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Direct Absorption Receiver System Studies

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INTRODUCTION

The DOE Solar Thermal Program has funded a number of projects in high temperature, central receiver technology. These projects aim at identifying efficient and low-cost receiver concepts, as well as conversion systems. The direct absorption receiver (DAR) concept offers several potential advantages. It is clear, however, that the component and system advantages of DAR systems have not been adequately assessed.

The DAR concept may greatly extend the range of operating temperatures compared to metal tube receivers of conventional design. Pressurized metal tube receivers become less practical beyond about 600°C because of the low material strength. Low pressure, metal alloy tube receivers may be used at temperatures up to 750°C, but the alloys are very expensive and more reactive to corrosive environments. Ceramic tubes can be used at high temperature, but this is an emerging technology whose feasibility has not been established. Overall, the DAR concept, where the concentrated solar flux is absorbed by the working fluid with no intermediate tube heat transfer surface, is a potentially very simple design. The simplicity of the design may result in good performance and both low capital and operating costs. The candidate working fluid, molten eutectic carbonate salt, can be used as the storage medium, thus eliminating one heat exchanger in the system design.

OBJECTIVE

The primary objective of our system studies (in addition to separate studies of the technical feasibility of the DAR concept reported elsewhere in this compendium) was to assess the anticipated system performance and cost benefits of the DAR concept in high temperature, central receiver applications. To accomplish this objective, it was necessary to analyze component and system performance, estimate component costs, and then calculate a figure of merit for system economics. The results of the study identified both advantages and limitations of the concept, identified further design and research issues, and helped to establish recommendations and DOE program direction for this concept.

APPROACH

The system studies were performed in two phases; the first was an assessment of the DAR concept in electric power applications, and the second phase was an assessment of industrial process heat (IPH) applications. High temperature electric power systems were investigated since they may be able to take advantage of more efficient power cycles. Electric power generation has also been the thrust of the DOE program. There may be, in addition, a potentially significant market for IPH that could be satisfied by high temperature central receiver systems.

We used available design tools to evaluate component performance and simplified analyses to evaluate system cost and economics wherever possible. Since the electric power and IPH phases of the study used slightly different analysis methodologies, the two phases will be discussed separately in this paper. A more detailed discussion of these system studies can be found in two special reports [1,2] issued as briefing documents for DOE.

In both phases, our approach optimized system performance, and then costs were estimated for the selected cases. Sensitivity analyses were performed to identify performance and cost trends and dependence on particular variables.

ELECTRIC POWER SYSTEMS

The central receiver system for electric power generation consists of a heliostat field, a direct absorption receiver, tower, storage, electric power generation system (EPGS), and the balance of plant (BOP).

Component Performance and Cost Characterizations

The heliostat and receiver performance in this phase are based on the work of DeLaquil and Anderson [3] on high temperature central receiver systems. Their study assumed certain design characteristics which we adopted. They include a north heliostat field with a single cavity receiver. The heliostats are each 50 m^2 with a reflectivity of 0.89, using a single-point aiming strategy, and mirrors focused and canted at the slant range. The design point is noon on the summer solstice with a solar irradiance of 950 W/m^2. DELSOL2 [4] was used by DeLaquil and Anderson as a basis for the heliostat field layout and basic system performance. They modified the DELSOL2 receiver performance calculation to accommodate the latest analytical and experimental work on high temperature cavities.

Heliostat costs were parameterized to reflect a wide range of costs. Although heliostats can be bought today for approximately \$250/m^2, they could potentially cost as little as \$50/m^2 with low-cost designs and mass production.

The collection system (heliostat and receiver) performance is affected by many design parameters, but especially operating temperature and desired flux level. There is a complicated set of trade-offs with aperture size, spillage, flux level, radiation and convective losses. This trade-off was performed by DeLaquil and Anderson over a range of field sizes, temperatures, and flux levels. Figure 1 shows the receiver efficiency (not including spillage) at the design point for a field size of 100,000 m^2 as a function of average absorber flux. We have added a comparison with a hypothetical tube receiver operating at the same average fluid temperature and flux. Under these conditions the tube receivers perform less efficiently than a DAR receiver because the tube surface is slightly hotter than the fluid and thus has higher radiant and convective losses. Achieving higher efficiencies at higher temperatures requires higher fluxes, as is evident in the figure. There is a flux at which an optimum receiver performance is reached for each operating temperature. At a normal receiver outlet temperature of 900°C the optimum flux is approximately 0.4 MW/m^2. We used this value for all subsequent receiver calculations. When combined with heliostat performance, the collection system efficiency at design point can be calculated and is shown in Fig. 2 for a 1,000,000-m^2 field. Annual performance is calculated by DELSOL2 using parameters that describe the weather at the chosen location, in this case Barstow, Calif.

Costs for DAR receivers are difficult to estimate because no detailed design studies have yet been undertaken. To estimate the receiver cost for this study we chose to take an existing, detailed, nitrate salt, tube type cavity receiver design for lower temperature and replace those major components required for a DAR system. The only major component in this case is the absorber. The detailed nitrate salt design used was for the Saguaro [5] repowering plant. We estimated that a DAR absorber would cost 5% more per unit area than a tube receiver, but because of the higher flux levels the absorber can be smaller by 20%. This results in a net cost difference for a DAR receiver of 15% less than a nitrate salt receiver delivering the same thermal power.

The cost of the tower is based on the Saguaro design and adjusted for various heights by a cost/height relationship described in Battleson [6]. We assumed that the cost of and heat losses in both tower piping and field piping would be small and thus were ignored in this phase of the study.

One advantage of the carbonate salt working fluid is the ability to also use it as the storage media. A storage tank design using molten carbonate salt has been proposed and costed by Copeland, West, and Kreith [7]. We used the cost of their design at 1800 MWh and 900°C as a baseline and scaled the costs for other storage capacities according to volume and surface area requirements.

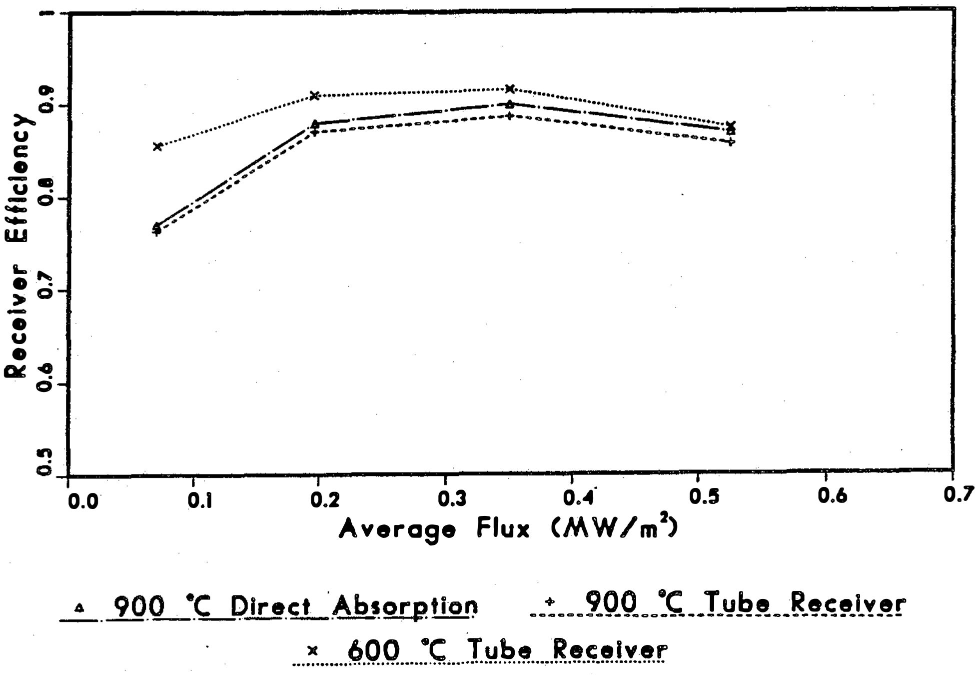

Figure 1. Receiver efficiency with a 100,000-m^2 heliostat field for both direct absorption and tube receivers as a function of average absorber flux. Temperatures refer to nominal receiver outlet temperature.

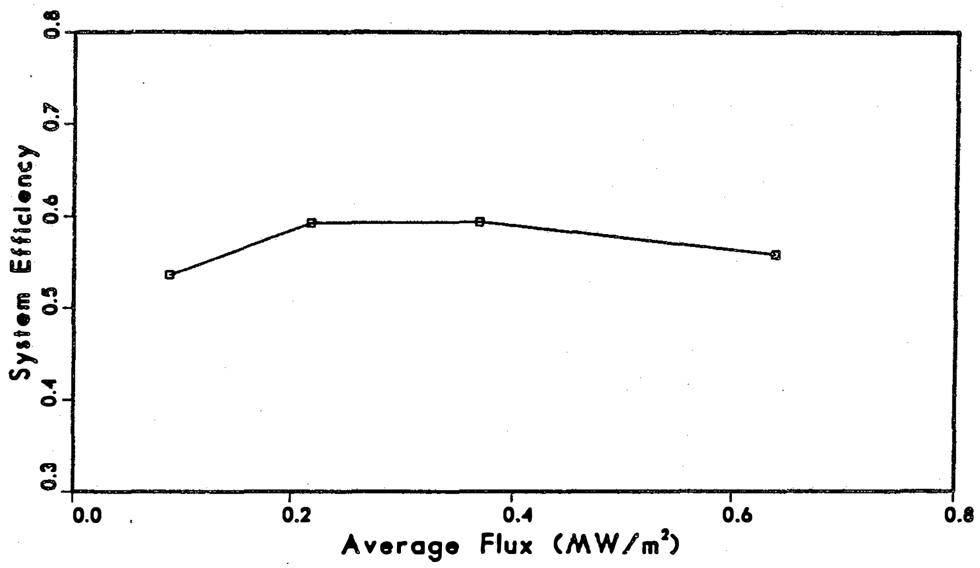

Figure 2. Collection system efficiency (heliostat and receiver) with a 1,000,000-m^2 heliostat field for a direct absorption receiver at a 900°C outlet temperature.

Many high temperature power cycles exist that might be utilized in a DAR system. It was not the purpose of this study to conduct a detailed assessment of specific power cycles and their suitability for DAR systems. However, a brief assessment yielded a range of cycle efficiencies and potential costs that might be applicable to these high temperature systems. The baseline power cycle efficiency at a900°C temperature was assumed to be 40% at an assumed cost of $\$400/kW_e$ installed, including appropriate heat exchangers.

The BOP costs include land and site preparation, site facilities, and master control system. Both the land and site costs scale with field size, but the master control system is fixed. Costs for these items were taken from both Battleson and the more recent Saguaro design.

System Performance and Cost

To generate a range of plant sizes, combinations of two plant ratings (50 and 100 MW_e) and four capacity factors at each plant rating were studied. For a given plant rating, a heliostat field size that would provide the plant rating at design point was determined; i.e., no storage. Then, to achieve higher capacity factors, the no storage heliostat field size was increased by factors of 1.5, 2.0, and 2.5. This resulted in a storage capacity determined by the excess energy delivered, above plant rating on the design day. For the maximum storage cases the storage capacity was nearly 24 hours on the design day. At each combination of rating and capacity it was possible to size and thus cost each of the components in the system.

Total system costs were determined with heliostat costs of both $\$50/m^2$ and $\$250/m^2$. For the electric power system study we used a simplified, levelized busbar energy cost using the procedure described in Battleson. A fixed charge rate of 20% and an interest rate of 20% were used in the economic analysis. All costs are in 1980 dollars.

In addition to these basic DAR system studies, a comparison was made with a lower temperature, nitrate salt electric power system. The same analysis techniques and methodologies were used to evaluate the nitrate salt system. The basic trade-offs with the lower temperature system are a lower EPGS efficiency and a higher collection system efficiency. Higher receiver costs are also traded against lower EPGS costs. The results of this comparison and the results of the basic system studies are shown in Fig. 3 as levelized energy cost (LEC) as a function of capacity factor with heliostat cost as a parameter.

It can be seen clearly in the figure that the lower heliostat cost results in significant decreases in the LEC of all the systems. There also appears to be very little change in LEC with capacity factor. Primarily, however, it can be seen that there is little difference in LEC between the lower and higher temperature systems for electric power generation for a given heliostat cost.

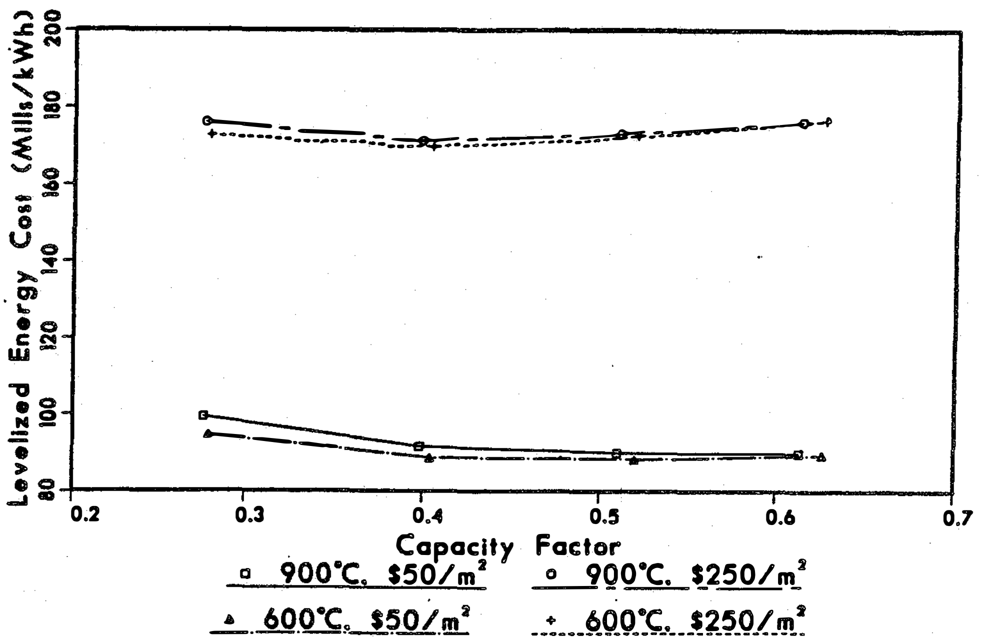

Figure 3. **Comparison of levelized energy cost (in 1980 mills/kWh) for electric power generation between a 900°C direct-absorption carbonate salt system and a 600°C nitrate salt system.**

IPH SYSTEM

There were several changes and improvements in the methodology in this phase of the study. During this phase the assumptions used to derive the DOE Five Year Research and Development Plan component goals [8] became available. This plan included a set of system and component cost goals as well as a more detailed methodology for LEC calculations. These LEC calculations utilized different economic parameters to reflect differing financial assumptions used by electric utilities and IPH users. We used the same IPH economic parameters and LEC methodology as in the Five Year Plan. In this approach, all costs are in 1984 dollars.

The methodology of DeLaquil and Anderson was modified slightly, and new data was generated for collection system performance to be more specific to this phase of the study. Annual performance was now calculated by DELSOL2. We also added the cost and performance of high temperature transport to the study. The LEC is that of thermal energy delivered to the IPH user.

Component Performance and Cost Characterizations

Heliostat size for the IPH study was increased to 100 m^2 to more accurately reflect the current state of the art. The modified methodology was then used to explore several design sensitivities in the collection system performance. Fluxes beyond an average of 0.4 MW/m^2 were found to increase the performance slightly. These improvements were balanced by accounting for the absorber temperature differential from top to bottom. Thus, it was concluded that a uniform temperature absorber was adequate for further receiver performance calculations using the original design flux. The modified methodology resulted in nearly indistinguishable results from the first phase data.

With the exception of adding cost and performance of the transport system, there were no additional changes in the components for the IPH system. The piping cost was based on a conceptual design using Inconel 600 pipe on the hot side of the receiver piping sections and a stainless steel pipe on the cold sections. The piping length was calculated for delivery of thermal energy to a point the distance of the farthest heliostat from the tower. The cost and performance of a heat exchanger to interface with the IPH user were not included in our study because of the wide range of potential IPH working fluids and the associated uncertainty in heat exchanger design.

System Performance and Cost

The same basic system studies were performed for the IPH phase, but with plant sizes of 100, 300, and 500 MW_{th}. Heliostat cost goals from the Five Year Plan are set at $100/$m^2$. Heliostat costs were again parameterized, but at $100/$m^2$ and $250/$m^2$.

LEC methods from the Five Year Plan were used with cost data in 1984 dollars. In the LEC calculation, the cost data are based on fixed or "real" dollars, where inflation is deliberately not taken into account. O&M costs are required in this LEC calculation, but reasonable O&M cost data are not available for DAR systems; therefore, the cost goal for O&M of $5/$m^2$ of heliostat area was used.

A system LEC goal of $8.5/GJ ($9/MMBtu) was established for IPH systems in the Five Year Plan. The data show that the system LEC either approaches or exceeds the goal for a wide range of system combinations. An example is for the 300 MWth DAR system at 900°C shown in Fig. 4. Both $100/$m^2$ and $250/$m^2$ heliostat systems are shown. For the lower heliostat cost, the cost goal can be met. With current heliostat costs, the cost goal is exceeded by a considerable amount. The effect of capacity factor is to increase the LEC in all cases. This effect becomes more severe with the larger plant sizes and less severe with smaller sizes.

A summary of all the combinations of plant size and capacity factor is shown in Fig. 5, where LEC is plotted as a function of plant size, and capacity factor as a parameter. This figure indicates a minimum in LEC between 300-400 MW_{th}. The minimum is a function of capacity factor; e.g., the minimum shifts to higher plant sizes with smaller storage capacities. These minima occur because of the opposing effects of higher plant cost, lower plant efficiency, and higher capacity factor as storage capacity is increased.

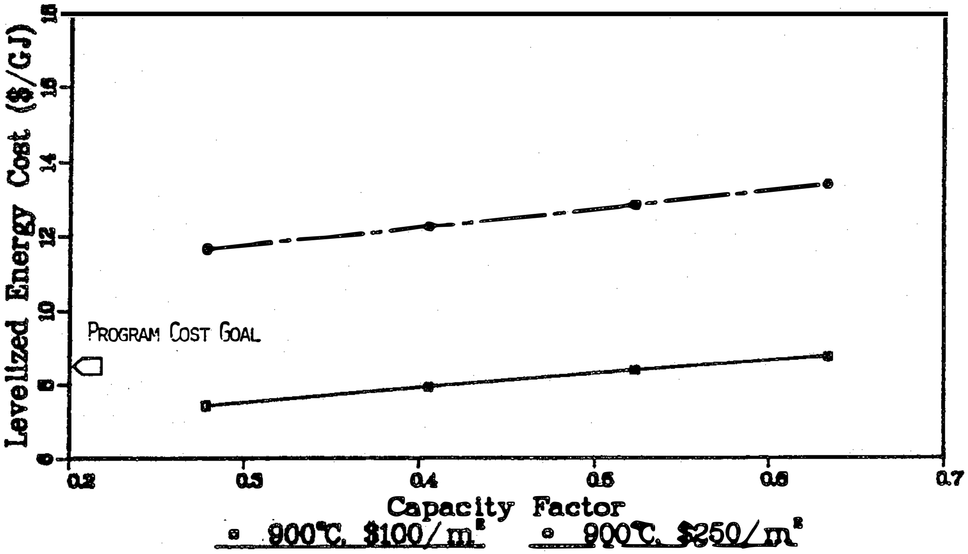

Figure 4. Levelized energy cost (in 1984$/GJ) for a 300 MW_{th}, 900°C direct absorption system.

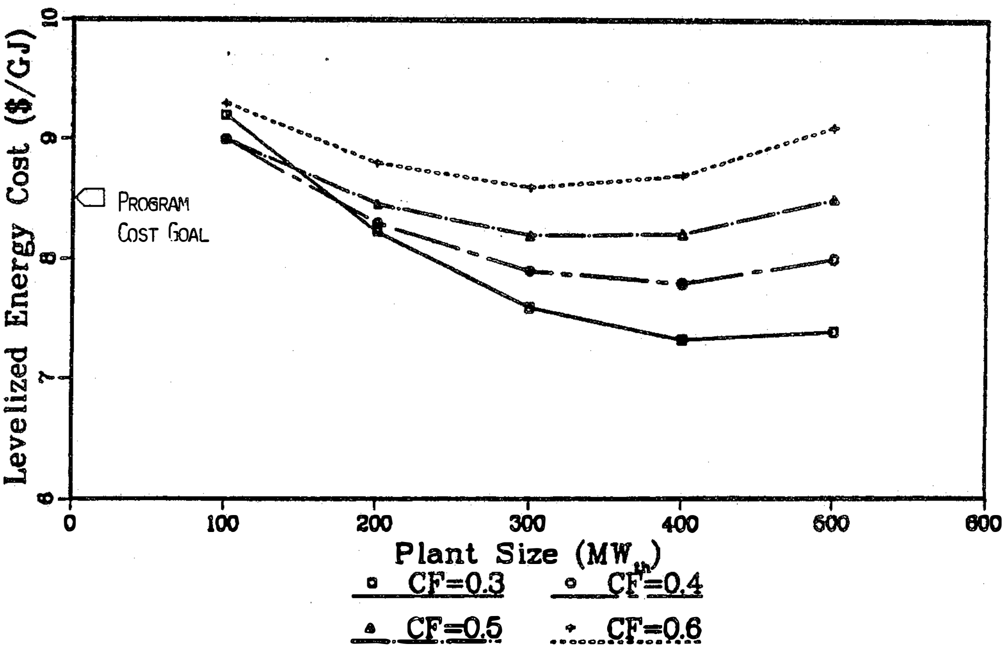

Figure 5. Levelized energy cost (in 1984$/GJ) for a 900°C direct absorption system over a range of plant sizes and capacity factors using $100/m² heliostats.

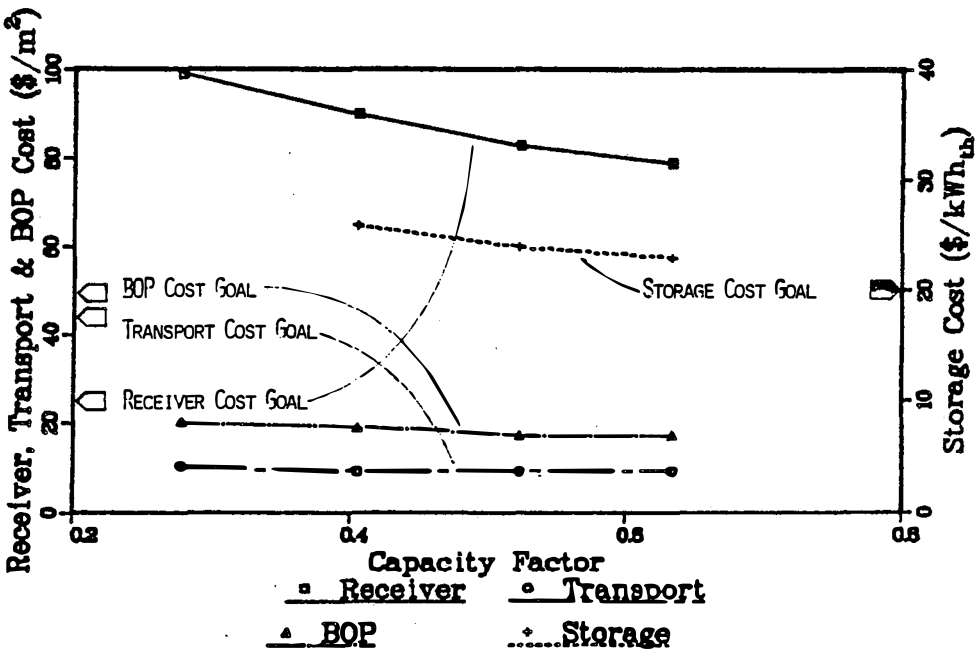

Figure 6. Comparison of component costs with Five Year Plan cost goals for a 900°C, 300 MW_{th} direct absorption system using $\$100/m^2$ heliostats.

We also compared the costs for our IPH system components with the respective goals in the Five Year Plan. The results of this comparison are shown in Fig. 6 for a 300 MW_{th} plant. The cost goals for receivers, transport, and BOP are given in terms of cost per heliostat area, and storage goals in terms of cost per kWh of storage. The figure clearly indicates a wide discrepancy between goals and our estimates for every component except storage. Both the transport and BOP goals are exceeded considerably, while the receiver cost is still well above the goal. The receiver cost is clearly not a linear function of heliostat area as evidenced by the decreasing slope of the curve.

CONCLUSIONS

There are several conclusions concerning DAR systems that apply to specific components and are true for both electric power and IPH applications. Potentially, DAR receivers are slightly more efficient than conventional cavity designs using tubes operating at the same flux and temperature. DAR receivers also appear to have lower costs (by 15%) than tube type nitrate salt receivers of the same thermal output. Both tube type nitrate salt and DAR receivers analyzed to date appear to exceed the Five Year Plan cost goals for the receiver. The addition of storage to both electric power and IPH systems has little effect on the LEC and for large plants results in an increase in the LEC.

Based on the assumptions used, electric power system studied shows that LEC for DAR systems at 900°C is approximately the same as for tube type nitrate salt systems at 600°C. This is because increase in cycle efficiency is offset by the lower collection system performance. We did not analyze combined cycle conversion, nor combined electric and IPH applications that may utilize the advantages of both systems.

Overall, it appears that DAR systems deserve additional attention to determine if the technical feasibility assumed in this study can be verified by experiments. This additional attention should take the form of continued receiver analysis and experiments to verify performance and more detailed design studies to provide a basis for more confident cost estimates. Finally, additional study may be warranted to evaluate innovative high temperature electric generation systems as well as higher flux receivers.

ACKNOWLEDGMENTS

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