SERI/SP-253-2592

DIRECT ABSORPTION RECEIVER SYSTEM STUDY

PHASE 2

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DIRECT ABSORPTION RECEIVER (DAR) SYSTEM STUDY

PHASE 2

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DIRECT ABSORPTION RECEIVER SYSTEM STUDY - PHASE 2

Contents

NEED (Phase 1 and 2)

- Lower cost, more efficient receivers for high temperature applications are needed to improve system efficiency.

- Several new receiver concepts offer potentially significant advantages. One approach is the Direct Absorption Receiver (DAR) concept.

- The component and system advantages of the DAR approach have not been previously adequately assessed.

ACKNOWLEDGEMENT

We would like to acknowledge both the previous and current work by Bob Copeland of SERI on the direct absorption receiver concept. He has provided numerous inputs to this study and his help and advice have been invaluable.

POTENTIAL ADVANTAGES

- o The major advantage of the direct absorption receiver can be described relative to metal and ceramic tube receivers.

  - The direct absorption concept may greatly extend the range of operating temperatures compared to a metal tube receiver. The direct absorption receiver allows operation at temperatures above $1000^{\circ}C$, where a pressurized metal tube receiver is not practical beyond about $600^{\circ}C$. Also, low pressure, alloyed tube receivers do not appear practical beyond about $750^{\circ}C$. Furthermore, metal alloys for use at high temperatures tend to be very expensive and they tend to be much more reactive to corrosive environments at elevated temperatures than do ceramics.

  - Higher operating temperatures imply the need for higher absorber flux levels. A direct absorption receiver may allow the use of higher flux limits than a metal or ceramic tube design.

  - When compared to ceramic tube receivers, the direct absorption concept may have a significant advantage in cost because fabrication and engineering design requirements may be less stringent. Significant benefits may also accrue in maintenance due to the relatively simple direct absorption design. Though the DAR concept was conceived as a high temperature approach, such benefits may also accrue at low and medium temperatures.

POTENTIAL ADVANTAGES - cont'd

- There is a potential performance advantage of direct absorption receivers since an intermediate absorber (i.e., tube wall) is not required to transfer the incident radiant energy to the working fluid. This was shown in Phase 1 to be small.

o There may also be system advantages with a high temperature DAR. Inexpensive candidate working fluid salts with high temperature capability can also be used as the storage medium. This may result in reduced energy costs for high capacity factor systems and hence also better use factors for the end-use subsystems (e.g., load heat exchangers).

OBJECTIVE - PHASE 2

- o Assess the performance and cost of a DAR system as a high temperature central receiver concept in IPH applications

  - Analyze component and system performance
  - Estimate component cost
  - Identify fundamental limitations and advantages
  - Identify design and research issues
  - Help to establish recommendations and program rationale in support of DOE

SUMMARY

METHODOLOGY

- This briefing package describes the Phase 2 results of a DAR system study. Phase 1 was a preliminary assessment of electric power applications. In Phase 2 the emphasis has been on IPH applications.

- Phase 2 activities generated performance and cost estimates for DAR systems producing thermal energy only. Power plant ratings of 100, 300 and 500 MW_{th} were considered at receiver outlet temperatures of approximately 900°C and 1200°C.

- The Phase 2 results presented were generated using state-of-the-art field and receiver design models. These were combined with simplifying assumptions or estimates which allowed the consideration of important system response effects and sensitivities. The analysis tools including DELSOL II, RADSOLVER and SHAPEFACTOR computer codes were used to determine a maximum in performance for a given set of system parameters. The component costs were then determined based on size or area requirements.

WHAT WE DID

- Performance and cost estimates were generated for all major system components including heliostat field, receiver, tower, storage, transport and balance of plant. The transport cost analysis was added to this phase of the DAR study.

- The effects of heliostat field size and receiver size on system performance are of particular interest. As field and receiver size increase, performance decreases, as it does with increasing receiver operating temperature. It is the relative magnitude of these performance effects which play an important role in energy costs, particularly for systems with storage.

- Cost data for the receiver was obtained by comparison with a recent nitrate salt, repowering design. Those elements within the nitrate salt receiver-tower subsystem which have potentially large differences relative to a conceptual DAR design were identified and costed separately.

WHAT WE DID - cont'd

- Piping system cost and performance were included in this phase of the study resulting in a more complete analysis.

- System results were generated for the three specified plant sizes (100, 300, and 500 MW_{th}) and two operating temperatures (900°C and 1200°C). For each possible combination of rating and temperature a range of storage capacities were studied. Total plant capital costs and plant efficiency were used to determine a levelized energy cost value based on the methodology and assumptions from the Solar Thermal Technology Five Year Research and Development Plan [1].

FINDINGS

- DAR IPH systems appear to approach or meet the Five Year Plan levelized energy cost goals for a range of plant sizes and capacity factors at both 900^{o}C and 1200^{o}C operating temperatures.

- Meeting heliostat cost goals is critical to achieving system cost goals.

- Adding storage to the DAR IPH systems studied appears (as with the electric power generation cases of Phase 1) to offer little advantage in the cost of delivered energy. This is because the benefits of increased storage (which allows for larger capacity factors) is at least partially offset by the decreased performance of much larger fields.

- The effects of plant size on thermal energy cost appear to be small for the range of parameters studied in this assessment. At low capacity factors, as plant size is increased from 100 to 300 MW_{th}, a slight decrease in levelized cost is observed; however, no further benefits are gained by increasing plant size from 300 to 500 MW_{th}. At higher capacity factors, the effects of plant size are similar but smaller in magnitude, while the 100 MW_{th} case shows a relatively constant levelized energy cost. In all cases, a minimum in levelized energy cost occurs between 300-400 MW_{th}. Levelized cost increases slightly as operating temperature is increased.

FINDINGS - cont'd

- DAR receivers may have the potential for lower costs than a corresponding metal or ceramic tube receivers. However, it should be noted that very large uncertainties in the cost of high temperature components exist because of numerous unknowns including design details, fabrication costs, long-term material response and reliability.

- Piping costs are a very small factor (approximately 3%) of overall plant costs at all plant sizes. Heat losses from piping are less than 1% of the design point plant output. While still a problem from a design standpoint, the cost of piping does not appear to be a concern. This conclusion is significantly different from that reached for distributed, high temperature systems.

RECOMMENDATIONS FOR FY85

- A more detailed receiver study should be undertaken to identify specific design and cost issues. The current receiver program addresses only proof-of-concept experimental issues.

- Extend the field/receiver performance data base beyond the range of parameters utilized in this study so that additional design data can be obtained.

- Specific high temperature applications for DAR systems need to be identified and assessed to take advantage of the extended high temperature capabilities and possible other unique advantages of the concept relative to the tube receiver systems.

- Lower temperature applications of DAR systems should also be studied to determine if operational and cost advantages gained at high temperature may also extend to lower operating temperatures.

METHODOLOGY

Phase 2: Preliminary IPH Assessment

- o Update Cost/Performance Estimates
  - Refine the previously utilized field/receiver design tools and extend the performance data base to a wider range of field sizes, and temperatures
  - Calculate annual performance using DELSOL 2
- o Update Capital Costs and Levelized Energy Costs
  - Use Five Year Plan economic analysis and assumptions
- o Cost/Performance Sensitivity
  - Establish major uncertainties in costs and performance
  - Determine potential effect of uncertainties on energy costs
- o Identify Research Issues
  - Specify the areas or parameters that have major impact on system
  - Integrate recommendations with other DOE work

PHASE 2 RESULTS

COMPONENT PERFORMANCE AND COST CHARACTERIZATIONS

- o Field
- o Receiver
- o Tower
- o Storage
- o Piping
- o Balance of Plant

HELIOSTAT FIELD

- Field performance is based on the methodology initially reported by DeLaquil and Anderson [2] for high temperature performance of central receiver systems. The following parameters were used in this updated study and are assumed for this preliminary assessment.

  - North field, single cavity receiver with canted aperture
  - 100 m^2 heliostats, reflectivity = 0.89
  - Single point aiming strategy, heliostat mirrors focused and canted at slant range
  - Design point parameters
    - 950 W/m^2 NOON
    - Design day - from theoretical clear day, direct normal profile, summer solstice
  - DELSOL2 used in to generate both design point and annual collection system performance

- Heliostat costs
  - $250/$m^2$ representing today's installed cost (in 1984$).
  - $100/$m^2$ representing the Five Year Plan [1] cost goals.

o The method used by of DeLaquil and Anderson has been modified to generate the field and receiver performance specific to the Phase 2 study. The methodology is used to generate field/receiver/tower designs. The general process followed here involves three stages:

1. assuming some initial receiver characteristics, calculate the basic tower/field geometry, and estimate the receiver dimensions.

2. for the tower/field geometry and receiver dimensions determined in the first stage, calculate the receiver losses (both radiative and convective), and

3. with the improved receiver losses calculated in the second stage, go back to DELSOL2 and do the final optimization on the aperture dimensions.

These three stages are noted in the flowchart shown in Fig. 1. The process is iteratively repeated until the desired accuracy is attained. Experience has shown that a single iteration of these stages gives results within an acceptable tolerance (approximately 1/2%). Therefore, the process was terminated after a single pass.

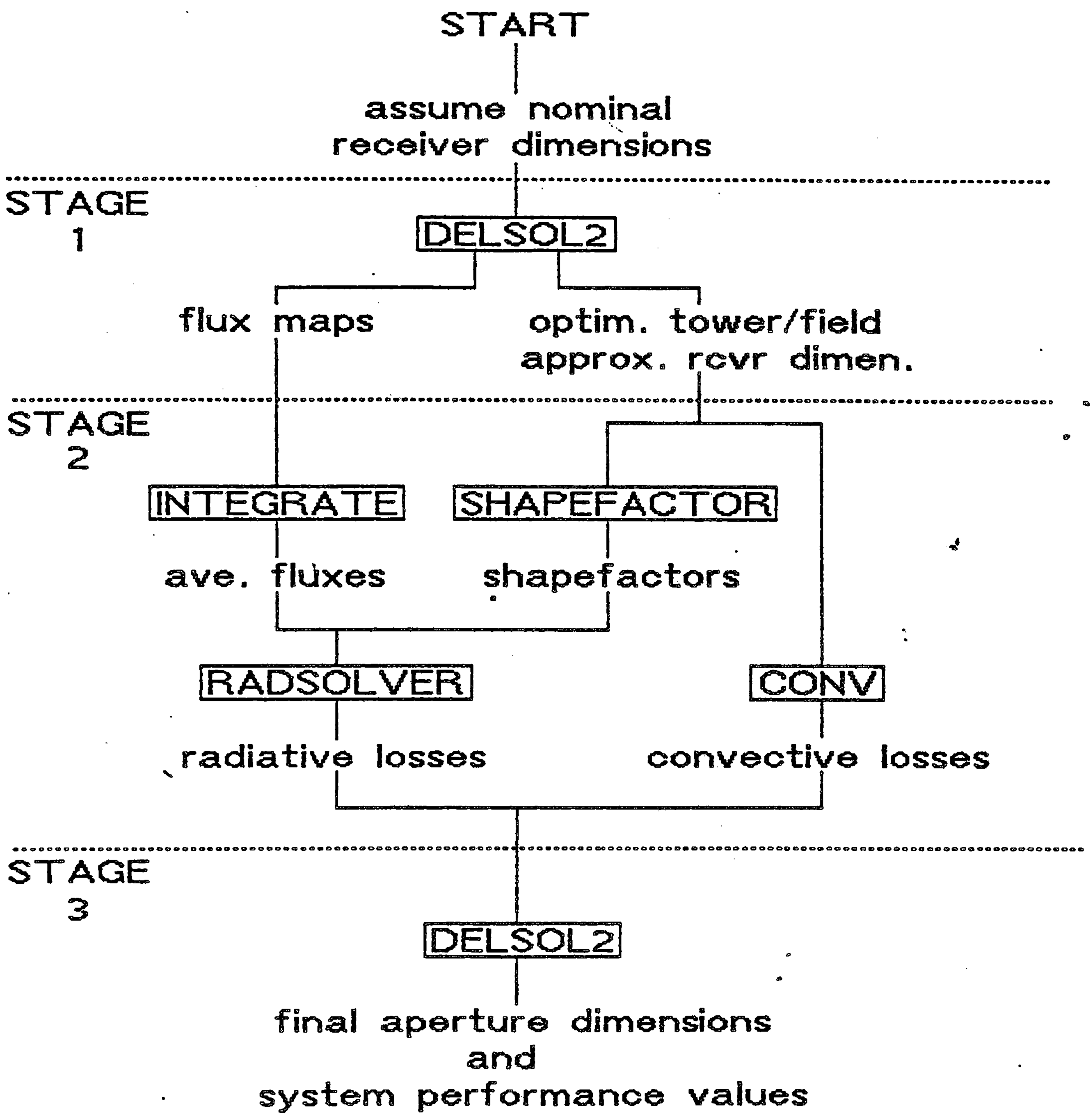


Fig. 1. Flowchart of Design Procedure

- Figures 2 and 3 show both the design point and annual field efficiencies, respectively, for various field sizes using DELSOL2 [3] with parameters as previously described. These efficiency values exclude spillage; however, spillage effects are considered in the receiver and system efficiency discussed later. Note that field performance drops off very slightly with increasing size due to increased shading and blocking and to greater atmospheric attenuation as average distance to the receiver increases. Not shown is the effect of field size on spillage which also increases rapidly with larger fields and is discussed in later sections on receiver performance. The results shown in Figs. 2 and 3 are from a series of runs for two different temperatures, 900°C and 1200°C. Slightly different performance, at the same field size, were computed for the two temperatures, resulting in the somewhat jagged curves. This is due primarily to the finite step size utilized in approaching an "optimum" in performance.

- In Phase 1 we generated field/receiver results by interpolating between the existing data base for 100,000 m^2 and 1,000,000 m^2 heliostat fields. In this study, we have generated a refined data base that includes three field sizes between the original values used in the Phase 1 study [4].

- These field performance values will be combined in later sections with receiver efficiency (also a function of size) to determine collection system performance for various size plants.

HELIOSTAT FIELD - cont'd

- Annual field performance is approximately 10-15% less than design point performance due to the less favorable incident angles which exist at times other than solar noon.

- Collector costs will be parameterized in terms of the cost per unit area of installed reflector area. The range of assumed costs ($100-$250/m^2) includes the Five Year Plan cost goal and extends to roughly today's cost for heliostats.

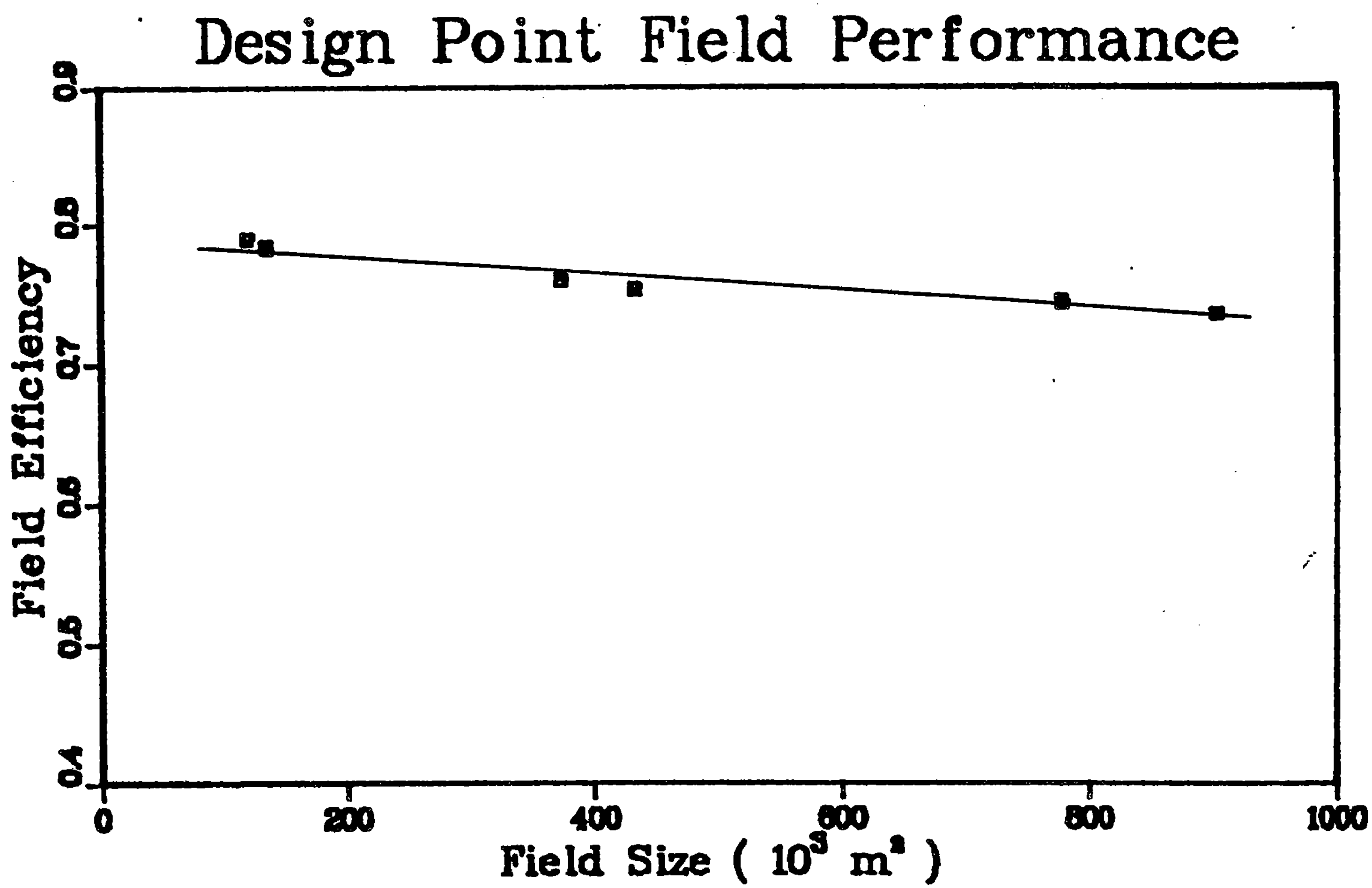
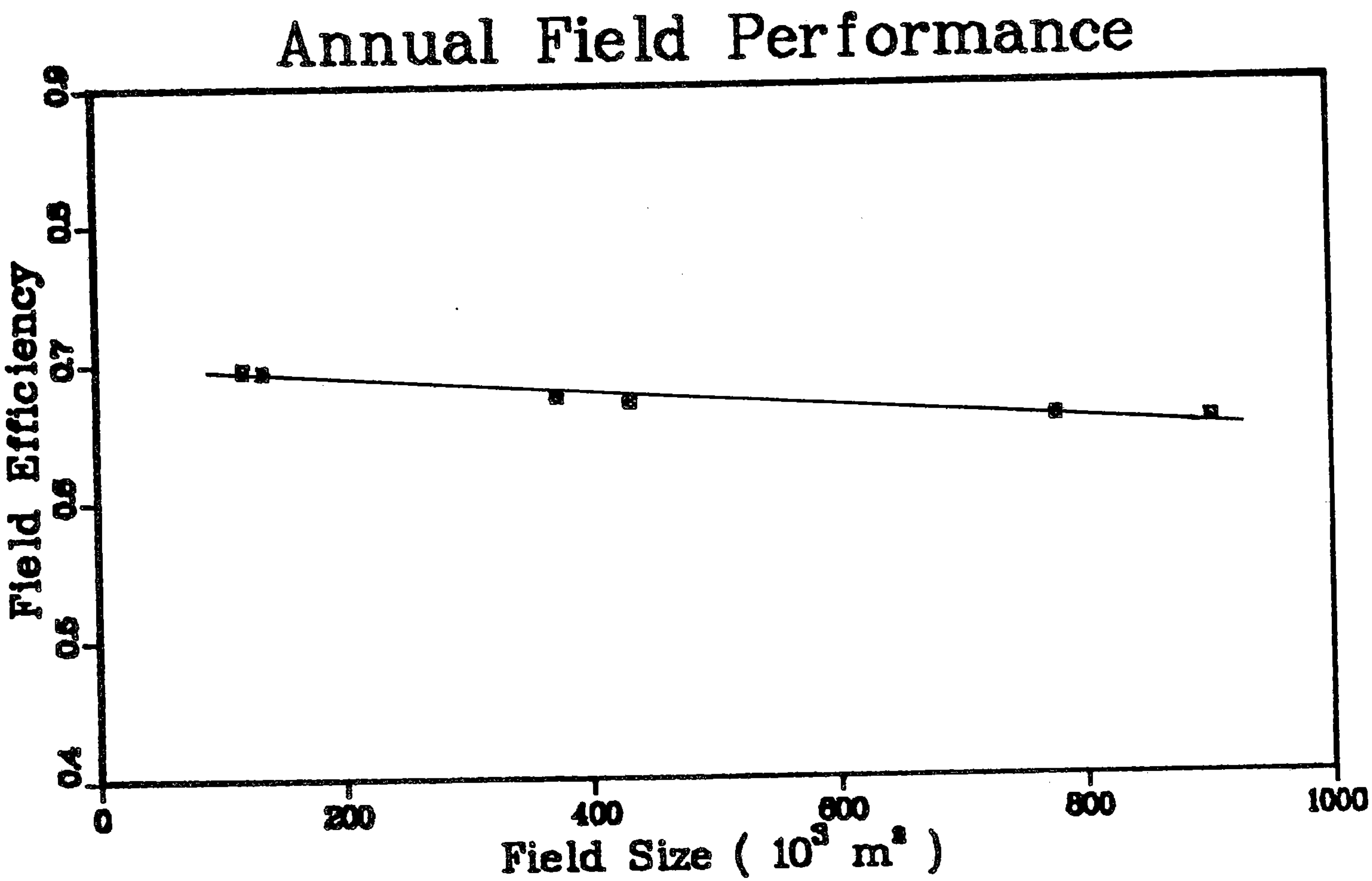

Design Point Field Performance
Field Efficiency
0.9
0.8
0.7
0.6
0.5
0.4
0
200
400
600
800
1000
Field Size (10^3 m^2)

FIGURE 2.



Annual Field Performance
Field Efficiency
0.9
0.8
0.7
0.6
0.5
0.4
0
200
400
600
800
1000
Field Size (10^3 m^2)

FIGURE 3.

- The cavity design with a 30° from vertical inclined aperture shown in Fig. 4 is the basis for the receiver performance calculations.

  - Radiative losses were calculated by RADSOLVER [5] and SHAPEFACTOR [6] using flux maps generated by DELSOL2, with an effective surface reflectivity of 0.1. The optical characteristics of both the direct absorption and tube wall cavities are assumed to be the same for this study. The detailed optical performance of the direct absorption surface (salt film) is currently under study at SERI.

  - Convective losses are calculated according to Siebers and Kraabel [7]. These losses are higher than predicted by other correlations as shown by Anderson [8]. This results in lower relative performance, especially with larger receivers.

  - Conduction losses were ignored as they are assumed to be very small compared with the radiative and convective losses.

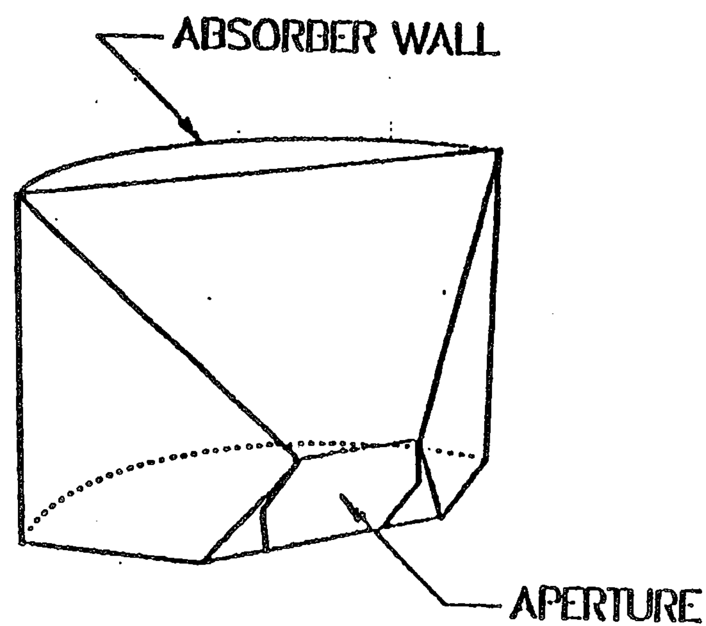


Fig. 4 - Cavity Receiver Isometric View [1]

- Spillage varies with aperture area. Receiver performance is optimized at a given flux level and average receiver temperature by a trade-off between receiver losses and spillage losses.

- Receiver design point performance results corresponding to a range of temperatures is shown in Fig. 5. Receiver performance is based on average receiver temperature. A 600^{o}C average temperature corresponds approximately to a 900^{o}C outlet temperature and a 900^{o}C average temperature corresponds approximately to a 1200^{o}C outlet temperature.

- The sensitivity of receiver performance to both solar flux levels and absorber temperature differential were studied and were found to be both small and offsetting. Increasing flux levels (from a peak flux of 0.6 MW/m^2 to 1.0 MW/m^2) improves performance slightly (approximately 1%). Absorber flux is increased by positioning the absorber closer to the aperture, resulting in smaller absorber area for essentially the same total flux. An isothermal receiver compared to an absorber with an inlet-to-outlet temperature difference of 600^{o}C with the same average temperature, was found to have a slightly increased performance (approximately 1%). Therefore, the overall effect of higher fluxes and non-isothermal receivers is negligible for the general cavity configuration considered.

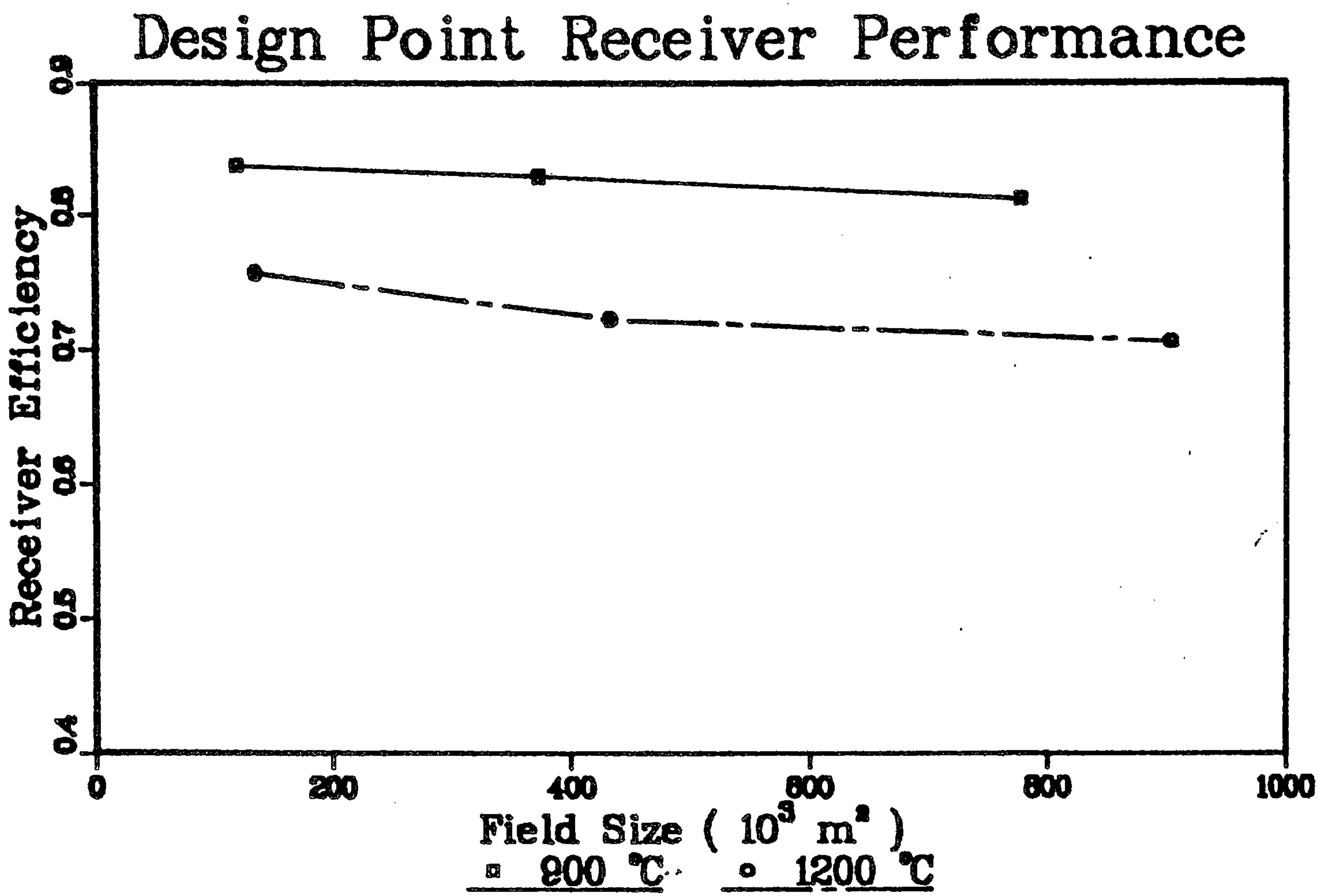
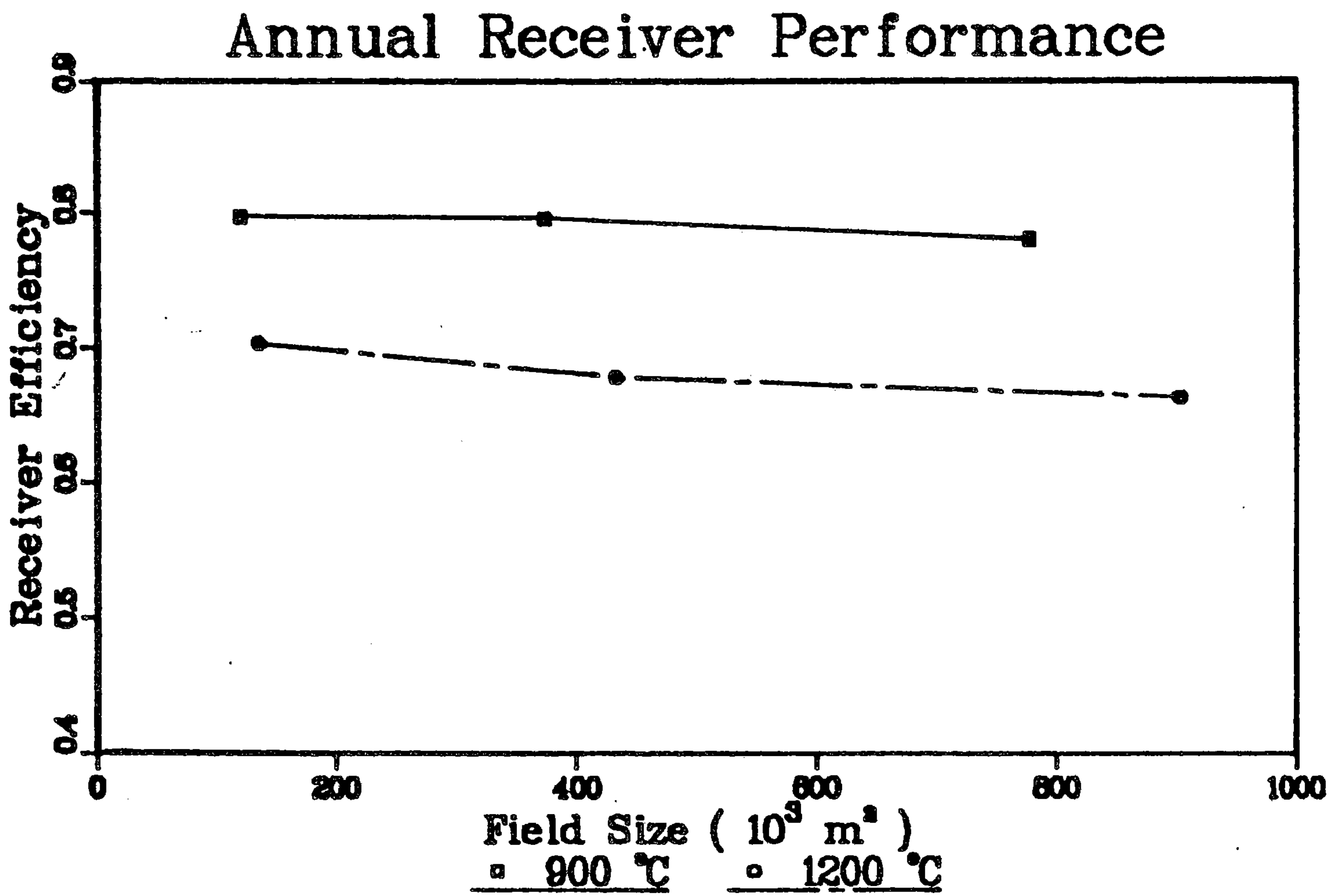

Design Point Receiver Performance
Receiver Efficiency
0.4
0.5
0.6
0.7
0.8
0.9
0
200
400
600
800
1000
Field Size (10^3 m^2)
800 °C
1200 °C

FIGURE 5.

RECEIVER - ANNUAL PERFORMANCE

- The annual receiver performance is based on a straightforward, simplified procedure utilized by DELSOL 2. Given the design point incident power, a receiver heat loss rate can be calculated. In this study, that rate is assumed to be constant for all operating hours. Then for a given location the annual receiver efficiency can be calculated based on the available solar radiation. The location chosen for this study is Daggett, California, with the following characteristics.
  - Annual solar radiation: 2723 kWh/m^2
  - Average daytime hourly solar radiation: 800 W/m^2
  - Cloudiness: 0.83
- Daggett, of course, is an excellent solar location and will yield one of the highest annual thermal outputs per unit area of heliostat. Less favorable locations with lower annual solar radiation values will have lower annual receiver performance since, at a given operating temperature, the receiver loss rate is constant resulting in a lower net amount of energy transferred to the working fluid. The annual receiver performance, including spillage losses, is shown in Fig. 6 for Daggett.

- The field and receiver performance are combined to give the collection system efficiency at design point in Fig. 7. Annual system efficiency is shown in Fig. 8. The large range of field sizes allows for a number of combinations of plant rating and capacity factor.



Annual Receiver Performance
Receiver Efficiency
0.4
0.5
0.6
0.7
0.8
0.9
0
200
400
600
800
1000
Field Size (10^3 m^2)
900 °C
1200 °C

FIGURE 6.

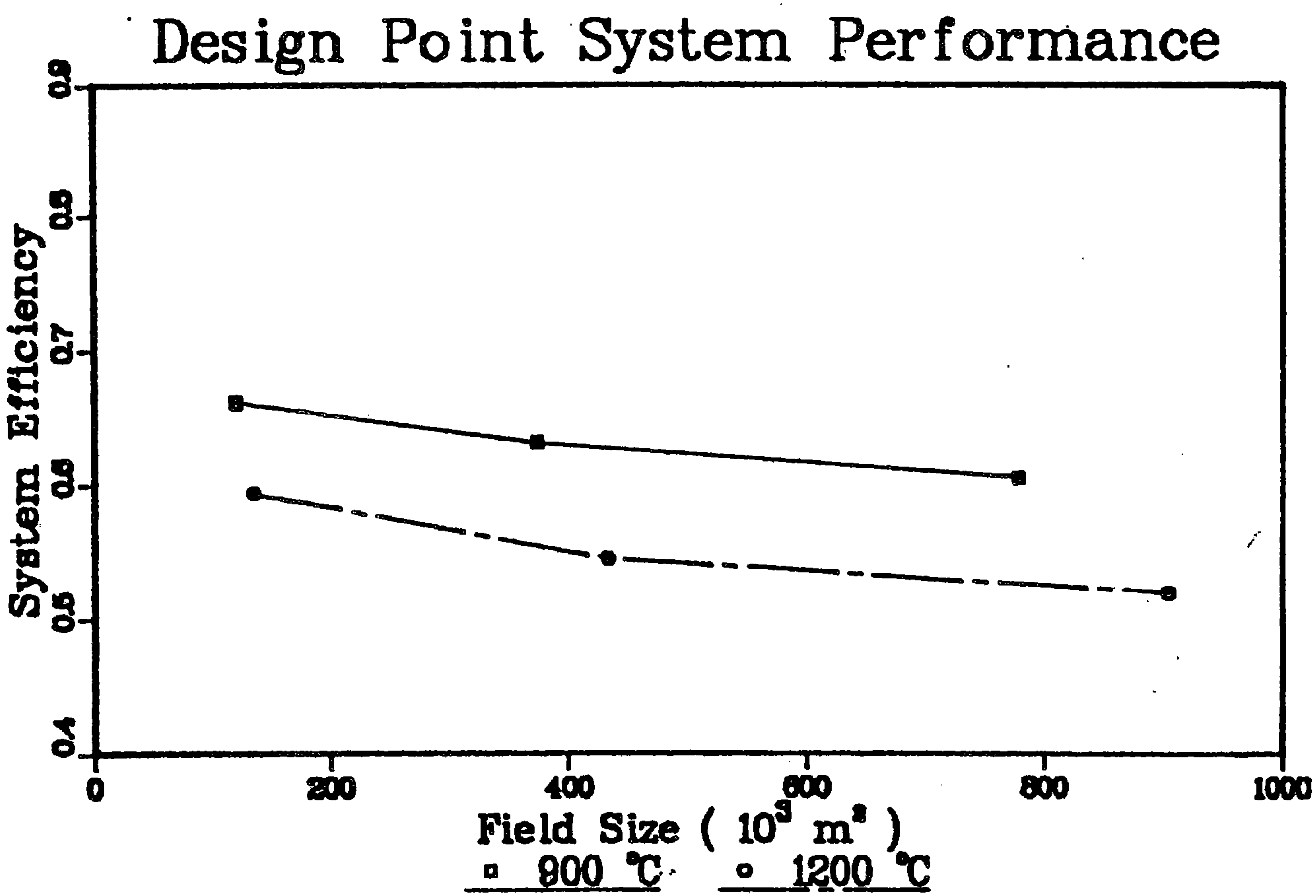

Design Point System Performance
System Efficiency
0.4
0.5
0.6
0.7
0.8
0.9
0
200
400
600
800
1000
Field Size (10³ m²)
900 °C
1200 °C

FIGURE 7.

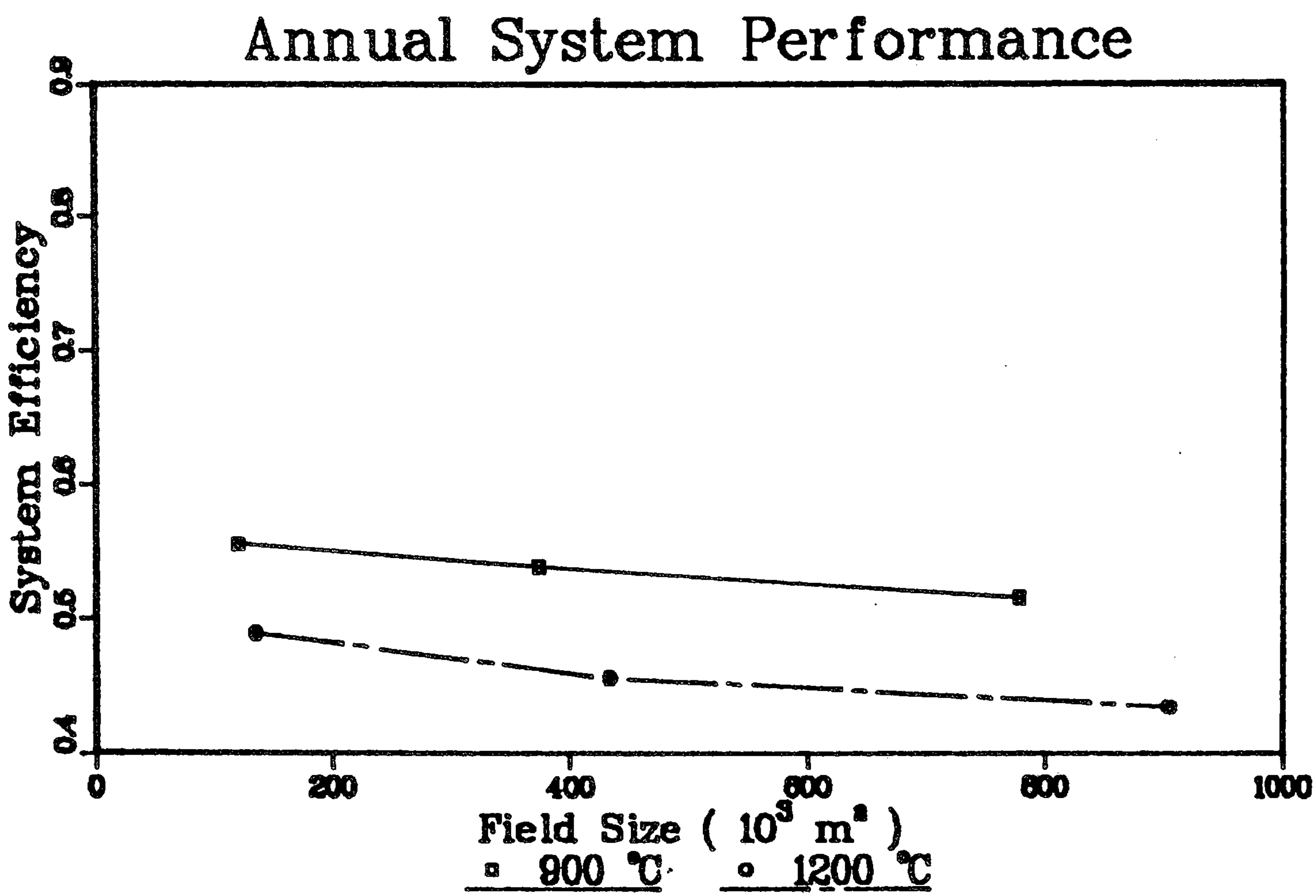

Annual System Performance
System Efficiency
0.4
0.5
0.6
0.7
0.8
0.9
0
200
400
600
800
1000
Field Size (10³ m²)
900 °C
1200 °C

FIGURE 8.

- To determine the approximate cost of a direct absorption receiver, a comparison with the Saguaro cavity design and cost data [9] was utilized. The major design changes necessary to adapt the 600°C Saguaro design to a 900°C DAR were identified and the effect of these changes on the cost elements was determined. The comparison was made with both receivers sized to produce 190 MW of thermal output. It was assumed that the cost differences were strictly a function of the major design differences necessary to replace the tube receiver with a DAR. Design differences result from the different configurations of the temperatures and the material requirements of the respective receivers. A summary of the design details is shown below:

	Direct Absorption	Saguaro
Average Fluid Temperature (°C)	600	422
Average Flux (MW/m^2)	0.4	0.25
Aperture Area (m^2)	144	335
Absorber Area (m^2)	475	761
Cavity Height (m)	16.7	19.8
Flow Rate (kg/s)	229	429
Inlet Temperature (°C)	450	277
Outlet Temperature (°C)	900	566*
Absorber Arc (°)	140	210
Absorber Radius (m)	12	10.7
Arc Length (m)	29.3	39.2

*For the purposes of our comparison study we considered the Saguaro design to be nominally 600°C.

RECEIVER COST - cont'd

- Only the impact of major design differences were considered, since the receiver at Saguaro [9] is only 20% of the total project cost and hence small cost differences should have insignificant effects on the overall plant capital cost. The following table shows the results of the cost analysis for a direct absorption receiver when compared with the Saguaro design. These results are slightly different from Phase 1 due to a small refinement in costs.

Cost Element	Effect on Overall Receiver Cost	Remarks
Absorber Cost/Unit Absorber Area	4%	+23% cost/m^2, Absorber is 19% of total receiver cost
Absorber Area	-19%	DAR has 37% less absorber area due to higher average flux
Absorber Structural Support	-0%	18% increased DA absorber weight is offset by reduced absorber area
Net Cost Difference	-15%	

- Based on the above assumptions, the net difference in receiver cost to replace a Saguaro cavity receiver with a direct absorption receiver, will be about -15%, or only approximately 3% of the total system cost at Saguaro.

RECEIVER COST - cont'd

- o Though the above cost results are only approximate, the actual cost advantage of the direct absorption receiver concept, relative to a tube receiver (if both are assumed to be operating at the same application temperature) may be greater than is implied above. This is because as the design temperature is increased, more severe design requirements, along with the materials limitations, can be anticipated to result in increased receiver cost for the tube receiver.

TOWER

- Only the cost element of the tower structure and foundation is considered here. Cost of the tower riser and downcomer piping is considered in the piping section.

- Tower height as a function of field size was taken from updated field/receiver methodology for the field parameters listed in the heliostat field description.

Field Size (m^2)	Tower Height (m)	Tower Cost
\$ 1.3×10^5	160	\$ 2.8×10^6
\$ 4.0×10^5	250	\$ 5.5×10^6
\$ 8.4×10^5	380	\$ 11.4×10^6

- The tower cost is based on concrete tower construction. A slightly non-linear functional relationship between height and cost as described in Battleson [10] was applied in this study, with adjustment for the recent Saguaro tower cost data.

PIPING

- Piping is a crucial and potentially very difficult design issue since there does not appear to be an established experience base for the design of piping systems in the scale required nor for the required operating temperatures and environments (salts, cycling, etc.).

- Specific technology issues for metal piping systems and, in particular, Inconel 600, which is a leading candidate because of its good compatibility with carbonate salts, are numerous. For instance, these issues include:

  - severe temperature cycling, can lead to plastic ratcheting and fatigue failures which will be particularly bothersome at joints and other discontinuities

  - very high operating temperature where the elastic yield can be reduced below 10% of the room temperature value. This makes the design for large pressure heads associated with the tower riser particularly difficult

  - design for large thermal expansion excursions including that for joints, connections, vertical and horizontal insulated supports, and insulation compatibility.

- For costing purposes and in the absence of any specific design data, we selected an Inconel 600 concept which has never been engineered, but has the potential to resolve several known technology issues and which we believe adequate for a first order cost approximation.

o The concept design for the vertical section of the downcomer section, used in this study for cost estimating purposes, is shown in Fig. 10. This design allows free fall of the hot fluid in a series of drops (analogous to a river flowing between a series of falls and pools). This approach eliminates the high head problem associated with tower height and provides a potential expansion problem solution as well. The horizontal section of the downcomer is assumed to be totally filled as in the riser section shown in Fig. 11.

o Piping costs, generated by a SERI cost engineering consultant, include pipe material and fabrication, heat trace, insulation and jacketing, installation and a 25% allowance for fittings, valves, and pumps. The table below shows the per meter costs associated with various thermal plant ratings.

	Downcomer (Inconel 600)				Riser (SS 304)	
	Vertical Run		Horizontal Run			
Plant Size (MW_{th})	Pipe Size (nominal)	Cost ($/m)	Pipe Size (nominal)	Cost ($/m)	Pipe Size (nominal)	Cost ($/m)
75	5"	795	5"	795	5"	258
225	6"	902	12"	1682	8"	328
450	8"	1260	16"	2544	12"	461

o The total piping cost is calculated for a given thermal plant size by conservatively assuming the horizontal pipe runs to the farthest heliostat and, of course, vertically up the tower. An additional factor of 25% is added to the total cost to account for valves, pumps and fittings.

DOWN COMER PIPE

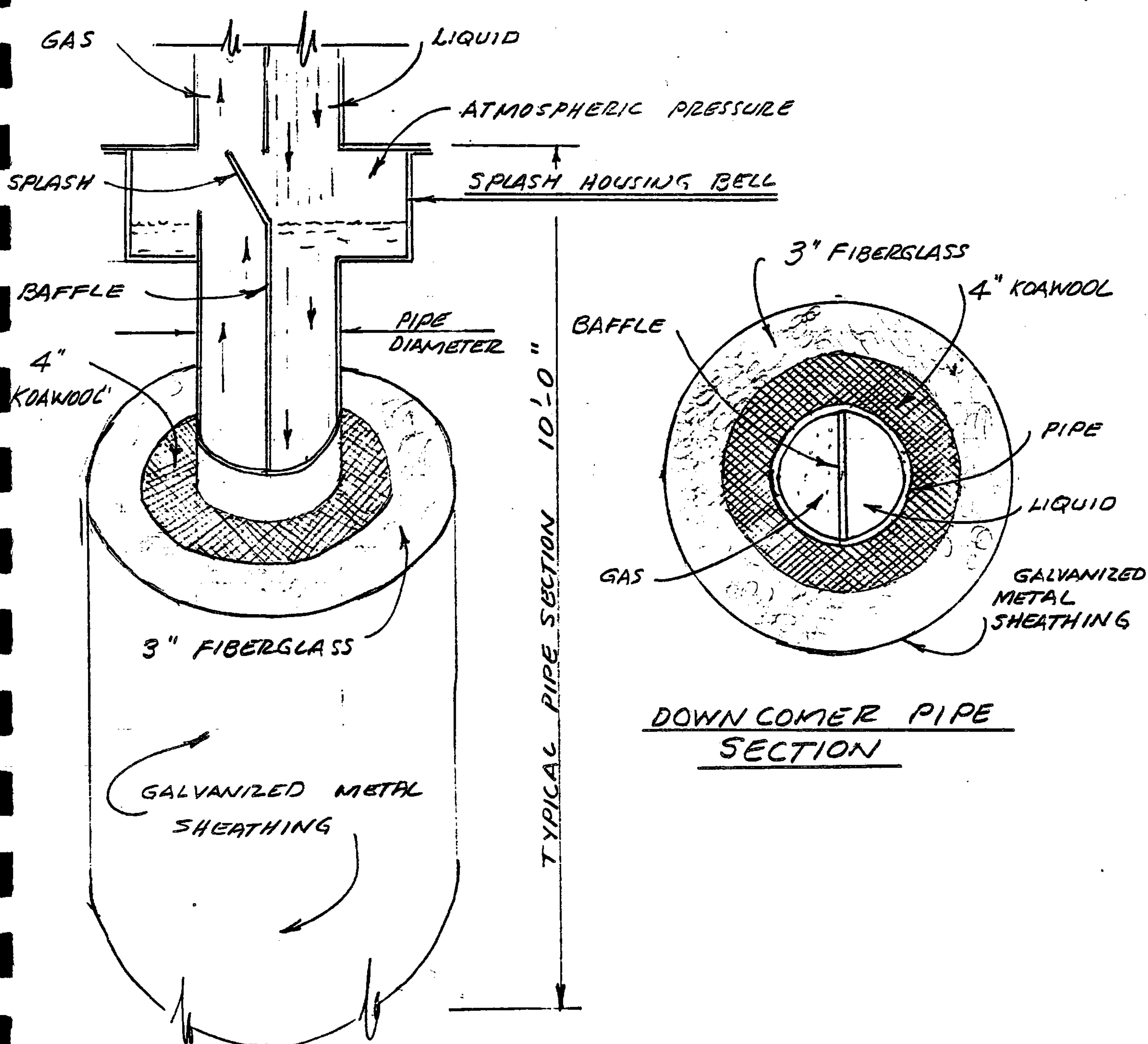


FIGURE 10.

RISER PIPE

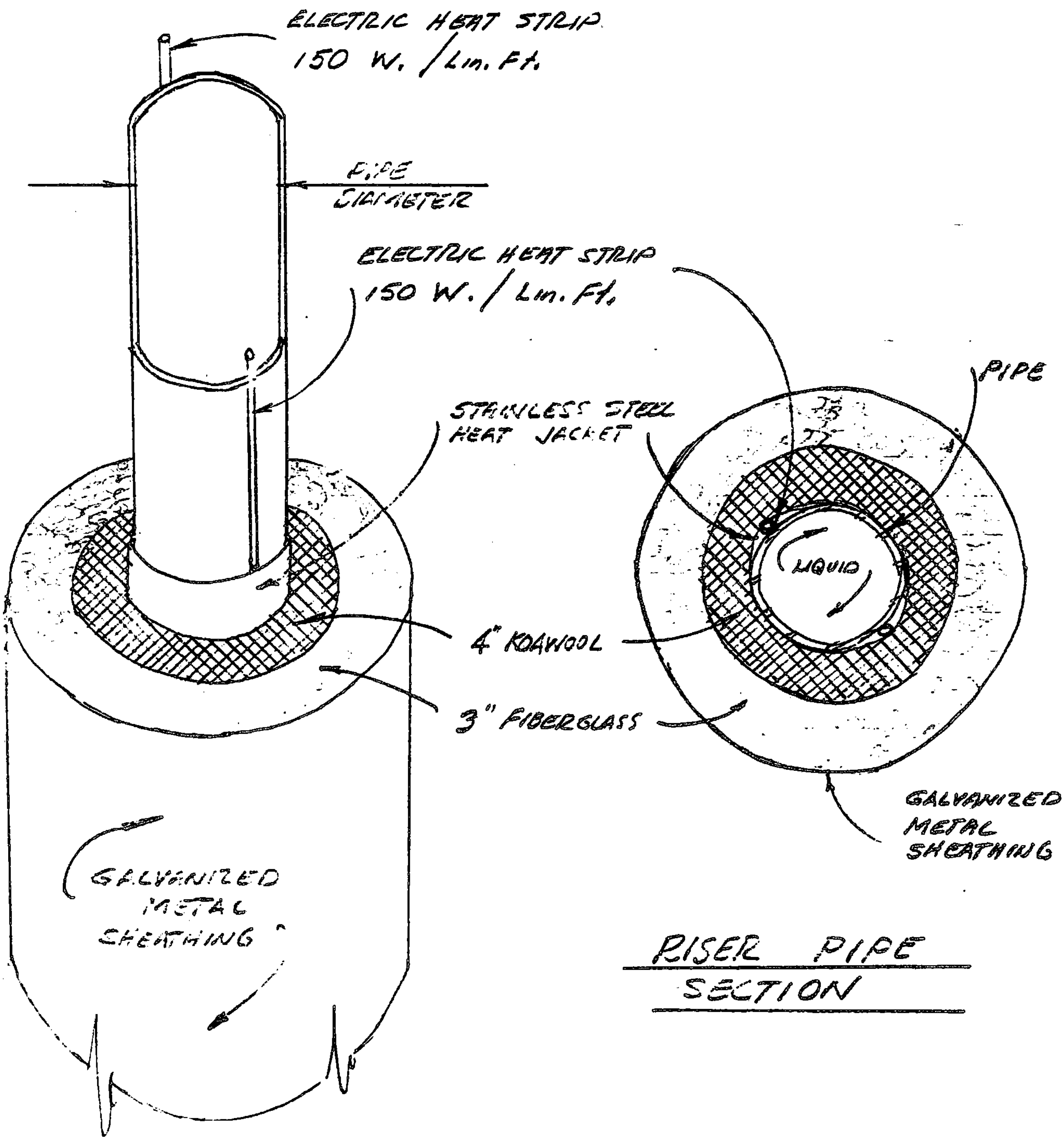


FIGURE 11.

- These piping costs (not including the 25% factor) are approximately 30% higher than those generated by SNLA in their distributed system cost estimates for the same size Inconel 600 pipe in a 1500°F carbonate salt system. A major difference is the low wall thickness they assumed (Schedule 10 pipe). At their slightly lower temperature (815°C vs 900°C), the material strength is considerably greater and since their system operates at low pressure, this design difference is reasonable. For the same size plant (40 MW) the distributed system has approximately 50 times more pipe than a central receiver plant and therefore, penalties for both performance and cost should be small for central receivers.

- Heat losses at design point have been calculated for the size and length of pipe assumed for each plant size in the previous table. These calculations show that losses are slightly less than 1% of design point power. Based on this result, the impact of piping heat loss on overall performance is negligible and is not considered in the system results.

- It is likely that a completely new design for 1200°C outlet DAR systems will be necessary. The effect of this increased temperature on piping design and cost was not accounted for in this study, however.

STORAGE

- For a direct absorption system using a carbonate salt mixture as both the working fluid and the storage media, two storage designs have been proposed by Copeland, West and Kreith [11]. These are cylindrical and conical, thermocline, dual media tank design. Preliminary costing indicated that these two are the most promising of several concepts studied. Since the costs and designs are preliminary, a range of costs were developed for an 1800 MWh thermal capacity, with temperature extremes at 425°C and 900°C as considered in [11]. Cost estimates range from $\$20X10^6$ to $\$45X10^6$.

- To calculate costs for other storage capacities, the cost elements for the two designs are scaled according to the area (walls, top, bottom) and volume (media) required to achieve the desired capacity. This results in a slightly non-linear cost vs. capacity curve. This non-linearity is washed out, however, by the range of costs associated with the cost estimates. For the most pessimistic costs, the following table shows the cost for various storage capacities corresponding to the 425°C to 900°C temperature range as in [11].

Capacity (MWh)	Cylindrical Tank	Conical Tank
900	$\$24X10^6$	$\$17X10^6$
1800	$\$44X10^6$	$\$33X10^6$
3000	$\$69X10^6$	$\$53X10^6$

- The cost of storage per unit storage capacity for the 1200°C maximum temperature case was assumed to be the same as for 900°C storage. Although there will probably be larger costs associated with 1200°C storage, the uncertainty in current cost estimates is probably large enough to allow ignoring the effects of this higher temperature.

- An allowable heat loss rate of 2% per day was used to size the required insulation thickness in the previously mentioned work. Assuming heat is lost 24 hours/day at the specific storage temperature, this results in an instantaneous rate of loss of 1.5 MW. This loss and its effect on system performance as well as any effect of temperature on storage cost were ignored in this phase of the study.

BALANCE OF PLANT

- The costs associated with the remainder of the plant include
  - Land and Site Preparation
  - Site Facilities
  - Master Control

- Both land and site preparation and site facilities costs are assumed to vary with heliostat field size. The master control cost is assumed to be constant for all plant sizes. Land cost, including site preparation, of $7500/acre is assumed based on data from Battleson [12]. To relate land cost with heliostat field size, the packing density must be known. The value used in this study is 0.18 based on average DELSOL2 values and data from the Saguaro design. Site facilities add another $2700/acre and include buildings, security fence, storage and maintenance equipment. Master control costs is fixed at $\$2.0 \times 10^6$.

PHASE 2 RESULTS

SYSTEM PERFORMANCE AND COST

- System Studies
- Cost Comparisons

SYSTEM STUDIES

- Plant sizes of 100, 300, and 500 MW_{th} and four capacity factors (fraction of an average 24 hour day the plant provides full power) at each plant size were specified to determine the effects, if any, of power plant rating and storage. For each plant size, receiver outlet temperatures of 900°C and 1200°C were studied. For the cases without storage, a heliostat field size was determined that would provide the plant rating at design point. To achieve larger capacity factors (at the same plant power rating) the 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, above plant rating, available to charge storage on the design day. The calculation of excess energy was performed for each hour of the design day and the total excess energy results in the system storage capacity.

- The levelized energy cost (LEC) methodology utilized is taken from Appendix A of the National Solar Thermal Technology Program Five Year Research and Development Plan [1]. We also used the same economic assumptions for IPH applications so that comparison with program goals can be accomplished in a straightforward manner. The basic equation for LEC is:

$$\text{LEC} = \frac{(\text{Capital Cost} * \text{PVC} * \text{FCR}) + (\text{First Yr O\&M}) * \text{PVO} * \text{CRF}}{\text{Annual Energy Output}}$$

where PVC = Present Value Factor for Capital = 1.1033

FCR = Annualized Fixed Charge Rate = 0.1334

PVO = Present Value Factor for O&M = 8.5136

CRF = Capital Recovery Factor = 0.1175

These values are based on fixed or "real dollar" calculation, where inflation is deliberately not taken into account. This results in a nominal discount rate of 10%. Since O&M for a DAR system has not been evaluated, we used the program goals of $\$5/m^2$-yr for first year O&M costs.

- The results of the system studies are shown in Tables 2-7. Each table shows the four capacity factors for a specific plant rating and operating temperature. Listed are the size and performance parameters, component costs, total system costs and levelized energy cost. Plots of levelized energy cost as a function of capacity factor are shown for the 100, 300 and 500 MW_{th} plants in Figs. 12-14. Each plot shows results for both 900°C and 1200°C systems using $\$100/m^2$ and $\$250/m^2$ heliostats.

TABLE 2. SYSTEM RESULTS

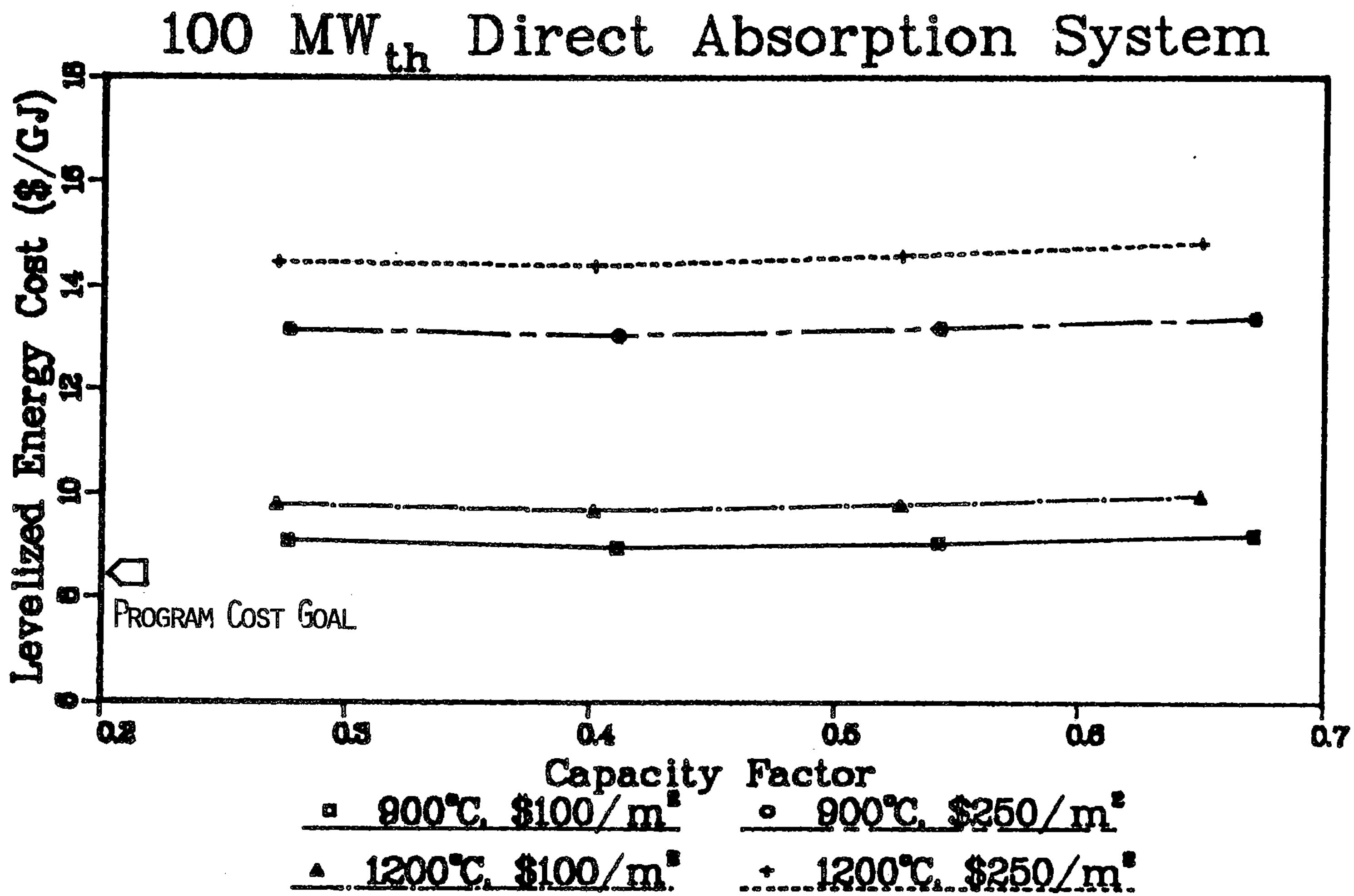
100 MW_{th} 900°C

SIZE AND PERFORMANCE				
Peak Thermal Power (MW)	100	148	196	242
Capacity Factor	0.276	0.411	0.543	0.672
Storage Capacity (MWh)	0	228	567	939
Heliostat Area (m^2)	160804	241206	321608	402010
Tower Height (m)	176	202	229	256
Peak Efficiency	0.655	0.648	0.641	0.625
Annual Efficiency	0.553	0.548	0.543	0.538
COSTS (10^6\$)				
Heliostat @\$100, \$250/m^2	16, 40	24, 60	32, 80	40, 101
Receiver	25	31	37	43
Storage	0	7	15	23
Transport	2	2	3	4
BOP	5	6	7	9
TOTAL SYSTEM COSTS (10^6\$) @\$100, \$250/m^2	48, 73	71, 107	94, 142	119, 179
LEVELIZED BBEC COST (\$/GJ) @\$100, \$250/m^2	9.1 13.2	8.9 13.1	9.0 13.2	9.2 13.4

TABLE 3. SYSTEM RESULTS

100 MW_{th} 1200°C

SIZE AND PERFORMANCE				
Peak Thermal Power (MW)	100	148	194	239
Capacity Factor	0.271	0.401	0.527	0.650
Storage Capacity (MWh)	0	224	553	913
Heliostat Area (m^2)	180848	271271	361695	452119
Tower Height (m)	175	201	226	252
Absorber Area (m^2)	250	370	485	598
Peak Efficiency	0.582	0.574	0.565	0.557
Annual Efficiency	0.481	0.475	0.469	0.463
COSTS (10^6\$)				
Heliostat @\$100, \$250/m^2	18, 45	27, 68	36, 90	45, 113
Receiver	25	31	36	42
Storage	0	6	14	23
Transport	2	2	3	4
BOP	5	7	8	9
TOTAL SYSTEM COSTS (10^6\$) @\$100, \$250/m^2	51, 78	74, 114	98, 152	123, 191
LEVELIZED BBEC COST (\$/GJ) @\$100, \$250/m^2	9.8 14.5	9.7 14.4	9.8 14.6	9.9 14.8



100 MWth Direct Absorption System
Levelized Energy Cost ($/GJ)
Program Cost Goal
Capacity Factor
0.2
0.3
0.4
0.5
0.6
0.7
900°C, $100/m²
900°C, $250/m²
1200°C, $100/m²
1200°C, $250/m²

FIGURE 12.

TABLE 4. SYSTEM RESULTS

300 MW_{th} 900°C

SIZE AND PERFORMANCE				
Peak Thermal Power (MW)	300	435	560	674
Capacity Factor	0.278	0.405	0.523	0.634
Storage Capacity (MWh)	0	617	1478	2396
Heliostat Area (m^2)	504474	756711	1008949	1261186
Tower Height (m)	290	373	457	541
Absorber Area (m^2)	750	1087	1399	1686
Peak Efficiency	0.626	0.605	0.584	0.563
Annual Efficiency	0.532	0.516	0.501	0.485
COSTS (10^6\$)				
Heliostat @\$100, \$250/m^2	50, 126	76, 189	101, 252	126, 315
Receiver	50	68	84	100
Storage	0	16	35	55
Transport	5	7	9	11
BOP	10	14	17	21
TOTAL SYSTEM COSTS (10^6\$) @\$100, \$250/m^2	116, 191	180, 294	247, 398	313, 502
LEVELIZED BBEC COST (\$/GJ) @\$100, \$250/m^2	7.4 11.7	7.9 12.3	8.4 12.9	8.7 13.4

TABLE 5. SYSTEM RESULTS

300 MW_{th} 1200°C

SIZE AND PERFORMANCE				
Peak Thermal Power (MW)	300	428	540	638
Capacity Factor	0.273	0.391	0.497	0.591
Storage Capacity (MWh)	0	576	1341	2102
Heliostat Area (m^2)	579776	869664	1159552	1449440
Tower Height (m)	298	371	454	537
Absorber Area (m^2)	750	1069	1350	1595
Peak Efficiency	0.545	0.518	0.490	0.463
Annual Efficiency	0.454	0.434	0.414	0.394
COSTS (10^6\$)				
Heliostat @\$100, \$250/m^2	58, 145	87, 217	116, 290	145, 362
Receiver	50	67	82	96
Storage	0	15	32	48
Transport	5	7	9	11
BOP	11	15	19	23
TOTAL SYSTEM COSTS (10^6\$) @\$100, \$250/m^2	124, 211	191, 322	258, 432	323, 541
LEVELIZED BBEC COST (\$/GJ) @\$100, \$250/m^2	8.2 13.2	8.8 14.0	9.3 14.8	9.8 15.5

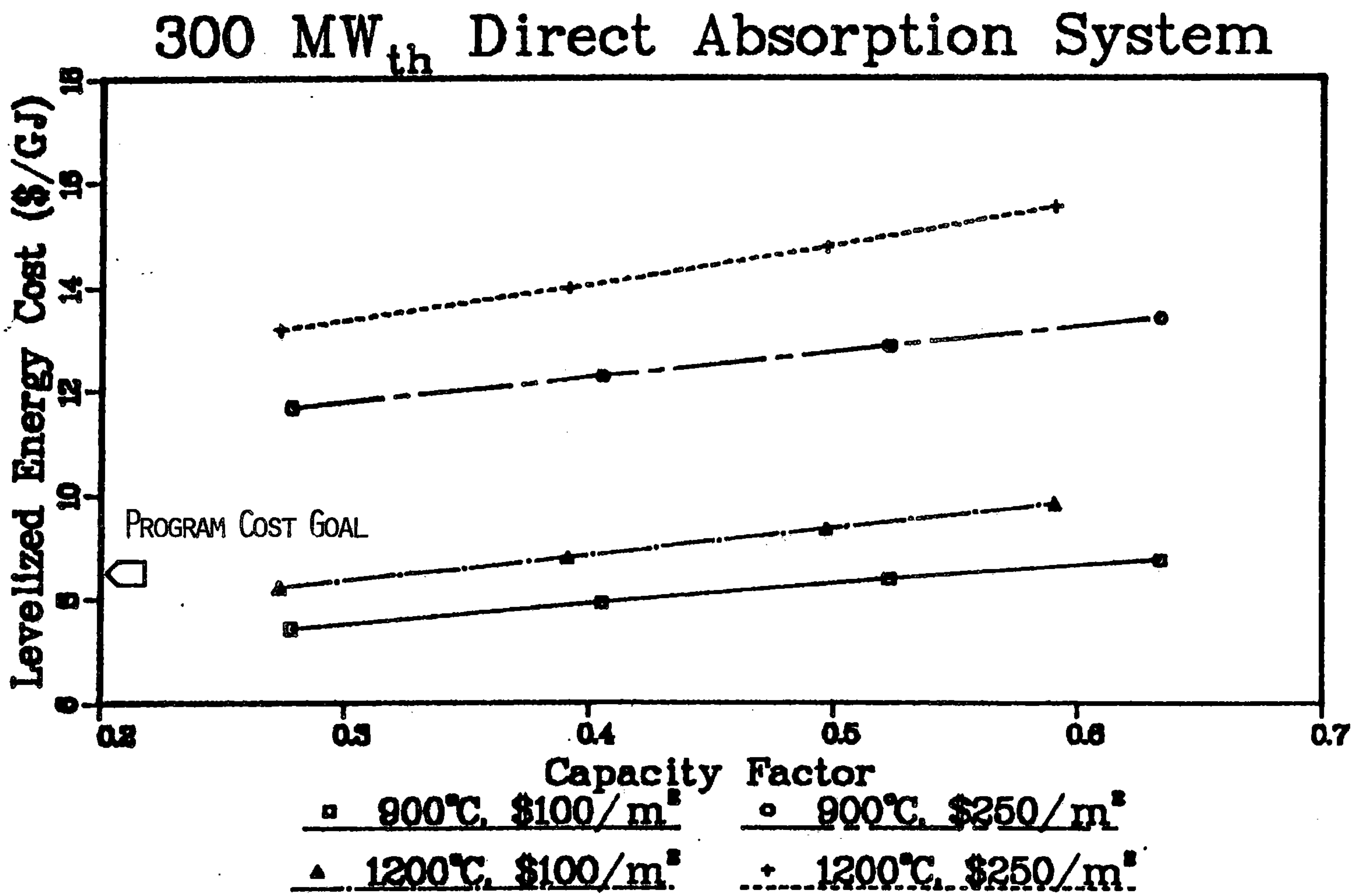

300 MW th Direct Absorption System
Levelized Energy Cost ($/GJ)
6
8
10
12
14
16
18
0.2
0.3
0.4
0.5
0.6
0.7
Capacity Factor
PROGRAM COST GOAL
900°C, $100/m²
900°C, $250/m²
1200°C, $100/m²
1200°C, $250/m²

FIGURE 13.

C

TABLE 6. SYSTEM RESULTS

500 MW_{th} 900°C

SIZE AND PERFORMANCE				
Peak Thermal Power (MW)	500	703	876	1017
Capacity Factor	0.280	0.397	0.499	0.586
Storage Capacity (MWh)	0	910	2066	3138
Heliostat Area (m^2)	885727	1328591	1771454	2214318
Tower Height (m)	416	563	710	857
Absorber Area (m^2)	1250	1759	2190	2543
Peak Efficiency	0.594	0.557	0.520	0.484
Annual Efficiency	0.508	0.481	0.453	0.426
COSTS (10^6\$)				
Heliostat @\$100, \$250/m^2	89, 221	133, 332	178, 443	221, 554
Receiver	76	104	128	150
Storage	0	22	48	70
Transport	8	12	15	17
BOP	16	22	28	34
TOTAL SYSTEM COSTS (10^6\$) @\$100, \$250/m^2	189, 322	293, 492	396, 661	492, 825
LEVELIZED BBEC COST (\$/GJ) @\$100, \$250/m^2	7.2 11.7	7.9 12.6	8.5 13.5	9.0 14.3

TABLE 7. SYSTEM RESULTS

500 MW_{th} 1200°C

SIZE AND PERFORMANCE				
Peak Thermal Power (MW)	500	676	803	881
Capacity Factor	0.275	0.377	0.455	0.510
Storage Capacity (MWh)	0	758	1563	2101
Heliostat Area (m^2)	1051666	1577500	2103333	2629166
Tower Height (m)	423	573	723	873
Absorber Area (m^2)	1250	1690	2008	2202
Annual Efficiency	0.421	0.385	0.348	0.312
COSTS (10^6\$)				
Heliostat @\$100, \$250/m^2	105, 263	158, 394	210, 526	263, 657
Receiver	77	102	121	136
Storage	0	19	37	48
Transport	8	11	13	15
BOP	18	25	33	40
TOTAL SYSTEM COSTS (10^6\$) @\$100, \$250/m^2	208, 366	315, 552	415, 730	502, 897
LEVELIZED BBEC COST (\$/GJ) @\$100, \$250/m^2	8.3 13.6	9.1 15.0	10.0 16.4	10.8 18.1

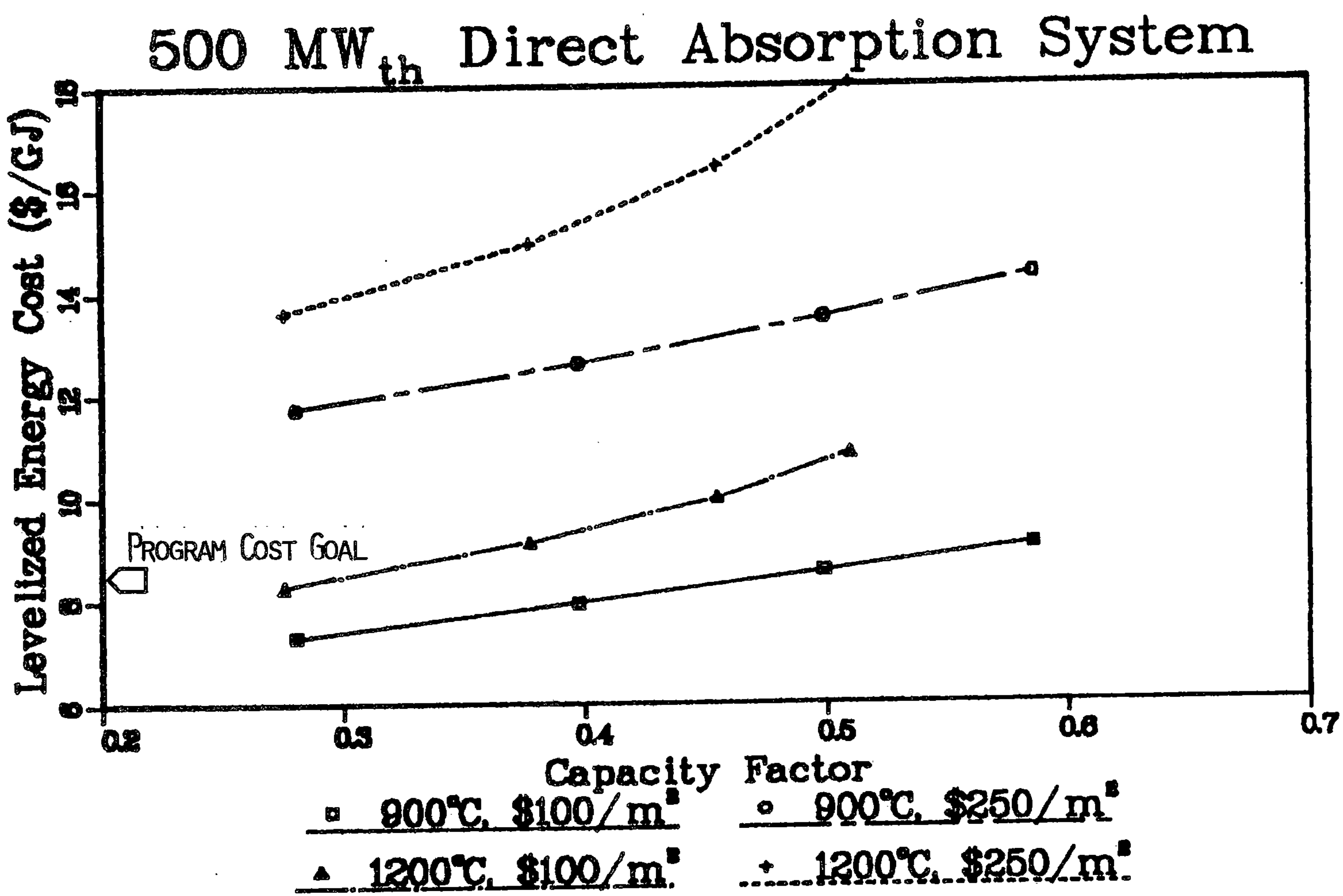

500 MWth Direct Absorption System
Levelized Energy Cost ($/GJ)
6
8
10
12
14
16
18
0.2
0.3
0.4
0.5
0.6
0.7
Capacity Factor
PROGRAM COST GOAL
900°C, $100/m²
900°C, $250/m²
1200°C, $100/m²
1200°C, $250/m²

FIGURE 14.

- It is clear from Figs. 12 - 14 that the lower field and receiver performance of the 1200°C system compared with the 900°C result in less favorable levelized energy costs. This is especially true for the $250/m^2 heliostats and becomes more significant at the larger plant sizes.

- The program goal for levelized energy cost for central receiver systems is $8.5/GJ ($9/MBtu). For a 100 MW$_{th}$ plant (Fig. 12) with $100/m^2 heliostats, this goal is nearly reached at the 900°C operating temperature.

- Based on the results of this study, the program cost goal will be met with both 300 and 500 MW$_{th}$ plants at low capacity factors at both operating temperatures. As plant size increases, either through increased capacity or larger rating, it becomes more difficult to meet the program goals.

- It is important that the heliostat cost goal of $100/m^2 be met in order to reach the system levelized the system cost goal.

- Figure 15 shows a comparison of levelized energy cost for a 100 MW$_{th}$, 900°C plant at heliostat costs of $250/m^2, $100/m^2, and $50/m^2. Note that if $50/m^2 heliostat costs can be achieved, program cost goals are easily exceeded.

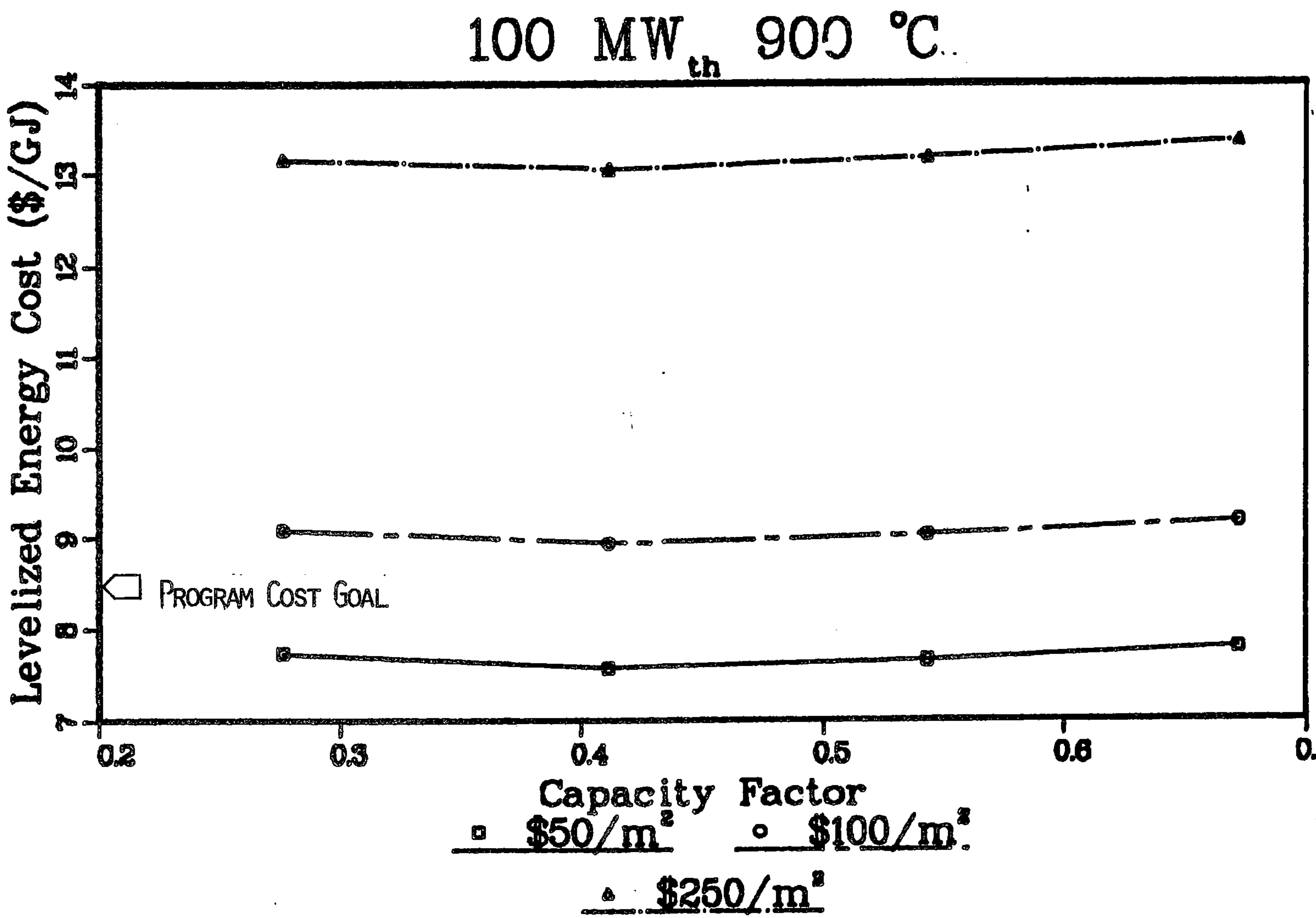

100 MW th 900 °C
Levelized Energy Cost ($/GJ)
14
13
12
11
10
9
8
7
0.2
0.3
0.4
0.5
0.6
0.7
Capacity Factor
PROGRAM COST GOAL
$50/m²
$100/m²
$250/m²

FIGURE 15.

COST COMPARISON

- DAR system costs generated in this study have been compared between the various plant sizes and operating temperatures and compared to the Five Year Plan system and component cost goals. Tables 8 and 9 compare a 900°C and 1200°C, 100 MW_{th} plant with no storage and approximately 24 hour storage. In Table 8 (no storage), it is clear that the heliostat field (at $\$100/m^2$) and the receiver/tower represent the bulk of the system cost. For the 24 hour storage case (Table 9), the heliostat field and receiver still represent the largest percent costs, with storage representing about one-half of either heliostat or receiver cost.

- 500 MW_{th} plant comparisons, for 0 storage and 24 hour storage are shown in Tables 10 and 11. Both of these show clearly the effect of decreased system performance (over the 100 MW_{th} cases) at these large field sizes. Table 10 (0 storage) shows the significant increase in heliostat costs resulting from lower field performance. Receiver cost increases, but not as dramatically. In fact, as a percentage of total system cost, the receiver cost decreases for the very large systems (both with and without storage) shown in Table 11.

TABLE 8. COST COMPARISON

DIRECT ABSORPTION AT 900°C and 1200°C, 100 MW_{th}, 0 Storage

Using $100/$m^2$ Heliostats

	DIRECT ABSORPTION 900 °C		DIRECT ABSORPTION 1200 °C	
Peak Power (MW_{th})	100		100	
Capacity Factor	0.276		0.271	
Heliostat Area (m^2)	160804		180848	
COSTS ($10^6$$)	Cost	% Total	Cost	% Total
Heliostat	16	33	18	35
Receiver	25	51	25	49
Storage	0	0	0	0
Transport	2	4	2	4
BOP	5	10	5	10
TOTAL	49	100	51	100

Note: All costs in 1984$

TABLE 9. COST COMPARISON

DIRECT ABSORPTION AT 900°C and 1200°C, 100 MW_{th}, Approx. 24 hr. Storage

Using \$100/m^2 Heliostats

	DIRECT ABSORPTION 900 °C		DIRECT ABSORPTION 1200 °C	
Peak Power (MW_{th})	242		239	
Capacity Factor	0.672		0.650	
Heliostat Area (m^2)	402010		452119	
COSTS (10^6\$)	Cost	% Total	Cost	% Total
Heliostat	40	34	45	36
Receiver	43	36	42	34
Storage	23	19	23	19
Transport	4	3	4	3
BOP	9	8	9	7
TOTAL	119	100	124	100

Note: All costs in 1984\$

TABLE 10. COST COMPARISON

DIRECT ABSORPTION AT 900°C and 1200°C, 500 MW_{th}, 0 Storage

Using $100/$m^2$ Heliostats

	DIRECT ABSORPTION 900 °C		DIRECT ABSORPTION 1200 °C	
Peak Power (MW_{th})	500		500	
Capacity Factor	0.280		0.275	
Heliostat Area (m^2)	885727		1051666	
COSTS ($10^6$$)	Cost	% Total	Cost	% Total
Heliostat	89	47	105	50
Receiver	76	40	77	37
Storage	0	0	0	0
Transport	8	4	8	4
BOP	16	8	18	9
TOTAL	189	100	208	100

Note: All costs in 1984$

TABLE 11. COST COMPARISON

DIRECT ABSORPTION AT 900°C and 1200°C, 500 MW_{th}, Approx. 24 hr. Storage

Using $100/$m^2$ Heliostats

	DIRECT ABSORPTION 900 °C		DIRECT ABSORPTION 1200 °C	
Peak Power (MW_{th})	1017		881	
Capacity Factor	0.586		0.510	
Heliostat Area (m^2)	2214318		2629166	
COSTS (10^6\$)	Cost	% Total	Cost	% Total
Heliostat	221	45	263	52
Receiver	150	30	136	27
Storage	70	14	48	10
Transport	16	3	15	3
BOP	34	7	40	8
TOTAL	492	100	502	100

Note: All costs in 1984$

- The Five Year Plan presents component cost goals for central receiver system components in IPH applications. Although in the Plan, IPH refers to 200°C-600°C system, a comparison with the present study results is instructive. Figures 16 and 17 show the component costs as a function of a capacity factor for the 100, and 300 MW_{th} plants operating at 900°C. The cost goals are shown on the figures as well. Both figures show that cost in $/m^2 is a function of capacity factor (and consequently field size). The Five Year Plan cost goals do not account for this effect. The receiver cost is still significantly above the cost goal, but the overall levelized cost for low capacity factor systems meets the system goal of $8.5/GJ ($9/MBtu). It is important to realize, as pointed out in the Five Year Plan, that various combinations of cost and performance can yield the desired system goals.

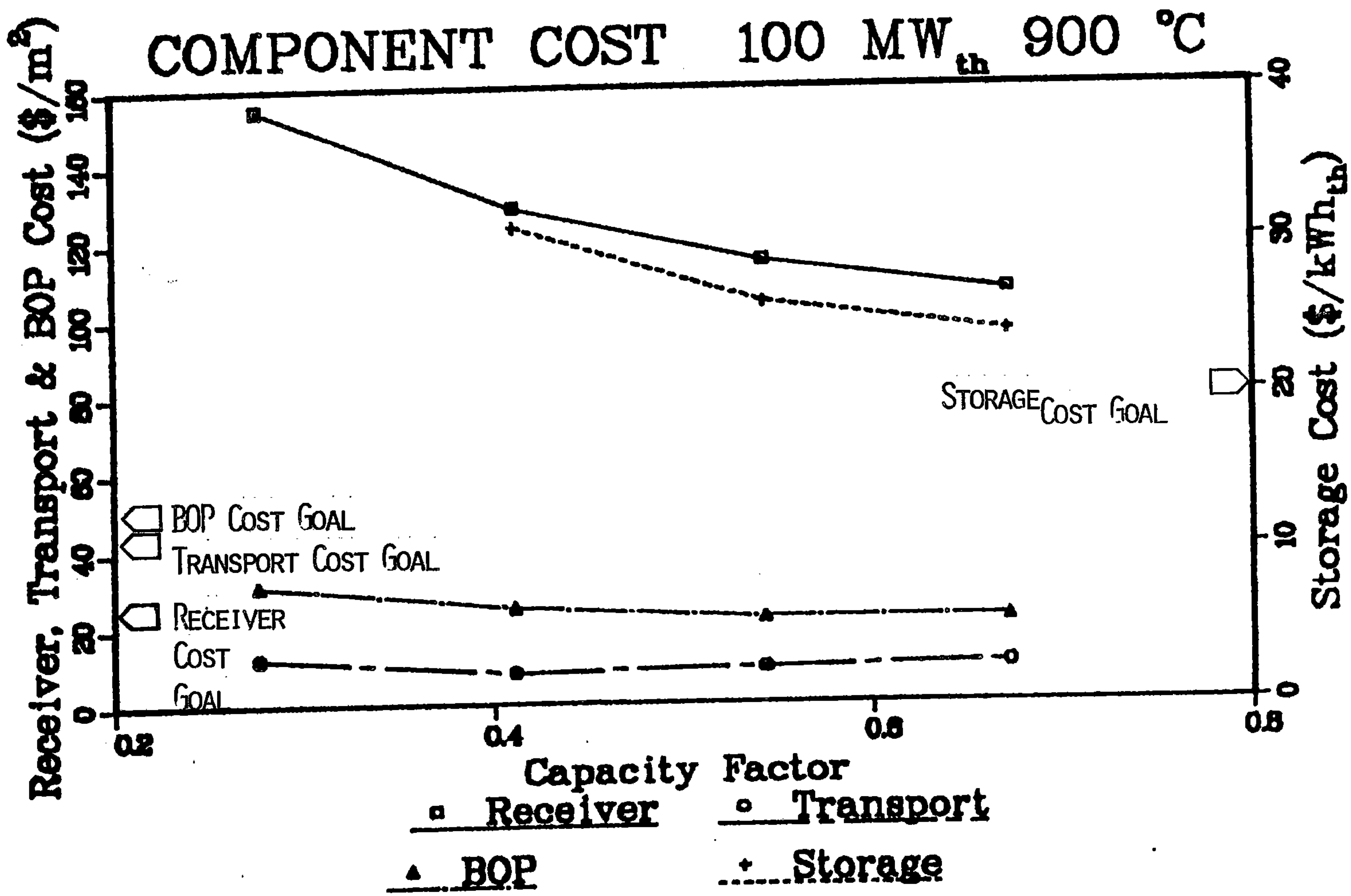

COMPONENT COST 100 MW$_{th}$ 900 °C
Receiver, Transport & BOP Cost ($/m^2)
Storage Cost ($/kWh$_{th}$)
Capacity Factor
0.2
0.4
0.6
0.8
0
20
40
60
80
100
120
140
160
0
10
20
30
40
BOP Cost Goal
Transport Cost Goal
Receiver Cost Goal
Storage Cost Goal
Receiver
Transport
BOP
Storage

FIGURE 16.

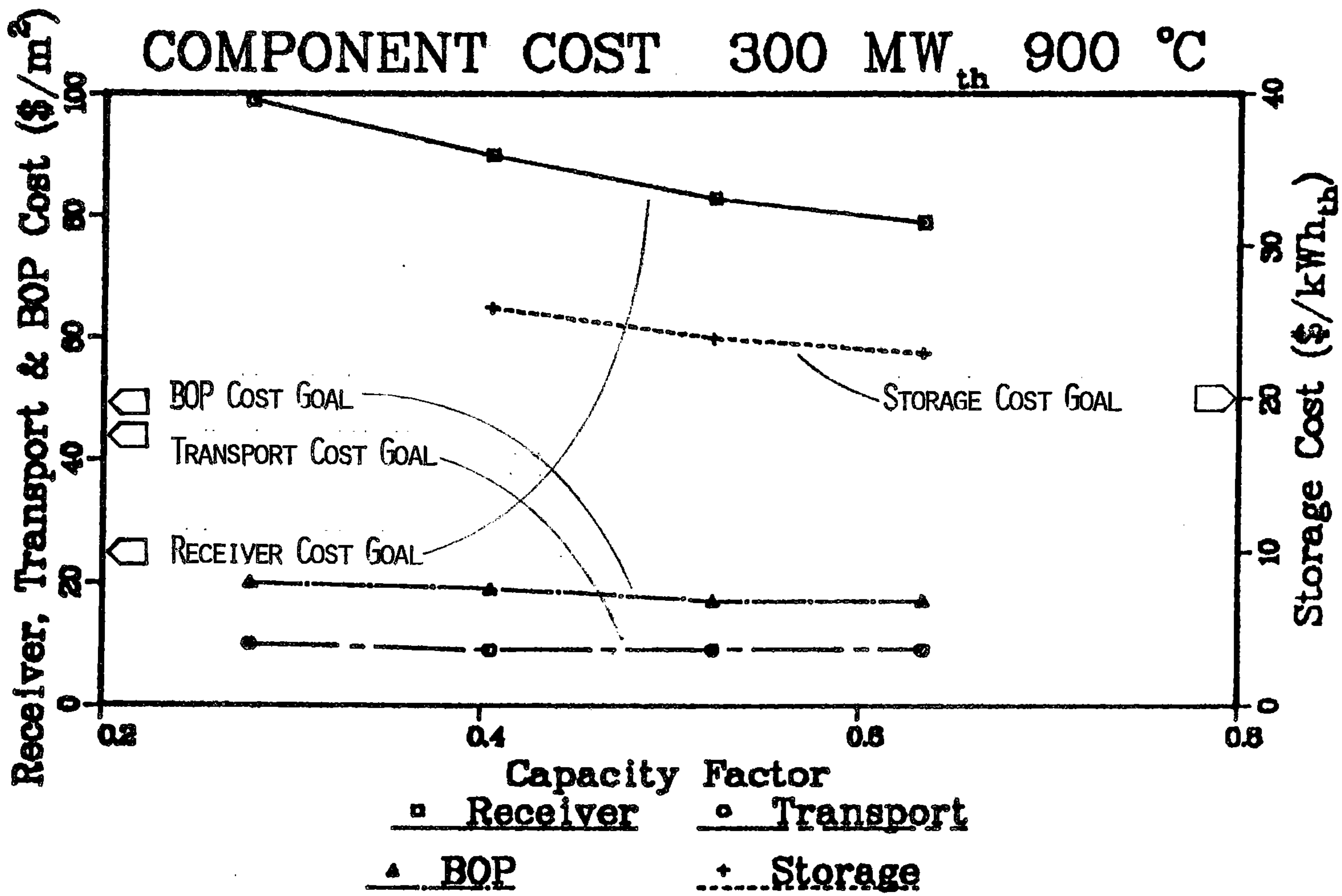

COMPONENT COST 300 MW th 900 °C
Receiver, Transport & BOP Cost ($/m²)
Storage Cost ($/kWh th)
Capacity Factor
BOP COST GOAL
TRANSPORT COST GOAL
RECEIVER COST GOAL
STORAGE COST GOAL
0
20
40
60
80
100
10
30
0.2
0.4
0.6
0.8
Receiver
Transport
BOP
Storage

FIGURE 17.

CONCLUSIONS

- DAR systems, as modeled in this study, can meet or come very close to meeting the Five Year Plan cost goals for a range of plant ratings and capacity factors at both the 900^oC and 1200^oC operating temperatures, assuming $\$100/m^2$ heliostats. A 900^oC, 100 MW_{th} plant at all capacity factors comes very close to the cost goal. Both the 300 MW_{th} and 500 MW_{th} plants at low capacity factors meet or exceed the cost goals at both 900^oC and 1200^oC. For high capacity factors at these plant sizes the penalties in performance with large field/receiver size results in levelized costs which slightly exceed the cost goals.

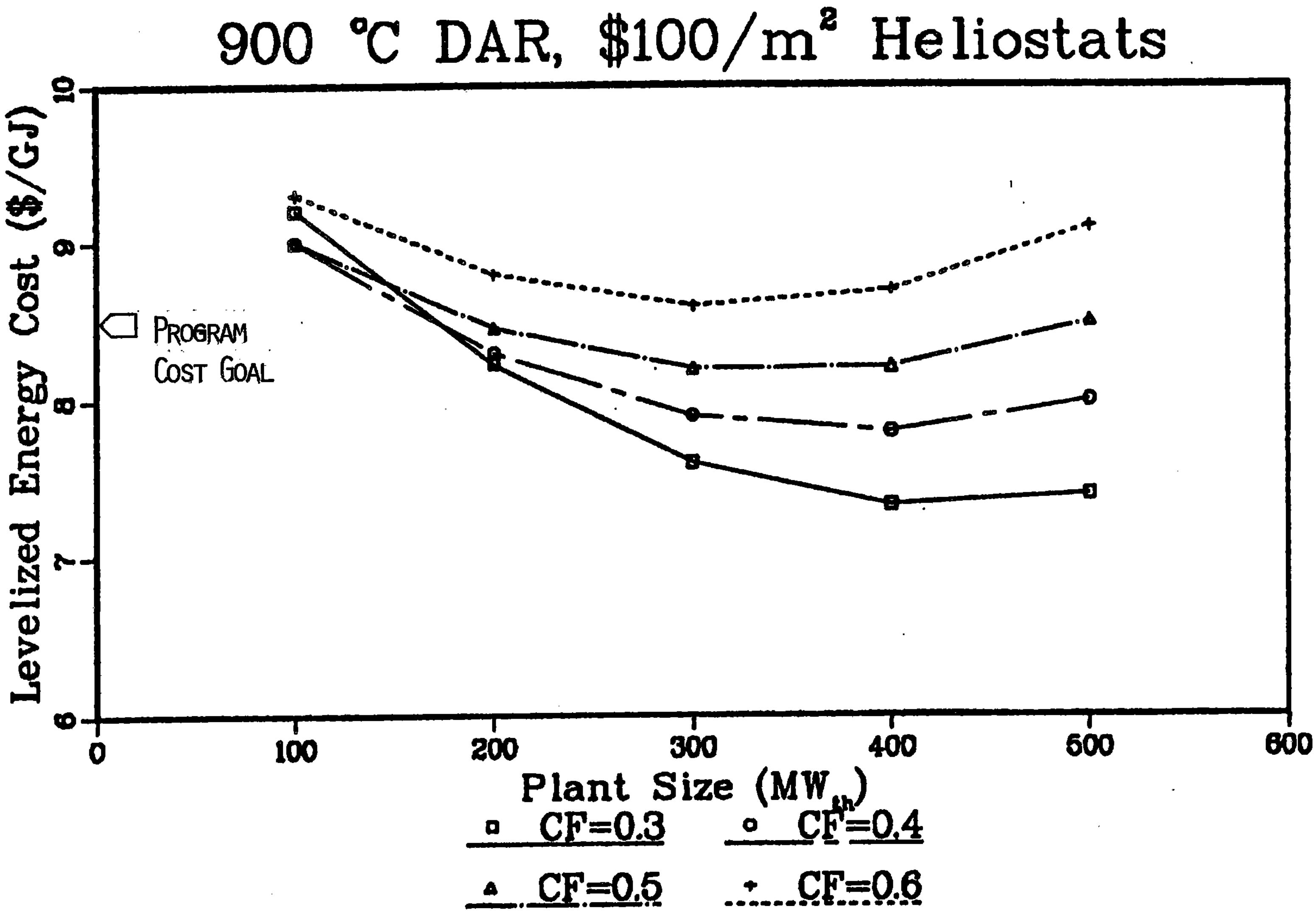
- With heliostat costs of $\$250/m^2$ the cost goals are not met at any plant size operating temperature or capacity factor. The cost of heliostats is a major factor in the total cost of any central receiver plant. As such, meeting the cost goals will depend heavily on achieving, or exceeding, the cost goals for heliostats. If costs lower than $\$100/m^2$ for heliostats can be realized, then the burden on other component costs will be reduced. Current heliostat costs ($\$250/m^2$) drive the LEC to about 1.5 times the cost goal and make achieving the cost goals almost impossible.

- Adding storage (to increase capacity factor) offers little or no advantage in levelized cost at any given plant size and temperature. As plant size is increased, greater penalties are associated with adding storage. For example, at 100 MW_{th}, 900^oC, there is almost no change in levelized cost, but at 500 MW_{th}, 900^oC, there is about a 25% increase as storage is increased from zero to 24 hours.

- At low capacity factors, the levelized energy cost decreases and then levels out as plant size increases. This is because energy output increases slightly faster than system cost for small capacity factor plants. As capacity factor is increased, a minimum in levelized energy cost occurs as plant size is increased from 100 to 500 MW_{th}. Beyond this minimum, the effect of large field sizes on overall performance results in system costs rising faster than annual output. These results are shown graphically in Fig. 18 for a 900°C plant with $100/$m^2$ heliostats. It appears from this study that at all capacity factors, a minimum in levelized energy cost occurs somewhere between 300 and 400 MW_{th}.

- Receiver cost results show that compared with a corresponding metal tube receiver, the DAR receiver costs less. This is due to simpler design and higher flux capabilities which allow for smaller receivers and slightly better performance (at the same operating temperature). However, compared with the cost goals, receiver costs are still quite high. The Five Year Plan receiver cost goals were developed with lower operating temperatures in mind and must be viewed with some question for high temperature applications.

- Transport costs represent a small fraction (approximately 3 to 4%) of overall plant cost and thus are not nearly as significant for high temperature central receiver systems as for distributed, sensible heat transport systems. Heat losses are also very small and are less than 1% of design point thermal energy delivery. However, the design of high temperature transport from a materials standpoint is of concern.



900 °C DAR, $100/m² Heliostats
Levelized Energy Cost ($/GJ)
10
9
8
7
6
PROGRAM
COST GOAL
0
100
200
300
400
500
600
Plant Size (MWth)
CF=0.3
CF=0.4
CF=0.5
CF=0.6

FIGURE 18.

RECOMMENDATIONS

- Upgrade the current DAR field/receiver analysis to determine the impact of recent experimental results and selected receiver performance improvement modifications.

- Select a specific, potentially attractive application for DAR which can more effectively use the 900°C thermal energy than does either a stand alone IPH or electricity system (suggestion: cogeneration).

- Configure and analyze a system for the selected application to establish system and component cost/performance estimates and sensitivities.

- Identify and assess potential limiting technology issues associated with the 900°C DAR system.

- Investigate the technology issues and potential benefits of DAR applications in the 600°C range.

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