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PA 140

DOE/SAN-0115/5

LINE-FOCUS SOLAR CENTRAL POWER SYSTEMS

Phase I

MASTER

Monthly Technical Progress Report
for the Period 31 January 1979 to 28 February 1979

Prepared by: Arthur J. Slemmons

March 1979

Work performed under Contract EY-76-C-03-0115
WO 3-78-482 PA#140

AT03-768T20550

SRI International
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Menlo Park, CA 94025

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March 1979

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U. S. Department of Energy
Solar Energy

Contract EY-76-C-03-0115
WO 3-78-482 PA #140

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ABSTRACT

This report summarizes the work performed during the fifth month of the Phase I study of the High Temperature Line-Focus Solar Central Power System. During the reporting period, the optical and receiver computer analysis programs and parametricized data have been combined in a computer program to give the projected annualized Bus Bar Energy Costs for a specified design. Although some of the data are incomplete or need further refinement, the program has been used to examine the sensitivity of some parameters, and to make preliminary optimizations.

1.0 Introduction

In accordance with the reporting instructions in Contract EY-76-C-03-0115, SRI International submits this report of project technical progress for the month of February 1979, the fifth month of the project.

2.0 General

The Department of Energy, through its Division of Solar Technology, is engaged in an effort to develop the technology for the practical and economic conversion of sunlight into electricity. The Solar Thermal Power Program presently being conducted by the Division of Solar Technology includes several contracts with industrial teams for the conceptual design, development, testing, and demonstration of a variety of Solar Thermal Power System concepts and applications. Efforts have been expended in two areas, central power applications and dispersed power applications. This contract falls into the central power applications area.

As prime contractor, SRI is analyzing the high-temperature line receiver (HTLR) central power concept. The SRI team includes Bechtel National, Incorporated, the Foster Wheeler Development Corporation, and the Acurex Corporation. The Pacific Gas and Electric Company is acting as consultant to the team. The team is conducting system and subsystem parametric analyses, and will complete a MW_e commercial plant conceptual design, power cost analysis and commercial assessment. A Phase II development plan that includes critical subsystem experiments will also be prepared.

3.0 Parametric Analysis

3.1 General

The SRI team members are performing parametric cost/performance studies for the various subsystems. The technique being used by SRI to make the system parametric analyses through the choice of the most cost-effective subsystem designs is shown in Figure 1. Starting with the capacity of producing $100 MW_e$ net at

Figure 1 FLOW CHART FOR CALCULATING BUS BAR ENERGY COST

2:00 p.m. on winter solstice, the program calculates the energy directed into the cavity receiver by the heliostat field per unit length of the system. All optical losses are taken into consideration. The amount of energy per unit length of the system absorbed by the molten salt is calculated. Conduction, wind, reflection, and radiation losses are considered. The losses in the Heat Transport Subsystem and Heat Storage Subsystem are then calculated on a per-unit-length basis for the system. For a given EPGS efficiency at the steam inlet temperature chosen, the length, L , of the system to produce 100 MW_e net is calculated. Then the computer calculates on an hourly basis the energy collected and transformed into net kilowatt hours for winter solstice, summer solstice, and equinox. A yearly kWh total is calculated. Using the cost parameters of the various subsystems estimated on a cost-per-unit-length, where applicable, and using known fixed and operating costs, the yearly average BBEC is calculated. The sensitivity of BBEC to variations of the various subsystem parameters are studied and optimized on the basis of yearly BBEC.

Some of the preliminary results will be discussed. Figure 2 shows the reduction in BBEC with increasing capacity factors. The utilization of the EPGS, computer, controls, and balance of plant for greater portions of the day gives a lower BBEC. Figure 3 shows the variation of the cavity receiver optical efficiency for various salt outlet temperatures, with and without selective surfaces. Convection and wind losses will reduce the value of efficiencies shown. The cryogenic wind tunnel test is planned to better determine wind losses. The cavity effect of reducing reflection and radiation losses accounts for about five of these percentage efficiency points.

Figure 4 shows how these practical receiver efficiencies are achieved at relatively low solar concentrations. At high concentrations the receiver efficiency is relatively insensitive to the emissivity of the receiver surface. As the concentration decreases, however, the receiver efficiency becomes more sensitive to the emissivity of the receiver surface. As the emissivity approaches zero, the receiver efficiency approaches the value of the solar absorptance, α_s , for all solar concentration ratios. SRI has chosen to use a conservative value

Figure 2 BBEC AS A FUNCTION OF CAPACITY FACTOR
FOR HTLF SOLAR CENTRAL POWER SYSTEM

Figure 3 OPTICAL EFFICIENCY OF HTLF SOLAR CENTRAL POWER SYSTEM RECEIVER AS A FUNCTION OF OUTLET TEMPERATURE — INLET TEMPERATURE = 500 °C

Figure 4 SOLAR RECEIVER EFFICIENCY

of $\epsilon_{5250} = 0.06$ for the trade-off studies, although passivated selective surfaces have been shown to retain an emissivity (ϵ_{5000}) of 0.045 for the 500°C black body spectrum after 1000 hours at 500°C. Heretofore, only point focus systems were able to achieve these high receiver efficiencies.

Figure 5 shows another condition where the capacity factor is important. The figure shows the effect of heliostat spacing on the BBEC. The upper line, with a constantly increasing cost as the spacing is increased, is for a design to produce the required amount of power at 2:00 p.m. winter solstice. The curve seems to indicate that close spacing is preferred. Comparison of the variation in capacity factor along the curve reveals that another phenomenon is occurring. Due to shading and blocking in the north-south direction, the close spacing is less efficient during winter for close row spacing. The field size must be increased so that the minimum required power is delivered at 2:00 p.m. winter solstice. The larger field means that at other times during the year a great deal more energy is being produced, thereby increasing the capacity factor. The advantage of the higher capacity factor is overcoming the relative operating inefficiency during the winter. The lower line on Figure 5, showing a minimum in the BBEC with spacing, compares several field designs at the same capacity factor. It shows an even lower BBEC at what appears to be an optimum spacing of about 5.5 meters. The rationale for the choice of salt/steam over water/steam for the working fluids is shown in Table 1. The combination of conservative and low cost selective surfaces with the reheat steam cycle shows the overall efficiency advantage both direct and from storage. It has been estimated that selective surfaces will add about 1½% to the cost of stainless steel tubes.

3.2 Concentrator Subsystem

Preliminary cost vs. accuracy parametrics have been developed on the basis of a torque tube design. The torsional deflection of this concept is excessive. A second generic design family is being examined for improved torsional stiffness and reduced cost.

HTLF HELIOSTAT SPACING vs. BBEC

Figure 5

Table 1

HTLF SOLAR POWER SYSTEM ABSORBER FLUID TRADE-OFF

ABSORBER FLUID	CAVITY RECEIVER EFFICIENCY		EPGS EFFICIENCY	SELECTIVE SURFACE EFFICIENCY PRODUCT
	$\alpha_s = 0.90$ $\epsilon_{525^\circ\text{C}} = 0.70$	$\alpha_s = 0.88$ $\epsilon_{525^\circ\text{C}} = 0.06$		
Water at 950°F	0.824	0.920	0.336 Direct 0.247 Storage	0.31 Direct 0.23 Storage
Salt at at 1050°F	0.688	0.903	0.400 (with reheat)	0.36 Direct 0.36 Storage

Collector Foundations

Designs for collector foundations were developed for three alternate foundation arrangements as follows:

<u>Arrangement</u>	<u>Support Spacing (ft)</u>	<u>Quantity Required</u>
A	60	36,000
B	40	50,000
C	20	94,000

For each arrangement, three different designs were developed with various pier diameters and depths. These nine designs are currently being costed.

3.3 Receiver Subsystem

Receiver designs with module lengths from 40 feet to 120 feet (the maximum shippable length) are being evaluated. Smaller tubes are desirable to increase the heat transfer to the working fluid. but consideration has thus far been limited to 1/2-inch diameter tubes for fabrication reasons. Fabrication by other than conventional welded boiler technology may be preferred and will be considered, since draw salt has a relatively low vapor pressure at the operating temperature.

A total receiver weight of 350 pounds per foot of length is currently being used for the tower design. Receiver height has been fixed at 200 feet, and several tower and bridge designs are being developed for alternate tower spacings. The ice loads on the receiver and tower are tentatively based on a 1/2-inch ice thickness as recommended by the ASCE for transmission tower design, pending a change from the two-inch thickness specified in the requirements definition.

3.4 Heat Transport Subsystem

A preliminary piping layout, including expansion loops and pipe supports, has been developed for the HTS. The layout is based on a salt flowrate of 10.12×10^6 lbm/hr, corresponding to a solar multiple of 2.1 and a 2400 psig/950°F/950°F EPGS cycle. Based on a capital cost estimate of the piping layout,

an exponential cost model has been developed for the HTS. The results of the parametric cost analysis, for throttle steam pressures of 2000 and 2400 psig and final feedwater temperatures of 350°F to 500°F, are shown in Figure 6. These data will be used in the systems program to determine the optimum EPGS operating conditions.

As with the EPGS, the parametric analysis was also carried out for solar multiples ranging from 1.4 to 2.9 for the 2400 psig/950°F/950°F cycle only. The results of the analysis, shown in Figure 7, will be used to determine the optimum solar multiples.

3.5 Energy Storage Subsystem

Based on preliminary estimates of tank costs, field piping costs, and salt pump power requirements, the dispersed location thermocline ESS was selected for the parametric analysis. Figure 8 shows the cost saving for using a distributed thermocline system over the alternatives. These costs include capital as well as pumping costs. As with the EPGS and the HTS, an exponential cost model was developed for the ESS.

The ESS located at the EPGS includes the steam generator. The results of the parametric analysis, for throttle steam pressures of 2000 and 2400 psig and final feedwater temperatures of 350°F to 500°F, are shown in Figure 9. These data will be used to determine the optimum EOGS operating conditions.

The parametric analysis was also carried out for solar multiples ranging from 1.4 to 2.9 for the 2400 psig/950°F/950°F cycle only. The results of the analysis, shown in Figure 10, will be used in system model to determine the optimum solar multiple.

3.6 Electric Power Generation Subsystem

Based on previous work, the parametric analysis for the EPGS will be limited to throttle and reheat steam temperatures of 950°F and throttle steam pressures of 2000 and 2400 psig. The 950°F steam temperature was selected based on the following receiver and EPGS efficiencies:

HTS COST AS A FUNCTION OF THROTTLE STEAM PRESSURE AND FINAL FEEDWATER TEMPERATURE

Figure 6 HTS COST AS A FUNCTION OF THROTTLE STEAM PRESSURE AND FINAL FEEDWATER TEMPERATURE

Figure 7 HTS COST AS A FUNCTION OF SOLAR MULTIPLE

Figure 8 SELECTION OF TYPE AND LOCATION OF THE ENERGY STORAGE SUBSYSTEM BASELINE PLANT DESIGN

Figure 9 ESS COST AS A FUNCTION OF THROTTLE STEAM PRESSURE
AND FINAL FEEDWATER TEMPERATURE

Figure 10 ESS COST AS A FUNCTION OF SOLAR MULTIPLE

<u>Salt Outlet</u> <u>Temp. (F)</u>	<u>Receiver</u> <u>Eff. (%)</u>	<u>Steam</u> <u>Temp. (F)</u>	<u>EPGS</u> <u>Eff. (%)</u>
850	91.5	750	34.62
950	91.0	850	37.38
1050	90.5	950	39.15

The 950°F steam temperature provided the best combination of EPGS and receiver efficiencies.

An exponential cost model was developed for the EPGS. Costs for the following combinations of throttle steam pressure and feedwater temperature, were calculated as an input to the systems model, Figure 1, which will determine the optimum EPGS operating conditions.

<u>Throttle Steam Pressure (psig)</u>	<u>Final Feedwater Temp. (F)</u>
2000 and 2400	350
	400
	450
	500

The results of the parametric analysis for the throttle steam pressure and final feedwater temperature are shown in Figure 11.

The parametric analysis was also carried out for solar multiples ranging from 1.4 to 2.9. To simplify the analysis, costs were calculated for only one EPGS combination; specifically, the 2400 psig/950°F/950°F cycle with a final feedwater temperature of 450°F. The results of the analysis, shown in Figure 12, will be used to determine the optimum solar multiple.

Research into the operation of cycling turbine-generators has shown that 2400 psig/1000°F/1000°F cycles are technically feasible. Once the optimum solar multiple, final feedwater temperature, and throttle steam pressure have been selected, a brief cost and performance parametric analysis will be performed to determine if the 1000°F/1000°F cycle is an improvement over the 950°F/950°F cycle. Note that the receiver outlet salt temperature of 1050°F will be held constant during the analysis.

Figure 11 EPGS COST AS A FUNCTION OF THROTTLE STEAM PRESSURE AND FINAL FEEDWATER

Figure 12 EPGS COST AS A FUNCTION OF SOLAR MULTIPLE

The final portion of the parametric analysis, which will be performed in the conceptual design, will determine the optimum condenser pressure and pre-heater pinch point temperature.

3.7 Master Control Subsystem

The basic features of the master control subsystem have been described in a previous report. The system will not be a significant driver in the parametric analysis as it is extremely inexpensive. Further work on the control system will await definition of the commercial system selection.

4.0 Commercial System Selection

Through the Parametric analysis, basic features of the commercial system are becoming clearer. Significant features identified during this performance period are the use of thermocline thermal storage and the distributed storage throughout the heliostat field. Economics have shown that the heliostat field and storage will be sized to give a significant increase in the capacity factor over the minimum specified in the requirements definition. The land required will be about a square mile.

5.0 Subsystem Experiment

The scale model of the cavity receiver and its support structure is being designed. Stainless steel will be used instead of copper for the model's heat transfer surface, as a result of recent tests at the University of Illinois cryogenic wind tunnel.

6.0 Assessment of Commercial HTLF System

The assessment of the market potential for commercialization of the HTLF central power system is now waiting for final system costs and annualized BBEC. Preliminary results have shown a significant market based on a reheat cycle.

7.0 Phase I Management

Subcontracts with Foster Wheeler and Bechtel have been finalized. The subcontract with Acurex is in the final stage of negotiation. The delay in negotiating these contracts has not significantly adversely affected technical progress by the subcontractors. There has been some benefit from the delay, since the change in the working fluid from water/steam to salt/steam avoided spending a great deal of time and money optimizing the less cost effective water/steam system originally presented in the proposal.

A proposal and cost estimate to store and/or perform minimal testing at SRI of the HTLF heliostat module constructed by FMC was presented to DOE-SAN.

PROJECT STATUS REPORT

Number: DOE/SAN-0115-5
Date : 23 March 1979
Period: 1-31-79 - 2-28-79
BR : WO-3-78-482
DOE Program Manager: J. Weisiger, Jr.

PROJECT TITLE: Line-Focus Central Power System: Phase I

CONTRACT: Number: EY-76-C-03-0115
 Start Date: 9-29-78
 Completion Date: 9-30-79
 Contractor: SRI International
 333 Ravenswood Avenue
 Menlo Park, CA 94025

1.0 CONTRACT OBJECTIVE

The objective of this project is to provide a conceptual design of a commercial High-Temperature Line-Focus 100 MW_e Central Power Plant that can produce low cost electricity. To achieve this objective, parametric analyses of the subsystems will be performed to optimize the system. The cost of the electricity and the cost of the plant will be used to make an assessment of its potential for commercialization.

A Phase II plan to implement this optimization process through critical experiments will be prepared.

2.0 CONTRACT TASKS

- Task 1 Requirement Definition--Completed
- Task 2 Parametric Analyses--Subsystem performance and costs are being calculated and, when completed, will be used to complete the parametric studies.
- Task 3 Commercial Plant Configuration Selection--A draw salt/steam reheat cycle and distributed storage have been selected for the commercial plant.
- Task 4 Commercial Plant Conceptual Design--Not initiated.
- Task 5 Commercial Plant Cost and Performance Estimate--Some subsystem costs and performances have been calculated.
- Task 6 Receiver Subsystem Experiment--The model for the cryogenic wind tunnel test of receiver model is being designed.

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Task 7 Assessment of Commercial System--Preliminary assessment of potential markets for electric power plants by region and state has been completed.

Task 8 Development Plan--Not initiated.

Task 9 Phase II Plan and Proposal--Not initiated.

Task 10 Management--Foster Wheeler and Bechtel are under subcontracts. Negotiations with Acurex are under way.

3.0 TECHNICAL APPROACH OR WORK PLAN CHANGES

The working fluid has been changed from water/steam to draw salt/steam with a reheat cycle. The storage tanks have been moved from the EPGS out into the heliostat/receiver field.

4.0 VARIANCES

4.1 Cost and manpower effort less than scheduled.

4.2 It is believed the schedule slip can be made up by the end of April.
The commercial assessment is ahead of schedule.

5.0 OPEN ITEMS

Approval of Technical Brochure yet to be received.

6.0 RECENT AND PLANNED ACHIEVEMENTS

Cost and performance calculations for most of the subsystem have been completed. Optimization of the subsystems has been initiated. Upon completion the system will be optimized on the basis of annualized BBEC.

Arthur J. Slemmons
Project Manager
SRI International

ATTACHMENTS

- Contract Management Summary Report
- Data Item Deliverables Log

1. Contract Identification Line Focus Solar Large Power System Phase I		2. Reporting Period 1-31-79 through 2-28-79		3. Contract Number EY 76-C-03-0115 PA WO 3-78-482												
4. Contractor (Name and Address) SRI International 333 Ravenswood Ave. Menlo Park, Calif. 94025		DOE Program Manager J. Weisiger, Jr.		5. Contract Start Date 09/29/78												
				6. Contract Completion Date 09/30/79												
7. Months		O	N	D	J	F	M	A	M	J	J	A	S			8. FY 78
9. Cost Status																
a. Dollars																
X Thousands																
--- Planned																
--- Actual																
... Contractor's Latest Estimate																
b. B&R Numbers																
c. Planned 38.477.7 137.6 201.6 258.0 328.8 381.1 427.2 466.8 512.7 553.3 571.5																
d. Actual 13 56 84 137 186																
e. Variance (25) (21) (54) (65) (72)																
f. Cum. Variance (25) (21) (54) (65) (72)																
g. Cost Plan Data																
h. Planned Costs Prior FYs																
i. Actual Costs Prior FYs																
j. Total Estimated Costs for Contract 571,132																
k. Total Estimated Costs for Contract 571,132																
l. Unfilled Orders Outstanding																
m. Estimated Subcontract Reporting Period																
10. Manpower Status (Direct Labor)																
a. Man Hours																
X 1,000																
--- Planned																
--- Actual																
... Contractor's Latest Estimate																
Legend:																
--- Planned & Approved																
--- Actual																
... Contractor's Latest Estimate																
b. Planned .64 1.24 2.89 4.33 7.2 9.27 10.2 11.1 12.0 13.1 13.9 14.2																
c. Actual .32 1.41 2.07 3.25 4.37																
d. Variance (.32) .17 (.82) (1.08) (2.87)																
e. Manpower Plan Data																
f. Planned Manpower Prior FYs																
g. Actual Manpower Prior FYs																
h. Total Estimated Manpower for Contract 14,261 hrs																
i. Total Estimated Manpower for Contract 14,261 hrs																
11. Major Milestone Status																
a. Requirements Definition 100																
b. Parametric Analysis 75																
c. Commercial Configuration 30																
d. Commercial Conceptual Design 10																
e. Cost & Performance Est. 5																
f. Subsystem Research Experiment 30																
g. Assessment Commercial System 50																
h. Development Plan 0																
i. Phase II-- Plan & Proposal 0																
12. Remarks																
13. Signature of Contractor's Project Manager and Date 3/27/79																
14. Signature of Government Technical Representative and Date																

DATA ITEM DELIVERABLES LOG

Deliv- erable No.	Description	Date Due	Date Delivered	DOE Comments	Comments
a 1	Requirements Defini- tion Suggested Changes	10-15-78	10-13-78		DOE has issued revised Require- ment Definition
d 1	System and Subsystem Requirements & Speci- fications	6-15-79			
d 2	Diagrams	6-15-79			
d 3	Engineering Drawings	6-15-79			
d 4	Materials & Rationale	6-15-79			
d 5	Operating Modes Iden- tification	6-15-79			
e 1	Cost & Performance Estimate	6-30-79			
f 1	Subsystem Experiment Test Plan	12-31-78	2-8-79		Revised plan submitted
f 2	Subsystem Experiment Report	2-15-79			This schedule will slip
g 1	Commercial Assessment	7-31-79			
h 1	Development Plan	7-31-79			
i	Phase II Plan & Proposal	8-31-79			

MILESTONE SCHEDULE AND STATUS REPORT

LINE FOCUS SOLAR LARGE POWER SYSTEM - PHASE I										1-31-79		2-28-79		EY-76-C-03-0115 WO 3-78-482 PA#140													
SRI INTERNATIONAL 333 Ravenswood Avenue Menlo Park, CA 94025										Contract Start Date 09/29/78		Contract Completion Date 09/30/79															
7. Milestone Number (WBS)	8. Milestone Category (e.g., Design, Development, Test, etc.)	9. Fiscal Year and Months																								10. Percent Complete	
		O	N	D	J	F	M	A	M	J	J	A	S	O	N	D											a) Planned
100	Requirements Definition																									100	100
200	Parametric Analysis																									80	75
300	Commercial System Selection																									75	30
400	Conceptual Design																									40	10
500	Cost & Performance Estimate																									20	5
600	Subsystem Research Experiment																									100	30
700	Commercial System Assessment																									25	50
800	Development Plan																									0	0
900	Phase II Plan & Proposal																									0	0
1000	Phase I Management																									40	40
11. Remarks																											
12. Signature of Contractor's Representative and Date <i>A.J. Stevenson</i> 3-26-79														13. Signature of Government Technical Representative and Date													

1. Contract Identification Line-Focus Solar Large Power System Phase I		2. Reporting Period 1-31-79 through 2-28-79		3. Contract Number EY-76-C-05-0115 WO 3-78-482 PA#140					
4. Contractor (name and address) SRI International 333 Ravenswood Avenue Menlo Park, CA 94025		5. Cost Plan Date 10-13-78		6. Contract Start Date 9-29-78					
7. Contract Completion Date 9-30-79		8. Government Funding \$571,132		9. Contractor Funding ---		10. Total Invoice Amounts Billed		11. Total Payment Received	
12. Identification Number		13. Reporting Category (e.g., contract line item or work breakdown structure element)		14. Costs Accrued					
				a. Adj. Prior Project	b. During Period	c. Cum. to Date	d. Proj. Next Period	e.	f.
100		Requirements Definition		---	---	6,285	---		
200		Parametric Analysis		---	30,736	104,804	30,000		
300		Commercial System Selection		---	3,061	3,666	10,000		
400		Commercial Plant Conceptual Design		---	---	---	10,000		
500		Cost and Performance Estimates		---	---	---			
600		Subsystem Research Experiment		---	426	2,700	3,000		
700		Commercial Assessment		---	396	8,701	---		
800		Development Plan		---	---	---	---		
900		Phase II Proposal		---	---	---	---		
1000		Phase I Management		---	10,714	43,966	10,000		
Subtotal					45,333	170,122			
Fee					2,674	10,190			
15. Total					48,007	180,312	63,000		
16. Remarks									
17. Signature of Contractor's Project Manager and Date 3-26-79					18. Signature of Contractor's Authorized Financial Representative and Date				