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LINE-FOCUS SOLAR CENTRAL POWER SYSTEMS

Phase I

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

Prepared by: Arthur J. Slemmons

April 1979

Work performed under Contract EY-76-C-03-0115

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ABSTRACT

This report summarizes the work performed during the sixth month of the Phase I study of the High Temperature Line-Focus Solar Central Power System. During the reporting period, subsystem and system parametric analyses were essentially completed. The conceptual design of the system has been initiated. Annual levelized busbar energy costs of 59 mills/kWh are projected for the 80th plant.

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 March 1979, the sixth 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 100 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 parametric analyses for the subsystems and system are essentially complete. Detail design studies and trade-offs of the subsystems and system will continue during the conceptual design, however.

3.2 Concentrator Subsystem

The aiming accuracy of the heliostats has been taken at 1 mrad standard deviation and the spectral surface error at 1 mrad standard deviation. A 0.9 reflectivity has been assumed. Since the minimum projected cost of heliostats is not finalized, the values of \$5, \$7, and \$9/ft² have been used to determine the impact on this design variable on the BBEC. Costs of \$5/ft² are being approached for the fiber reinforced cement heliostat design.

Figure 1 shows the effect of changing the spacing between the heliostats on the BBEC. A smaller spacing gives increased blocking and shadowing and lower energy, whereas, an increased spacing gives greater losses due to image distortion and aiming errors.

Figure 2 shows the effect on the BBEC of changing the number of heliostat rows per receiver. It can be seen that energy cost is not sensitive to the number of heliostats. The minimum occurs at about 21 rows of heliostats. Future projections of variations in the heliostat cost/performance ratio could still alter this optimum number of rows somewhat.

3.3 Receiver Subsystem

3.3.1 The weight of the receiver has been estimated at about 200 lb/ft, including the metal and the salt. In addition, there is 150 lb/ft of sheet metal and insulation. A value of 350 lb/ft has been used by Bechtel in sizing and costing the towers and bridges between towers.

SRI has been advised by the researchers at the University of Arizona that a high temperature selective surface can be made available in the 1980s for use with a conservative absorptivity of 0.90 and an emissivity of 0.06. These values have been already achieved in surfaces which show no deterioration with time at 500°C. A stainless steel receiver design, including selective surfaces has been estimated for the 80th plant at \$500/ft. The receiver will be 6 feet in diameter with an aperture of 4 feet at an angle of 50° to the horizontal. Figure 3 shows the effect of changing the receiver size holding the ratio of the diameter to the aperture constant.

HIGH-TEMPERATURE LINE-FOCUS CAVITY RECEIVER CENTRAL POWER SYSTEM

Figure 1. *HELIOSTAT PITCH*

HIGH-TEMPERATURE LINE-FOCUS CAVITY RECEIVER CENTRAL POWER SYSTEM

Figure 2. *HELIOSTAT QUANTITY* $e = 0.06$

HIGH-TEMPERATURE LINE-FOCUS CAVITY RECEIVER CENTRAL POWER SYSTEM

Figure 3. APERTURE OPENING $A/R = 1.67$

The design presently proposed consists of thin walled, flattened tubes assembled by welding. The thin walled tubes would be formed with a flange on opposite sides. A section of this extrusion is shown in the Figure 4a. The purpose of the thick flange section is to facilitate automated welding. Welding of any kind would be extremely difficult on material of the wall thickness anticipated. This design has the features of being light in weight, automatable, thus inexpensive.

Even further cost reduction is possible in the heat transfer panel technology. This kind of technology has been used for years in refrigerators and hot process tanks, and has been improved in recent years for more demanding applications. Two sheets of metal would be used. The flow path is stamped into one or both, and the sheets are assembled by brazing or spot welding and seam welding around the edges. Many techniques for forming and assembling are available and will have to be selected for compatibility with the working fluid.

A schematic of the concept is shown in Figure 4b. The process is easily adaptable to any panel design and can be highly automated. Sheet steel would be delivered to the production facility. The sheets would be stamped and assembled by welding or brazing into panels. The panels would then be fitted with plumbing fittings and hangers. The panels would then pass through the atmospheric chemical vapor deposition oven to apply the selective surface. The sections would be bent into acylindrical shape and the back side would be insulated and wrapped with a protective layer. The circular cylinder sections would nest during shipment to the solar plant site. The cavity receiver convective heat loss is difficult to calculate in a receiver of the geometry proposed. Since the cryogenic wind tunnel studies at the University of Illinois are behind schedule, it was found necessary to bound the anticipated values. For the worst case, a flat plate, the width of the aperture at an average temperature of 700°F above the ambient, has been taken. The worst case, free convection, is given by $h = 0.22 (\Delta T)^{1/3} \text{ Btu/mft}^2 \text{ }^{\circ}\text{F}$ for a flat plate facing upwards which gives a convective loss of $1.6 \text{ kW}_{\text{th}}/\text{ft}$ of receiver length.

FIGURE 4a RECEIVER TUBE CROSS SECTION

FIGURE 4b POTENTIAL RECEIVER DESIGN

To estimate the worst possible case, forced convection, the Reynolds number power coefficient from the Nusselt-Reynolds correlation has been taken to be 0.731, a value from Jakob for a vertical flat plate. The crossover between forced and free convection has been estimated to take place at 5 mph. The best case assumption is that the convective loss is negligible.

The best and worst case convective loss assumptions were first used in the computer model used for parametric analysis and system trade-off studies. A comparison between the best and worst case designs is shown in Figure 5 in which the difference in performance can be seen as the difference in value of BPEC. For the trade-off studies a convective loss half of the worst case has been used. This is believed to be on the conservative side.

3.3.2 Receiver Towers.

A parametric study was completed of towers and connecting bridges required to carry the cylindrical solar line focus receiver at an elevation of 200 feet above grade. Each bridge is simply supported on top of self-supporting towers. The tower spacing was varied to determine the optimum size of the bridges and towers. A Warren truss was analyzed for the receiver support system because it is the least expensive of the parallel chord trusses. Augered, belled caissons were used for the tower foundations because of the uplift resistance required under lateral loads, and to avoid the high labor costs involved in spread footings. A guyed tower was not investigated in detail because even though it may provide some savings in steel weight, it would be considerably more flexible than a self-supporting structure.

Three truss spans and towers were analyzed corresponding to 150, 200 and 250 feet tower spacings. In each case the survival wind governed the design. The foundation design was governed by uplift and was arranged to have a factor safety of two. The general configuration is shown in Figure 6 and the resultant structural quantities are listed in Table A.

A cost estimate was prepared for the three alternative tower and bridge design and spacing arrangements listed in Table A. A material takeoff was made as to the quantities of excavation, concrete, rebar and steel.

HIGH-TEMPERATURE LINE-FOCUS CAVITY RECEIVER CENTRAL POWER SYSTEM

Figure 5. *EFFECTS OF CONVECTION LOSSES*

Figure 6. GENERAL ARRANGEMENT OF TOWERS AND BRIDGE TRUSSES

TABLE A
SUMMARY OF TOWER AND BRIDGE STRUCTURAL QUANTITIES

	Span (feet)		
	<u>150</u>	<u>200</u>	<u>250</u>
Structural Steel (tons)			
Bridge	11.6	20.9	40.0
Tower	16.1	18.5	22.1
Tower Foundation (per tower)			
Concrete (yd ³)	5.2	7.4	8.8
Rebar (lbs)	520	740	880

requirements. The estimate was subsequently based on previous Bechtel construction experience, as well as oral quotations from various contractors and material suppliers, with delivery to a jobsite located in the Southwestern part of the United States.

To calculate the cost of the various tower and bridge configurations, the estimate focused on the trade-off between shop or field assembly of the subject units. It was determined that the best alternative in terms of cost reduction would be to order the steel components fabricated, galvanized and bundled in the shop, and assembly would take place in a field fabrication environment.

In all cases, the labor input for field fabrication and assembly encompassed all possible savings due to the large amount of repetitive work involved. Subsequently, the labor input was estimated at the lowest possible rate. Additionally, estimated material costs were based on the magnitude of the quantities required.

The costs of the three alternatives are listed in Table B for a 2.1 solar multiple. These costs are based on the quantities shown in Table C. This estimate includes material, direct labor, and engineering costs at 10% of the direct costs and is in mid-1978 dollars, with delivery to a jobsite in the Southwestern United States.

TABLE B
FOUNDATION, TOWER AND BRIDGE COSTS
(1978 Dollars)

<u>Span (feet)</u>	<u>Foundations</u>	<u>Towers</u>	<u>Bridges</u>	<u>Total</u>
150	759,000	8,820,000	6,180,000	15,760,000
200	775,000	7,760,000	8,210,000	16,740,000
250	860,000	7,340,000	12,100,000	20,340,000

TABLE C
TOWER AND BRIDGE QUANTITIES

<u>Span (feet)</u>	<u>Towers/ Row</u>	<u>Total Towers</u>	<u>Bridges/ Row</u>	<u>Total Bridges</u>
150	25	400	24	384
200	19	304	18	288
250	15	240	14	224

It is apparent from the summary of total costs that the shortest span results in the least expensive combination. The 150 feet span case is therefore recommended for selection for the conceptual design.

3.4 HTS

The possibility of substituting 316 SS for the Incoloy 800 in the hot salt piping is being explored. If the stainless steel is found to be suitable, the HTS will require an additional economic optimization. The net effect will be a reduction on the HTS cost, a reduction in the HTS pressure drops, a small increase in the EPGS net cycle efficiency, and a small decrease in the cost of the collectors and receivers.

Three alternate schemes for HTS freeze protection during the overnight shutdown were briefly reviewed. These include the following:

- Electric heat tracing
- Overnight salt circulation with the thermal energy provided by additional collector, receiver, and storage tank capacities

- Overnight salt circulation with the thermal energy provided by oil-fired salt heater.

On an annual basis, the least expensive freeze protection is provided by the oil-fired salt heater. During system operation, receiver isolation valves are closed and a bypass valve at the end of each receiver row, joining the hot and cold headers, is opened. Salt is drawn from the cold storage tank at 570°F and is pumped through the cold headers, bypass valves, hot headers, salt heaters, and is returned to the cold storage tank at 570°F. The circulating salt is heated as it returns to the tank, rather than as it leaves the tank, to minimize the thermal losses during circulation. The salt flowrate is controlled to maintain a minimum salt temperature of 470°F, or approximately 40°F above the freezing temperature. The receivers are isolated for two reasons. First, they are not expected to freeze during an overnight shutdown and, second, the receiver temperature for the morning start-up will be maximized if it is isolated from the 570°F circulating salt. The evening power requirement for the salt circulation pumps is approximately 54 kW_e and the fuel oil consumption is approximately 50 bbls. per day.

3.5 ESS

A detailed cost comparison was made between the central and dispersed N + 1 tank systems to determine the optimum location of the ESS. The cost comparison included the following components:

- Tanks and foundations
- Hot and cold main salt headers between the ESS and the EPGS
- Hot and cold salt pumps
- Plant capacity to drive the salt pumps
- Thermal losses from the storage tanks

At the direct cost level, the dispersed tank system has an approximately \$480,000 advantage over the central tank system. Therefore, the dispersed location N + 1 tank system with N equal to 2, has been selected for the conceptual design.

3.6 EPGS

Parametric performance and cost data have been developed for 1800, 2000, and 2400 psig turbine cycles with throttle and reheat temperatures of 1000°F and a final feedwater temperature of 450°F. These data, shown below, will be used by SRI to determine the optimum EPGS operating conditions.

<u>Throttle Pressure (psig)</u>	<u>Net Cycle Efficiency (%)</u>	<u>Direct plus Engineering Costs (\$1,000)</u>			
		<u>EPGS</u>	<u>SG</u>	<u>HTS</u>	<u>ESS</u>
1800	39.02	16,481	2705	20,465	7344
2000	39.29	16,558	2909	20,492	7122
2400	39.64	17,031	3345	20,662	7260

As the 2000 psig turbine is not now a standard design, the selection of the throttle steam pressure for the conceptual design will probably be limited to a choice between the standard 1800 and 2400 psig turbine cycles.

3.7 Collector Foundations

Parametric collector foundation designs and cost data were developed to assist in the determination of low-cost foundations needed to support the collectors designed by Acurex for the line-focus system. Three collector configurations with different foundation spacings were defined by Acurex and formed the basis for nine alternative foundation designs by Bechtel. The design of a pedestal supported by the caisson and extending six feet above grade was also included at the request of Acurex. Three caisson diameters were assumed for each foundation spacing and their corresponding embedment depths were calculated in accordance with the UBC. The general arrangement is shown in Figure 7. The resultant sizes are listed in Table D and E for the drilled pier and pedestal, respectively. Type A, B and C caissons are for foundation spacings of 60, 40 and 20 feet, respectively.

Cost estimates were prepared for the nine alternative foundation designs. Initial estimates were made based on conventional construction practices, utilizing a subcontract for the augering work. Costs were derived from previous Bechtel construction experience and oral quotations from various contractors and material suppliers in the Southwestern U.S. Due to the highly repetitious

Figure 7. COLLECTOR FOUNDATIONS ARRANGEMENT

TABLE D
SIZE OF COLLECTOR FOUNDATIONS

<u>Caisson Type</u>	<u>Diameter (feet)</u>	<u>Depth (feet)</u>	<u>Concrete (yd³)</u>	<u>Rebar (lbs)</u>
A-1	3	10	2.6	200
A-2	2.5	10.75	2.0	170
A-3	2	11.75	1.4	140
B-1	2.5	9	1.6	110
B-2	2	10	1.2	120
B-3	1.25	12	0.6	100
C-1	2.33	7	1.1	110
C-2	2	7.5	0.9	90
C-3	1.25	9	0.4	70

TABLE E
SIZE OF COLLECTOR PEDESTALS

<u>Type</u>	<u>Size (inches)</u>	<u>Concrete (yd³)</u>	<u>Rebar (lbs)</u>
A	12 × 15	0.3	100
B	8 × 13	0.2	90
C	8 × 13	0.2	90

nature of the work involved, the focus of the estimate shifted to examining various cost reduction possibilities. Implicit in this examination was the assumption that the cost estimate reflects the first commercial plant. The possibility was explored of realizing a cost reduction through the use of advanced equipment which could reduce the labor input through mechanizing the augering, rebar placement and concrete filling process. It was found that the cost of the capital intensive new equipment outweighed the possible labor saving advantages. It was concluded, however, that for future generations of plants, more advanced construction equipment could be employed at an overall cost reduction if a firm commercial market was established for their use. The equipment cost could then be written off over a number of construction projects.

For the first commercial plant, it is conceivable that labor saving could be achieved over the standard installation rates for this type of work through the use of multiple crew units. In view of the extent of the repetitions involved, it was determined that a 95% learning curve could reasonably be employed over the duration of work resulting in an approximate 25% labor man-hour saving. Table F, which includes the learning curve effect, contains the results of the estimate for the first commercial plant. The estimate includes material, direct labor, and engineering costs at 10% of the direct costs and is in mid-1978 dollars.

TABLE F
COLLECTOR FOUNDATION COSTS
(1978 Dollars)

Type	Cost per Unit (\$)	Units per 100 MW _e plant*	Total Cost (\$)
A-1	273	36,000	9,840,000
A-2	236	36,000	8,500,000
A-3	202	36,000	7,290,000
B-1	192	50,000	9,610,000
B-2	166	50,000	8,320,000
B-3	127	50,000	6,370,000
B-3 (without pedestal)	94	50,000	4,680,000
C-1	138	94,000	13,000,000
C-2	123	94,000	11,600,000
C-3	93	94,000	8,700,000

*From Acurex

From Table F, it is apparent that the smallest diameter, longest length foundations are the most cost effective. The estimate was reviewed with Acurex, who indicated that the Type B-3 foundation was the most economical when considered in conjunction with the collectors. In order to permit Acurex to determine whether the pedestal would be more cost effective as part of the collector assembly, an alternate estimate was included in Table F for the Type B-3 foundation without a pedestal.

3.8 Master Control Subsystem

No further parametric analyses were performed on the master control subsystem during the reporting period.

4.0 Commercial Plant Selection

4.1 General

The 100 MW_e plant design specifications have been established. They are:

- 16 rows of collectors of nominal length 2925 feet each
- 21 rows of 3-meter wide heliostats per 60 meters high linear cavity receiver
- 6-meter spacing between heliostat mounting
- 550°F salt into the receiver
- 1050°F from the receiver
- 450°F feedwater to the steam generator
- 2000 psi, 1000°F steam to turbine
- 520 psi, 1000°F reheat conditions in turbine
- 3 equally sized salt storage tanks capable of hot or cold salt storage, for a system storage capacity of 750 MWh_e.

The resulting capacity factor is 0.6 on an average daily basis. That is, the plant operates at 100 MW_e for 0.6 of the day. The annual BBEC based on a heliostat cost of \$5/ft² is 59 mills/kWh_e. The largest remaining unknown in the plant design is the heliostat cost and its associated performance. Heliostat costs approaching \$5/ft² are being projected for the glass fiber reinforced cement heliostat with second surface glass on a fiber reinforced cement substrate. The BBEC has been also estimated for values of \$7/ft² and \$9/ft², in addition. Their BBECs are 66 mills/kWh_e and 74 mills/kWh_e, respectively. The values are in 1980 dollars for the 80th plant to begin operation in 1990.

Figure 8 shows the performance of several plants in the terms of BBEC vs. average daily capacity factor. For a given size storage system, the curves show a minimum in BBEC vs. the average daily capacity factor. The curves were generated by selecting a design and changing the length of the collector field only. As the additional collector area is added, the electrical generation system is more fully utilized (the average daily capacity factor increases). Thus,

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Figure 8. *EFFECT OF CAPACITY FACTOR WITH VARYING STORAGE*

the BBEC decreases as the capacity factor increases. At some point, more energy is collected by the increased collector size than can be used or stored. This excess energy is wasted and the increased collector field thus contributes to the cost without adding to the capacity.

An increase in the storage capacity of a plant allows operation at a larger capacity factor and generally at a decreased BBEC. The BBEC of the envelope decreases until a capacity factor in excess of 0.9 is reached. The plant design selected was sized to give a capacity factor of 0.6. This is because the projected cost of solar energy is not yet sufficiently low at this time to compete with other forms of base load energy used at higher capacity factors. The solar energy appears to be most competitive to the intermediate load plant at the present time.

This 100 MW_e plant design is the culmination of the parametric analysis. It provides us with a design that can still be improved to give better cost and performance. The selected design shows a minimum in BBEC with respect to changes in nearly all of the current input parameters. It is conceivable that improvement in performance or cost variables could result in minor changes from this optimized design.

4.2 EPGS

Parametric performance and cost data were developed for the 2400 psig/1000°F/1000°F turbine cycles with steam generator preheater pinch point temperatures of 20°F and 10°F. Twenty degrees Fahrenheit had been originally selected for the baseline plant design and 10°F was felt to be the minimum pinch point temperature for stable steam generator action. The results of the analysis are summarized below.

Pinch Point Temperature (F)	Salt T (F)	Efficiency (%)	<u>Direct plus Engineering Costs (\$1000)</u>			
			<u>EPGS</u>	<u>SG</u>	<u>HTS</u>	<u>ESS</u>
10	489	39.67	17,019	3650	19,996	7070
20	476	39.64	17,031	3345	20,662	7260

Based on preliminary receiver performance figures and receiver and collector costs from SRI, a 10°F pinch point temperature appears to be a better choice than 20°F.

5.0 Subsystem Experiment

The model of the receiver for convection and wind loss experiments in the University of Illinois is being constructed. The heating system is being built for steady state measurements, instead of transient as originally planned.

6.0 Assessment of Commercial HTLF System

There were no further market penetration studies during the reporting period. Now that the projected costs of electricity as a function of capacity factor are available, market penetration studies will be updated based on these projections during the next reporting period.

7.0 Phase I Management

A presentation was made at the semi-annual review at Reston, Virginia, on 21 March 1979. A strong case for an increased emphasis on the commercial development of annealed molybdenum and amorphous silicon selective surfaces being studied at the University of Arizona was presented.