Systems Analysis of Solar Thermal Power Systems

**Report on Task 1 - Determination and
Characterization of Solar Thermal
Conversion Options**

W. J. Apley

July 1978

**Prepared for the U.S. Department of Energy
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REPORT ON TASK 1 - DETERMINATION AND CHARACTERIZATION OF SOLAR THERMAL CONVERSION OPTIONS

INTRODUCTION

This report documents certain work performed during Task 1 of a project conducted by the Pacific Northwest Laboratory for the U. S. Department of Energy. The purpose of this project is to rank alternative high temperature, high performance solar thermal conversion systems that are potentially suitable for use as electric power generation facilities in the 1 to 10 MWe range, with initial commercialization by the mid-1980s. Task 1 encompassed the initial efforts to identify and describe the generic types of solar thermal conversion options to be analyzed.

LITERATURE REVIEW

An extensive review of available literature was conducted. Over 250 applicable articles, reports, and source items were collected, filed, and indexed. All Solar Energy Updates, ERDA Energy Resource Abstracts, Government Reports Announcements and Indices, Solar Directories, Solar Handbooks, Engineering Indices, and Physics Abstracts were reviewed, and a comprehensive computer search of all Energy Information Data Bases completed. From these sources information was extracted and catalogued by concept in a reference file of over 4500 pages.

This literature search, which will continue during the course of the project, was initiated to provide a reference library for use in both system identification and evaluation. This library is now indexed by an up-to-date bibliography maintained for ease of addition on magnetic card file. References which directly apply to solar thermal power systems are given in Appendix A.

CONTACTS WITH SOLAR THERMAL RESEARCHERS AND MANUFACTURERS

In conjunction with the literature review, a concerted effort was initiated to contact the major component manufacturers and system designers involved in the solar thermal power program. Currently, over 50 sources have been identified and contacted. These include individuals, institutions, and companies with experience in solar component design, power generation system layout, alternative thermal cycles, fluids for energy transport, and methods of advanced thermal, electrochemical, gravitational, and mechanical storage. As with the literature review, this continues to be an ongoing effort, with an established file on each information source. A list of the major contacts established during Task 1 is provided in Appendix B.

CONCEPT IDENTIFICATION

Information obtained from the literature review and contacts with solar thermal power field personnel was used to identify options for further analysis. Seven general solar thermal conversion concepts were selected initially:

1. Point-focus, distributed receiver system using thermal, chemical or electrical (heat engine at focus) energy transport, with either Rankine, Brayton or Stirling power conversion.
2. Point-focus, central receiver system using a field of two-axis tracking heliostats with thermal transport to large Rankine, Brayton or Stirling engines.
3. Fixed-mirror, distributed focus system under development by Texas Tech University and E-Systems.
4. Line-focus, central receiver system developed by FMC with suitable energy transport and power conversion subsystems.
5. Line-focus, single axis tracking collector, distributed receiver system with suitable energy transport and power conversion subsystems. Both solid surfaces (troughs) and slats (facets) will be considered.

6. Fixed mirror, line-focus, distributed receiver system (e.g. General Atomics).
7. Low concentration, nontracking system (e.g., compound parabolic concentrator or V-trough) with suitable energy transport and power conversion subsystems.

The literature review confirmed that these are the only concepts that are developed to a level suitable for inclusion in the comparative analysis to be performed during this project. A summary of information pertaining to these concepts is given in Table 1, and the concepts are briefly described in the following sections. The information presented is abstracted from applicable references listed in the bibliography.

CONCEPT 1: POINT-FOCUSING DISTRIBUTED RECEIVER SYSTEM

The general system consists of two-axis tracking, parabolic dish concentrators. The three transport options include steam, chemical, and electric systems.

Steam Transport

For the steam transport system shown in Figure 1, steam is generated by receivers mounted at the focal point of each dish. It is then transported through insulated pipelines to a central steam Rankine plant with dry or wet cooling towers. The dish collector field is arranged so that saturated steam is generated in the outer portion of the field with superheat occurring in the inner portion closest to the central power plant. The system generates superheated steam at about 1000 °F, with normal energy storage accomplished utilizing a sensible heat thermal system. The dish-steam system is potentially a near-term concept because it uses conventional power plant energy conversion technology.

Chemical Transport

The dish-chemical transport systems are based on using solar thermal energy to drive a reversible, endothermic chemical reaction. The chemical products of the reaction (either gases or liquids) are transported and stored.

TABLE 1. Summary of Solar Thermal Power Concepts

Major System Concept	Major Proponents	Specific Designs	Development Stage				Availability of Reference Material	Contact Personnel or Consultant Availability
			Collector	Receiver	Power Plant	Energy Storage		
1. Point Focusing Distributed Receiver	Garret/Airesearch Honeywell Raytheon Scientific-Atlanta	Dish Steam	Detailed Design	Detailed Design	Detailed Design	Conceptual Design	Excellent	Yes
		Dish Chemical	Detailed Design	Conceptual Design	Conceptual Design	Conceptual Design	Fair	Yes
		Dish Electric (Brayton/Stirling)	Detailed Design	Conceptual Design	Conceptual Design	Conceptual Design	Excellent	Yes
2. Point Focusing Central Receiver	Aerospace Argonne Atomics Int. Bechtel Black & Veatch Boeing Georgia Tech Honeywell Martin Marietta McDonnell Douglas Rocketdyne Sanders Assoc. Sandia Labs Sheldahl Singer Simulation Univ. of Houston	Barstow Facility	Prototype Constr	Detailed Design	Detailed Design	Detailed Design	Excellent	Yes
		Alternate Concepts	Conceptual Design through Prototype Constr.	Conceptual through Detailed Design	Conceptual Design	Conceptual Design	Very Good	Yes
3. Fixed Mirror/Distributed Focus	E - Systems Texas Tech	FMDF (Gridiron Concept)	Detailed Design	Detailed Design	Advanced Conceptual Design	Advanced Conceptual Design	Very Good	Yes
4. Line Focusing Central Receiver	FMC		Detailed Design	Detailed Design	Conceptual Design	Conceptual Design	Minimal	Yes
5. Line-Focus Single Axis Tracking Collector, Distributed Receiver	Acurex Corp Del Manuf. Hexcel Honeywell (U of Minn) Itek Penn State Univ Sheldahl	Solid Surface (Trough)	Detailed Design	Detailed Design	Conceptual Design	Conceptual Design	Adequate	Yes
		Slats (Facets)	Detailed Design	Detailed Design	Conceptual Design	Conceptual Design	Adequate	Yes
6. Fixed Mirror Line Focus Distributed Receiver	General Atomic	FMSC (Fixed Mirror Solar Concentrator)	Prototype Construction	Prototype Construction	Advanced Conceptual Design	Conceptual Design	Very Good	Yes
7. Low Concentration Non-Tracking	Argonne Arthur D. Little Bechtel Enrico Fermi Envir. Consulting	CPC	Prototype Constr.	Detailed Design	Conceptual Design	Conceptual Design	Very Good	Yes
		Vee Trough	Prototype Constr.	Detailed Design	Conceptual Design	Conceptual Design	Very Good	Yes
		Alt. Flat Plate Conc.	Prototype Constr.	Detailed Design	Conceptual Design	Conceptual Design	Fair	Yes

FIGURE 1. Parabolic Dish-Steam System (JPL)

When energy is required, the stored chemicals are reacted to release heat, which in turn drives an energy conversion system such as the central steam Rankine plant. Chemical systems may eventually become competitive where large quantities of energy must be stored; however, considerable research work is required before technical feasibility can be established. For this reason chemical transport systems will not be considered during this concept evaluation.

Electric Transport

The dish-electric systems (see Figure 2) are based on using dish-mounted, heat engine-generator sets (Stirling or Brayton) at operating temperatures approximating 1500 °F. An air-cooled Stirling engine would eliminate the need for cooling water, as well as allow use of irregularly shaped parcels of land. A small Brayton engine run on gases such as helium combined with xenon would have similar performance advantages.

Stirling as well as Brayton engines and receivers are the key components in the development of dish-electric systems. The Stirling engine is in the early prototype development stage. Major research programs are underway at Phillips, Ford Motor Company, NASA, and AGA. Brayton engines are further developed, with off-the-shelf commercial units available at reduced efficiencies. There are, however, prototype state-of-the-art systems with efficiencies approaching the theoretical maximum.

CONCEPT 2: POINT-FOCUSING, CENTRAL RECEIVER SYSTEMS

The general system shown in Figure 3 consists of a field of two-axis tracking mirrors (heliostats) which reflect the sun's rays to a receiver mounted on top of a tower. The current technology subsystem designs have been limited to low risk steam technology. The advanced system concepts are configured to take advantage of alternate subsystem techniques such as a sodium-cooled receiver and/or a sodium storage subsystem, open or closed Brayton cycles, and dry or wet cooling towers.

As normally configured, the heliostat is a two-axis tracking system with a single structural support member (see Figure 4). The two-axis system

FIGURE 2. Parabolic Dish-Electric System (JPL)

FIGURE 3. Point-Focus, Central Receiver System
(McDonnell-Douglas, Martin Marietta)

is much more complex than the one-axis. Likewise, the aiming requirements are much more stringent in providing a 1000:1 rather than 20:1 concentration ratio at the receiver. This has resulted in higher expected costs for the heliostats and control systems.

The collector field efficiency is another important aspect, for the losses associated with collecting and directing the solar rays to the receiver are major:

- Reflection losses $\approx 10\%$
- Transmission losses
(shadowing blocking) $\approx 30\%$
- Cosine losses $\approx 15\%$
- Overflow losses
(Aiming off-axis
aberration) $\approx 5\%$

Often, for many system designs, the field efficiency will approximate 50 percent.

The two receiver designs that are receiving primary attention for use in central receiver systems are shown in Figures 5 and 6. In the cavity receiver, Figure 5, an aperture or opening is placed at the focus, allowing the reflected energy to pass through and impinge on the enclosed absorbing surface. By insulating the receiver's outer walls, the only major heat loss is that which escapes through the aperture. The absorbing surface of the open receiver (Figure 6) is at the focus of the pseudo-paraboloid formed by the heliostats, acting as an unobstructed heat radiator. It should be noted that this surface openly convects heat to the surrounding air.

For small power systems the cavity receiver may be best; its major limitation is that its admission angle is sensitive to field size - the larger the field, the larger the admission losses. Receiver costs depend directly on power plant size and, correspondingly, tower height. Additional cost factors are dependent on the transport fluid selected. For many systems the cost of the tower structure, receiver, and piping transport in the tower remains the single largest expense.

Honeywell Heliostat

McDonnell-Douglas Heliostat

Boeing Heliostat

Martin Marietta Heliostat

FIGURE 4. Alternate Heliostat Configurations

FIGURE 5. Cavity Receiver Concept (JPL)

FIGURE 6. Open Receiver Concept (JPL)

The choice of working fluid for energy transport will vary with the type of conversion cycle selected. Superheated steam is one choice as a working fluid for the Rankine cycle plant and as the transport medium for heat from the receiver to the conversion plant (see Figure 7). Another approach is to use a closed Brayton cycle conversion unit mounted in the tower as close as possible to the receiver. This will minimize the heat and pressure losses in the working fluid. Helium, for example, introduces the problem of a gas as a heat transport medium. Actually, the major technical difficulty in using a gas is the lower heat transfer coefficient, which results in higher tube wall temperatures. There may be major difficulties with the use of a Brayton gas system in an open receiver with direct flux impingement due to the large temperature drop across the gas film. Its use in a cavity receiver at much lower tube fluxes may be possible. Open cycle (air) Brayton heat engines are also being considered, although they do operate at lower efficiencies. Although liquid sodium or sodium-potassium eutectic have been considered among the alternatives, they are subject to potential corrosion problems, high piping costs and potential safety hazards. They are also costlier than water as a fluid, and the temperature drop in the heat exchanger used to generate steam reduces the cycle efficiency. Hitec (a salt solution), is being proposed as the heat collection fluid for many alternate concept designs, and could be used in a closed loop arrangement.

CONCEPT 3: FIXED MIRROR/DISTRIBUTED FOCUS SYSTEM

The solar collector under development by Texas Tech University and E-Systems, Inc. is a fixed, hemispherical mirror producing a line focus which moves within the mirror region during the day. The receiver is a heat absorber, especially matched to the geometry of the focal region, which tracks the line focus. Concentration levels along the receiver are adequate for producing high pressure, superheated steam for solar thermal electric power system applications (see Figure 8).

The fixed mirror/distributed focus (FMDF) concentrator is an incremented reflecting surface comprising a spherical segment whose basic function is to receive the incident solar energy and concentrate it at a focal line. It is

FIGURE 8. Fixed Mirror, Distributed Focus System
(Texas Tech, E-Systems)

structurally supported so that its orientation relative to solar declination optimizes solar illumination. In the Northern Hemisphere, the concentrator is tilted to the south with tilt angles selected on the basis of the cost-performance trade-off analysis.

The FMDF receiver subsystem comprises a receiver (or absorber) along the axis of the high energy line focus; a heat transfer fluid loop to transport the thermal energy to the application; a mobile support structure to maintain the receiver in the line focus; and stationary support structure with tracking control for the mobile receiver. The receiver functions as a linear boiler, replacing the conventional fossil-fueled or gas-fired boiler in a normal steam cycle. The receiver will most probably be configured as a truncated cone, with design optimization to minimize radiative and convective heat losses.

Water was selected as the working fluid for the primary power generating system. Superheated steam will pass through insulated stainless steel piping, while feed and condensate return lines will be carbon steel.

A water/steam Rankine cycle with regenerative feedwater heating is used to power steam turbine generators. Several FMDF modules, each module 200 ft. in aperture diameter, will be operated in parallel supplying a set of turbine units. The basic plant layout, including an oil/rock thermal storage system, is presented in Figure 9.

CONCEPT 4: LINE-FOCUS CENTRAL RECEIVER SYSTEM

The FMC concept shown in Figure 10 uses an array of single-axis focusing heliostats and a cavity-type line central receiver. The system is the large analog of the parabolic collector/receiver, as the central tower concept is the large analog of the paraboloid collector/receiver. This concept combines some of the simplicity of the single-axis parabolic cylinder collector with a reduction of piping insulation loss and pressure drop associated with a distributed system.

The cavity receiver (see Figure 11) allows a reduction in radiation losses, while simultaneously housing the boiler tubes. The cavity doors

FIGURE 9. Fixed Mirror/Distributed Focus System

FIGURE 10. Line-Focus, Central Receiver System (FMC)

FIGURE 11. Cavity Receiver (FMC)

used to close the cavity at night to conserve heat also have reflective surfaces to collect reflected light not passing directly through the aperture.

Both natural and forced convection tube boiler concepts have been developed, each producing superheated steam for use with a standard Rankine cycle plant. At the present time the FMC concept does not include design details of the plant or storage system.

CONCEPT 5: LINE-FOCUS DISTRIBUTED RECEIVER SYSTEM

The collector consists of a single-curvature reflecting surface which concentrates incident solar insolation on a linear receiver (see Figure 12). The reflecting surface is articulated about one axis to minimize blocking problems while increasing concentration. The reflecting surface may be a parabolic trough or a series of flat mirror strips (facets) which can be individually articulated so that each strip reflects energy onto the linear receiver as the sun orientation varies.

Utilizing a steam Rankine conversion cycle as in Figure 13, it is possible to achieve outlet temperatures of 650 °F with the trough and 850 °F with the variable slat concentrators. This collector and receiver concept is currently being developed commercially by several companies for intermediate temperature range utilization (500 to 900 °F). If this commercialization results in significant component cost reduction, then despite its lower operating temperature and therefore reduced performance characteristics, the system may be able to compete as an electricity producer.

CONCEPT 6: FIXED MIRROR LINE FOCUS DISTRIBUTED RECEIVER SYSTEM

The General Atomic Company fixed mirror solar concentrator (FMSC) employs a fixed mirror trough that produces a sharp line focus regardless of sun position. The heat receiver is moved in a circular arc to track the focal line (see Figure 14).

The basic reflector, shown in Figure 15, is a concave array of long, narrow, flat mirror facets fixed on the segment of a cylinder. The mirror is symmetric about the tangent facet and is tilted to optimize heat collection.

FIGURE 12. Line-Focus Collectors
(McDonnell Douglas, JPL)

FIGURE 13. Line-Focus, Distributed Receiver System (JPL)

FIGURE 14. Prototype Fixed Mirror Solar Concentrator (FMSC) System (General Atomic)

FIGURE 15. FMSC Mirror Unit (General Atomic)

FIGURE 16. FMSC Receiver (General Atomic)

The fluid transfer pipe transports the fluid through the receiver and is the focal point for the light concentration. The present design (see Figure 16) is a deep rectangular steel pipe with a black chrome selective coating to absorb solar radiation and reduce heat reradiation. A compound parabolic secondary concentrator is used to increase the concentration factor and to improve the uniformity of the heat distribution on the receiver tube. On the illuminated side, the pipe is covered by a single Pyrex glass plate, which leaves a stagnant air gap.

Hitec heat transfer salt solution, carbon dioxide gas, and Dowtherm A have been compared as alternate coolants by General Atomic. Eventually, Hitec was selected as the primary heat transfer fluid. Hitec is pumped through the heat receivers and directly to a central plant steam generator and heat storage unit (see Figure 17). The steam drives a turbogenerator and is then condensed and fed back to the steam generator as feedwater. The nitrogen purge system indicated is used to drive the molten Hitec out of the system ducting and into the heat storage unit during an interruption of solar insolation for more than 1 hour.

CONCEPT 7: LOW CONCENTRATION NON-TRACKING SYSTEMS

It is feasible to use a low concentration collector such as the compound parabolic concentrator (CPC) shown in Figure 18, or V-trough (see Figure 19) coupled with a vacuum tube thermal receiver in a fixed orientation to produce output temperatures as high as 350 °F. Using an organic Rankine conversion cycle, it would be possible to generate electrical power without incorporating complex and expensive tracking systems. The reflectors can be asymmetrically designed so they will need to be reversed only twice a year, at the March and September equinoxes.

A CPC or V-trough electrical power generation system (see Figure 20) will, however, require a significantly larger collector area due to low obtainable concentration ratios. Along with increased piping costs, this may make the concept unattractive for commercial power production.

FIGURE 17. FMSC Plant Configuration

FIGURE 18. Compound Parabolic Concentrator
(Argonne National Laboratory)

FIGURE 19. V-Trough Collector (JPL)

FIGURE 20. Low Concentration Non-Tracking System (JPL)

APPENDIX A

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APPENDIX B

PERSONNEL IDENTIFIED DURING TASK 1
AS POSSIBLE SOURCES OF INFORMATION
CONCERNING SOLAR THERMAL POWER SYSTEMS

CONTACT PERSONNEL/CONSULTANTS FOR
GENERAL SYSTEMS ANALYSIS OF SOLAR
THERMAL CONVERSION OPTIONS

1. Point-Focusing Distributed Receiver Systems

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Livermore, CA 94550
Phone: 415/422-2711

ADDITIONAL CONTACT/CONSULTANT REFERENCES

A. Thermodynamic Cycles

1. Rankine Cycle

PNL has a strong background in Rankine system evaluation--with the only possible exception involving organic fluids:

Mr. Robert E. Barber
Barber - Nichols Engineering Co.
6325 W. 55th Avenue
Arvada, CO 80002
Phone: 303/421-8111

2. Brayton Cycle

PNL has worked on both open and closed cycle concepts, but has established contact with:

Mr. Dan Fayrweather
Airesearch Manuf. Co.
P.O. Box 5217
Phoenix, AZ 85010
Phone: 602/267-3011

Mr. W. D. Beverly
Boeing Engineering & Construction
P.O. Box 3707
Seattle, WA 98124
Phone: 206/773-2441

3. Stirling Cycle

A large amount of information has been collected and contact points established:

* Dr. William R. Martini
Joint Center for Graduate Study
University of Washington
100 Sprout Road
Richland, WA 99352
Phone: 509/942-7241

Mr. A. P. J. Michels
345 Scarborough Road
Phillips Laboratories
Briarcliff Manor, NY 10510
Phone: 914/762-0300

Mr. G. M. Benson
ERG, Inc.
952 57th St.
Oakland, CA 94608
Phone: 415/658-9785

Mr. W. T. Beale
Sunpower, Inc.
Bromley Bldg.
48 West Union
Athens, OH 45701
Phone: 614/593-8878

4. Energy Storage

Several members of the PNL staff have strong backgrounds in the evaluation and development of energy storage systems. To ensure the most recent concepts are examined PNL has contacted the Lewis Research (NASA) Center in Cleveland. The Lewis Center monitors and directs research and development relating to high temperature (above 500°F) thermal storage systems. In addition, a large number of contacts with individual contributors have been established.

Mr. Bill Maskica
Thermal & Mechanical Storage Section
Lewis Research (NASA) Center
21000 Brook Park Rd.
Cleveland, OH 44135
Phone: 216/294-6862

Individual Contributors:

Bechtel Corporation (CA)
Boeing Engineering and Construction (WA)
Comstock & Wescott, Inc. (MA)
Dow Chemical (TX)
General Electric - Space Div. (CA)
Honeywell (MN)
Jet Propulsion Laboratory (CA)
Lawrence Berkeley Lab (CA)
Martin Marietta (CO)
McDonnell Douglas (CA)
Monsanto (MO)
Public Service Gas & Electric Co. (NJ)
R&D Associates (CA)
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* Prospective Consultants.

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