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EVALUATION OF LINE FOCUS SOLAR CENTRAL POWER SYSTEMS

Volume 1, Executive Summary

MASTER

March 15, 1980

Work Performed Under Contract No. EY-76-C-03-1101-014

The Aerospace Corporation
Energy and Resources Division
El Segundo, California

U.S. Department of Energy

Solar Energy

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EVALUATION OF LINE FOCUS
SOLAR CENTRAL POWER
SYSTEMS

Volume I
Executive Summary

Prepared for
U.S. DEPARTMENT OF ENERGY
Solar Energy Division, DOE/SAN

Contract No. EY-76-C-03-1101(PA #14)

15 March 1980

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EXECUTIVE SUMMARY

1.0 INTRODUCTION

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. In support of this effort, the Division of Solar Technology's San Francisco Operations Office has recently conducted a program with three industrial teams for the analysis, conceptual design, and limited testing of three line focus concepts for central utility power generation.

This report describes The Aerospace Corporation analysis and evaluation of these line focus designs and technology and compares their potential with that of the central receiver point focus concept. The report is in two volumes: Volume I is the Executive Summary and Volume II contains the System Evaluation and the Appendices.

1.1 PROGRAM OBJECTIVES

The major goal of the program is to assess the applicability of line focus technology for generation of large scale electrical power. The specific objectives of the current program are to:

- Develop the optimum line focus solar central power plant system conceptual design.
- Compare the line focus solar central power plant with the first generation point focus central receiver technology on the basis of cost effectiveness.
- Identify the most attractive utility and commercial line focus application and assess the overall market potential.

To achieve these objectives, DOE, via solicitation RFP No. ET-78-R-03-2073 dated July 1978, funded three contractors to perform detailed designs of 100 MWe line focus power systems. The contractors' study approach is described below.

1.2 STUDY APPROACH

The overall program methodology which served to guide the system analysis, design and evaluation is depicted in Figure 1. The program was composed of 10 interrelated tasks:

Task 1 Requirements Definition	Review the DOE requirements definition document and provide comments and recommendations.
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Task 2 Parametric Analysis	Evaluate a wide range of subsystem configurations and sizes to obtain preliminary subsystem data on design cost and performance. Subsystem level optimizations are made and system-dependent data are provided to Task 3.
Task 3 Selection of Commercial System Configuration	Perform system level tradeoff studies to select the preferred commercial system configuration based on maximizing the potential worth of the system to the utility.
Task 4 Commercial Plant Conceptual Design	Prepare a conceptual plant design for the concept selected in Task 3.
Task 5 Commercial Plant Cost and Performance Estimates	Prepare preliminary cost and performance estimates for the commercial scale plant conceptual design developed in Task 4.
Task 6 Limited Subsystem and Component Experiments	Design, fabricate, perform, and report on limited experiments.
Task 7 Assessment of Commercial Line Focus Plant	Assess the economics, performance, potential improvements, and limitations of the line focus plant.
Task 8 Development Plan	Deleted during the study. ⁽¹⁾
Task 9 Phase II Plan and Proposal	Deleted during the study. ⁽¹⁾
Task 10 Program Planning and Management	Provide planning, management, and reporting to accomplish the study.

1.3 CONTRACTORS AND TECHNICAL MANAGEMENT

The program organization is summarized in Figure 2. DOE selected three contractor teams to design 100 MWe systems each using a different line focus approach:

- The BDM Corporation (BDM) concept incorporates a parabolic trough collector system to provide heat for a conventional low pressure non-reheat steam cycle. Thermal storage is based on the single tank thermocline principle.

⁽¹⁾ As originally planned, Phase I of this multi-phase program would develop line focus conceptual designs and the concepts with the best overall potential were to be further developed in subsequent program phases. DOE, however, chose not to continue the study beyond Phase I.

Figure 1. Program Overview

Figure 2. Line Focus Central Power System Organization

- The General Atomic (GA) solar collector is a fixed mirror tracking receiver configuration which heats a draw-salt working fluid to temperatures beyond 1000°F. The salt transfers heat to a conventional high pressure reheat steam cycle. Thermal storage uses the two tank principle.
- The SRI International (SRI) system consists of multiple rows of linear heliostats which reflect solar energy to a line receiver situated on a 200 ft tall tower bridge structure. The steam plant utilizes a modern high pressure reheat steam cycle. Thermal storage is a modified two tank configuration.
- The concluding phase of an existing FMC Corporation linear heliostat test program was also included within the scope of this program. These test results were principally applied to the SRI configuration.

The Aerospace Corporation served as the DOE technical manager for the program. Aerospace assisted DOE in program planning, provided technical guidance, and reviewed progress and approved technical results of the line focus contractors. Aerospace also performed independent technical analysis of contractor concepts, and performed comparative evaluation of these line focus concepts with competing central receiver designs.

Sandia Laboratory, Livermore, provided DOE/SAN with an independent evaluation and review of this line focus project.

2.0 SYSTEM DESCRIPTION

Preliminary Line Focus Power Plant (LFPP) requirements for the proposed 100 MWe system have been specified by DOE in the Requirements Definition Document. The contents of the DOE document are outlined in Table I and the document is provided in its entirety in Appendix A of Volume II.

The Requirements Definition Document provides a detailed description of the system, subsystems, and all applicable interfaces. The document also provides delineation of the Codes and Standards or references to specific documents, which will govern the ultimate design of the LFPP.

The key design requirement which sizes the plant is a power level of 100 MWe, available at least four hours on winter solstice, without use of thermal storage and assuming normal insolation. Although this design point was specified, for comparative evaluation purposes, the contractors were allowed to vary the plant rating and energy storage capacity if more attractive economic performance resulted. The plant environmental requirements were based on a plant site at Barstow, California.

The following sections briefly outline the contractor descriptions of the individual LFPP concepts. The key characteristics of the plant are given in Table 2. Detailed descriptions are available in the contractor Final Reports.

Table 1
SYSTEM REQUIREMENTS OUTLINE

- SYSTEM/SUBSYSTEM DESCRIPTION AND INTERFACES
 - Electrical Power Output
 - Operating Modes
 - Subsystem Requirements
- ENVIRONMENTAL CONDITIONS
 - Design Environments
 - Operating Environments
 - Survival Environments
- LFPP COST BREAKDOWN STRUCTURE

Table 2
LINE FOCUS SOLAR CENTRAL POWER SYSTEM - SUMMARY

<u>SYSTEM</u>	<u>SRJ</u>	<u>GA</u>	<u>BDM</u>
Plant Rating (MWe)	100	100	150
Thermal Storage Size (MWe-hr)	750	920	230
Average Daily Capacity Factor (N.D.)	0.6	0.5	0.4 (based on 160 MWe turbine)
Average Annual Efficiency (%)	16.5	12.9	11.5
<u>COLLECTOR SUBSYSTEM</u>			
Concentrator Type	One Axis HelioStat	Fixed Mirror	Parabolic Trough
Unit Area (ft ²)	1600	199 (11.8 x 18)	420 (20 x 21)
Collector Aperture Area (ft ²)	9.8 x 10 ⁶	10.4 x 10 ⁶	12.6 x 10 ⁶
<u>RECEIVER SUBSYSTEM</u>			
Receiver Configuration	Linear Cavity on Towers (Internal Heat Absorbing Tube)	Cavity, Steel Shell w/Tube Trussing	"D" Tube with glass cover
Receiver Module Dimensions	6 ft dia - 8 ft aperture x 80 ft length	1-3/4 ft absorber tube dia 5.3 x 5.2 x 36 ft	4.5 ft dia tube, 140 mm dia pyrex glass cover
Number of Receiver Rows	10	922	604
Receiver Length/Row (ft)	4420	900	1000
Coolant Inlet/Outlet Temp (°F)	450/1050	544/1069	452/592 LT Field 557/740 HT Field
<u>ENERGY STORAGE SUBSYSTEM</u>			
Storage Media	Draw Salt	Draw Salt	T33/Taconite LT Field Syltherm 800/Taconite HT Field
Storage Configuration	Modified two-tank	Two tank	Thermocline
Storage Temperatures (°F/°F)	450/1050	561/1050	452/591 LT Field 558/739 HT Field
<u>ELECTRICAL POWER GENERATING SUBSYSTEM</u>			
Turbine Inlet conditions (psi/°F/°F)	2400/1000/1000	2400/1000/1000	415 psia/700°F
Net Heat Rate (Btu/kW-hr)	8615	8600	11173 at 165 MWe 11899 at 100 MWe

The BDM plant satisfies the design power requirement of 100 MWe for four continuous hours every day of the year, and has sufficient thermal storage to generate an additional 230 MWe of energy. BDM selected a low pressure 165 MWe steam turbine, with 150 MWe net output for power conversion. This choice was based on a tradeoff between efficiency and cost of routing solar energy indirectly through storage or directly through the turbine. A resultant capacity factor of 0.40 (based on a rating of 150 MWe) places this LFPP in the intermediate plant category.

The collector layout consists of two fields totalling 12.68 million ft² of reflector aperture area. About 85 percent of the field operates at low coolant temperatures (<592°F) using Monsanto's Therminol 55, and the remaining portion operates at higher temperatures (~740°F) using Dow-Corning's Syltherm 800 inorganic coolant. The objective of the dual field is to minimize the quantity of high cost Syltherm. In operation, the low temperature field provides energy to the boiler, preheaters and low temperature storage, hence setting the turbine throttle pressure, while the high temperature field provides energy to the superheater and high temperature storage, thus setting throttle temperature.

The BDM collector is a single axis tracking linear parabolic trough oriented in the north-south direction. The basic collector, shown in Figure 3, is a 20 ft long, 21 ft aperture parabolic trough assembled on concrete pylons.

Figure 3. T-2100 Solar Collector Construction

Thermal storage design is based on the single tank, sensible heat, thermocline principle using a dual storage medium. For low temperature storage, T-55 and taconite are used as the storage media, and for high temperature storage Syltherm and taconite are used.

2.2 GA PLANT DESCRIPTION

The GA plant design contains a solar collector field which heats draw salt coolant to 1070°F. The molten salt is then transported either to a thermal storage system of 420 MWe-hr capacity or to a salt-to-steam generator. Steam is generated at 2400 psi and 1000°F and passed through a single reheat turbine.

The collector field utilizes GA's fixed mirror solar concentrator (FMSC) collector, Figure 4, with movable receiver. The collector field contains 10.4 million ft² of mirror surface arranged into 972 rows, each 900 ft long, spaced 25 ft apart.

Figure 4. GA Concentrator Design

The receiver is a tube to which is clamped a removable nickel-clad copper cap which has been coated with a selectively absorptive coating ($\text{Pt}/\text{Al}_2\text{O}_3$ cermet). The receiver is insulated on the back with calcium silicate and has a borosilicate glass window. It has a shallow secondary concentrator which is integrated into the thin steel sheet casing of the receiver shell.

The energy storage uses the two tank sensible heat principle. The warm tanks are decentralized to minimize the overall cost of the field.

The steam turbine is a commercially available tandem compound unit operating at 3600 rpm and rated at 106.2 MWe gross. At maximum guaranteed load, the throttle steam conditions are 2400 psig/1000°F and reheat steam conditions are 421 psig/1000°F.

2.3 SRI PLANT DESCRIPTION

In the SRI system (Figure 5) the sun's radiation is reflected from second surface mirror panels mounted on the heliostat frame to cavity line receivers located at the top of a 200 ft tower truss structure. The single axis concentrators are each 10 ft wide and 160 ft long and are controlled by a central computer. Each heliostat is aimed by a single motor and all heliostats move in synchronization.

Figure 5. SRI Cement Heliostat

The receiver is a horizontal cylindrical cavity 6 ft in diameter with a 4 ft aperture. The receiver aperture faces downward to the north at an angle of about 40° to the horizontal. The top edge of the aperture has doors, the reflective inside surfaces of which act as a secondary concentrator, and which close at night to conserve heat. The inside of the cavity is lined with horizontal heat-exchanger tubes backed by fiber insulation. The hot salt is delivered through insulated downcomers and an insulated common horizontal pipe directly to the storage hot tanks and to the heat exchanger that generates steam for the turbine generator. The function of the energy storage subsystem is to buffer the electrical power generating subsystem (EPGS) from the results of excessive variations in insolation, and to extend the plant's generating capabilities into periods of low (or no) insolation.

The EPGS uses commercial reheat steam cycle technology. The steam throttle conditions are 2400 psig/ 1000°F and the reheat conditions are 421 psig/ 1000°F .

3.0 CONTRACTOR COST AND PERFORMANCE DATA

The BDM annual plant efficiency is 14.4 percent and plant output is 5.38×10^8 kWe-hr based on a solar availability of 90 percent. This corresponds to a 40 percent capacity factor based on a turbine rating of 150 MWe. GA's annual efficiency is 12.9 percent and the plant output is 4.26×10^8 kWe-hr which corresponds to a 45.6 percent capacity factor. The SRI efficiency is 14.9 percent and the annual output is 5.26×10^8 kWe-hr with a plant capacity factor of 60 percent.

Each of these values is based on different subsystem performance assumptions and various plant operation strategies. In Section 4 the performances of the plants are compared using similar performance assumptions and operating strategy.

The contractor capital cost estimates were based on the conceptual design and engineering information prepared in the study in the form of engineering drawings, specifications, and equipment lists. The construction cost estimate is composed of field costs, engineering services, contingency and fee. The largest category, field costs, contains the direct costs of permanent plant equipment and labor, and the indirect costs of temporary construction materials, supervision, etc. to be distributed across the facilities. The estimates anticipate direct-hire operation employing field construction labor forces.

All estimates use second quarter 1979 price and wage levels. No allowance has been made for future escalation. The capital cost summary in Table 3 follows the DOE specified accounting format.

4.0 PERFORMANCE AND COST EVALUATION

Before judgment could be made on the relative merits of systems, the plant data summarized above were reviewed to insure that the same design, performance and cost assumptions had been used by each contractor. Based on these equivalent assumptions, new contractor annual energy costs were then developed. Finally, the line focus systems data were compared to the advanced central receiver technology (Martin Marietta salt receiver) to determine the relative merits of two types of systems for large plant electrical utility applications.

Table 3
PLANT COST ESTIMATE SUMMARY BY ACCOUNT (x \$1000)

ACCOUNT NO/DESCRIPTION		BDM	GA ⁽¹⁾	SR ⁽²⁾
5100	Land, Site Preparation	3,430	4,380	4,720
5200	Administration Areas	1,129	830	302
5300	Concentrator Subsystem	62,280	82,701	15,737
5400	Receiver Subsystem	8,800	55,915	12,131
5500	Master Control Subsystem	2,908	406	400
5600	Heat Transport Subsystem	30,039	26,428	16,935
5700	Thermal Storage Subsystem	9,914	4,651	7,467
5800	EPGS Subsystem	35,234	24,635	22,357
Total Direct Field Costs		153,776	199,050	101,429
Indirect Field Costs		7,176	28,712	37,225
Total Field Costs		160,950	227,762	138,654
Engineering & Home Office Costs		3,363	11,390	6,930
Total Field & Home Office Costs		164,313	239,152	145,580
Contingency		1,812	34,061	20,100
Fee		—	10,245	6,216
Total Construction Cost		166,125	283,458	171,906
Coolant Costs		—	3,564	7,376
Total Cost		166,125	287,022	179,280
Cost per kW ⁽²⁾		1,661	2,870	1,793

(1) First Plant Cost Estimate

(2) This number is based only on engine rating, not on plant energy output and, therefore, is not a good indicator of plant energy costs.

4.1 EVALUATION APPROACH

The system evaluation approach is shown in Figure 6. The contractor designs were based on a common set of requirements; however, each concept was also based on different levels of uncertainty in their design practices and performance and cost assumptions. The first step in the evaluation or rating of the candidate power systems was the selection of a set of performance attributes. The attributes calculated in detail are busbar energy cost (BBEC), capacity factor, and system efficiency. Other nonquantitative attributes such as development risk and growth potential were discussed separately. These sets of attributes were first prepared based on the performance and cost data provided by the contractors. Only the top level economic conditions were equalized.

Because of the nonuniform assumptions made by the contractors, the next step in the analysis was to normalize the contractor performance and cost data. This was done by collecting and apportioning the individual contractor datum into separate performance and cost accounts. Each account was then individually normalized using common assumptions. The data were entered into the computer where the performance attributes were calculated and the individual systems rated.

Figure 6. Evaluation of Power Plant Design Concepts

An initial busbar energy cost parametric analysis was performed to determine the sensitivity of this parameter to the key system independent variables, including annual system efficiency and specific cost (\$/ft² aperture) for the collector, receiver and heat transport subsystem. The remaining economic variables were defined with common models. These included:

- Specific cost for land, buildings, EPGS, MCS, and thermal storage
- Economic model
- Indirect costs, cost contingency and profit percentage.

The objectives of this analysis were first to make an initial system comparison and then to identify the cost and performance objectives for these systems to bring them into a competitive range. These analyses are described in greater detail in References 1 to 3.

The busbar costs as a function of the independent variables are shown in Figure 7 with the contractor values for these variables superimposed on the matrix. The Martin Marietta (MM) central receiver system has the highest plant efficiency. The central receiver also claims lower specific cost than GA and SRI thereby giving it a substantial busbar energy cost advantage. Only BDM claims a lower specific cost than does the central receiver contractor and this provides BDM with essentially equal busbar costs at this lower capacity factor.

Figure 7. Busbar Energy Cost vs Plant Efficiency and Field Specific Cost, 100 MWe Turbine

4.3 COST AND PERFORMANCE NORMALIZATION

Unfortunately, in the evaluation of the line and central receiver systems, only rough, first order, comparisons could be made due to lack of definitive proof-of-principle test data and the preliminary state of real cost data. Additional difficulties resulted from the differences in design and development policies between the two solar communities. The central receiver developers typically identify ambitious performance and cost goals as future objectives to strive for while the line focus community has stressed near term development and test. As a result, the line focus contractor designs, which were in the most part growth versions of existing hardware, are somewhat more conservative than the advanced central receiver designs.

The Aerospace approach for cost and performance normalization is summarized below:

- Use contractor data on central receiver performance.
- Use Aerospace modified performance data on line focus.
- Equalize the effects of unresolved issues such as startup problems, O&M, construction schedule, etc.
- Use common cost estimating algorithms for common subsystems.
- For unique subsystems such as collectors and receivers, divide subsystems into common elements such as reflective unit, drives, piping and structure and compare costs on that basis.

The key elements of the cost normalization were the collector and receiver specific costs which are summarized in Tables 4 and 5. The derivation of these numbers is included in Section 4 of Volume II.

4.4 NORMALIZED BUSBAR ENERGY COST COMPARISONS

Figure 8 shows a comparison of the busbar energy costs for the competing systems at the 100 MWe power level. The GA and SRI costs are higher than those of the advanced central receiver (ACR) primarily due to lower annual efficiencies which were not compensated by lower capital cost. The baseline BDM plant is competitive in the peaking and intermediate load capacity factor region and the ACR displays lower cost at the higher capacity factors.

5.0 LINE FOCUS APPLICATIONS

The contractors investigated only the large scale (≥ 100 MWe) stand alone plant. The technology identified in this program, however, can be applied to other applications noted in Figure 9.

5.1 SOLAR MARKET POTENTIAL

The solar market potential for line focus technology is summarized in Figure 10. The estimates for the peak, intermediate and base load utility market were taken

Table 4
NORMALIZED COST BREAKDOWN FOR HELIOSTAT AND COLLECTORS (\$/ft² aperture)

	ACR 2 Axis Heliostat	BDM Parabolic Trough	GA Fixed Reflector	SRI 1 Axis Heliostat
Mirror Surface	1.16	1.16	2.736	1.16
Reflector Backing	3.24	—	—	2.4
Structure	1.08	2.31	3.81	1.027
Drives	1.22	0.0445	0.035	0.079
Actuators	0.85	0.56	0.25	0.28
Control & Wiring	0.72	0.11	0.093	0.324
Pedestal/Foundation	0.75	0.87	0.7485	0.29
Installation (12.5%)	1.128	0.63	0.96	0.70
Total	10.16*	5.68	8.63	6.32

*Does not include inverted stow capability; adding this capability would ensure a 15% cost penalty.

Table 5
NORMALIZED RECEIVER COST BREAKDOWN (\$/ft² aperture)

	Central Receiver	BDM	GA	SRI
Absorber Unit & Headers	0.506	0.22	0.34	1.75
Glass Cover & Fastening	—	0.17	—	—
Structure	0.307	0.149	0.845	1.3122
Insulation	0.022	—	0.5	0.423
Tower & Foundation	0.792	—	—	1.41
Crane	0.15	—	—	—
Total	1.394	0.342	1.685	4.293

Figure 8. Envelope of Busbar Energy Cost, 100 MWe Turbine: Normalized Design

Figure 9. Potential Line Focus Applications

Figure 10. Summary of Potential Line Focus Markets

from an SRI evaluation (Reference 4). SRI estimated the utility electrical generation capacity to the year 2000 by careful review of the requirements of 61 major electrical utilities representing approximately 75 percent of the total generating capacity of the western United States, and an estimated 90 percent of the total market. The electricity growth was projected at 5.3 percent for the period 1975-1985, and 3.8 percent for the period 1985-2000. This was corrected for each category (base, intermediate and peak) for expected retirements (after 30 years) and expected transfers from base to intermediate units (<400 MWe and >15 years old).

The potential market for electrical repowering and industrial process heat (equivalent aperture area) were both estimated to be as high as 18,000 MWe (References 5, 6). Both these estimates are expected to be reduced when other limitations such as plant life, availability of solar equipment plant cycling capability and institutional and political constraints on the utilities are considered.

The estimate for new industrial process heat was based on a Battelle Laboratories study (Reference 7). Battelle predicts that industry will require 12.4×10^{15} Btu per year of process heat by 1985 and 16.8×10^{15} Btu per year by the year 2000. This market converted to equivalent collector size units is greater than the combined new electrical market potential.

5.2 "COMBINED" LINE FOCUS PLANT

An attempt was made to develop an optimal line focus plant by combination of the most effective design features and analytical approaches identified by the three line focus contractors. The plant consisted of a parabolic trough solar collector subsystem combined with the high performance but lower operating temperature internal reheat electrical power generation subsystem similar to those used by the nuclear industry. The key design features of this approach are listed below:

- T-2100 large aperture parabolic trough collector (BDM)
- Glass protected receiver tube operating at low average temperatures to reduce convection and radiation losses (BDM)
- Integrated collector field, heat transport configuration to minimize piping size and costs (GA)
- Increased length of collector rows to reduce heat transport cost
- Single stage primary loop with high ΔT to reduce flow rate
- High ΔT across the thermal storage to increase storage effectiveness.

The busbar energy costs for this plant, shown in Figure 11, are below those of other candidate systems. The increased performance is due to reduced receiver losses which result from operating at lower temperature, higher conversion efficiency due to the use of a modified nuclear type steam cycle and deletion of the costly high temperature Syltherm 800 heat transport loop used by BDM.

The "combined plant" design is described in some detail in Section 5 of Volume II. However, other than its basic elements which were taken from the contractor studies the plant has not been analyzed to a sufficient level of detail to fully justify the promising cost data.

5.3 HYBRID PLANT

Each of the utilities which participated in the studies indicated a preference for systems for which they could claim full capacity credit independent of solar insolation. Each of the contractor units can be readily converted to solar fossil hybrid designs and one contractor has already located an optional fossil heater in his plot plans.

The "combined plant" was modified to the hybrid combination and the design is described in Section 5 of Volume II. The busbar energy costs for this plant are higher than the stand alone plant due to the added expense of the fossil heater and fuel. However, the plant can provide capacity credit for the utility.

5.4 LINE FOCUS REPOWERING APPLICATIONS

The following factors prevent line focus systems from being effective candidates for full boiler repowering of conventional plants:

- Economics are less favorable than central receiver.

Figure 11. Energy Cost for "Combined" and Hybrid Plants

- Technology development will probably not be completed within the repowering window (pre-1990).
- The necessary early system integration studies have not been initiated.

However, by repowering the lower temperature elements of the steam cycle, significant solar fractions can be achieved. The regenerator, economizer and the evaporator sections of the steam cycle can be repowered with low temperature nearer term technology elements. Even with reheat plants these elements can input over 65 percent of a plant's required heat.

As an example, a study was performed to determine the feasibility of using low temperature solar feedwater heating on conventional fossil fired power plants to reduce the amount of fossil fuel required to preheat boiler feedwater. Solar feedwater heating also takes advantage of unused turbine-generator capacity by passing boiler steam completely through the turbine rather than using bypass flow for regenerative heating. This earns capacity credit for the utility and the added

capacity may be used for peaking loads. The system can also be used with or without storage as a fossil fuel saver. An analysis of this plant is given in Section 5 of Volume II.

The economics of line focus repowering are summarized in Figure 12. For full boiler repowering the line focus plants do not make economic sense ($C/B > 1.0$) without some sort of subsidy. The regenerative repowering plant, however, does make economic sense using Nth plant or nearer term collector costs.

5.5 INDUSTRIAL PROCESS HEAT APPLICATIONS

A large potential solar process heat market has been identified as noted in Figure 9. The bulk (~60 percent) of this energy is required in the form of process steam at temperatures below 600°F. The high temperature applications are for furnaces, gas turbines and other engines for shaft power, heaters, and direct fired reactors. Approximately 50 percent of this energy is provided by miscellaneous fossil fuels such as oil or gas and the remainder are fuels which are byproducts of the plant process itself.

A study was performed to determine the performance and cost characteristics of solar process heat energy sources using the line focus technology identified in this program. The specific designs developed included 300 MWt (rated at summer solstice) plants with operating temperatures of 375 to 600°F, 60 to 300°F and 60 to 200°F.

A comparison of line focus and central receiver systems for this application is given in Figure 13. The annual efficiencies of the two plants are equivalent, and therefore the annual energy cost difference is due primarily to the collector specific cost differences assumed in this study.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The potential of line focus designs for large scale electrical power applications and some of the important issues concerning line focus systems are summarized below. The issues addressed include technical, performance and cost goals, technology requirements, and market potential.

6.1 GENERAL CONCLUSIONS

- All three contractors performed careful, thorough, and technically responsive studies. As might be expected, however, there remains a substantial uncertainty over annual energy costs.
- There are no fundamental technical limitations on the deployment of any of the proposed line focus systems up to power ratings of 300 MWe given that the development issues outlined below are achieved.
- Each of the contractor designs will require additional development and system integration effort to obtain the performance levels defined herein.

Figure 12. Line Focus Repowering

Figure 13. IPH Energy Costs

- Two of the line focus system (LFS) contractors claim lower busbar energy costs than the first generation strawman point focus system; only the parabolic trough design, however, appears to have the potential to match the advanced central receiver system (ACR) cost performance goals.
- The full potential of advanced second generation parabolic trough systems was not completely identified in the contractor study. Of particular interest would be the matching of a single stage parabolic trough collector system operating at lower temperatures combined with conventional steam cycles now used in the nuclear industry which achieve gross conversion efficiencies greater than 35 percent with steam conditions of 550°F and 1000 psia (see Section 5.3 of Volume II).

6.2 COMPARISON OF CENTRAL RECEIVER AND LINE FOCUS SYSTEMS

A rigorous comparison of the two technologies at this time is difficult to accomplish due to lack of definitive performance and cost data for all concepts, and due to the different technology development philosophies of the two solar communities. Even a heavily funded detailed evaluation, based on the review of manufacturing drawings, fabrication processes, installation procedures, and review of performance data, etc., would not today provide a definitive answer, since some of the components under the study have not passed proof of principle as yet. As a further example of the difficulty of this problem, even a cost comparison of basic components such as heliostats and parabolic troughs could be misleading due to different design approaches taken by the developers. The heliostat community has emphasized advanced mass produced cost effective design to provide cost goals, while the line focus community stresses prototype construction and test. As a result the line focus designs are somewhat more conservative than their central receiver counterparts.

The comparison approach utilized in this report thus can best serve to identify leading candidates and key technology issues. With this understanding the following points of comparison are offered.

- The GA and SRI high temperature salt systems, though less risky than ACR, show less promise than the ACR salt system and, to a large extent, their further development would be a duplication of effort.
- The advanced central receiver system is superior to the three LFS configurations at high plant capacity factors associated with base load utility units.
- The lower temperature parabolic trough appears to be an excellent candidate for large power system applications in the peaking and intermediate capacity factor regions. This is the area in which solar plants are most likely to penetrate the utility market. Further, single stage lower temperature parabolic trough technology in combination with the low temperature internal reheat steam cycle technology of the nuclear industry could increase this system's cost effectiveness throughout the capacity factor range.

- The line focus collector hardware appears to be inherently less costly than central receiver heliostats due to: fewer and less intense structural loads, inherent structural stability provided by multiple supports; fewer drives, actuators, power supplies, and controllers per unit aperture area, lower installation costs due to field linearity, simpler components, lower weight, and ground level construction. Also, O&M costs for line focus system appear to be lower than central receiver due to fewer pieces of equipment in the field, the use of linear arrays, and (for the parabolic trough) lower operating temperature. Finally, development costs for the parabolic trough should be the lowest of all concepts due to the use of nearer term technology, lower temperatures, and system modularity.

6.3 OUTLOOK FOR APPLICATIONS OF LINE FOCUS SYSTEMS

Estimates of the electric utility market available to solar within the next 30 years are problematical. The line focus market penetration studies all indicated that the best solar opportunities were in peak and intermediate load applications. The LFS contractors agreed that it will be difficult for solar plants to compete with nuclear and coal plants for the base load market, even when using optimistic projections for Nth plant solar energy costs. It was further concluded that hybrid solar designs are needed to gain capacity credit and to gain acceptance by the utilities.

In the area of repowering of existing utility power plants, it is improbable that near term line focus technology can be applied to conventional high temperature ($\sim 1000^{\circ}\text{F}$) systems because of coating development problems and poor economics. Repowering the regenerator of conventional plants, however, with low temperature solar collectors not only makes economic sense for fuel displacement, but for some turbine conditions, may even provide capacity credit. Field sizes (approximately 10 to 14 percent of the plant rated capacity) are large enough to demonstrate the potential of solar to the utility.

Industrial process heat (IPH) applications appear to provide a market for solar systems which is larger than that of utility applications. This market is concentrated at temperatures below 600°F and, if institutional factors could be resolved, the line focus solar technology, especially low cost and highly efficient parabolic troughs, is ideally suited for this application.¹

6.4 NECESSARY LINE FOCUS SYSTEM TECHNOLOGY DEVELOPMENTS

The performance of all three line focus configurations studied herein strongly depends on the development of stable low emissivity selective-surface coatings. This appears to be the basic need of the line focus community.

In addition, each configuration has its own specific problems. The BDM design requires the successful development of the large aperture glass reflected collector. The GA design requires the development of a low cost factory assembled collector with the performance characteristics noted in the study. The SRI receiver technology has not been demonstrated at the prototype level, and receiver loss estimates must be verified.

In line with the comments and points made in the preceding paragraphs, potential areas for further line focus work include the following:

- A study of the low temperature parabolic trough system in combination with current state-of-the-art low temperature steam cycles. The design should address solar/fossil hybrid capability to match the requirements of the utilities.
- A study of selected repowering designs for utility applications. Of particular interest is the repowering of conventional plant regenerators, preheaters and evaporators with low temperature parabolic troughs.
- A study of the application of the low temperature parabolic trough collector to IPH applications. The application of similar collectors and receivers to both electrical and IPH applications can reduce costs by increasing production levels.
- Construction and evaluation of a prototype of the T-2100 21 ft aperture parabolic trough collector as proposed in the BDM study.
- Further development of the lightweight concrete fiber reinforced structure identified in the SRI study for application not only to the single axis heliostat but to other collectors such as parabolic troughs and two axis heliostats.

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