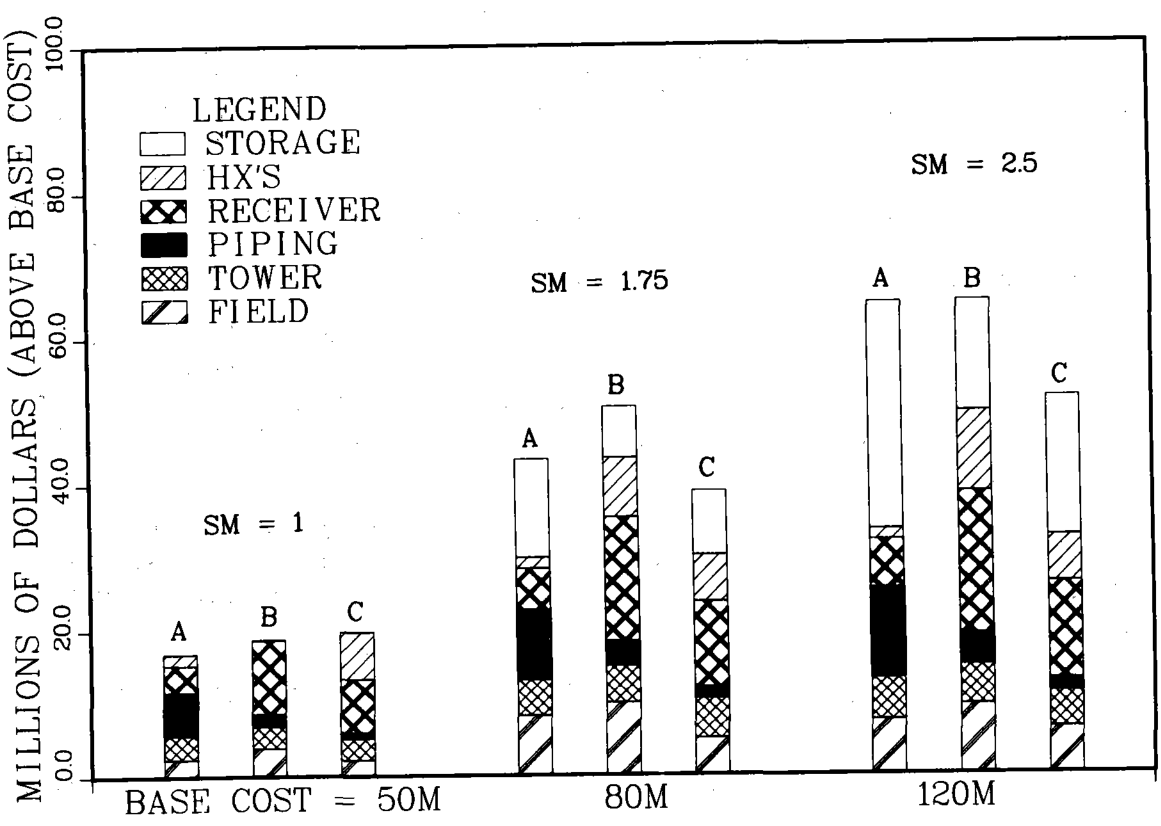


Figure 10. Cost breakdown for 350°F Application: Receiver: (A) 1050°F Draw Salt, (B) 620°F Saturated Water/Steam, (C) 550°F Oil

Although the results indicate that the oil systems are the most cost-effective for a 350°F application, many uncertainties exist. As mentioned in Section 3.1, the oil system designs were scaled from a 12 MW_t conceptual design. The oil degradation figures reported above are for Caloria in a storage mode. Degradation in a receiver, where peak temperature under transient situations might go much higher than design temperatures, has not been considered.

VI. Conclusions and Implications

An important conclusion of this study is that for conditions of little or no storage several different technologies can be used to supply saturated steam for industrial process heat applications at roughly equal cost. Two significant implications can be drawn from this result:

1) A potential user can choose a solar central receiver system with a heat transfer fluid for which he has experience and feel relatively confident that no other system is substantially more cost effective.

2) Process steam represents an additional market for the 1050°F molten salt receiver system currently receiving program emphasis for electrical power production. All of the work in support of that effort is directly applicable and timely for this industrial application.

For conditions of large amounts of storage, advantages of collecting energy at temperatures considerably higher than the application temperature are clearly demonstrated. For the 550°F application, energy costs with the 1050°F salt system increased by less than 13% between a capacity factor of 0.27 and a capacity factor of 0.66. For the 350°F application, energy costs with the 550°F oil system were constant over a range of capacity factors from 0.27 to 0.67. The possibility of constant energy cost over a large range of capacity factors is of extreme programmatic interest. It provides clear justification for continuing development of storage subsystems.

For both application temperatures, the most cost-effective systems directly store the receiver fluid; salt for the higher temperature, and oil for the lower temperature. Direct storage reduces complexity by eliminating the need for charging heat exchangers and maximizes temperature swing across the storage subsystem.

Based on the results of this study, oil receiver systems appear quite attractive. There are, however, uncertainties. At least two questions should be answered before embarking on a major oil receiver development program:

1) Is it possible to build a 300 MW_t oil receiver system for the cost assumed in this study?

2) How severe is oil degradation under conditions of high temperatures for short periods of time?

Finally, all of the systems compared in this study delivered 300 MW_t to the process. The ranking of the systems, however, should be the same for considerably smaller systems. For no component of the system is there a large economy of scale. Differences in the systems are fundamental in nature: temperature swing, system complexity, type of storage.

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