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Solar Thermal Power Systems Project
Parabolic Dish Systems

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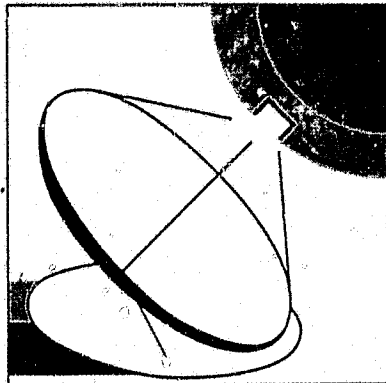Distribution Category UC-62b

Proceedings of the First Semi-Annual Distributed Receiver Systems Program Review

January 22-24, 1980
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April 15, 1980

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California Institute of Technology
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ABSTRACT

These Proceedings present the papers given at the First Semi-Annual Distributed Receiver Systems Program Review. The Review was held in Lubbock, Texas on January 22-24, 1980. It was sponsored by the U.S. Department of Energy, Jet Propulsion Laboratory, Sandia Laboratories, Albuquerque, and Texas Tech University.

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OPENING SESSION

INTRODUCTORY REMARKS

G. W. Braun
United States Department of Energy

Good morning! I am pleased to be here speaking to you on behalf of our division director, Dr. Howard Coleman, at the first Semi-Annual Distributed Receiver Systems Program Review. I hope that this review is not only successful, but is the prototype in a series of reviews that will provide improved communication among all participants in the present Solar Thermal Distributed Receiver Systems Program.

I would like to express my personal appreciation to those at the Jet Propulsion Laboratory who assisted in the organization of the Review and those at Texas Tech who provided arrangements and on-site coordination.

Looking back over the past few years, it is easy to gain a very positive perspective of the overall Distributed Receiver Program. Less than three years ago in the area of linear concentrators there was only the beginning of a test facility, the Willard Irrigation System had not yet been placed in operation, and the recently dedicated system at Coolidge, Arizona was but a gleam in the eye of those leading the Program at that time. Now, Coolidge is in operation and two new linear concentrator projects are underway in connection with solar enhanced oil recovery applications. The progress in parabolic dish technology has been even more impressive. Three years ago not only was there no program in the United States related to this technology, but there were no immediate prospects of having one. Now, two major projects are underway using this technology, and a fine test facility is in preparation and about to be placed in operation. Overall, the Distributed Receiver technology efforts in the United States have come from a position of clearly second priority in funding to a point where our fiscal 1981 Solar Thermal Program budget will provide more funds for Distributed Receiver Programs than any other major program element, including central receivers.

Of equal importance to budgetary consideration, we are rapidly approaching implementation of management plans for both the Distributed Receiver Program and related efforts in the area of advanced development. The critical issues now relate to our headquarters organizational relationship to the Albuquerque Operations Office and the Solar Energy Research Institute.

Much of what I have to say by way of conclusions is driven by the fact that we now have new goals which derive from goals for National Energy Programs that accordingly have national visibility. Our Solar Program goals must be adjusted accordingly. And, the new goals are more ambitious by several steps than any we might have set for ourselves. We are now talking in terms of quads per year by the turn of the century, when a few short months ago such comments would have been greeted by a high degree of incredulity. Indeed within my memory, the goal for solar thermal, that is three quads per year was viewed as not only unrealistic for solar thermal, but perhaps impractical for solar at all.

Let me now briefly discuss our organizational arrangements and plans as they relate to these new goals. As you know, the reorganization of solar programs is underway at DOE. The general trend is to bring technology development and commercialization functions, which had been separated during the early days of DOE, back together.

My personal hope is to see programs aimed at getting systems qualified for production and user acceptance more closely coupled with aggressive market development and stimulation programs, as well as legislative, incentive and regulatory initiatives. The latter initiatives I believe are needed to take the embryonic concentrator industries and assist them through a natural birth and a healthy childhood. For each concentrator program, I expect to see long-term programs geared to the activity necessary to establish an adequate industrial base for each concentrator system. The plans should be consistent with the idea of assisting companies involved in qualifying systems for major near-term markets, particularly for those markets where there is an opportunity for early sales in a strict economic competition with conventional alternatives.

Relative to each major near-term market, I expect to see complementary plans develop to overcome institutional barriers, maximize the receptivity of potential industrial and utility customers to solar thermal systems, and generally focus and engage the full resources of our society on programs, tasks and initiatives that support our goals. We hope to use the capabilities of industry, universities, laboratories and government at all levels in this commitment.

In all of this I see the Department of Energy as a catalyst, a source of funds for activity that only accelerates what would be done in response to future conditions of energy supply in economics later.

Likewise, we should and will support programs of advanced research and development undertaking those tasks which pave the way to the broadest possible adaptation of solar thermal concentrator systems to our energy needs. As with the market development programs, this Advanced Research and Development Program is to be founded on the assumption that efforts to establish viable concentrator industries will have met success.

Finally, multiple system prototypes and applications projects will be conducted in relation to the major near-term markets for solar thermal systems. These will be managed by DOE so as to provide users and suppliers alike with the experience that is truly representative and instructive relative to later commercial commitments and investments.

These will include central receiver repowering projects totaling four in the next phase of the central receiver program aimed at both utility and industrial plant applications. Smaller-scale experiments related to cogeneration will also be undertaken.

For parabolic troughs, low to mid-temperature industrial heat applications based on modular system packages will be undertaken and enhanced oil recovery applications will be vigorously explored and encouraged.

Parabolic dish systems will be deployed in applications with potential customers who would install diesel and gas turbine electric generation plants if the latter were economically justifiable.

The fixed hemispherical bowl concept will continue to be evaluated in relation to near-term markets and the economic characteristics of competing concepts.

Clearly, all of the solar programs must shift gears in response to the goals established by President Carter and a clear national need. I think the critical portion of what must be done can be accomplished over a period of five years. It is not unrealistic to contemplate the need for a federal investment in necessary technology development and market related programs on the scale of two billion dollars over such a period. Nor is this a staggering sum when viewed in terms of what is at stake (i.e., half or more of the energy displacement to be expected from direct collection of sunlight at the turn of the century). Indeed, the Solar Thermal Energy Association (a division of the Solar Energy Industries Association) has outlined such a need related solely to product qualification activity. Imaginative plans and programs would have to be laid down. These must allow prudent and cost conscious implementation of industry proposals.

Clearly, exciting times are ahead for those of us privileged to occupy positions of decision and influence related to allocation of federal funds. Much depends on our ability to apply these funds at the points of highest leverage. Generally, this will involve helping industrial firms to acquire all of the necessary expertise to proceed on their own. The efforts of federal program managers and federal laboratories will be evaluated not based on what they developed but on what they helped others accomplish. Our laboratories will learn the role not as leading actors competing for the spotlight, but rather as patient and thoughtful stage mothers for the industries they can effectively assist.

Thank you for your kind attention, and I wish you a successful and productive meeting.

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OVERVIEW OF DISTRIBUTED RECEIVER PROGRAM

James E. Rannels
Solar Thermal Branch
Department of Energy

As we enter the 80's, a transition from solar thermal research and development to deployment of hardware in user environments is occurring. The early stages of a commercial structure are beginning to emerge, and, as we move towards the cost goals of 1990, solar thermal systems demonstrate great potential for relieving much of the energy burden in the U.S. Below, a brief description of how we arrived where we are, and where we're going in distributed receiver solar thermal technology development is given.

Solar Thermal History

The earliest recorded use of solar thermal energy was by Archimedes for military purposes in 212 B.C. A fleet of the enemy's ships was set on fire with large, focused mirrors. I. a. Haitam and Roger Bacon, in 1000 and 1263 respectively, burned various substances with curved mirrors and glasses, as part of their experiments in optics. And Lavoisier, the famous French chemist, experimented with solar furnaces in the late 1700's, achieving temperatures high enough (1760° C) to melt platinum and other materials.

The Reverend Doctor Stirling invented the hot air engine in 1816 (later versions of which now bear his name) and, together with Watt's steam engine, provided a base for further development of solar collectors with engines to provide power. During the period of 1864-1878, Mouchot built and operated several solar powered steam engines, at least one of which was a truncated cone made of copper with an inside coating of silver leaf. Unlike modern day distributed receiver systems, this tracked the sun "manually," and was reported to have a maximum calculated efficiency of .854.[1] Ericsson, an engineer well-known for his

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[1] Abbot provides the following data on testing Mouchot's "solar plant" and explains the high value for the maximum calculated efficiency:

	Cal.	Max. Cal.	Date
Direct heat received	616.1	945.0	April 25
Heat utilized	258.8	547.5	June 15
Efficiency calculated	0.491	0.854	June 14

As for the column of maxima, it is obvious enough that one would not expect to get the maximum efficiency value on June 14 by dividing the heat absorbed on June 15 by the heat received on April 25. Very likely the maximum heat absorbed on June 14 was nearly equal to that of June 15, but the heat received on June 14 was far inferior to that received on April 25, thus yielding the surprisingly high efficiency stated.

development of the __Monitor__ and similar battleships during the Civil War, constructed seven solar hot air engines using paraboloidal collectors between 1870 and 1884. The first design produced steam in a metallic tube which was placed longitudinally above a trough shaped reflector. Pifre demonstrated his solar engine in Paris in 1878 with a parabolic reflector (cone-shaped), operating a steam engine which ran a printing press. The largest solar irrigation plant of that period was constructed in 1913 on the Nile, south of Cairo. Shuman and Boys built 13,000 square feet of parabolic reflector troughs which were used to operate a 75-kW (100 hp rated) engine.

Charles Greeley Abbot, the fifth Secretary of the Smithsonian Institution (1928-1944) published many articles on solar energy from 1926 until his death in 1973 at the age of 101. At the International Power Conference in Washington, in 1936, he displayed a 1/2 hp solar steam engine, and in 1938 in Florida an improved version of the solar engine, rated at 1/5 hp with a flash boiler. In his book, __The Sun and the Welfare of Man__, published in 1929 by the Smithsonian Institution, he analyzes the potential of existing solar collector systems.

> With these points in mind, it will be appreciated that on account of their high concentration of the solar rays, and the resulting high temperatures, the conical reflectors (parabolic dish), especially if parabolic, like that of Pifre, give maximum theoretical possibilities of engine efficiency. On the other hand, the hot-box principle (flat plate collectors) of de Saussure, as used by Willsie and Boyle, must necessarily give low engine efficiency. The cylindrical-mirror (parabolic trough) type stands between them in this respect. On the other hand, the cheapness of installation and operation of heat collectors of the three types runs in the opposite order. What could be simpler than a glass-covered, black-bottomed pond, like Willsie and Boyle's, or what more cumbrous than an immense conical mirror, driven with the march of the sun, like that of Eneas? Cylindrical mirrors, horizontally mounted, as is possible at the equator, unite some of the high temperature possibilities of the conical collector, with some approach to the cheapness of the black-bottomed pond.

From this period to about 1970, little attention was focused on solar energy, due to the cheapness and abundance of fossil fuels. One highlight was the creation of the Association for Applied Solar Energy (later renamed the Solar Energy Society).

Evolution of the Federal Program

In 1971, the National Science Foundation (NSF) awarded several grants to investigate solar energy utilization in buildings, and biomass and solar thermal conversion systems. Thus began the sequence of events leading to the present day DOE solar thermal program. The results of these first studies were sufficiently attractive to warrant further increases in

funding for work that was more diversified and broader in scope. Other studies were funded and panels of experts were formed to evaluate the use of solar energy, including solar thermal, OTEC, photovoltaics, biomass, and renewable fuels synthesis. One such study authored by the NSF/NASA Solar Energy Panel, "Solar Energy as a National Resource," eventually became the keystone of the Federal solar program.

In 1973, Federal laboratories became involved in solar research. As part of this effort, the Atomic Energy Commission (AEC) funded the Solar Total Energy Program at Sandia Laboratory in Albuquerque (SLA).

During the Arab oil embargo of 1973-74, America became aware of the need for alternative energy sources. This eventually led to the creation of the Energy Research and Development Administration (ERDA) in 1975. Programs sponsored both by NSF and AEC were transferred to the newly formed Division of Solar Energy within ERDA. Under ERDA's aegis, Sandia Laboratory at Livermore (SLL) began the Central Receiver Program, and the Jet Propulsion Laboratory (JPL) initiated the Small Communities Project.

In 1977, the Department of Energy was officially chartered, and the Thermal Power Systems Division (later to become the Solar Thermal Branch) emerged. Within this Division the Small Power Systems Program (to be renamed the Distributed Receiver Program) was organized in 1977, combining the Solar Total Energy and Small Communities Projects. At the same time, the Advanced Technology Program was initiated.

The Distributed Receiver Program

Today, the Solar Thermal Branch emphasizes two major technology development efforts: the Central Receiver Program and the Distributed Receiver Program. Advanced Technology is a separate but critical element within the Distributed Receiver Section and supports high technology (i.e., materials, components, etc.) development for both central and distributed receiver applications. Figure I shows the decentralized program organization.

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		— Projects (ALO) — Projects (ALO)
		— Troughs (SLA) — Dishes (JPL)
		— Bowls (SLA) — PDTS (JPL)
		— MSSTF (SLA)
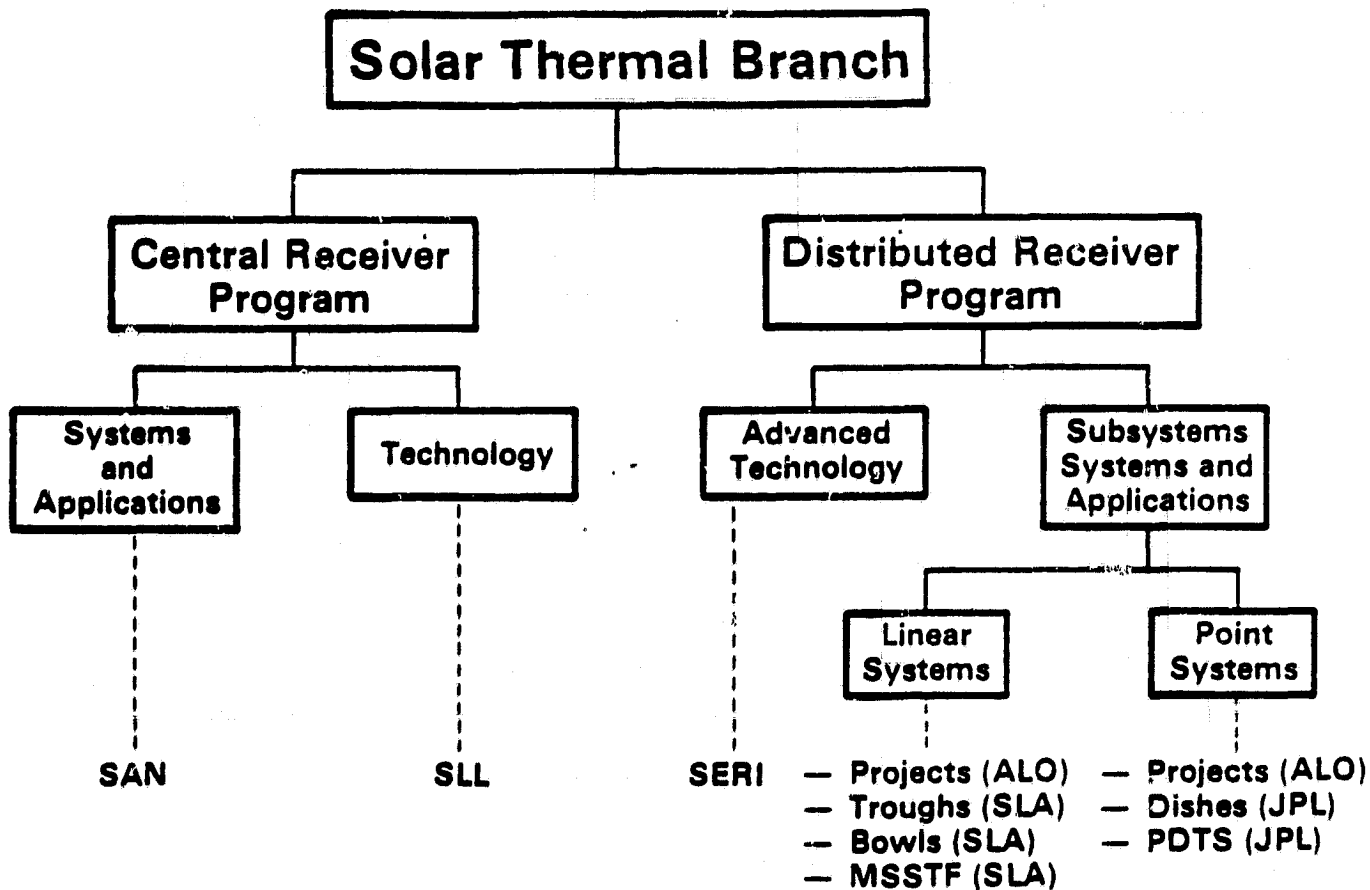
Figure I. Decentralized Program Organization

Management of projects involving both linear and point systems within the Distributed Receiver Program is the responsibility of the Albuquerque Operations Office. Development of linear systems, including parabolic trough and hemispherical bowls, is directed by Sandia Laboratories at Albuquerque (SLA). Point focus (parabolic dishes) systems development is managed by the Jet Propulsion Laboratory (JPL) in Pasadena, California (JPL also manages an effort investigating the use of naturally occurring salt ponds as a means of collecting solar energy). Responsibility for operation of the Parabolic Dish Test Site (PDTS) and the Mid-Temperature Solar System Test Facility (MSSTF) has been assigned to JPL and SLA,

respectively. The Solar Energy Research Institute in Golden, Colorado coordinates all Advanced Technology efforts.

Overview

The President stated in his message to Congress on June 20, 1979 that solar energy and renewable resources must satisfy one-fifth - 20% - of our energy needs by the year 2000. In addition, the Domestic Policy Review (DPR), prepared under the President's direction, estimated that solar thermal systems could displace up to three quads per year of primary fuel by 2000 (0.4 quads electric, 2.6 quads industrial process heat). Other analyses have indicated that a market of 17 quads/year may exist in 2015.

In pursuit of these goals, the specific solar collector technologies being developed within the Distributed Receiver Program are: parabolic troughs, parabolic dishes, hemispherical bowls, and naturally occurring salt ponds. These collectors are modular, allowing their use in any size application, but are best suited for smaller (under 10 MWe or 100 MBtu/hr) onsite applications.

These systems can provide heat and electricity for use in the industrial, commercial, residential, and small utility markets. Potential applications include industrial process heat, enhanced oil recovery, total energy systems for industrial, commercial, and residential buildings, irrigation pumping, and remote and small community electric generation.

Proximity to the energy load these systems serve will enhance their economies by reduced transmission costs and losses. Total energy will be more feasible than in central electric utility applications which are often distant from thermal loads. And local environmental standards requiring decreased emission of pollutants favor their deployment because of the "clean" energy from the sun.

Early market opportunities exist in the repowering or retrofitting of dispersed onsite applications. Electrical, mechanical, and thermal energy can be produced by small solar thermal energy systems to substitute directly for or augment the combustion of petroleum or natural gas. The long-term market penetration rate is dependent on the technology development of the solar thermal collection, storage, and power-conversion subsystems, the

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costs of competing fossil fuel and alternative energy systems, collector cost reductions achieved after the initial early opportunity market penetration, industrial acceptance. and the development of a solar thermal industrial base.

The overall objective of the Distributed Receiver Program is to provide a sound technological and industrial base on which a viable industry can be founded, thus reducing our fossil fuel dependence. More specifically, parabolic troughs are to be ready for commercialization by 1985 and parabolic dishes by 1987. In pursuit of this objective, funding for distributed receiver technology development has grown from $20.1 million in FY 77 to $33.5 million in FY 80. In comparison, initial funding in FY 71 for solar thermal R&D was a mere $60,000. Table I shows the Federal funding levels of solar thermal (FY 71-76) and distributed receiver (FY 77-80) R&D from the inception of the programs.

FEDERAL FUNDING OF SOLAR THERMAL (FY 71-76)[1] AND DISTRIBUTED RECEIVER (FY 77-80) R&D
(Millions of dollars)

	FY 71	FY 72	FY 73	FY 74	FY 75	FY 76	FY 77	FY 78	FY 79	FY 80
Solar Thermal	0.06	0.55	1.43	2.20	13.2	26.9*				
Distributed Receiver Technology							20.1	28.1	28.0	33.5**

[1]Data for FY71-74 from Solar Energy Research and Development: Program Balance, Annex, Vol. I, February 1978. (HCP/M2693-01). Includes funding for all solar thermal efforts.

*Includes transition quarter.
**Includes Capital Equipment Construction Funding.

Table I. Federal Funding of Solar Thermal (FY 71-76) and Distributed Receiver (FY 77-80) R&D

Steps being taken to insure fulfillment of the Distributed Receiver Program objectives are:

1. Improvement of the efficiency, durability, and reliability of distributed collectors through SLA development activity,

2. Improved system designs based on experience gained in early experiments, which will lead to reduced costs,

3. Survey and assessment of industry to identify the most promising early market opportunities,

4. Providing user operating experience through system experiments, and

5. Encouragement of mass production of distributed receiver systems through cost-shared engineering experiments.

Although distributed energy systems have proven their technical feasibility and no fundamental scientific breakthroughs are needed for their deployment, substantial cost reductions and improved reliability/durability must be realized before these systems become competitive with conventional energy sources and achieve user acceptance. The success of the program hinges on attaining sufficient reductions in collector costs through a combination of marketing efforts (volume production) and improvements in performance of the system. The 1990 energy cost goals ($1980) for small solar thermal energy systems are between 72-180 mills/kWhe for electric applications and 20-23 mills/kWht ($6.00-6.60/MBtu) for process heat applications. Beyond 1990, the goal ($1980) is to reduce these costs to 50-60 mills/kWhe and 14-17 mills/kWht ($4.00-5.00/MBtu) by 2000. These cost goals represent levelized life cycle energy costs. It is estimated that the 1990 energy cost goals will be achieved with parabolic troughs of $108/m^2 ($10ft/^{2}) and parabolic dish costs of $129/m^2 ($11.90/ft^2). Table 2 shows DPR and program goals for 1990 and 2000.

GOALS
($ 1980)

Energy Cost[1]	1990	2000
• Thermal	20-23 mills/kWht ($6.00-6.60/MBtu)	14-17 mills/kWht ($4.00-5.00/MBtu
• Electric	72-180 mills/kWhe	50-60 mills/kWhe

Collector Cost

• Parabolic Trough	$108/m²	25-50% Less
• Parabolic Dish	$129/m²	25-50% Less

Fuel Displacement[2]

• Electric	.4 quads
• Industrial Process Heat	2.6 quads

[1]Based on levelized life-cycle costs.
[2]From <u>Domestic</u> <u>Policy</u> <u>Review</u>; These are for all solar thermal systems.

Table 2. DPR and Cost Goals for 1990 and 2000.

<u>Status of Technology</u>: Within the Distributed Receiver Program four collector technologies are under development: parabolic troughs and hemispherical bowls under SLA management, and parabolic dishes and naturally occurring salt ponds under JPL management.* The status of each is briefly given below.

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*Other technologies are also under consideration, e.g., point focus fresnel lenses, etc.

Parabolic troughs are the furthest along, developmentally, of the distributed receiver technologies which DOE is pursuing. They have been technically demonstrated, are commercially available, and are being utilized in a number of experimental projects. Emphasis is upon upgrading the thermal performance of these systems and sponsoring engineering development, which will reduce costs, increase lifetime, and improve operation and maintenance characteristics. In conjunction with this, mass producibility studies are being undertaken. Troughs are being used for applications in the 212°-600 $^{\circ}$ F range, with higher temperatures being investigated. Their use is planned in electric, mid-temperature IPH, and industrial total energy markets. Currently, activities are centered on exploiting near-term trough potential in enchanced oil recovery, irrigation, and process heat applications.

Several parabolic trough systems are in operation, the most notable of which are the Willard, New Mexico and Coolidge, Arizona projects. The former was first operated in 1977, while the latter, dedicated in November 1979, is currently the largest solar thermal system in operation in the U.S. A 500 kWe plant is being built in Almeria, Spain under the auspices of the international Energy Agency. This plant will use both U.S. and German supplied collectors. Under investigation is the use of parabolic troughs for supplying steam for enhanced oil recovery. Also under investigation is the development of a modular trough system to provide heat for industrial processes. This activity would culminate in the solar equivalent of a packaged boiler.

Parabolic dishes are point focusing collectors which will be applicable in the 750°-2000° F and above temperature range. Subsystem and component activities are divided between concentrator and receiver development. Design and fabrication of two Test Bed Concentrators, for use in concentrator performance testing and as test beds on which other subsystems will be evaluated has been completed. Development of a low-cost concentrator has also been initiated. On the receiver side, no commercial products are currently available in the required temperature ranges. First-generation dish receivers are in the final design stage and will go into test at the Parabolic Dish Test Site in mid-FY 80. Both air and steam receivers are being developed.

Complementing these subsystem activities, three systems using parabolic dish technology are under development: a total energy experiment which will generate 750° F steam to provide electricity, heating and cooling, and industrial process heat for a knitwear factory in

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Shenandoah, Georgia; a 1 MWe small community electric application for which a site solicitation has been released; and a 100 kWe modular military power experiment.

Hemispherical bowl development is proceeding on a much smaller scale than the other distributed receiver options. A conceptual analysis of the performance and cost of these systems was completed in FY 77. Conceptual designs for a 20 m (65 ft) diameter module has been completed in March 1979 and construction has been completed. Test and evaluation of the module is scheduled for completion March 31, 1980.

Solar ponds can be an economically attractive source of collecting heat, especially in a naturally occurring site such as the Salton Sea. JPL has recently initiated a feasibility study of using the Salton Sea to produce electricity. In addition to being an economical source of electricity, this could serve to reduce the salinity of the Salton Sea, thus solving a major environmental problem.

Conclusion

From a modest beginning in 1971 with a budget of $60,000, solar thermal R&D has grown and evolved. New concepts such as hemispherical bowls and solar ponds are now being evaluated and tested as parabolic dishes and parabolic troughs approach commercialization. Evaluation of trough prototypes as well as commercial collectors will continue at the MSSTF. Testing on dish systems has been initiated at the PDTS, while tests of early dish prototypes were conducted at the MSSTF. Certification of independent laboratories for testing of commercial collectors has also begun.

Industry's interest in the program is growing, and their participation is welcomed. Both existing commercial system suppliers and potential suppliers are involved in component/subsystem development, and in projects at the system level. An important thrust of the Distributed Receiver Program is to continue to encourage this industrial involvement, with an exchange of ideas on both technical and commercialization considerations. Projects now planned for the 80's will emphasize providing user operating experience and gaining system confidence. As fuel prices rise and the industrial infrastructure changes, market studies will continue and expand, in order to identify the most promising early market opportunities. Through these efforts, mass production of distributed receiver systems will be promoted and collector costs gradually reduced to be competitive with conventional energy sources.

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APPENDIX

For more detailed information on technology development of the various solar thermal systems, please contact the individuals listed below.

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Central Receivers/Technology Development

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Attn: 5711
Telephone: 505-264-3312

Distributed Receivers/Point Focus (Parabolic Dishes and Naturally Occurring Salt Ponds)

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Advanced Technology

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Ms. Margaret Cotton directs the Technical Information Dissemination Office at SERI and will provide price and product information, technical reports, and resources on general program activities.

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Golden, CO 80401
Telephone: 303-231-1135

The Solar Energy Industries Association can supply additional information on current commercial activities of solar systems manufacturers. For use of experimental facilities in testing collector components, the Solar Thermal Test Facilities Users Association should be contacted.

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Washington, D.C. 20036
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and   Solar Thermal Test Facilities Users Association
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Telephone: 505-268-3994

HEAT AND ELECTRICITY FROM THE SUN USING PARABOLIC DISH COLLECTOR SYSTEMS*

Vincent C. Truscello and A. Nash Williams
Jet Propulsion Laboratory

ABSTRACT

This paper addresses point focus distributed receiver (PFDR) solar thermal technology for the production of electric power and of industrial process heat, and describes the thermal power systems project conducted by JPL under DOE sponsorship. Project emphasis is on the development of cost-effective systems which will accelerate the commercialization and industrialization of plants up to 10 MWe, using parabolic dish collectors. The characteristics of PFDR systems and the cost targets for major subsystems hardware are identified. Markets for this technology and their size are identified, and expected levelized bus bar energy costs as a function of yearly production level are presented. Finally, the present status of the technology development effort is discussed.

INTRODUCTION

The solar thermal power systems work at JPL is sponsored by the Department of Energy, Thermal Power Systems Branch, for the purpose of developing systems capable of competitive-priced thermal and electric energy for utility, industrial, and isolated applications. Program responsibility resides with DOE Headquarters and project management with JPL, with engine and power conversion support provided by NASA Lewis Research Center.

Three principal configurations for thermal power systems being developed by DOE are the central receiver (CR), the line focus distributed receiver (LFDR), and the point focus distributed receiver (PFDR). The JPL work is based on a PFDR system with paraboloidal dish and integral receiver. This technology is expected to be initially applied to relatively small power systems (up to a few megawatts) made up of identical modules (each a few tens of kilowatts in capacity). Each module is capable either of generating electricity, or of supplying heat for industrial purposes, depending on the type of receiver used. A representative dish configuration is shown in Figure I.

For electric applications the module consists of three subsystems: the concentrator, the receiver, and the power conversion unit. An automatic control system enables each module to track the sun. In the simplest configuration of the system, the power conversion unit is located atop the receiver, at the focus. The optical portion of the concentrator is a parabolic reflector, although lens concentrators are also being considered. To produce thermal energy for industrial, commercial, or agricultural applications, the power conversion unit is replaced with an appropriate receiver having flexible lines to conduct the working fluid to a heat transfer network on the ground.
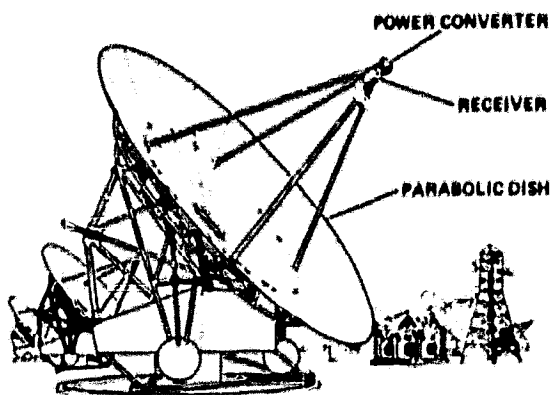

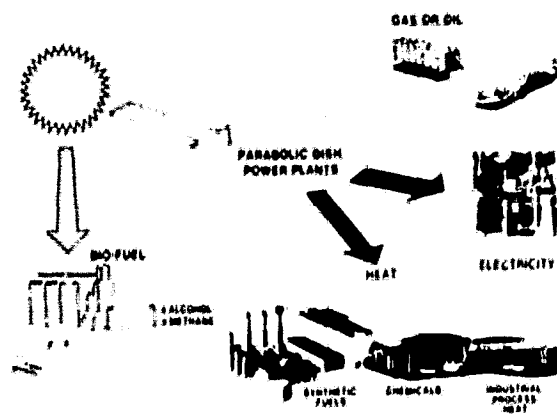Figure 1. Dish Concentrator with Power Converter at the Focus

Figure 2. Versatility of Parabolic Dish Power Plants

POINT FOCUS DISTRIBUTED RECEIVER (PFDR) ADVANTAGES

The principal advantages of dish solar concentrators are (1) the high temperatures attainable, (2) the inherent modularity of dish collectors, (3) the ease of collecting the power output of each dish in electrical form, and (4) the high percentage of the available solar insolation which is collected. The high temperatures available from dish systems results from their inherently high concentration ratio.

The attractiveness of the high temperature characteristic of dish systems arises from both the higher conversion efficiency achievable from heat engines as the temperature of the working fluid is increased and the wide range of temperatures achievable for thermal applications.

The ready adaptability of dishes to two-axis tracking insures maximum utilization of the direct beam radiation at near maximum efficiency from sun up to sun down. Two-axis tracking combined with the high geometric concentration ratio provides high temperatures at the focus, which in turn allows high efficiencies to be derived from Brayton or Stirling heat engine power converters. PFDR systems offer broad applicability, including both small and large utilities, power for remote sites, agriculture (especially pumping), and a wide range of industrial and commercial process heat applications.

Versatility as shown in Figure 2 is a key attribute of solar thermal systems, especially of dishes because of their high temperature potential. Versatility can be illustrated in terms of the end product produced: electricity, process heat, steam, chemicals and fuels.

Dish systems can readily be designed to provide for hybrid operation in which conventional fuels provide heat on a transient or steady state basis to compensate variations in insolation. Along with the hybrid operational capability, there is the potential for using numerous conventional fuels. A potentially attractive hybrid mode is the coupling of the solar plant to a biomass system to supply it with low Btu biogas produced by a digestive process. The most appropriate fuel would be selected for each application.

PROJECT GOALS

The primary goals of the project are (I) to produce electricity or heat at a cost competitive with conventional alternatives, and (2) to develop the technical and economic readiness of cost-effective PFDR technology necessary to accelerate market penetration of small power systems. Market penetration requires a mature technology coupled with favorable preconditions within the commercial and industrial infrastructures which govern the effectiveness of supply and demand forces. To facilitate the establishment of preconditions increasingly more favorable to market penetration, the project will attempt to enter market areas of high-cost energy first and to enter large markets with corresponding lower energy costs later. Figure 3 displays this overall market strategy. The projected size of the isolated load market (a near-term, relatively high-cost energy market) in the 1990-2000 time period is 300 to 1000 MW/year. Although this market is small in comparison to the grid connected utility market, the graph also indicates that by assuming only a 20% market penetration, up to 10,000 power modules per year would be required to meet this need.

In addition to the electric market, both grid and non-grid connected, there exists a large market for a combination of both thermal and electric power. Industrial process heat is a typical application in this category.

In summary, it is clear that to build manufacturing volume most expeditiously, the high cost, isolated load markets should be penetrated first. To compete in the low cost grid-connected market will require both experience and production volume which can result from the successful prior pursuit of the higher cost, isolated markets.

CONCEPT OF FIRST AND SECOND GENERATION TECHNOLOGY

From a technology standpoint, the project strategy is to first develop hardware suitable for entering the near-term isolated load market. First-Generation equipment, based on gas turbine technology, will entail less developmental risks and permit the early introduction of solar plants into the marketplace. Satisfying the demands of the near-term market will help to mature all the infrastructures essential to solar power plant sales, especially with regard to collectors. Just as importantly, this strategy will also make solar power plant technology more visible and thus encourage its large-scale use in other applications.

To meet the long-term goal of the project (i.e., entering the grid-connected market with baseload coal-steam and nuclear plants), improved system efficiency is needed. This will be achieved through use of advanced engine (second generation) technology. Additional cost reductions are expected from continuing improvements in dish collector design, and through increased production.

Solar power plants produced from first generation technology have system goals of 100 to 120 mills/kW hr. Such plants can compete with conventional systems in the near-term isolated load market, and in the oil-fired, intermediate-peaking, grid-connected market, but will need to be improved for the baseload grid-connected power plant market. The main attraction of these plants is that they will enter the near-term market, develop the required infrastructure and require only a modest R&D investment by the government to mature.
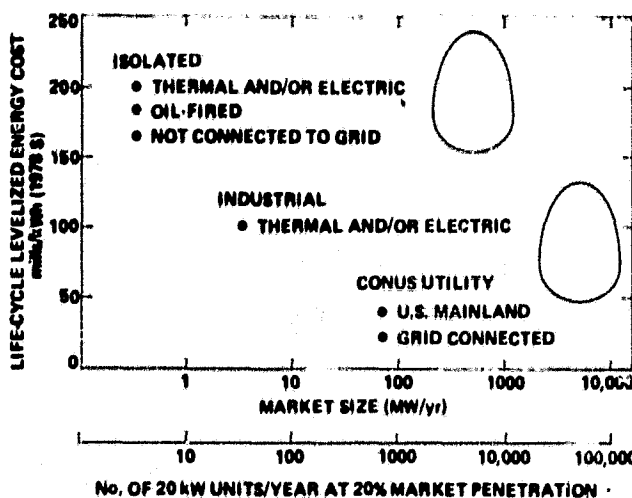
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Figure 3. Energy Cost and Market Size

Table 1. Cost and Performance Targets for Electric Power Generation (1978 Dollars)

SUBSYSTEM	PARAMETER	TARGETS FOR FY	
		1ST GENERATION (1982)	2ND GENERATION (1985)
CONCENTRATORS	COST IN MASS PRODUCTION*	$100 — 150/m²	$70 — 100/m²
	REFLECTOR EFFICIENCY	90%	92%
RECEIVERS	COST IN MASS PRODUCTION*	$40 — 60/kWe	$20 — 40/kWe
	EFFICIENCY	80%	85%
POWER CONVERSION	COST IN MASS PRODUCTION*	$200 — 350/kWe	$50 — 200/kWe
	EFFICIENCY	25 — 35%	35 — 45%

* RANGE OF 1ST GENERATION PRODUCTION: 5,000 - 25,000/YEAR.
* RANGE OF 2ND GENERATION PRODUCTION: 10,000 - 1,000,000/ YEAR.

Power plants using second generation dish technology will require more time to bring on line (3 to 4 years of additional technology development) and consequently will require more resources to develop. Work on second generation systems has already begun. These plants have system cost goals of 50 to 60 mills/kWh, which are clearly competitive with coal and nuclear systems in the grid-connected market. Utilizing the above costs for electricity, cost targets have been developed for both first and second generation subsystems hardware. These are shown in Table 1.

PROJECTED POWER PLANT BUS BAR ENERGY COSTS

Estimates of levelized bus bar energy costs from dish-electric power plants have been made based on projected component performance and costs. The results of these studies are presented in Figure 4 as a function of the number of dish power modules (~25 kWe peak) produced per year. Information is presented in this fashion since power module cost is a strong function of the collector and engine costs which are in turn affected by the production rate. Figure 4 also indicates the assumed costs for the basic module components (concentrator, receiver and engine) in various production rates, and the assumed balance of plant and O&M costs. At a production rate of 25,000 units/year and assuming no energy storage, levelized bus bar energy costs of 75 mills/kWeh are projected (1979 dollars). These numbers are based on what is believed to be a conservative estimate regarding engine-generator conversion efficiency (40%) for the 1990 time period. With a more optimistic estimate of efficiency (i.e., 45%), the bus bar cost decreases to about 67 mills/kWeh. At very large production rates (400,000 modules/year), the costs decrease to 58 mills/kWeh. Clearly such costs permit penetration of the grid-connected utility market.

PROJECT STRATEGY AND STATUS

The TPS project goal is to demonstrate technical, operational, and economic readiness of PFDR technology for electric and thermal power applications. To reach this goal in a timely manner, the project has three parallel but complementary activities or elements: Advanced Development is R&D oriented, with emphasis on feasibility testing and component and materials development.
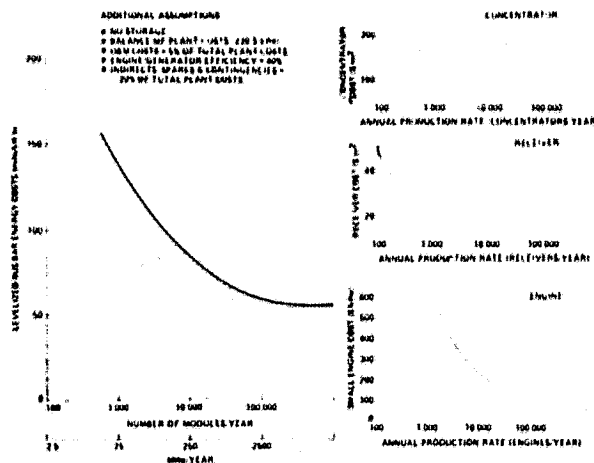
Figure 4. Effects of Mass Production on BBEC

Advanced designs from this activity are utilized by the Technology Development element which does the detailed engineering and fabricates and validates (tests) a complete module (concentrator, receiver and engine). The third element of the project, Applications Development, is responsible for developing complete power plant systems and demonstrating the technology through a series of engineering experiments sited in a variety of potential user environments. The status of each of these three project elements is described below.

Technology Development

The present thrust of this project element is to develop first generation subsystems (including concentrators, receivers/transport and power converters) which can be utilized in the Applications Development element for engineering experiments. The major products of this project element are proven hardware and acceptably low capital equipment and production costs (Ref. 1).

First generation hardware emphasizes proven gas turbine technology for the power conversion equipment, and an injection molding process for fabrication of the plastic petals or gores for the dish concentrator structure. This manufacturing technique already exists and is used in the production of a number of commercial products such as refrigerator doors. It should facilitate the attainment of mass-producible, low-cost concentrators. A first-generation dish concentrator proposed by General Electric and configured for injection molding is shown in Figure 5. Similarly, existing small gas turbine technology, very much like that developed for automobile turbochargers, cruise missiles, torpedoes, and auxiliary power units, is being studied for the eventual mass production of power conversion subsystems. The first-generation engine and receiver, presently being developed by Garrett Corporation, is shown in Figure 6.

Design, fabrication and test activities for both first- and second-generation hardware lead to two key events: a Brayton module on test in mid CY 1981, and a Stirling module on test early in CY 1984. The subsystems involved are concentrators, receivers, and power convertors. Second generation subsystems will be selected for incorporation in the Technology Development element of the project on the basis of the status of competing concepts emerging from the Advanced Development element of the project

Testing and evaluation of these dish power modules are performed at the JPL desert test site shown in Figure 7. Evaluation of early dish hardware is already taking place at this site. A 6-meter diameter dish module purchased
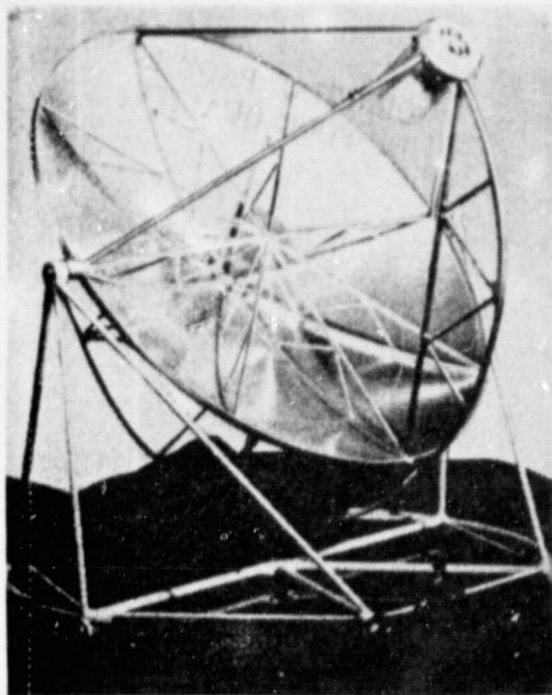
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Figure 5. General Electric Low-Cost
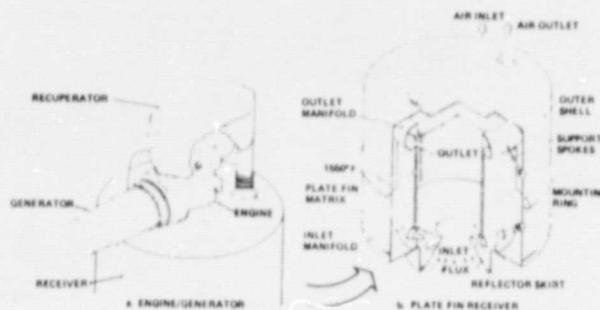Collector Concept

Figure 6. First Generation Brayton Engine/
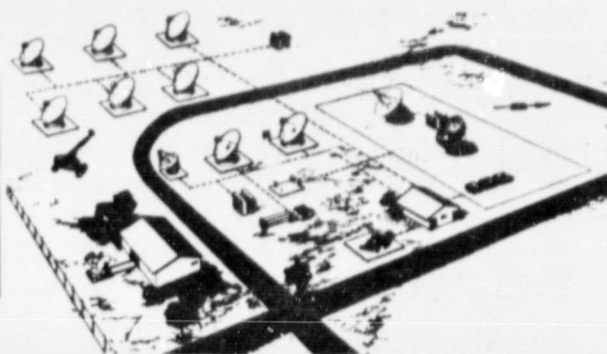Generator and Receiver

Figure 7. JPL Desert Test Site (PFSTS)

commercially from the Omnium-G Company of Anaheim, California has been under evaluation at the test site since early 1979. By September 1979, an 11-meter dish designed and constructed by E-Systems of Garland, Texas will be under test and evaluation at JPL. It is called a test bed concentrator (TBC) and will be used to test and evaluate receiver and engine units prior to installation on either first or second generation concentrators for full power tests.

Advanced Development

The work of this project element is directed to the development of materials and dish subsystems which meet the cost and performance goals of second and subsequent generation dish power plants. Example components are cellular glass monolithic gores for concentrators; both heat pipe and non-heat pipe hybrid high-temperature receivers for both power conversion and high temperature thermal applications; thermal transport and buffer storage; and under LeRC technical management, both free piston and kinematic Stirling engines for power conversion. This advanced work is in direct support of the Technology Development effort described previously.

An important part of the Advanced Development effort is the development of second-generation point focusing components (Ref. 2). The main thrust regarding engine concept is the Stirling engine although consideration is also being given to high temperature Brayton engines ($\sim 2000^0$F), and/or combined-cycle engines (which combine Brayton and Rankine technologies). Work for JPL on a Stirling engine and receiver is underway in a joint effort between Fairchild Stratos and United Stirling of Sweden based on the USS model P-40 engine.

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Applications Development

The third project element is concerned with market applications of dish systems (Ref. 3). Implementation of engineering experiments in various user environments is the major activity of the Applications work. It has the goal of demonstrating technical, operational, and economic readiness of dish systems in both electric power and process heat applications. The experiments are identified in terms of market sector in Figure 8. Three series of experiments have been defined, each related to a different market sector. These three series of experiments are described below.
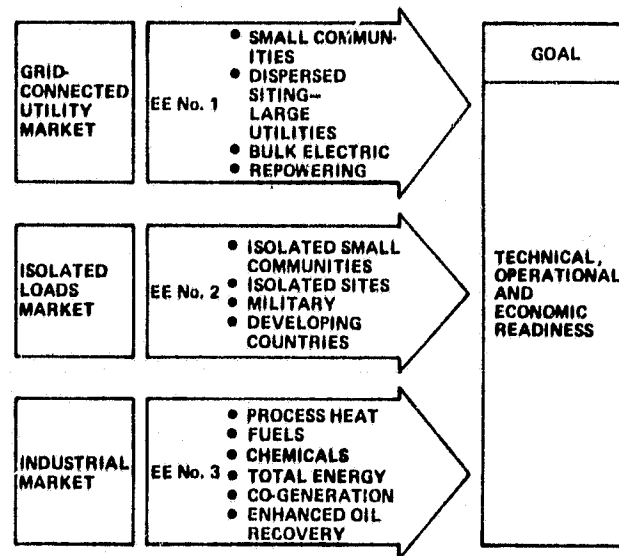
Figure 8. Engineering Experiments

EE No. 1 is known as the "Small Community Solar Thermal Power Experiment," and is one megawatt in size. As noted in Figure 8, it looks toward the grid-connected market of the continental United States. Because this market is as important as it is difficult, work is under way through EE No. 1 to gain early experience in that highly competitive market. It is scheduled to be on-line in early CY 1983. The systems contractor will select the power converter but the collector will be first-generation technology as developed by the Project.

EE No. 2 is known formally as the "Isolated Application Experiment Series," and addresses island sites, rural electricification in foreign countries, and other applications remote from the grid. Plant sizes will be about 100 kilowatts (electrical). A joint effort is now under way with the Navy Civil Engineering Laboratory on a co-funded basis. The EE No. 2a power plant will use receivers of hybrid design, and Brayton power converters. EE No. 2a is the first of the series, and is scheduled to be operational in late CY 1982.

The EE No. 3 series, addressing the industrial market, will initially be implemented through a series of very small experiments (less than 20 KWe) for thermal, electric and combined (cogeneration) applications. These small experiments known as the dish module experiments will be conducted using available hardware to the maximum extent possible. Because they are small they

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can be constructed and installed in a very short time. Although not a direct product of the JPL program, an example of such an experiment is the ongoing effort co-funded by DOE and the Southern New England Telephone Company for an industrial cogeneration application, using the Omnium-G power module. The primary function of this power unit is to produce electricity for a switching center, but excess power will be used for space heating and for absorption cooling. The unit is to be operational early in CY 1980. A number of other units of this class are scheduled by JPL for operation in CY 1981.

Experiments in all three series will follow an improved technology path with each new experiment utilizing the then current state-of-the art dish-engine technology.

ACKNOWLEDGMENT

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2.   "Solar Stirling System Development," J. W. Stearns, et al, AIAA Terrestrial Energy Systems Conference, Orlando, Florida, June 4-6, 1979.

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LINE-FOCUS CONCENTRATING COLLECTOR PROGRAM

Abstract

The Line-Focus Concentrating Collector Program has been in effect since about 1973. This program has emphasized the development and dissemination of concentrating solar technology in which the reflected sunlight is focused onto a linear or line receiver. Although a number of different types of line-focus concentrators have been developed, the parabolic trough seems to have gained the widest acceptance and utilization within the industrial and applications sectors. The trough is best applied for application scenarios which require temperatures between 140° and 600°F. Another concept, the bowl, is being investigated for applications which may require temperatures in the range between 600° and 1200°F. Current technology emphases are upon the reduction of system installation cost and the implementation of production oriented engineering.

Introduction

During the time of a national resource shortage, there are a number of responsibilities which the government of the United States must exercise. These responsibilities are outlined in Figure 1. The first of these responsibilities is to develop and disseminate alternative energy technologies. The expediting of this responsibility involves assisting industry in defining viable alternative resource options and assisting in establishing and disseminating a technological understanding sufficient to allow public decisions with high confidence. A second major responsibility is the application of economic incentives. In general, it is very important for these incentives to be simple, that is, that they be established at a high level of economic leverage. This tends to move energy utilization sectors away from the resource in short supply and toward other more abundant resources. A third responsibility of government is the coordination of the resource transition. This coordination is required to ensure that technological understanding is in place prior to the application of economic leverage or incentives. The Line-Focus Concentrator Program is primarily oriented toward the technical responsibilities of government relative to this particular classification of solar collectors.

Program Definition and Justification

The direct thermal conversion of solar energy using concentrating collectors may be considered under two classifications of receiver geometries: distributed receivers and central receivers.

GOVERNMENTAL RESPONSIBILITIES IN TIMES OF A NATIONAL RESOURCE SHORTAGE

- DEVELOP AND DISSEMINATE ALTERNATIVE TECHNOLOGIES

- APPLY SIMPLE ECONOMIC INCENTIVES -- AVOID DETAILED REGULATION

- COORDINATE THE RESOURCE TRANSITION

FIGURE 1

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Central receivers may be considered to be either concentrating or nonconcentrating systems. In this particular document we will be considering only concentrating types of collectors and the distributed receiver category will be decomposed into line-focus concentrators and point-focus concentrators.

As is outlined in Figure 2 line-focus concentrators may be separated into a number of categories or classifications. These classifications can be described based upon whether or not the reflector is fixed or tracking the sun and whether or not the receiver is fixed or in motion. The Line-Focus Concentrator Program has considered each of the concepts outlined in 'igure 2. There are advantages and disadvantages to each one of the alternatives. In general, systems which have fixed nontracking reflectors will collect less energy over a year than a system which has tracking reflector. Also, systems which have higher concentration ratios of sunlight on the receiver are more capable of generating higher temperatures at higher efficiencies. In general, the cost of the various systems depends upon materials used for construction and the construction technique that is used. Some of these systems require more site specific construction activity as compared to other systems which can be more completely assembled within a factor environment. In general, the systems which can be more completely assembled within a factory are less expensive when considered throughout the installation phase.

Figure 3 outlines the possibilities for the application of solar thermal energy from line-focus concentrating collectors. The first and most obvious application is to utilize the heat directly. Currently, approximately 13 quads of energy are used each year in industrial process heat applications at temperatures below 550°C. In fact, almost 11 quads per year are applied at temperatures below 300°C. In addition to industrial process heat, there is the potential for using process heat from line-focus collector systems for enhanced oil recovery operations and for commercial cooling. If desired, the heat from these systems may be used to operate heat engines which supply shaft power or shaft power plus thermal energy in cogeneration applications.

Program Activities

The Solar Thermal Line-Focus Concentrating Collector Program has been broken up into six major activities. An outline of these activities is demonstrated in Figure 4. Also shown in this figure is a description of these various activities as a function of time. As can be seen, most of the activities at the various levels of integration have preceded in parallel since the early to middle 1970s. As the development and commercialization process moves into the 1980s, the emphasis tends to shift from component and subsystem development to systems development, commercialization assessment, and system utility and reliability demonstration.

Figure 2

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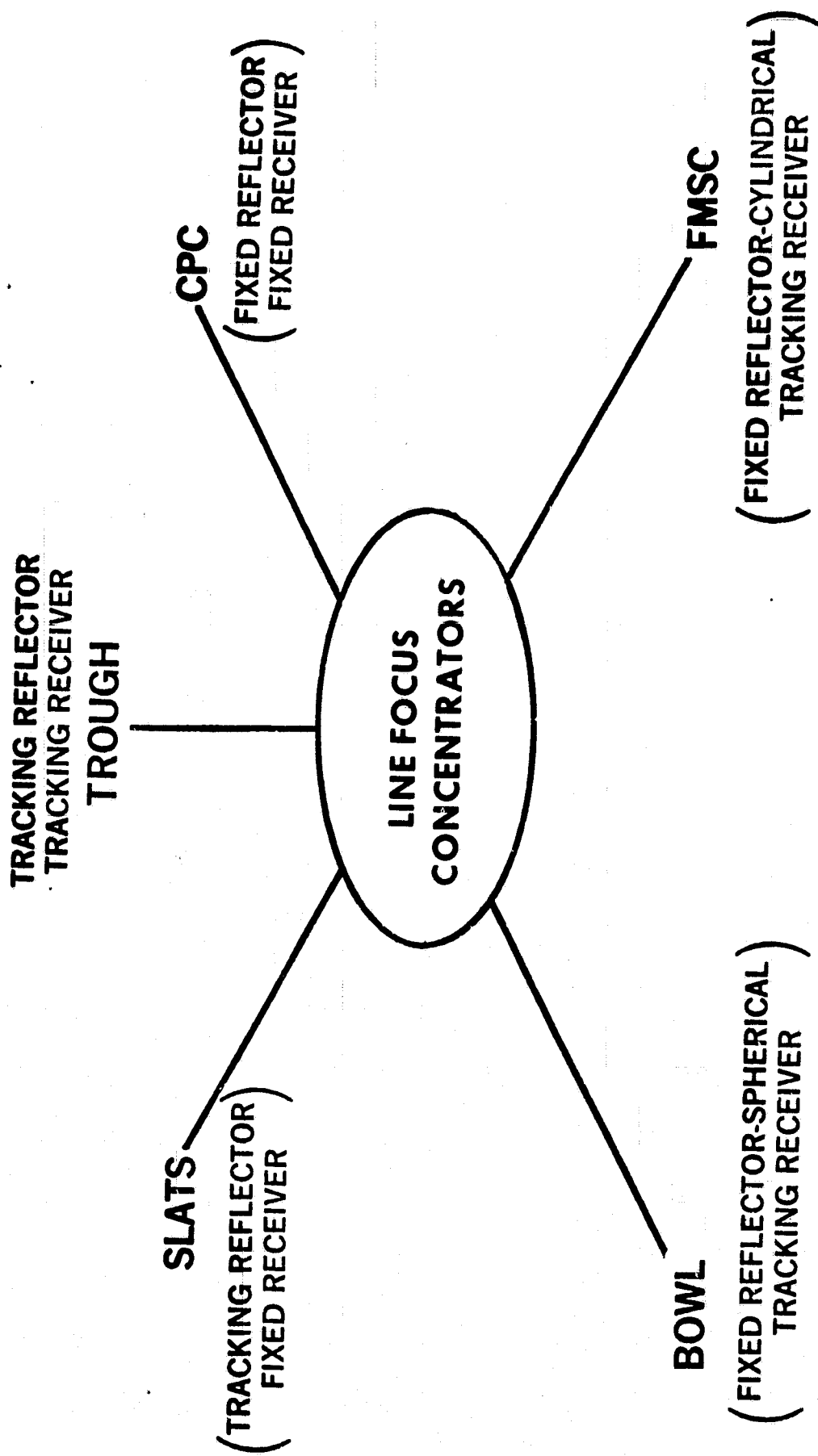
LINE-FOCUS CONCENTRATING COLLECTOR
PROGRAM JUSTIFICATION

SOLAR THERMAL
LINE-FOCUS
CONCENTRATING ➡ SOURCE OF
COLLECTOR HEAT (<550°C) ⤵ + HEAT ENGINE ➡ + HEAT RECOVERY ⤵
TECHNOLOGY

    — INDUSTRICAL PROCESS   — MECHANICAL DRIVE: — COGENERATION
      HEAT (13 Q/YR)   IRRIGATION
    — ENHANCED OIL   — ELECTRICITY: — TOTAL ENERGY
      RECOVERY (0.2Q/YR)   INDUSTRIAL
    — COMMERCIAL HEATING
      & COOLING (7 Q/YR)
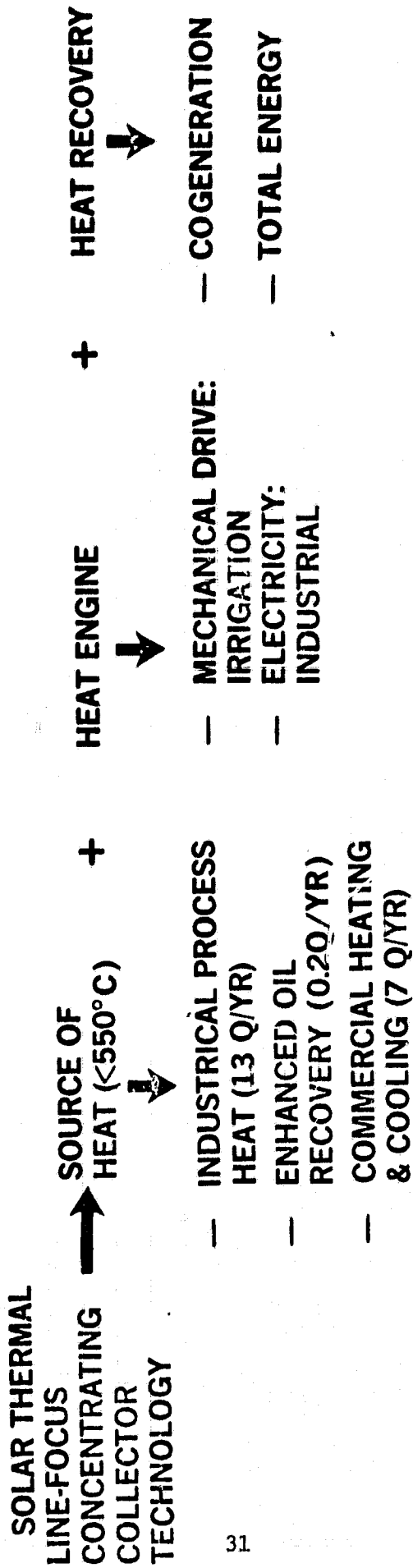
FIGURE 3

SOLAR THERMAL
LINE-FOCUS CONCENTRATING COLLECTOR PROGRAM

FISCAL YEAR

75 , 76 , 77 , 78 , 79 , 80 , 81 , 82 , 83 , 84 , 85 , 86 , 87 , 88 , 89 , 90

PROGRAM ACTIVITY

I. MAJOR COMPONENT DEVELOPMENT
   A. DESIGN & ENGINEERING DEVEL.
   B. PRODUCTION ENGINEERING

REFLECTORS, STRUCTURES, RECEIVERS
TRACKERS, DRIVE SYSTEMS
STRUCTURES, REFLECTORS
TRACKERS

II. SUBSYSTEM DEVELOPMENT
   A. COLLECTOR CONCEPT EVALUATION
   B. COLLECTOR SUBSYSTEM ENGINEERING
   C. STORAGE & ENGINE SUBSYSTEM ENGINEERING

TROUGH, FMSC, SLATS, BOWL, CPC
TROUGH, BOWL
SENSIBLE HEAT, SMALL RANKINE ENG.

III. SYSTEM DEVELOPMENT
   A. SYSTEM CONCEPT EVALUATION
   B. SYSTEM ENGINEERING

IPH, SMALL ELEC., TOTAL ENG.
SMALL ELEC., TOTAL ENG., MODULAR IPH

IV. COMMERCIALIZATION ASSESSMENT
   A. PRODUCTION COST & RESOURCE PROJECTIONS
   B. APPLICATION IDEN. & ALTER. COMPARISONS

TROUGH, BOWLS
TROUGH, SLATS, CPC, BOWLS

V. SYSTEM UTILITY AND RELIABILITY DEMON.

MODULAR IPH AND TOTAL ENERGY

VI. COMMERCIALIZATION ACCELERATION
   A. TECHNOLOGY DISSEMINATION
   B. ECONOMIC CATALIZATION

?

FIGURE 1:

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Major emphases in the 1980, 81, and 82 time frame will be (1) the demonstration of production prototype parabolic trough hardware, and (2) the implementation of a Modular IPH Program. The Modular IPH Program is oriented in its first cycle towards reducing the installation cost and improving the overall system reliability of current hardware. The production prototype demonstration effort will provide the initial technology which will allow parabolic trough hardware to move into mass production levels of effort as soon as markets have been established for this alternative energy system.

SESSION I
CONCENTRATOR DEVELOPMENT

TEST BED CONCENTRATOR (TBC)

by

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ABSTRACT

A point focussing concentrator design was adapted from an existing communications antenna for use in a solar test bed application. The structure design, configured for use with JPL's spherical radius mirror panels, made no attempt toward optimization. The key objectives of stiffness, pointing accuracy, and timely delivery were exceeded. The system weight is approximately 16,000 Kg (36,000 lbs) and has a calculated 1 sigma system error of 0.03 degrees. The completed installation of two concentrators was accepted one month ahead of schedule.

INTRODUCTION

The Test Bed Concentrator construction program required the integration of an existing proven satellite communications antenna design, with the latest development in mirrored panels, toward the objective of providing a high concentration point focussing solar collector. It is planned that this device be used to test receiver-engine systems operating on gas cycle principles as well as on high temperature steam cycles. Thus, it was imperative that the concentrator exhibit unusually high stiffness characteristics and pointing accuracy. Moreover, because of the increasing urgency of the overall solar programs, it was necessary that the TBC be ready for use in a relatively short time scale.

The Jet Propulsion Laboratory contracted with E-Systems to provide the collector primarily because of the company's extensive background and inventory of applicable structural designs. The program that ensued represented a truly cooperative effort between client and contractor that met or exceeded all technical and schedule goals.

REQUIREMENTS

The key contractual technical requirements for which E-Systems was responsible included:

- The development of a concentrator structure by adapting an existing, proven antenna structure design
- The design of the mirror panel geometry and mounting requirements (for integration into the JPL mirror design)
- The design of an interface structure for integrating the spherical radius mirror panels with the concentrator structure
- The design of a sun tracking control system which interfaces with existing JPL facilities
- The fabrication, installation, (including mirrors) and checkout of two TBC's at the JPL Edwards AFB site.

In support of these activities JPL was responsible for:

- Monitoring and approving the design activity
- Constructing the foundation to the E-Systems design
- Fabricating the mirror panels
- Aligning of the mirror panels after installation
- Providing site power and control system facilities and interfaces

Within the framework of these general requirements, the key design criteria are shown in Table 1.

<div align="center">TABLE 1 - KEY DESIGN REQUIREMENTS</div>

- **PHYSICAL**
  Aperture Diameter   11 M (35 feet)
  Rim Angle   45 Degrees
  F/D Ratio   0.6
  Focal Point Load   500 KG (1100 pounds)
  Receiver Mounting   76 CM (30 inch) inside dia. ring
- **TRACKING CONTROL**
  Azimuth
    Travel   ± 178 Degrees
    Slew Rate (13 M/S Wind)   2028 Degrees/Hour
  Elevation
    Travel   0 to 90 Degrees
    Slew Rate (27 M/S Wind)   168 Degrees/hour
  Tracking Accuracy (Operating Wind)   0.05 Degree
  Pointing Accuracy   1.0 Degree
- **ENVIRONMENTAL**
  Operating Wind   13 M/S (30 MPH) Gusting
  Survival Wind   45 M/S (100 MPH)
  Seismic   0.25 G, Any Direction
  Ice   0.4 CM (1 inch) Radial
  Snow   0.4 KG/M^2 (10 lb/ft^2)

These specifications define a full motion structure, one capable of boresight pointing anywhere within a hemispherical envelope at rates deemed consistent with defocussing necessities. With only few exceptions, the requirements are also consistent with normal design criteria of antenna structures.

The most notable difference is in the anticipated focal point load. The collector requirement of 500 Kg (1100 pounds), the expected weight of the receiver and gas cycle engine, is an order of magnitude greater than the subreflector or feedhorn weight of comparably sized microwave antennas. Moreover, the f/D ratio of the TBC (0.6) is about double that normally encountered in microwave dishes. Thus, the moments and bending loads induced by the focal point requirements have an unusually high impact on the stiffness requirements of the structure and the accuracy characteristics of the design.

Additional design requirements were imposed relative to the mirror panels. The JPL designed mirror facets employ a thin, second surface glass mirror bonded to a spherically contoured foam glass substrate. The maximum size of foam glass blanks available from the manufacturer was 61 x 71 cm (24 x 28 inches). Thus the size of the mirror panels was limited accordingly. Other requirements included:

- Minimizing the number of panel sizes and shapes for maximum manufacturing and cost efficiencies
- A three point mount to minimize installation stresses
- Two degrees of radial adjustment to allow installation latitude
- Minimum inter panel gaps to maximize surface utilization

DESIGN

A 13 meter diameter communication antenna was selected for the TBC application. The antenna was originally designed for the RCA Domestic Satellite System and five units were subsequently constructed in continental U.S. Only the reflector structure was used for the TBC since the antenna was a limited motion satellite tracker with a maximum of 60 degrees of azimuth coverage. Therefore, an entirely new pedestal was designed for the TBC to enable full sky coverage.

Figure 1 shows the completed Test Bed Concentrator. The primary subsystems comprising the assembly are described below.

Reflector Support Structure

The Reflector Support Structure is a structural steel space frame consisting of eight truss beams radiating from a central hub, all interconnected with appropriate diagonal and intercostal members. The hub, which employs shear webs, is unusually large (it is unchanged from its 13 meter configuration) and exhibits exceptionally high stiffness characteristics. The only major modification required to adapt this structure to the TBC was an increase in the section modulus of the members comprising the two vertical radial beams which form the primary load path for the focal point mass. A parallel tube matrix serves as the interface structure for mounting the rectangular mirror panels on the radial reflector structure. Mirror attachment is effected by specially designed clamps which provide maximum adjustability for panel gapping and alignment.

Receiver Support

The receiver support structure is a tubular bipod interfacing the toroidal receiver ring at the focal plane with the periphery of the Reflector Support Structure. It is stabilized laterally and torsionally by adjustable rods which also attach at the periphery of the dish. The total structure thus minimizes the amount of surface blockage as compared to the more conventional, but no more stable, quadrapod mount.

Pedestal

The pedestal is an elevation over azimuth, wheel and track alidade. It is a fully triangulated, structural steel space frame, designed to transmit all loads from the elevation axis to ground in tension or compression. The azimuth axis is defined by the pintle bearing which is bolted to the foundation and reacts all radial and uplift loads. Gravity loads are reacted by the three railroad type wheels which ride on a 9 meter (29 ft) diameter track bolted and grouted permanently to the foundation.

Drives and Control

In azimuth, a 3 HP DC servo motor drives one of the three alidade wheels through a 740 to 1 gear reducer. Since the wheel to track ratio is 23 to 1, the overall speed reduction is over 17,000 to 1.

An identical 3 HP motor is used in elevation to drive a 20 ton screw type linear actuator through a single helical gear box. The total speed reduction in this axis is 160,000 to 1.

The control system provides for active sun tracking as well as program tracking. Active tracking (auto tracking) is accommodated via two photocell sensors, one for each axis, which generate error voltages as a function of position error. The auto tracking mode is used only after the concentrator has been positioned by program (or manually) to within 2.5 degrees of the sun.

Program tracking (Memtrack) employs the closed loop position control method, implemented through the use of a microprocessor. Azimuth and elevation angle data may be entered into memory as a function of time by recording actual sun position when in the autotrack mode. Ephemeris data may also be entered manually.

The Concentrator Control Unit (CCU) generates motor drive commands in all modes of operation. The motor commands are produced as a result of input commands from the front panel rate controls, from the internal tracking routine, or from the position commands. The closed loop output of the CCU is a low voltage analog signal proportional to the concentrator position error for each axis. Identical DC motor

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controllers provide the interface between the command output of the CCU and the high current requirements of the drive motors in both axes. The angular position of the concentrator is reported through the use of a multispeed synchro (analog) data package mounted on each axis and a synchro-to-digital converter within the CCU. The converted synchro information is also used to provide position loop feedback.

Weight Summary

A weight summary of the system is shown in Table 2. It is important to recognize here that no attempt was made to optimize the design of the TBC. The design employed was expedient and achieved the primary purposes of stiffness and a timely delivery.

TABLE 2 - STRUCTURE WEIGHT SUMMARY

E-Systems
- Reflector Support Structure 12,000
- Receiver Support 1,300
- Panel Support Tube Matrix and Clamps 800
- Alidade 9,500
- Track 2,500
- Ancillary Equipment/Hardware 4,500

      Subtotal   30,600 pounds

JPL
- Mirror Panels & Bkts 3,600
- Focal Point Package 1,100

      Subtotal   4,700

      TOTAL WEIGHT ON CONCRETE   35,300

Analysis

The structure was comprehensively analyzed using both computer and manual methods. Several proprietary and library programs were employed of which the principal one was SPACE. This is a finite element program which relates applied loads to displacement and rotation at the joints, which in turn are used to calculate internal loads and stresses in the structural elements.

The system design was predicated on stiffness consideration rather than on stress. Thus, as the result of maintaining deflections within specified limits, the members are relatively lightly loaded and exhibit stress ratios generally well under 1.

In Table 3 the calculated system error analysis is compared to the specified requirements.

TABLE 3 - ERROR ANALYSIS

1 SIGMA

	SPECIFICATION	PREDICTED
Reflector Assembly		
• Reflector Support Structure	-	.0070
• Panel Support Tube Matrix	-	.0248
• Receiver Support Structure	-	.0019
TOTAL STRUCTURAL ERROR	$.02^{\circ}$	$.0258^{\circ}$
Control System		
• Servo Limit Cycle	-	.0001
• Servo Angular Error	-	.0001
• Servo Wind Gust	-	.0003
• Servo Bias	-	.0010
• Sensor Error	-	.0067
TOTAL CONTROL ERROR	$.05^{\circ}$	$.0068^{\circ}$
Combined System Error	$.07^{\circ}$	$.0267^{\circ}$

The predicted combined system error is thus only about one third of that specified. As a result of this increased accuracy, improved performance of the TBC in the form of higher concentration ratios can be anticipated.

Installation

The design, as well as the program plan for the TBC, gave heavy consideration to minimizing on site installation time. To accomplish this objective it was necessary to ensure that all parts fit properly prior to arrival on site. Thus, the key acceptance criteria for the steel fabrication phase was trial assembly of the reflector structures and pedestals at the fabricator's facility in Birmingham, Alabama.

The reflector structure was designed so that it could be completely constructed at ground level, including mirror panels and placed on the pedestal in a single lift. A 45 ton, 100 ft. boom hydraulic crane was employed for a total of 3 days to place both reflector assemblies. (see Fig. 2) This served the dual purpose of minimizing both assembly time (construction directly on the pedestal is commonplace in antennas) and costly large crane expenses. For the remainder of the installation, an inexpensive 7 ton crane served more than adequately. It is noteworthy that the E-Systems installation team consisted of one supervisior and three ironworkers full time, supported part time by the control system subcontractor. Installation of the TBC's, including tracking and control system operational checkout, required a total of two months.

Acceptance of the installation by JPL on 17 October 1979 represented completion of the entire contract one month ahead of schedule.

TABLE 4 - KEY EVENTS

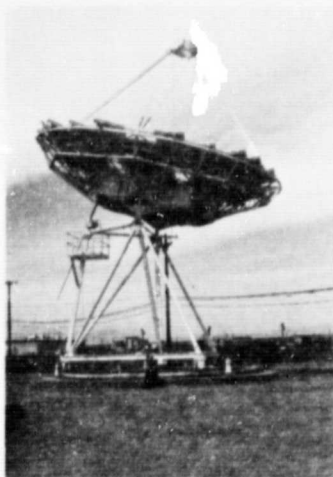|	CONTRACT	ACTUAL
DESIGN START	13 Sept. 1978	13 Sept. 1978
FABRICATION START	—	5 Apr. 1979
INSTALLATION START	—	13 Aug. 1979
FINAL ACCEPTANCE	13 Nov. 1979	17 Oct. 1979

Fig. 1

Fig. 2

TEST BED CONCENTRATOR MIRRORS*

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ABSTRACT

The Test Bed Concentrator (TBC) was designed to test components of point-focusing distributed receiver (PFDR) systems. The reflective surface of the concentrator was fabricated using mirror-facet designs and techniques previously developed at JPL. The facets are made by bonding mirrored glass to spherically-contoured substrates. Several aspects of the earlier work were reevaluated for application to the TBC: optimum glass block size, material selection, environmental test, optical characteristics, and reliability. A detailed explanation of tooling, substrate preparation, testing techniques, and mirror assembly is presented.

INTRODUCTION

In an earlier program at JPL, development work was performed on mirror facets which were made by bonding a second-surface mirror to a spherically-contoured substrate of a variety of materials including quartz, plastics, honeycombs, metal weldments, fiber resins and spun epoxy.

Foamglas,** a soda-lime cellular glass material used for insulation, was selected as the substrate for the mirror facets due to its coefficient of expansion compatibility with the mirror, light weight, ease of shaping, general stability and durability.

Rectangular blocks, 46 cm x 61 cm (18 in. x 24 in.) were the largest available, therefore facet shapes were restricted to a maximum area of .28 m^2 (3 sq ft). Tests indicated that mirrors fabricated with a radius of curvature of 13 m (43 ft) had slope errors less than 0.1° (1.74 mr). Figure 1 shows a mirror at this early stage of development.

APPROACH

A review of existing facet designs indicated that revisions in block size, selection of materials, and structural characterization of Foamglas were required to adapt there designs to the TBC.
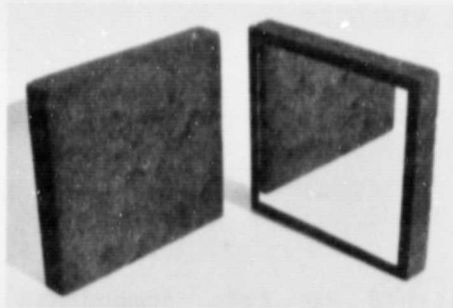

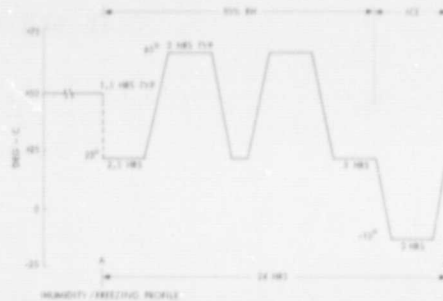FIG. 1.   EARLY DEVELOPMENT
MIRROR FACET

FIG. 2.   ENVIRONMENTAL TEST
CYCLE

Analysis showed that block sizes greater than 46 cm (18 in.) would give satisfactory performance. Somewhat larger sizes would be no more difficult to fabricate and a smaller number of facets would be required for the TBC. Pittsburgh Corning Company produced a 61 cm x 71 cm x 5.1 cm (24 in. x 28 in. x 2 in.) block as a special run through their commercial process. This was adopted as the maximum envelope from which to make the TBC mirrors.   In addition, the rectangular facet configuration was analyzed for its structural adequacy to withstand 160 km/hr (100 mph) wind loads.   A support geometry was chosen using three flexure tabs bonded to the edges of the facet substrate.

An investigation was made of readily available materials which would best perform the functions required for the facet.   This included the mirrors, adhesive for the mirrors and support tabs, and sealant coatings for the substrate edge of mirror to substrate interface.   Several candidates were reviewed for each function.

A composite test program was undertaken to select the material combination to be used for fabrication.   In addition to the important criterion of ease of workability, an environmental test program was used to screen the materials.   A severe temperature-humidity cycling test was used to demonstrate the mechanical integrity of the materials.   This test cycle, Figure 2, consisted of three cycles per day, two from 23°C to 65°C (73°F to 150°F) and one from 23°C to -13°C (73°F to 8.6°F).   Humidity was maintained at over 95% during the heating cycles and ice was formed on the mirrors during the freezing cycle.   The test uncovered no mechanical degradation. However, degradation of some mirror surfaces in the form of black speckles began to occur after 16 days.   This was attributed to the adhesive system used to bond the mirror to the substrate, aggravated by the moisture penetrating the edge to wet the mirror-substrate interface.

Laboratory tests had shown that a system having a near neutral pH caused the least mirror degradation.   To confirm this, eight facets were fabricated using different adhesive systems. Half of the facets were edge-sealed.   All were subjected to the cyclic environmental test.   Evaluation of the speckling degradation of the mirror and considerations of previous experience at JPL led to the decision to use Furane 9427 with the Dow Epoxy Resin 332 as the adhesive system.

A short test program was also conducted to evaluate the strength sensitivity of Foamglas to freeze-thaw cycles at a 95% humidity environment. Samples were tested both uncoated and coated with Pittcote 404/Chemglaze. It was concluded that the coating greatly increased the freeze-thaw resistance of Foamglas and that the sealant must be carefully applied to prevent pinholes in the coating through which water might penetrate.

Although hail is not expected to be a severe hazard at the Parabolic Dish Test Site near Lancaster in the California desert, tests were conducted with ice balls impacting the facet perpendicular to the surface. Balls 3.2 cm, 2.54 cm and 1.9 cm (1-1/4 in., 1 in. and 3/4 in.) in diameter were fired into the coated Foamglas back side and mirror surface. All tests were at approximately 96.6 km/hr (60 mph). Figure 3 shows the effects. The 1.9 cm (3/4 in.) diameter ball caused no damage. Additional tests are planned with impact on the edge of the facet.

ASSEMBLY

The materials selected for construction of the TBC mirror facets are listed in Table 1. The glass for the mirrors was procured from the Corning Glass Works, who subcontracted Falconer Plate Glass for the silvering process. The substrate blocks were made using special molds. However, Pittsburgh Corning's standard commercial process was employed for the special production run.

Mirrors with three silvering configurations were purchased and will be evaluated on the TBCs. Most mirrors were cut to size and silvered, but some were silvered and then cut. Some have a 4.83 mm (3/16 in.) silk screen protective edge seal. A small number of mirrors were assembled using Epicure 855 with an accelerator as a near-neutral pH epoxy-resin catalyst.

All materials were shipped to JPL on the same non-commercial carrier truck to ensure minimum damage from handling and the road environment. Precautions not withstanding, flaws were present in the materials and significant damage occurred in shipping. The suppliers replaced all material not meeting specification.

Tooling for the mirror assembly was arranged to produce groups of ten facets daily. The typical flow for the assembly starts with trimming the substrate to size. Rough-grinding to a nominal radius of curvature of 1524 cm (600 in.) was accomplished using a fly cutter tool on a milling machine (Figure 4). The final radius of curvature was obtained by a hand-grinding operation on a master spherical mold covered with 120 grit abrasive paper (Figure 5).

The back surface of the mirror was cleaned in preparation for bonding. A thin layer of adhesive was applied to the painted back surface using a paint roller (Figure 6). The mirror is placed on the contoured surface of the substrate and vacuum-bagged and cured for eight hours (Figure 7). After cure, the facet was inspected, dated and serialized.
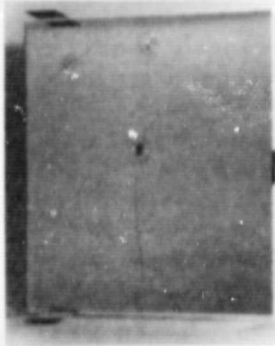
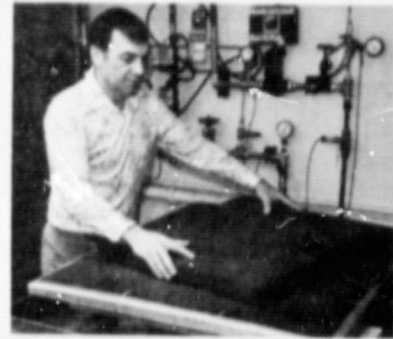FIG. 3. RESULTS OF HAIL TEST   FIG. 4. MACHINE-GRINDING   FIG. 5. HAND-GRINDING
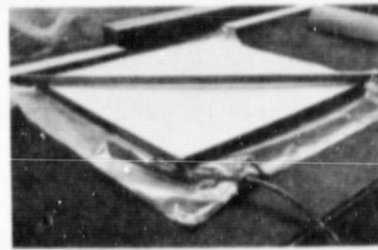

FIG. 6. ADHESIVE APPLICATION   FIG. 7. VACUUM BAGGING

TABLE 1. MATERIALS SELECTED FOR TBC MIRROR FACETS

Substrate	61 cm x 71 cm x 5.1 cm (24 in. x 28 in. x 2 in.) Foamglas High Load Bearing 136.17 kg/m^3 8.5 lbs/ft^3 density) - Pittsburgh Corning
Mirror	60 cm x 70 cm x .15 cm (23-3/4 in. x 27-3/4 in. x 0.058 in.) Corning Glass Code 0317 - Silvered by Falconer
Mirror Adhesive	DER 332 - Dow Epoxy Resin 9427 Hardener-Furane Plastics
Support Tabs	0.032 Aluminum with 5.1 cm x 7.6 cm (2 in. x 3 in.) contact area with Foamglas
Support Tab Adhesive	PC-88 two-part adhesive - Pittsburgh Corning
Mirror Edge Seal	Vulkem 116 Urethane Sealant - NAMECO
Foamglas Sealant	Pittcote 404 Acrylic Latex - Pittsburgh Corning
Paint	Chemglaze II A276 White Polyurethane

Before proceeding with assembly, the optical characteristics of each facet were measured and compared to the acceptance criteria. The focal length and slope error were measured in an optical tunnel assembled for this purpose (Figures 8 and 9). The technique used for slope error acceptance tests is described in the PFDR Technology Project's Annual Technical Report for FY 1978 (JPL Publication 79-1). For our case, discs of varying sizes (Figure 10) determined by the calculated aperture size of cones of 0.29 mr to 1.74 mr (1 to 6 minutes) slope error were mounted sequentially on the optical axis of the system. Each disc will block light from points on the mirror with slope errors less than that for which the disc is sized. Thus, a photograph of the lighted image will show the area with slope errors greater than the error represented by the disc diameter (Figure 11).

A technique was devised to determine the amount of light reflected from the mirror by utilizing a photometer in lieu of the camera. The appropriate spread of discs was sequentially placed in front of the Fresnel lens and the percentage change in energy received at the photometer taken as a figure of merit for the mirror.

It was difficult to obtain high sensitivity in measurement of the focal length. Many mirrors were checked by measurement to the location of the smallest image using the sun or the moon as the light source. Tests using the moon gave good results, but the image using the sun was too bright to be used.

Reflectance measurements were made at five positions on each facet to give an initial reference value for use in later degradation and cleaning tests. Figure 12 shows the reflectometer equipment.

The mirror supports, consisting of three flexure tabs, were bonded to the substrate using a fixture for accurately locating the tabs relative to the mirror surface. Set-up time for the adhesive permitted bonding of tabs on two facets per day in each of ten fixtures (Figure 13).
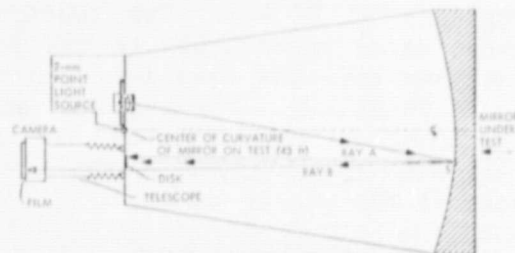

FIG. 8.   TEST INSTRUMENTATION

FIG. 9.   TEST SET-UP DIAGRAM

After a 24-hour cure of the tab bonding adhesive, substrate corners were rounded and the mirror was cleaned in preparation for application of the sealant along the interface between the substrate and the edge of the mirror. The Vulkem 116 sealer was applied with a syringe, forcing the sealer into the cells at the joint and completely covering the mirror edge (Figure 14). The excess on the mirror surface was removed and the seal allowed to cure for eight hours.
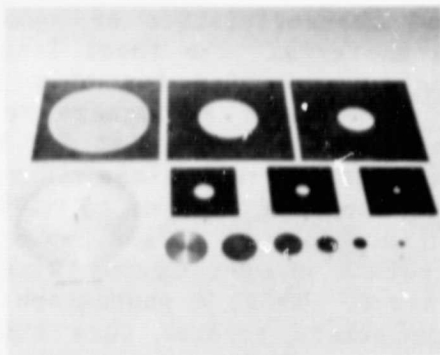
FIG. 10.   CALIBRATED APERTURES
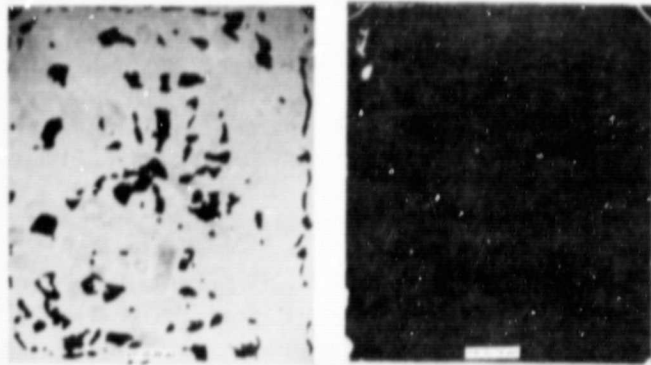   AND DISCS

FIG. 11.   MIRROR SLOPE TEST
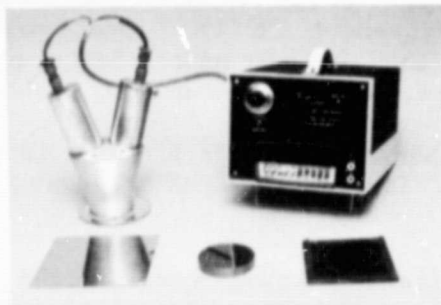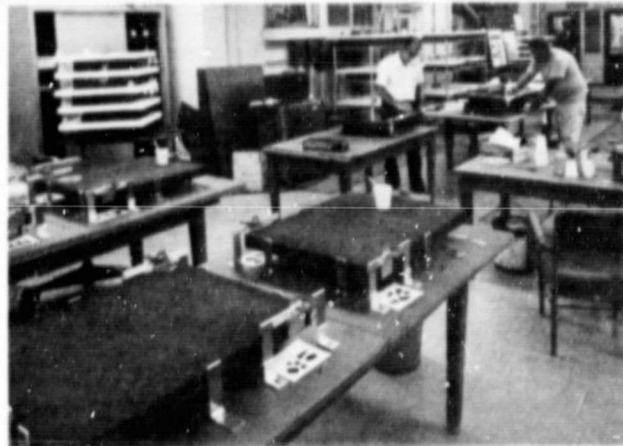   RESULTS

FIG. 12.   REFLECTOMETER

FIG. 13.   TAB INSTALLATION

The final step in the assembly process was to cover the entire exposed Foamglas with PC 404. Two coats were applied to fill the open cells and prevent water penetration to the Foamglas through pinholes in the seal. An eight-hour cure was used for each coat. The surface was then painted with a coat of Chemglaze. The mirrored surface on each completed facet was given a final cleaning with alcohol and a commercial glass cleaner and the facet serial number stenciled on the back of the facet. Figure 15 illustrates a completed TBC mirror facet.
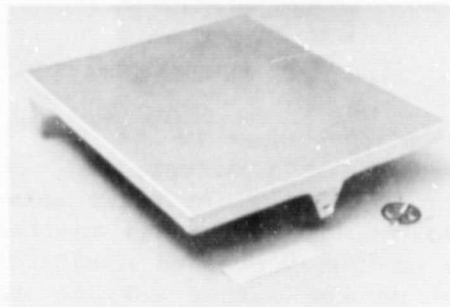

FIG. 14.   EDGE SEAL

FIG. 15.   TBC MIRROR FACET

INITIAL TEST BED CONCENTRATOR CHARACTERIZATION*

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ABSTRACT

This paper reports on the operational characterization of the Test Bed Concentrator (TBC). The control system responsible for tracking and safe operation of the TBC is discussed in detail. The techniques used for mirror alignment and verification are also described. Finally, the paper briefly addresses the plans for future tests using the TBC.

INTRODUCTION

Two TBCs were designed, fabricated, and assembled by E-Systems, Inc. at the Parabolic Dish Test Site (located near Lancaster, California) operated by the Jet Propulsion Laboratory (JPL). (See Figure 1.) JPL retained responsibility for the optical design and mirror alignment of the TBC. Electrospace, Inc., the control system subcontractor to E-Systems, Inc., instructed JPL test personnel in the operation, circuitry, maintenance, and trouble-shooting of the control unit.

This paper is limited to three areas concerning the initial characterization of the TBCs. First, the operational characteristics of the control system will be discussed. Next, the alignment technique and results, including verification tests using the moon as the light source, will be presented. Lastly, the near-term testing which is planned to characterize the thermal performance of the TBCs will be outlined.
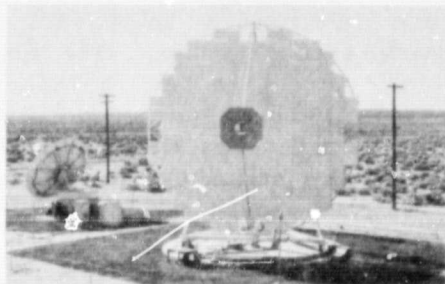

FIGURE 1.   TEST BED CONCENTRATOR

CONTROL SYSTEM OPERATIONAL CHARACTERISTICS

The final design of the TBC control system provided one axis of fast slew capability so that either the sun acquisition or emergency off-sun mode could be obtained in a minimum time. Due to differences in the mechanical design, the azimuth axis has the higher rate capability. The azimuth drive is a wheel and track system driven through a two-stage gear box by a three-horsepower, DC electric motor. The elevation axis drive is a low efficiency jack screw which would require a very large electric motor to accomplish the same drive rate as the azimuth drive. Since this drive system is based on a modified antenna design, it was not cost-effective for E-Systems, Inc. to increase the slew rates of both axes. The slew velocities of the two axes are 2028°/hr (0.56°/sec) for the azimuth and 168°/hr (.05°/sec) for the elevation. These rates are achieved with 48 km/hr (30 mph) wind loadings; calm day velocities are slightly higher.

The procedure for getting on and off sun is to run the elevation axis up to the approximate elevation of the sun for the particular time of acquisition and then slew the concentrator on sun in azimuth. This prevents the sun spot from crossing the bipods or guy rods. The sun spot, defocused slightly, does cross the receiver ring structure. A preliminary, worst-case thermal analysis showed that ring temperatures could enter the 1093°C+ (2000°F+) range in seconds. The results of this thermal analysis led to the installation of 5-cm (2-in.) thick Fiberfrax insulation material on the ring structure and over the bipod joints. The remaining upper half of the bipods and guy rods was covered with 3-mm (1/8-in.) thick Fiberfrax.

The TBC base, or alidade, has the capability of rotating 178° from south due to its wheel and track design. Therefore, during maintenance or malfunctions the concentrator dish can be pointed towards north. The dish can be moved about the elevation axis between the zenith position and the horizon, or 0°-90°.

The automatic sun-acquisition system is controlled by two sun sensors, one for each axis. Each of the sun sensors has a ±2° acquisition cone angle within which the concentrators are programmed to point. Pointing within ±2° is accomplished through a memory track system. The memory track consists of a computer memory bank device which stores ephemeris data from the prior tracking period; the data can also be updated by keyboard or by an external computer to provide the sun's ephemeris data for the day of interest. The stored data is used to point the concentrator close to the sun's position. The sun sensors then take over and point the concentrator dish to within a few hundredths of a degree of the sun.

As the sun sensor system views the edge of the sun disk it reduces the slew velocity rate of the drive motor. This in turn makes the sun spot track across the receiver ring support structure at a very slow rate. The early slow slew speed can be changed by a keyboard input from the control unit to insert a time lag between the first acquired sun signal and the speed reduction in the motor. This time lag allows the sun spot to track at full speed across the ring and not slow down until it reaches the receiver.

The concentrator control units have the capability of correcting for gravitational deflections as a function of elevation angle. The sensitivity of the sun sensors can also be changed to compensate for seasonally variable insolation levels or for atmospheric conditions. This feature allows the sensors to pick up less than optimum sun intensities and diminishes their tendency to track bright spots at the edge of clouds.

The control unit can also be used to roughly determine the sun sensor mechanical misalignment through the use of the sensor sun presence signal (sun intensity) and the axis angle readout dial. If the sensor mechanical misalignment is 1° or less it can be corrected electrically by inputting data through the keyboard.

MIRROR ALIGNMENT

Light sources considered for mirror alignment were moon, sun and an incandescent lamp. The technique chosen utilized a semi-distant incandescent light source which produced a reflected image on the focal point target. The target surface is composed of a series of concentric rings 2.54 cm (1 in.) apart. The moon was not selected because of its cyclic appearance and potential occlusion by clouds. The sun was not used due to weather and safety considerations. Both of these discarded methods would have required the TBCs to track which would have introduced a tracking error into the mirror alignment.

Only one TBC mirror facet could be aligned at a time. This necessitated the development of individual mirror covers which could be removed and reinstalled easily. (See Figure 1.) Opaque plastic covers with Velcro fasteners were chosen. The alignment of one entire concentrator (224 mirrors) took about two weeks of night work.

The light source was located at a NASA facility atop a hill 5.8 km (3.6 miles) southwest of the test site. This allowed protection for the equipment and provided convenient electrical power, even though the equipment was designed to be weather resistant and portable. The light was attached securely to the roof of the building and the rest of the equipment was placed indoors. The light was aimed towards the concentrators until a maximum brightness could be observed at the TBC site.

Once the light source was aimed, the TBC was boresighted to it. This was done using two sets of cross hairs and two disks which were replaced by a series of disks with successively smaller apertures. The cross hairs were placed at the front (outer end) of the receiver mounting ring and at the rear of the concentrator dish structural hub on the geometrical center. The disks with variable size circular apertures were placed at the mirror surface plane and at the focal plane of the receiver. By moving the concentrator while sighting along the cross hairs and through the apertures in the disks to the light source, the concentrator was boresighted to the light. The final aperture size in the two disks was 1.27 cm (0.5 in.) in diameter, resulting in the

maximum pointing error being within $\theta = \tan^{-1} 0.5 \div 259.8$ or 0.11^o. The cross hairs used in conjunction with the dish apertures and the light reduced the boresighting error by half, or $\theta = .05^o$. The control system position repeatability for the concentrator system was designed to be $\pm.01^o$. When it was programmed to move the concentrator to the boresighted position of the light source, a visual alignment check was performed several times by physically sighting the light source along the cross hairs and through the two disks. This verified that the image was geometrically centered at the focal plane target location.

The mirror alignment is implemented by using a three point adjustment system (see Figure 2). Each mirror facet is attached to the concentrator structure with three flexures (see Figure 3). The three flexure halves bonded to the mirror facet are bolted to a matching bracket on the concentrator structure. Both halves of the joint have slotted holes to allow for adjustment or movement. One at a time, each of the 224 mirror facets was loosened at the flexure joint and adjusted to center its image on the focal target. When the image was centered the three flexure joints were tightened in place (see Figure 4).

FIGURE 2. MIRROR FACETS WITH
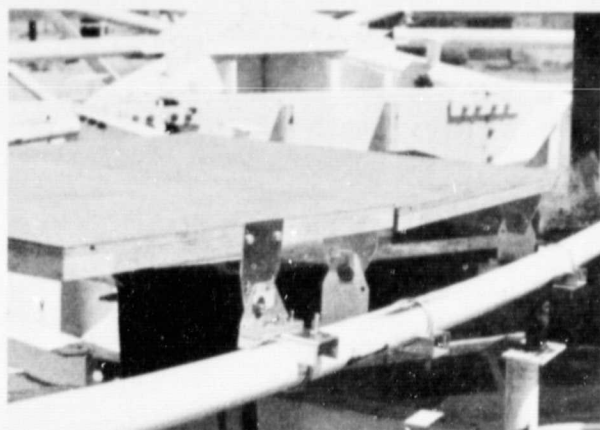   FLEXURE ATTACHMENT
          HARDWARE

FIGURE 3. MOCK-UP MIRRORS WITH
          FLEXURE ASSEMBLY

Additional alignment verification checks were made periodically by removing a cover from a previously aligned mirror and re-verifying its light image position. No displacement was evident in these checks. After all mirrors were aligned, the opaque target at the focal plane was replaced with a translucent target and a picture was taken of each individual mirror image. All mirror covers were then removed and the resulting image was recorded on film (see Figure 5). A further alignment check was made by pointing the concentrator at the moon and imaging the moon on the target; this image was also recorded on film (see Figure 6). The moon's image was approximately 20 cm (8 in.) in diameter. This matched the predicted image size and further verified that the mirrors were aligned satisfactorily. On several occasions one edge mirror was uncovered while the concentrator was pointing at the sun.
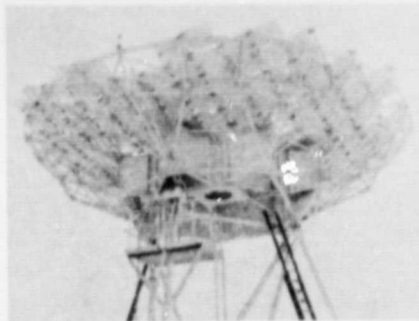
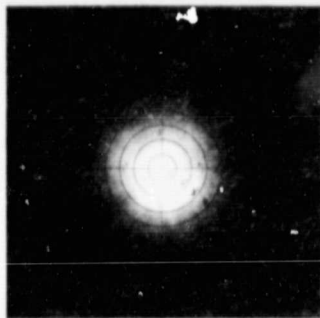FIGURE 4. REAR VIEW OF TBC WITH MIRRORS ALIGNED

FIGURE 5. LIGHT SOURCE IMAGE
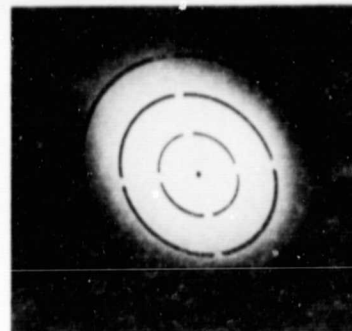
FIGURE 6. MOON IMAGE

This provided increased confidence in the mirror alignment because the sun produced an elliptical image from these edge mirrors of approximately 20 cm (8 in.) maximum dimension, as determined by eye observation from the ground. The edge mirrors produce the maximum elliptical image size because they are the furthest off axis.

FUTURE TESTING

Test preparations are underway to install a solar flux mapper to characterize the solar spot. It will measure the size, shape and intensity of the sun's image.

Upon completion of flux mapper testing, cavity cold water calorimeter testing will be initiated. This will provide information on the thermal characteristics of the TBCs. Both test sequences will be done using three regions of mirrors individually and then all mirrors at once. Testing will be done with both clean and soiled mirrors. The reflectivity of sample mirrors will be measured as necessary to coordinate the reflectance with the solar test results.

Upon completion of the characterization tests, the TBCs will be ready for the various receivers and engines scheduled to be tested.

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THE OMNIUM-G HTC-25
TRACKING CONCENTRATOR

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Anaheim, California

ABSTRACT

On May 3, 1978, OMNIUM-G installed its first point focusing, two axis-tracking, high concentration ratio parabolic reflector. Since then, OMNIUM-G has delivered and installed thirteen additional concentrators throughout the world. As a result of these initial installations, field data has been plentiful and the data has given OMNIUM-G the ability to invoke design refinements in several areas. The improvements have manifested in a design that is economic in the areas of manufacturing, packaging, delivering, installing, and commissioning the system into operation.

OMNIUM-G's unique field experience coupled with engineering improvements is paving the way for long life, highly reliable, and economic fields of point focused distributed receiver solar thermal power systems.

This paper deals specifically with OMNIUM-G's model HTC-25 Tracking Concentrator, the initial problems and their subsequent solutions. These solutions have guaranteed the continued success in dramatically reducing the costs of the concentrator to the extent that large field applications may now be realized economically and to a high degree of reliablility. The HTC-25 Tracking concentrator has found applications in educational institutions because of its ability to operate at extremely high focal point temperatures in excess of 4000°F. When the HTC-25 is operated as the nucleus of a solar thermal power system, the ability to operate water-to-steam converters at 1100°F and air converters at temperatures of 1800°F has opened the door to applications as electrical power generation, enhanced oil recovery, and water purification and desalination to the extent that these applications may be served more economically than from any other means of solar thermal technology.

SOME WORDS ABOUT THE PRODUCT

In mid 1973, OMNIUM-G began design of the model HTC-25 Tracking Concentrator. This device, a two-axis tracking, imaging, high concentration ratio reflector is the nucleus product of OMNIUM-G. This product is embellished with two types of converters (receivers). One is a direct water-to-steam converter operating at 1100°F with pressures of up to 3000 psia at rates from between 47-74 pounds per hour with a nominal thermal power input to the fluid of 21 KW_t

In the case of air, air can be moved through the converter at pressures of up

to three atmospheres at temperatures from 800-1800°F at rates from between
37-85 cfm also with a nominal thermal power input to the air of 21KW$_t$. These

converters serve a multitude of application areas at temperatures and pressures
heretofore deemed impractical and perhaps even impossible. With the innovation
of the hot-air converter, applications requiring either buffering or storage
may now be economically served. OMNIUM-G continues to provide thermal storage
modules, converters, and prime movers to serve customers requiring complete
turn-key solar thermal power systems.

THE CONCEPT BEHIND THE HTC-25 TRACKING CONCENTRATOR

Choice of Concentration Ratio

A peak concentration ratio of 10,000:1 was chosen for the initial design goal.
The primary reason was for the total reduction of thermal losses due to con-
vection cooling due to wind. The only loss at this high of concentration
ratio would then be attributed to only the losses expected due to radiation.
Early studies showed that concentration ratios in excess of 3,000:1 had the
unique property of being insensitive to wind and subject only to minor radiation
losses particularly advantageous when desiring to operate at extremely high
temperatures of 1100-1800°F.

Although OMNIUM-G was confident that this design goal had been met by virtue
of being able to maintain this parameter in our factory environment, field
results indicated that such a concentration ratio had not been maintained.
As the field data was reported back to OMNIUM-G it became clear that the early
units sufferred from wind buffeting, man-handling, and misalignment. Steps
were taken within the factory to improve the wind buffeting problem and sub-
sequent systems were modified as well as those in the field. The alignment
problem stemmed from the fact that alignment was done with near field optical
techniques that introduced intolerable error. Alignment techniques are now
done swiftly in the evening using far field optical sources which has proven
to improve the system efficiency dramatically. Man-handling continues to
be the major problem and to this extent, the converters have been slightly
modified with a larger aperature of 7-8 inches from the ideal size of 4 inches.
The new generation converters now match the proper volume to the new aperature
size. The instantaneous average concentration ratio still measures over 4000:1
which results in a performance unmatched in the commercial market place.

Choice of Reflecting Material

The reflecting material used by OMNIUM-G still continues to be ALZAK, a reg-
istered electro-polished annodized aluminum process from Alcoa. Choosing
front surface reflecting material in lieu of glass is still considered optimum
by OMNIUM-G based on the concentrators 20 year projected life. Factors include
availability, cost, ease of handling, ease of maintaining, and its ever so
slight and graceful degradation from maximum efficiency to 90% over its
20 year life.

Reflector Material Problems

Although several processes and materials have emerged for front surface reflecting techniques, ALZAK continues to be the best but does have its own problems.

The most severe problem with the material is in the basic milling process. Since this material is produced to serve a market that has very relaxed specifications on specular reflectivity, the average sheet falls below OMNIUM-G's minimum acceptable criteria. As such the rejection factor holds at about 60%. As OMNIUM-G continues to grow, plating facilities will be installed that will serve a two-fold purpose. One purpose will be to realize a dramatic increase of reflector efficiency, and secondly, a substantial reduction in manufacturing costs will also be realized.

Mirror Fabrication

In 1977 OMNIUM-G finalized its manufacturing development of the petals and their field success has been very exciting. In 1978, refinements were made to the process which lead to some field failures. Since petal fabrication is clearly the critical path of the system manufacturing process, any reduction in man-hours and total elapsed time is a significant factor in the goal of ultimately reducing manufacturing costs.

In experimenting with time reduction techniques and simultaneously meeting customer delivery requirements, several petals were shipped to site that appeared to have sustained factory testing yet failed in the field. Failures in the field were delamination of the aluminum from its substraight and creeping creases. Since the factory keeps a comprehensive record of each petal made whether shipped or not, it was an easy matter to precisely trace the location of the fabrication process attributing to the petal's ultimate failure.

OMNIUM-G has gained incredible insight in the petal fabrication process and has clear visibilty of how the ultimate costs of this process will lessen. Since this area of the concentrator represents a significant cost factor, it is mainly in this process that enables OMNIUM-G to offer its concentrator today at a quantity purchase price to the end user of $14,000. In fact the improvements in manufacturability have maintained the cost of the HTC-25 at virtually the same cost over the last two years in view of our current inflationary crisis.

TRACKING

Early problems associated with tracking accuracy were attributed to relaxed specifications on the electrical components themselves. All such electronically related problems have been solved in the field in both the open and closed loop modes of operation.

There have been subtle tracking problems that have resulted due to installation related activities. Though the system design is quite forgiving because of dimensional inaccuracies in fabrication, installation, especially in levelness, does play a significant role in the system's ultimate operation. Sloppyness of installation has the effect of causing the system to break into tracking oscillations both in the azimuthal and elevation planes.

Most of the significant design improvements have been in the elevation gimbal axis. The system's tolerance to high velocity wind buffeting and its virtual non-susceptability to mechanical gear backlash has improved the overall performance of the system significantly.

INSTALLATION AND MAINTENANCE

Installation of the tracking concentrator has become a routine function here at OMNIUM-G. A concentrator is deemed commissioned on Wednesday noon if installation begins on Monday morning. Installation costs and site preparation costs are considered minimum and OMNIUM-G does foresee common labor having the ability of completely assembling and commissioning a unit virtually in hours. Factory attention is focusing on installation equipment and tools to ease installation and design modifications are usually intended now for the ultimate swiftness of installation. Maintenance of the concentrator is minimal for perhaps periodic cleaning and lubrication. Although several concentrators of been installed in extremely harsh environments, no device today has sufferred a catastrophic failure once properly mounted and secured.

THE FUTURE

OMNIUM-G is solely dedicated to the fostering of solar energy. Without incentive other than self motivation, OMNIUM-G has taken the complete brunt of having to design, build, install, and maintain what it claims to be a commercially available off-the-shelf item. Our customers have been our most valuable asset in fostering a close working relationship and the valuable reporting of data and problems. None of the initial systems delivered by OMNIUM-G were without some operational problems. By our customer's dedication to the advancement of solar energy, we have continued to grow and perhaps some day may even prosper. OMNIUM-G is expanding its manufacturing facilities and is delighted to have played a role in point focusing development.

SUMMARY

Fourteen concentrators have been installed and virtually all field related and environmental problems encountered to date solved. As more field data is received and improvements designed, OMNIUM-G will continue to up-grade its systems in the field along with producing and delivering the most economic and efficient concentrator in the world today.
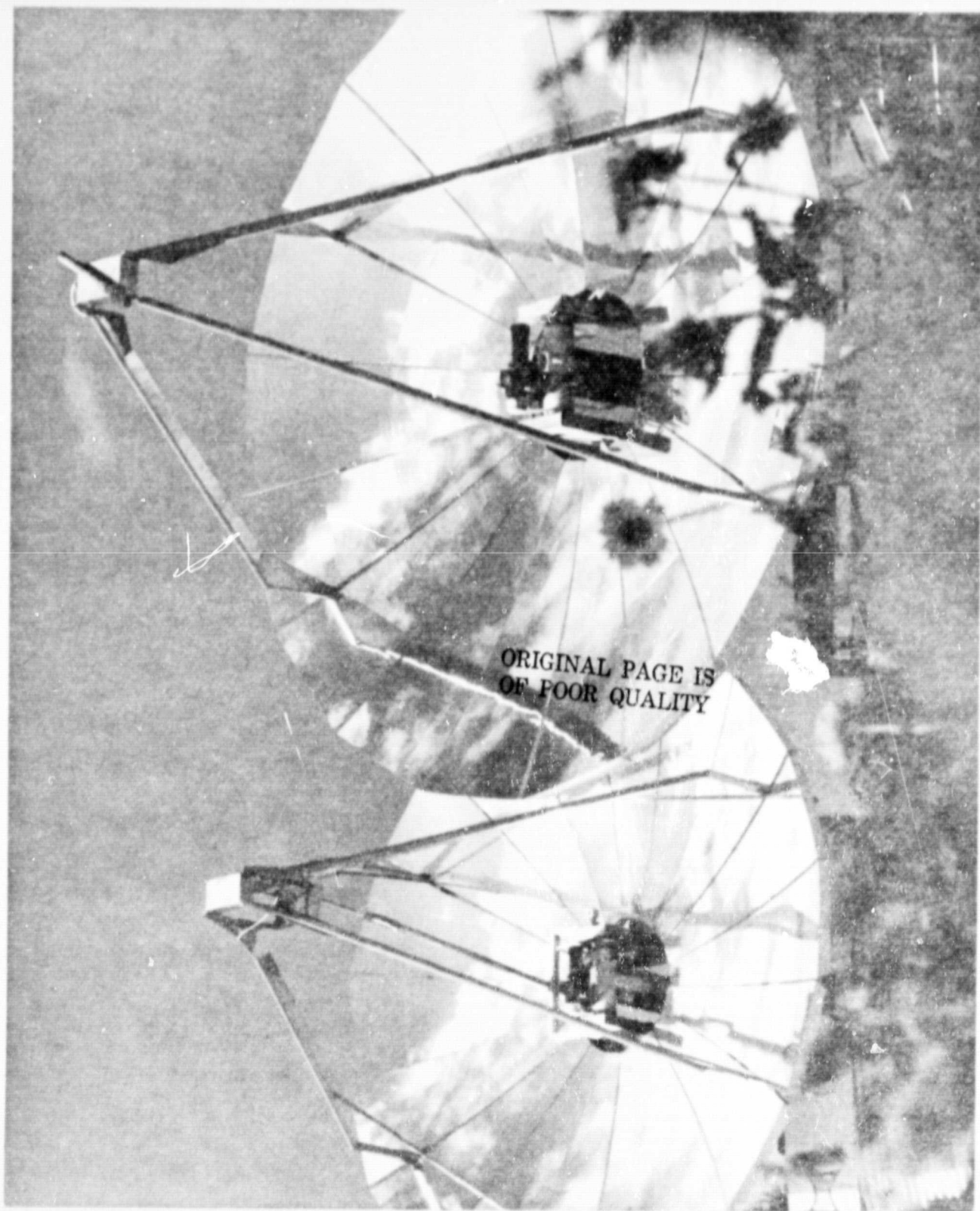
THE SHENANDOAH CONCENTRATOR

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ABSTRACT

A 7-meter diameter, parabolic dish solar collector has been designed and developed for first application at Shenandoah, Georgia by the U.S. Department of Energy Solar Total Energy Project. Key features and requirements for the collector are outlined. Performance test results for collector testing at Sandia Laboratories in Albuquerque are summarized. The key features, requirements and performance of the solar collector subassemblies/subsystems are discussed: mount and drives, reflector, receiver and collector control unit. Problems experienced during collector testing in Albuquerque are identified and solutions described.

INTRODUCTION

Tradeoff studies performed during the Conceptual Design Phase (1) identifies the significant inherent performance advantages of point focusing solar collectors over line focusing solar collectors, for the Shenandoah, Georgia environment and Solar Total Energy System (STES) application. Roughly twice as much energy is collected per day per square foot of aperture with a point focusing collector. With point focusing, energy can be collected efficiently at higher operating temperatures, leading to higher STES electric power conversion efficiency via thermodynamic cycle.

After selection of the parabolic dish point focusing collector for the Shenandoah Project, optimization studies were performed during the Preliminary Design Phase (2) to determine the optimum collector size, and other key parameters. Studies considered the following:

- Solar collector costs, solar collector design and manufacturing processes and pipefield costs, as a function of size.

- Solar collector performance, as a function of size.

- Pipefield energy losses, as a function of solar collector size, and number of solar collectors required.

The optimum solar collector reflector was determined to have a diameter of 7 meters (23 feet).

Subsequently, preliminary and final solar collector development tests and designs have been completed. This paper gives key information and data on the final collector design, and on development testing results.

SOLAR COLLECTOR

The Shenandoah parabolic dish solar collector, shown in Figure 1, consists of four subassemblies/subsys-
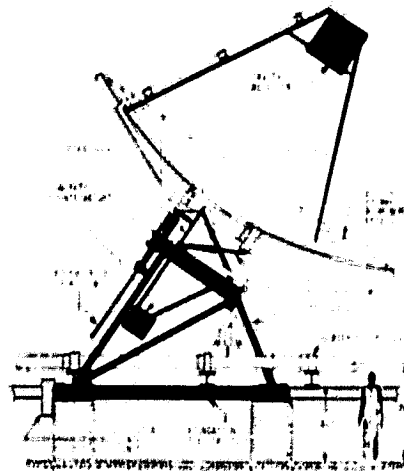

FIGURE 1. STES 7-METER PARABOLIC DISH SOLAR COLLECTOR

tems: (1) mount and drive, (2) reflector, (3) receiver, (4) collector control. Key features of the collector are:

- Reflector diameter - 7 meters (23 feet)
- Receiver aperture diameter - 18 inches (46 cm)
- Geometric concentration ratio - 234
- $f/D = 0.5$ (focal length to diameter ratio)
- cavity type receiver with coil-type heat exchanger
- Segmented reflector assembled from 21 die-stamped petals
- Polar and declination axes of rotation
- Motor and jackscrew drives
- Hybrid pointing control (computer and optical)
- Fabricated tripod mount structure with counter weighted, rotating yoke
- Drilled pier concrete foundations (3 per collector).

Key system requirements on the solar collector are:

- Energy output of 46000 Btuh (13482 watts) at 200 Btuh/ft^2 (630 W/m^2) direct insolation
- Fluid inlet temperature - 500°F (260°C)
- Fluid outlet temperature - 750°F (399°C)
- Heat transfer fluid - Syltherm^{TM} 800
- Operate in winds to 30 mph (13.4 m/s)
- Survive winds of 90 mph (40.2 m/s)
- Maximum direct insolation - 325 Btuh/ft^2 (1025 W/m^2)
- Minimum direct insolation - 75 Btuh/ft^2 (237 W/m^2)
- Polar axis rotation - $\pm$ 90°
- Declination axis rotation - $\pm$ 23$\frac{1}{2}$°

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Solar collector specifications include the following:

- Collector overall efficiency - 56% min. @ 200 Btuh/ft^2
- Collector optical efficiency - 76% min., clean
- Receiver efficiency - 77% min. @ 200 Btuh/ft^2
- Parasitic power (average) - 62.5 watts.

Four prototype Shenandoah collectors were installed and tested at Sandia Laboratories in Albuquerque. Results are summarized in Figure 2. One collector had a FEK 244 (3M) metal acrylic reflective surface; one collector had a chemically brightened 5657-H241, one side bright aluminum reflective surface protected by an anodized coating; and two collectors had the same chemically brightened aluminum reflective surface, but were protected by a RTV 670 silicone coating. Results of testing are summarized, essentially, in Figure 2. The collector with a FEK 244 reflective surface had the best performance and met design specifications. FEK 244 was selected as the reflective surface for the Shenandoah collectors.
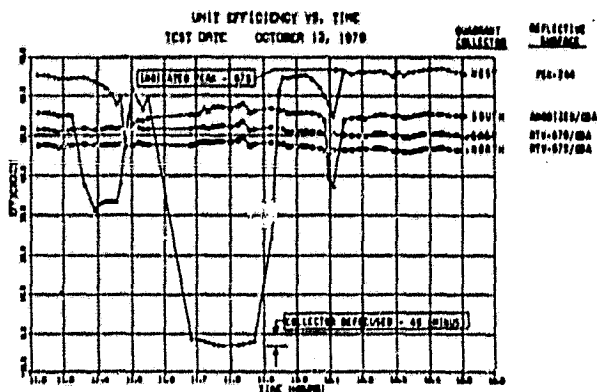

FIGURE 2. QUADRANT TEST SOLAR COLLECTORS

MOUNT AND DRIVES

The collector mount is a tripod structure fabricated from standard low-carbon/steel tube sections. The mount includes polar axis bearings and a bearing-mounted, concrete counter-weighted yoke structure. The yoke structure supports the hub via declination axis pivot points (2). The 3 legs of the mount tripod structure rest on a triangular base, which is fabricated from standard low carbon steel wide flange sections. The triangular base rests on and is bolted to the tops of the drilled pier concrete foundations (3).

Two, 1/10 hp, ac motor-driven jackscrews in series provide $\pm$ 90° rotation around the polar axis, and one such jackscrew provides $\pm$ 23$\frac{1}{2}$$^\circ$ rotation around the declination axis. Fluid supply and return lines to and from the receiver each include 2 flexible lines. The polar flex lines (1 supply and 1 return) are in a common boot enclosure, and the declination flex lines are in a common boot enclosure.

REFLECTOR

The segmented reflector assembly consists of 21, die-stamped aluminum petals, 21 supporting aluminum sheet metal ribs, and a fabricated steel hub weldment. Each petal is 10.6 feet long, 41.2 inches wide at the outside radius, and 2.4 inches wide at the inside radius. The FEK reflective film is applied to the flat sheet blanks prior to forming petals to contour. Slope error of the petal surface is 0.5 degree rms. Total reflectance of the FEK is 86%, and effective reflectance is 82%.

The petals, support ribs and hub are bolted together to form the reflector assembly. Aluminum struts (3) fabricated from standard low carbon steel tube section are then bolted to the reflector assembly to support the receiver.

RECEIVER

The cavity-type receiver has a cone/cylinder configuration, coil-type heat exchanger inside. The coil has turns, and is wound from 1/2 inch O.D. x 0.035 inch wall, Type 409 stainless steel tubing. The coil is coated with Pyromark-Black. The cannister is Type 430 stainless steel, 0.0175 inch thick, rolled and spot welded into a 36-inch high x 32$\frac{1}{2}$ -inch diameter cylinder. Keowood B (4 pcf) is the insulation used between the coil and the cannister. The aperture plate, on the bottom of the cannister cylinder, consists of 4, 90-degree segments of 0.120 inch thick, type 430 stainless steel. These segments are covered with Astroquartz #570 and are assembled to form an annular aperture plate with an 18-inch aperture. The aperture plate design, including addition of Astroquartz, was developed to solve over-temperature and warping problems experienced with the first aperture plates (of different designs) tested. Tips of fiber optics cables (4) protrude through the aperture plate, at quadrant points near the inner radius of the aperture plate. The mounting design of the fiber optics tips were also changed to increase temperature capability and solve early problems encountered in test. Figure 3 shows an isometric cataway of the Quadrant Test Receiver.
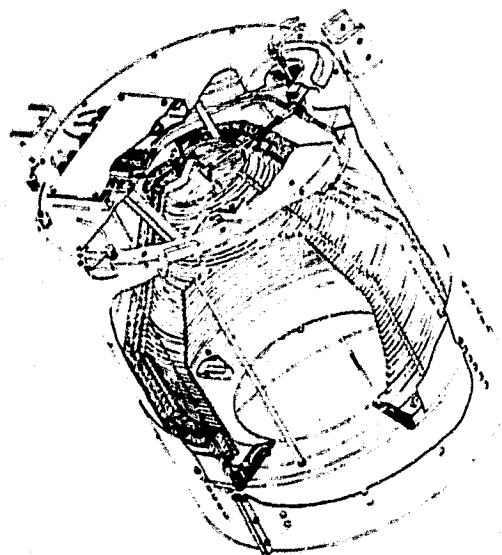

FIGURE 3. QUADRANT TEST RECEIVER
ISOMETRIC CUTAWAY

COLLECTOR CONTROL

A collector control unit (CCU) is mounted on each col-
lector. It interfaces with the control room/central
control system, which generates by digital computer,
pointing commands for coarse (< 0.6°) pointing of
each collector. The CCU contains the following
major functions:

- 4 sun energy tracking sensors (at fiber optics
  terminals)
- Sun tracking electronics
- 2 RTD signal conditioners
- 2 potentiometer position signals
- Control electronics and relays for 3 Collector
  movement motors
- Serial data link communications station and
  associated control functions.

The major CCU operating modes are:

- Manual
- Computer track
- Auto-track
- Defocus
  - Emergency/overtemperature (760°F)
  - Commanded

In the auto-track mode, differential signals from opposing
pairs of fiber optics/transducers are used to cause
appropriate contact closures/openings for each col-
lector drive motor, for fine tracking control (< 0.25°).

ACKNOWLEDGEMENTS

FIG. 4. QUADRANT TEST SOLAR COLLECTORS

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1ST GENERATION LOW COST POINT FOCUS SOLAR CONCENTRATOR

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ABSTRACT

The General Electric Company is under contract to the Jet Propulsion Laboratory to design, fabricate, install and test a point focus solar concentrator that, given a high volume of production, will optimize the ratio of performance to cost. The concentrator design approach has evolved by a systematic process of examining the operating requirements particular to the solar application, minimizing material content through detail structural design and structurally efficient subsystem features, and utilizing materials and processes compatible with high volume production techniques. This paper briefly describes the design approach, the rationale for the configuration and subsystem selections, and the development status.

INTRODUCTION

The General Electric Company is currently under contract to the Jet Propulsion Laboratory to design, fabricate and test prototype 12 meter diameter point focus solar concentrators. Several key objectives were established at the outset of this development program to ensure that the resultant concentrator design represented a cost effective component and that, when coupled with thermal receivers and heat engines, would hold potential for the competitive generation of electricity from solar energy. The first of these objectives was to establish a design that can be optimized for solar applications. The majority of existing point focus concentrators have been derived from the technology of communications and RF antennas where many requirements and desirable features are not necessary for the solar application. Secondly, the design had to maximize the ratio of performance to cost. Thus, while good performance is certainly necessary for total system effectiveness, the cost of that performance must be carefully examined. The third major objective was to select approaches to the subsystem and component designs that were compatible with and derived from accepted and commercially available manufacturing techniques. Low cost can only be achieved with systems of this size and complexity when high production volume techniques can remove much of the fabrication labor cost and let material costs dominate.

CONCENTRATOR DESCRIPTION

The design that has evolved out of an effort to meet the key objectives is depicted in Figure 1. The concentrator is 12 meters in diameter with a focal length to diameter ratio of 0.5 and a geometric concentration ratio of 1800. The concentrator dish is constructed of molded glass reinforced plastic with

an integral structural rib pattern on the back side to provide for stiffness. There are twelve internal truss assemblies within the dish to provide for support and alignment of the dish gore segments as well as added strength to the assembled structure. The internal ribs add considerable stiffness to the design while minimizing the loads and thus weight of plastic material in the gores. The additional blockage developed is small and the weight reduction benefits are well worth their inclusion. The baseline reflector material selected is an aluminized plastic film. This film is UV resistant, conforms to the double curvature of the paraboloid, has excellent specularity and very low cost. Silvered glass reflectors are also being investigated as potential high performance options.

The mount subsystem is an azimuth-elevation configuration. A significant advantage of this mount approach is that it permits the stow orientation depicted in Figure 1. The photo does not show the counterweight which has been incorporated into the design. The inverted stow significantly reduces survival wind loads, provides for convenient access to the complex receiver/engine and offers good protection for the reflector surface. The inverted night time stowage of the reflector provides for the minimum cleaning of the reflector film.

The drive subsystem that was selected consists of a cable and a drum. The cable is provided with a rolled guide from receiver to counterweight. Major features of this approach are low cost, low motor parasitic power, high drive stiffness and insensitivity to environmental factors. The drive system provides for a slow tracking rate of 0.1^o per second and a fast defocus of 2° per second. The control subsystem is a hybrid system with a position predictive mode for coarse control and a fiber optic based closed loop control on the receiver for final positioning.

The foundation consists of a rolled I-beam section mounted on simple concrete pilings. The foundation has a large foot print and thus concrete is minimized. This approach to the foundation lends itself to quick assembly and a minimum of site preparation.

CONCENTRATOR DESIGN AND ANALYSIS

The concentrator, as it exists in its present configuration, is the product of a systematic approach to maximizing the ratio of cost to performance. This approach consists of a thorough evaluation of the design requirements, minimizing material content through structural efficiency, and judicious choice of component materials and processes to ensure producibility.

The first element, requirements evaluation, is a fundamental step that must be taken to ensure that the concentrator was not overdesigned and that the requirements are met in a cost effective manner. Figure 2 illustrates this point. Much of the material content is the result of the environmental loads. Initial studies concluded that substantial structural requirements were needed depending on the concentrator orientation at survival load conditions. By presenting the low profile stow position to the survival winds, the structure then became designed for stiffness to resist operating deflections. Likewise a careful evaluation was made to choose a realistic operating wind speed. The

design specification, shown in Figure 2, represents the result of a relaxation of requirements until performance became expensive.

The second element of achieving cost effective performance involves designing the structure as efficiently as possible. Figure 3 depicts several of the subsystem features that help provide stiffness with a minimum material content and thus low cost potential. The internal ribs, azimuth-elevation mount and integral gore segment ribs all provide high stiffness to weight ratio's.

Perhaps the most important aspect to designing the concentrator structure has involved an in-depth structural analysis. Figure 4 depicts this analytical approach. The concentrator has been modelled on a finite element computer program where many load cases have been examined. The deflections are then input into a solar ray trace program to predict the image flux intensity and spread. The process involves minimizing structure until performance is significantly affected.

The final element involves the careful choice of materials and processes. Figure 5 depicts this process as it relates to the dish gore material. Molded reinforced plastic was chosen due to its accuracy potential, ability to supply high stiffness-to-weight in one rapid, automated production operation and its low material cost. Reinforcement was chosen due to its superior blend of properties needed in this application. Many molding processes have been studied with the final choice depending on the production volume.

A significant material choice involves the reflector. Evaluations are proceeding with two approaches: aluminized plastic film and silverized glass. Each has its own advantages and disadvantages as presented in Figure 6. The films offer low cost and compatibility with relatively soft structures, while lower performance and operating life present drawbacks. Glass is a proven and durable superstrate for silver reflectors and yet it is more costly. The higher cost is both in material and process costs as well as the costs of providing a stiffer structure to control stresses in the glass itself. This latter impact can be significant with unstrengthened glass. Designs are being generated for utilizing both reflectors. A choice is to be made based on application cost effectivity.

DEVELOPMENT STATUS

The concentrator design discussed above is presently in its detailed analysis and design phase. Design of tooling and production planning is in progress. Fabrication of the prototype concentrators are scheduled for mid 1980 with installation and test completed by the end of 1980. Units will be available for solar applications in early 1981.

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

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A CELLULAR GLASS SUBSTRATE
SOLAR CONCENTRATOR

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ABSTRACT

Acurex Corporation, under contract to the Jet Propulsion Laboratory, is developing a second generation point focusing solar concentrator. The design is based on reflective gores fabricated of thin glass mirror bonded continuously to a contoured substrate of cellular glass.

To date the preliminary design effort is complete and is reviewed in this presentation. The concentrator aperture and structural stiffness has been optimized for minimum concentrator cost given the performance requirement of delivering 56 kW_{th} to a 22 cm (8.7 in) diameter receiver aperture with a direct normal insolation of 845 watts/m^2 and an operating wind of 50 kmph (31 mph). The reflective panel, support structure, drives, foundation and instrumentation and control subsystem designs, optimized for minimum cost, are summarized. The use of cellular glass as a reflective panel substrate material is shown to offer significant weight and cost advantages compared to existing technology materials. Lastly, a design summary and key results are presented.

INTRODUCTION

Acurex Corporation, under contract to the Jet Propulsion Laboratory, is developing a second generation point focusing solar concentrator. The scope of this project currently encompasses three tasks, namely:

1. Preliminary design of a cellular glass substrate advanced solar concentrator
2. Detail design of reflective gore panels
3. Mass production cost assessment

The overall objective of this project is to develop a minimum cost per kilowatt solar concentrator design within the constraints of 1985 mass production technology. As the thermal output of the concentrator has been specified, this goal can be expressed in terms of $/$m^2$ of aperture area. An installed cost of $70 to 100/$m^2$ in 1978 dollars is the target.

The key element of the second generation concentrator design is the light weight, self-supporting reflective panel made possible by the use of cellular glass as a reflective mirror substrate material. The effect of the low weight of the panels cascades down through the other concentrator subsystems. A light-weight, self-supporting panel allows the design of a

light-weight supporting structure, which in turn, yields low drive and foundation loads and low installation labor which all leads to a low cost concentrator design. Cellular glass is a desirable reflector substrate material because of its high stiffness to weight ratio, thermal expansion match to mirror glass and environmental durability. It is a low cost material, selling for approximately $0.30 per board-foot in large volume production in the self-supported insulation market.

DESIGN DESCRIPTION

The design of the cellular glass substrate concentrator is shown in Figure 1. The concentrator is an 10.9 meter diameter, two-axis tracking, parabolic dish solar concentrator. The reflective surface of this design consists of inner and outer groups of mirror glass/cellular glass gores. The gores are attached as simply supported overhang beams to a ring truss support structure to form a complete but physically discontinuous reflective surface. There are five structural support subsystems; the gore support a quadripod receiver support, a counterweight support, a tripod center pedestal and a tilted pyramid drive structure. Elevation motion is produced by a ball screw and azimuth motion by a chain and sprocket perimeter drive. The foundation consists of concrete piers for the center pedestal and a raised steel track also on concrete piers.

The reflective panel or gore design is a sandwiched mirror glass/cellular glass/unsilvered glass configuration. The mirror glass is backsilvered 0.040 thickness Corning 7809 aluminoborosilicate fusion glass. The cellular glass is 12 lb/ft^3 Pitt-Corning Foamsil®75 and is specifically tailored to match the coefficient of thermal expansion of the 7809 mirror glass. The backsheet is an unsilvered piece of 0.040 thickness Corning 7809 glass. The sandwich configuration was selected as the design which resulted in the minimum weight gore. The concentrator design consists of 40 outer gores and 24 inner gores. The maximum gore width was limited by the allowable membrane stress for a single panel per gore. Gore weights, less the attachments, are 49 and 32 lbs for the outer and inner rings, respectively.

The support structure design features welded steel shop subassembly construction using standard size, commercially available, structural steel members. Finite element analysis techniques were used to optimize the support structure for minimum weight. The concentrator design has a total structural steel weight of 4,335 lbs and a concrete counterweight of 10,000 lbs.

The drive design features positive traction, rugged, state-of-the-art components. Approximately 100 different combinations of drive power, actuation mechanism, and drive and foundation structure alternatives were evaluated. Life cycle costs were developed for each of the alternative concepts. Chain/sprocket and cable/drum azimuth drives were found to provide essentially equivalent minimum life cycle costs. The chain sprocket design was selected because of its greater stiffness over a cable/drum design. A ball screw was selected as the minimum life cycle cost elevation drive

Inner/Outer Reflective Gores

Gore Support Structure

Ball Screw Elevation Drive

Tripod Center Pedestal

Concrete Counterweight

Tilted Pyramid Drive Structure

Pier/Raised Perimeter Track

Quadripod Receiver Support Structure

Counterweight Support Structure

Chain & Sprocket Azimuth Drive
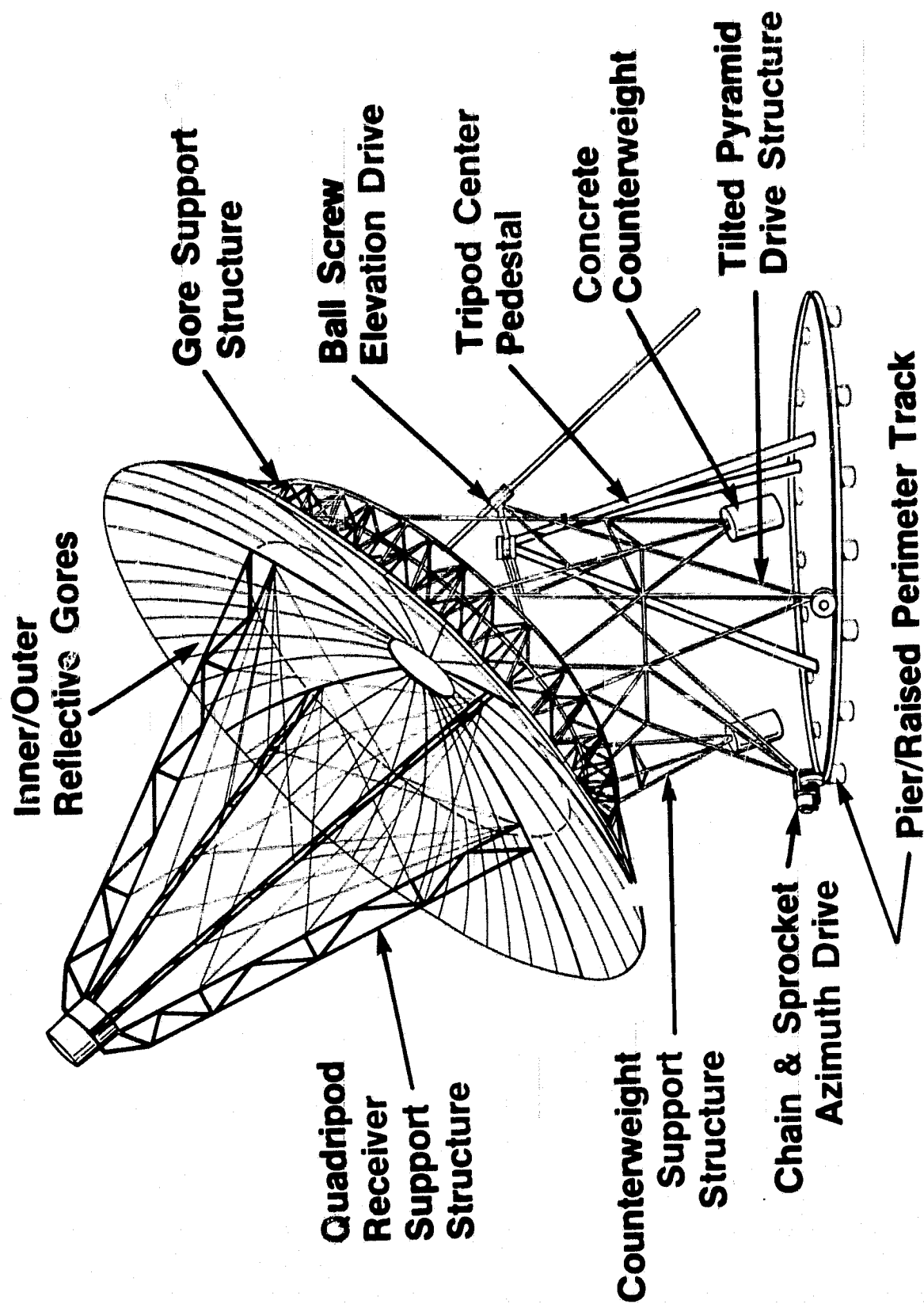
Figure 1. Design description.

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design. Due to the requirement for failsafe stowing capability, electric motors and a fossil fuel generator were selected for drive motors and emergency power respectively under the assumption that a single generator set would provide power to at least four concentrators in a multi-unit field.

The foundation design features simple installation and adaptability to sloping or rough terrain. The foundation consists of a tubular steel tripod pedestal which supports the azimuth bearing and a raised steel track upon which the drive structure rides. Both the pedestal and track are anchored to simple drilled and poured concrete piers. The pedestal angle and number of piers were optimized for minimum cost.

The electrical subsystem consists of off-the-shelf components providing for power distribution and lightning and grounding protection. The instrumentation and control subsystem consists of the tracker control and shaft encoders. A hybrid, two-axis, image tracking system is recommended. Coarse synthetic tracking will be achieved through a microcomputer based control system. Accurate active tracking will be achieved by a two-axis photodetector located at the focal plane and sensing the position of the reflected image. Image sensing not only provides inherent gravity compensation but also compensates for steady-state wind deflections.

KEY RESULTS

The key results of the project, through the preliminary design phase, are as follows:

- Optimized Concentrator Diameter = 10.9 meters
  The concentrator aperture diameter and structural stiffness have been optimized given the performance requirement of delivering 56 KW_{th} to a 22 cm (8.7 inch) diameter receiver aperture with a direct normal insolation of 845 watts/m^2 and an operating wind of 50 kmph (31 mph).

- Developed Minimum Weight Preliminary Design
  Extensive design/analysis efforts have produced a minimum weight concentrator design. In mass production, a minimum weight design, based on low-cost materials, will provide a minimum cost design. The use of cellular glass as a reflective panel substrate material offers significant weight advantages compared to alternate substrate materials

- Preliminary Cost Estimate = $87/$m^2$ Installed
  Cost estimates made from vendor contacts and rule-of-thumb cost per pound guidelines indicate that a cellular glass substrate concentrator meets the JPL cost target on a dollar per unit aperture area basis.

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- Projected Future Cost Reduction = 5 to 10 Percent
  A cost reduction of 5 to 10 percent is anticipated as a result
  of detailed production planning and weight reductions achieved
  in detail design.

- Recommended Cellular Glass Reflective Panel Technology
  Development
  The use of cellular glass as the structural support for glass
  mirrors is not state-of-the-art technology. As such, a
  development effort is required. Acurex has recommended a
  specific program leading to the test demonstration of fullsize
  engineering gores. This effort consists of bonding and
  grinding studies, subscale gore fabrication and optical,
  structural and environmental testing and fullscale engineering
  demonstration.

SESSION II
RECEIVER DEVELOPMENT

THE DEVELOPMENT OF AN AIR BRAYTON AND A STEAM RANKINE SOLAR RECEIVER

by

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ABSTRACT

This paper describes both an air Brayton and a steam Rankine solar receiver now
under development for the Department of Energy under contract to the Jet Propul-
sion Laboratory. These cavity receivers accept concentrated insolation from a
single-point focus, parabolic concentrator, and use this energy to heat the
working fluid. Both receivers have been designed for a solar input of 85 kw.
The air Brayton receiver heats the air to 816°C (1500°F). A metallic plate-fin
heat transfer surface is used in this unit to effect the energy transfer. The
steam Rankine receiver has been designed as a once-through boiler with reheat.
The receiver heats the water to 704°C (1300°F) to produce steam at 17.22 MPa
(2500 psi) in the boiler section. The reheat section operates at 1.2 MPa (75
psi), reheating the steam to 704°C (1300°F). The paper discusses the thermal
and mechanical design features of the Brayton receiver and reviews the design of
the Rankine receiver.

AIR BRAYTON SOLAR RECEIVER

Design Requirements

The solar input is 85 kw. This energy is used to heat the working gas (air)
of the highly recuperated open-cycle gas turbine engine from 565° to 816°C
(1049° to 1500°F). The flow rate is 0.28 kg/sec (0.57 lb/sec) at an inlet
pressure of 0.25 MPa (36.75 psia). The pressure drop goal is 2 percent $\Delta P/P_{IN}$.
The solar input is provided by an 11-m (36-ft)-dia parabolic dish concentrator
that has an assumed slope error of 1.75 milliradian, as well as a zero tracking
error. (Slope error is a measure of the surface inaccuracies of the actual con-
centrator compared to that of an ideal surface.) In addition to the performance
requirements, the environmental conditions included a 48.3-km/hr (30-mph) steady-
state wind with a 20-percent gust factor; temperature extremes of -18 to 52°C
(0° to 125°F); humidity extremes of 0 to 100 percent; and blowing dust. Survival
environmental conditions such as 161 km/hr (100-mph) winds, seismic loads up to
3 g, and snow and ice loads also were imposed.

Receiver Description

The major elements of the receiver are shown in Figure 1. The outer cylindrical
case is approximately 0.76 m (30 in.) in diameter by 1.71 m (46 in.) long.
Mounting brackets attached to the surface of the case mate to a mounting ring
that is part of the concentrator structure. A second inner cylindrical assembly
forms the receiver cavity. Approximately 0.11 m (4.5 in.) of insulation are
placed between the outer case and inner cavity. The wall of the receiver cavity
consists of a single-sandwich, plate-fin heat exchanger panel. Air from the
recuperator is ducted to a toroidal manifold at the bottom of the panel, where
it flows up the annular passage that defines the vertical walls of the cylindri-
cal cavity. It is subsequently collected in another toroidal manifold at the
top of the cavity assembly, where it is ducted to the turbine inlet.
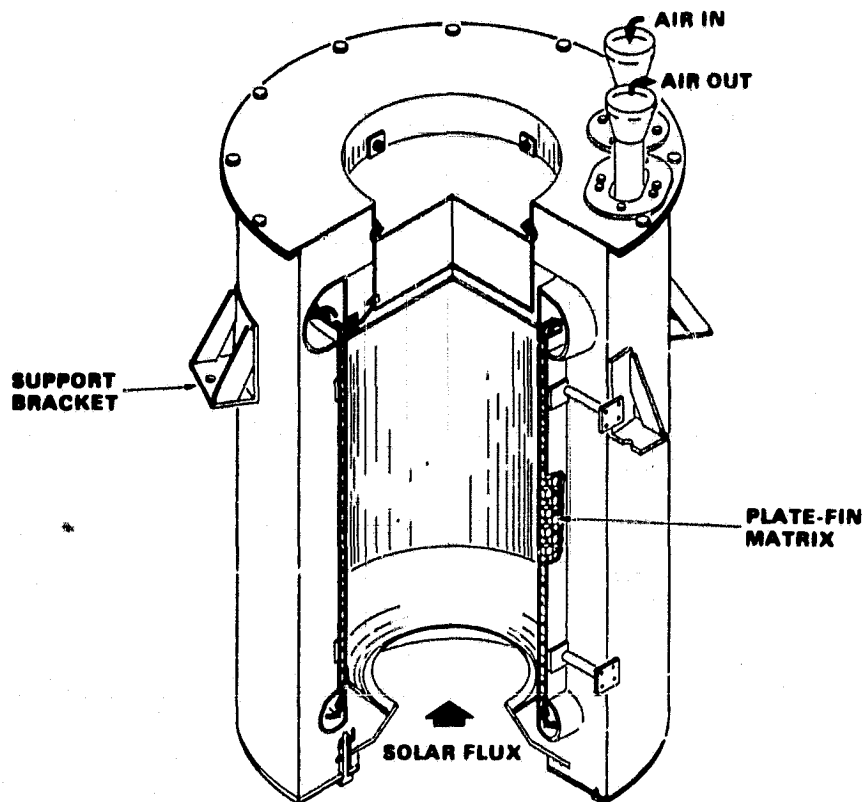
FIG. 1.   PROTOTYPE AIR BRAYTON SOLAR RECEIVER

The single-sandwich cylindrical panel contains a high-density offset fin matrix.
This matrix has 4.72 fins/cm (12 fins/in.), which are 1.27 cm (0.50 in.) high,
0.01 cm (0.004 in.) thick, with a 1.27 cm (0.50-in.) offset length.   The fins
are brazed to the two metal sheets that form the cylindrical panel.   The heat
exchanger is made from Inconel 625 material.   The receiver is positioned so the
focal point of the concentrator is located at the plane of the receiver aperture.
The aperture end is a cone assembly made from silicon carbide, which forms a
circular opening at the bottom of the cylindrical cavity.   The top surface of
the cavity is an uncooled circular ceramic plate, also made of silicon carbide.
This circular plate is supported by insulated standoffs to the outer casing.
An annular plate made of Inconel 625 is attached to the bottom of the casing and
supports the ceramic aperture cone.

Optical and Thermal Design

Analysis of concentration-type solar receivers requires that optical and thermal
properties be considered.   This is because the solar receiver is directly coupled
to the optical system.   The optical input to the receiver depends on the detailed
characteristics of the receiver, the concentrator, and the orientation of these
two major elements.   Evaluation of the solar flux into the receiver is performed
with a model in which the sun is treated as an extended, finite-size source.   The
resultant radiation transfer can be accurately analyzed by using cones, rather
than optical rays, as the basic description for energy transport.

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Incident solar flux distributions on the receiver cavity walls, as generated by the mathematical solar simulator, are presented in Figure 2 for the 85-kwt design point case. In equation form, the solar concentration ratio is defined as

$$CR_S \overset{\Delta}{=} Q''/\rho \cdot S'' \cdot \eta_{coll} \tag{1}$$

where Q'' is the heat flux impinging on the surface

ρ is the concentrator reflectivity

S'' is the local solar insolation

η_{coll} is the aperture/concentrator collector efficiency

Collector efficiency is defined as

$$\eta_{coll} \overset{\Delta}{=} \frac{\text{energy collected in aperture opening}}{\text{energy reflected by concentrator}} \tag{2}$$
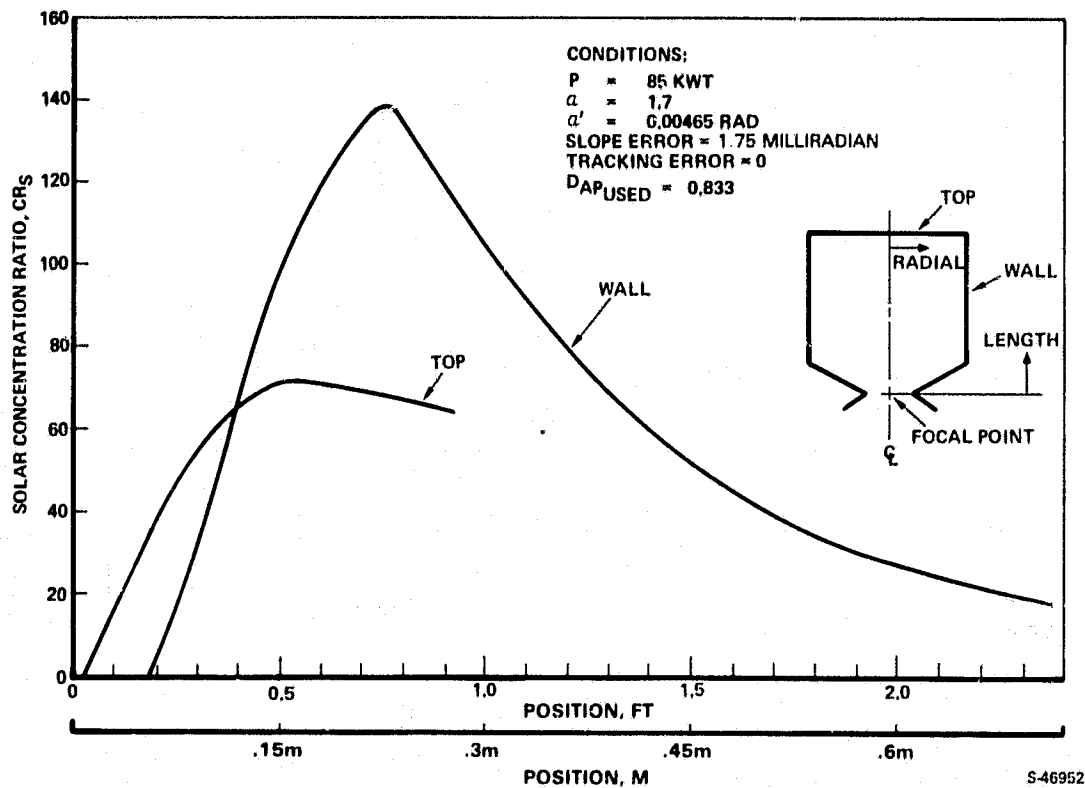
FIG. 2. CAVITY WALL SOLAR CONCENTRATION RATIO DISTRIBUTION

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In Figure 2, the cylindrical cavity wall solar concentration ratio is shown as a function of cylinder length, as measured from the focal point. The solar concentration ratio for the closed end (top) is shown as a function of radial position, as measured from the receiver centerline. Conditions used in obtaining these plots also are indicated in Figure 2. This type of incident radiant flux information is a required input for a detailed thermal analysis of the solar receiver.

Thermal analysis of the receiver is performed by a finite-element thermal analyzer computer code developed by AiResearch. The cavity wall incident flux information is input to the computer code, along with fluid flow data and geometry specifications. Multiple reflections and reradiation characteristics inside the cavity are calculated by the following relationship:

$$\underline{B} - A^{-1}\underline{C} \tag{3}$$

where $\underline{B}$ is the radiosity column matrix

A is an N X N characteristic matrix

$\underline{C}$ is a temperature-dependent column matrix

Equation (3) assumes a gray body and diffuse emittance and reflections. For solar applications, the gray body assumption is acceptable for rough metal surfaces with high emissivities (~ 0.8). This is because the difference between the solar absorption and the metallic emissivity is relatively small for metallic surfaces with high emissivities.

The net heat flux lost from the ith surface is obtained from the following equation:

$$Q_i'' = \frac{1 - \epsilon_i}{\epsilon_i} \ (E_{b_i} - B_i) \tag{4}$$

where ϵ is the emissivity

E_b is the black body emissive power

Q'' is the net heat flux lost from the ith surface

The cavity wall temperature distribution resulting from a steady-state thermal analysis of the receiver design is shown in Figure 3 for the three cavity sections--the aperture conical end (nodes 5 and 6), the cylindrical wall (nodes 8 through 15), and the closed end (nodes 17 and 18). A direct physical connection between the cylindrical section at both the aperture end and the closed end has been avoided, thereby eliminating large localized thermal gradients between these sections. Because the fluid is single phase and the inlet and outlet temperatures are fixed, and because a relatively high fluid heat transfer conductance (hA) exists, the wall temperature profile is controlled by the fluid temperature. Thus, minor variations in the concentrator performance (e.g., slope error = 2 milliradians) will not significantly affect the cavity efficiency for the aperture size selected.

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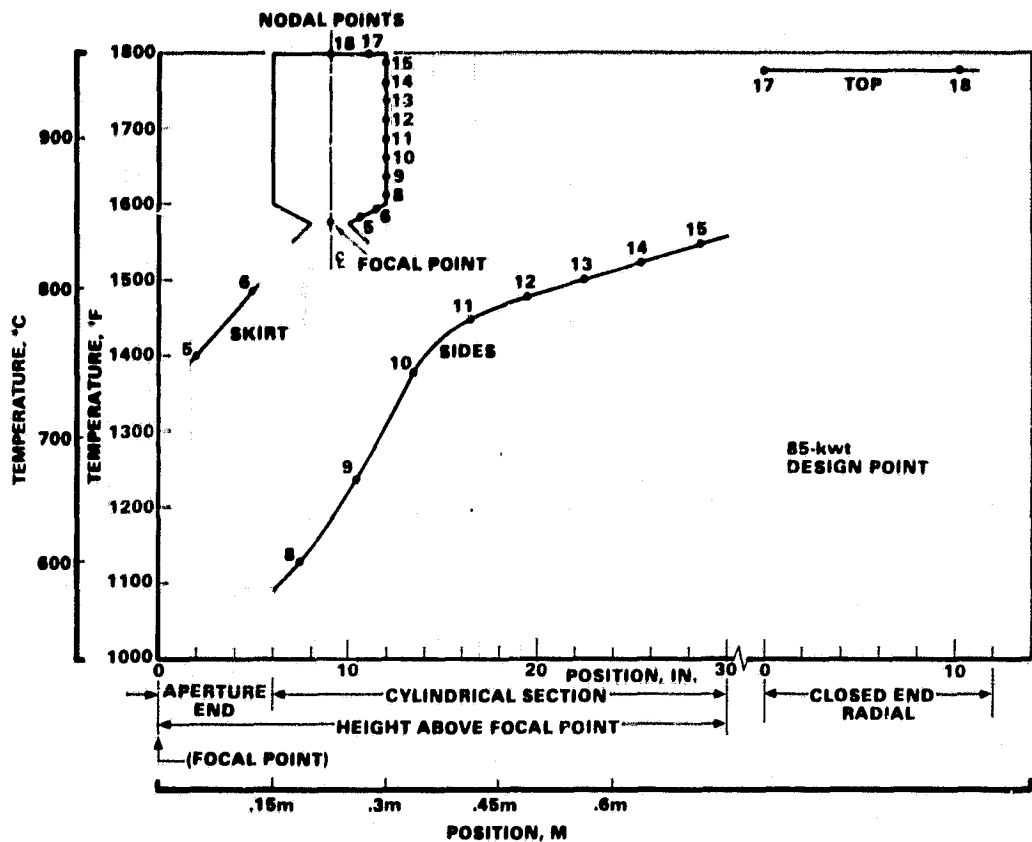
FIG. 3. STEADY-STATE CAVITY WALL TEMPERATURE DISTRIBUTION
FOR 85-KWT DESIGN POINT CASE

Aperture convection losses are accounted for by scaling test data in the
literature for open-cavity type solar receivers. This procedure indicates
losses will amount to approximately 2 percent of the incident power for a
40.25-km/hr (25-mph) wind condition.

The steady-state thermal analysis includes a complete nodal temperature distri-
bution throughout the receiver, fluid temperature rise, fluid pressure drop,
cavity efficiency, and energy tabulation. Table 1 presents the energy book-
keeping summary and cavity efficiency calculation for the design point operating
condition. The cavity efficiency presented is defined as

$$n_{cav} \stackrel{\Delta}{=} \frac{energy\ into\ fluid}{energy\ into\ aperture} \tag{5}$$

Cavity efficiency as a function of thermal input energy for three different
aperture sizes is shown in Figure 4. Note that the smallest aperture consistent
with the concentrator optics is the most desirable.

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TABLE 1

BRAYTON SOLAR RECEIVER PERFORMANCE

Thermal power level .... 85 kwt (nominal)

Design sun half-angle .... 0.007905 radian (slope error = 0.0573 deg, track error = 0 deg)

Actual sun half-angle .... 0.00465 radian

Incident solar flux .... 0.979 kw/m^2

Concentrator reflectivity 0.86

Energy bookkeeping

   Total energy into cavity, kwt (percent) 85.0 (100)
   Energy to fluid, kwt (percent) 78.6 (92.5)
   Energy losses, kwt (percent)
     Loss by radiation out aperture 3.62 (4.26)
     Loss by convection out aperture* 1.70 (2.0)
     Loss by radiation and convection from the outer surface .. 1.05 (1.24)
     Cavity efficiency, percent 92.5

*Assumed 2-percent loss due to aperture convection losses.
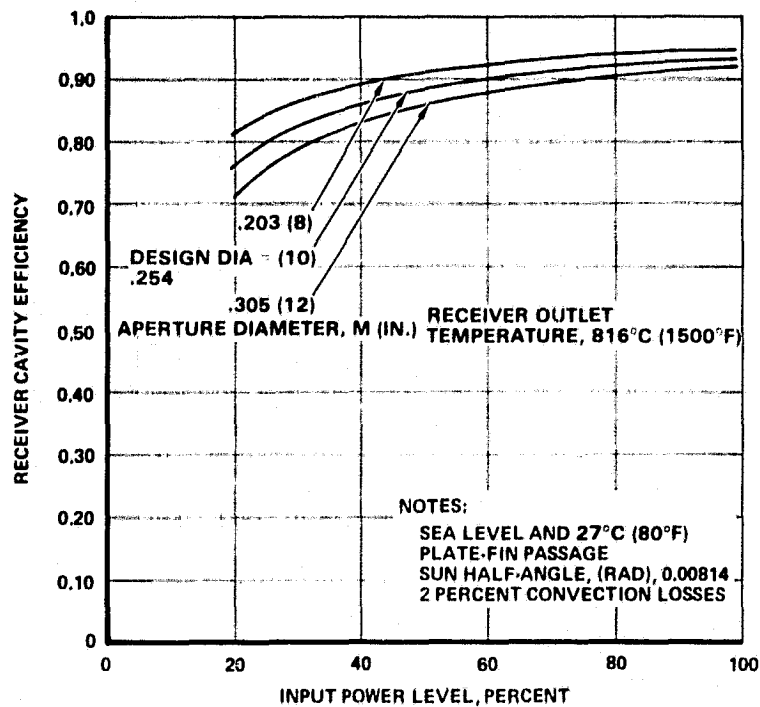
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FIG. 4. BRAYTON SOLAR RECEIVER CAVITY EFFICIENCY AS A
FUNCTION OF POWER LEVEL

Structural Design

The receiver heat exchanger is designed to withstand an operating pressure of 2.59 atm (38 psia) at a maximum temperature of 843°C (1550°F) and a proof pressure of 4.42 atm (65 psia) at room temperature without yielding. The fins brazed between the inner and outer walls of the heat exchanger react the internal pressure loads. The predicted life of the prototype heat exchanger unit is 6000 start/stop cycles or approximately 8 to 10 years.

The cavity panel heat exchanger is attached to the outer casing by four radial tubes located at two locations along its length. The upper set of support tubes allows for radial thermal growth and the bottom set allows for both radial and axial thermal growth. The aperture cone is supported from the case with insulated standoffs, as is the circular top plate.

Bellows on the air inlet and exit lines at the top of the receiver limit the loads that might be imposed on the heat exchanger from this source.

Test Program

As part of the development effort, one receiver heat exchanger with the appropriate ducting will be fabricated and assembled in the test device shown in Figure 5. A cylindrical electric heater is inserted in the test heat exchanger cavity. The heater consists of wire resistance elements arranged on the surface of the cylindrical heater. There are 10 separately controlled heating zones on the heater surface; this allows the imposition of the same net heat flux distribution on the heat exchanger wall that will be seen during operation with solar input. The assembly is installed in a low-pressure chamber that provides an argon cover gas for the electric heater assembly. Tests will be performed to obtain heat exchanger performance as well as to subject the heat exchanger to 500 startup and shutdown cycles.

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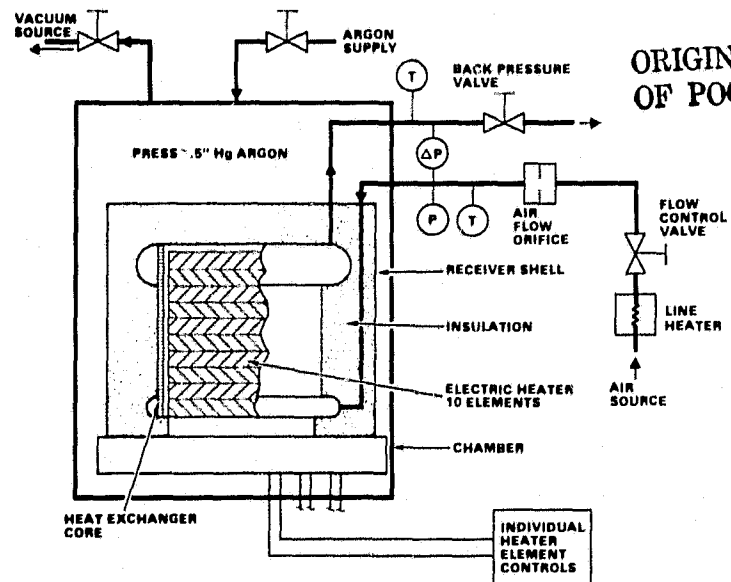
FIG. 5. HEAT EXCHANGER DEVELOPMENT TEST SETUP

STEAM RANKINE SOLAR RECEIVER

Design Requirements

The receiver is designed for two applications, each with a peak solar input of 85 kw. The first application is to supply heat to a steam power system and the second to supply process heat.

The steam power application is further divided so that in one case the receiver operates with a system employing reheat. In this case the boiler heats the inlet water at 17.22 MPa (2500 psi) and 49°C (300°F) to supply heat at 704°C (1300°F). The reheat section accepts steam at 1.20 MPa (175 pisa) and 343°C (650°F), heating it to 704°C (1300°F). The total pressure drop is not to exceed 10 percent $\Delta P/P$. Flow rate is determined from the energy balance.

The second steam power case eliminates the reheat section. The steam flow is routed directly from the discharge of the boiling section to the inlet of the reheat section. The flow rate is rebalanced to supply steam at 17.22 MPa (2500 psi) and 704°C (1300°F) at a $\Delta P/P$ of 10 percent.

The process steam application considered variable inlet temperatures and pressures without reheat up to the values defined for the steam power condition.

Receiver Description

The steam Rankine receiver is similar to the Brayton receiver in that they both use a 0.76-m (30-in.)-dia case and the same mounting provisions. Approximately 10.1 cm (4 in.) of insulation separates the case from the cavity heat transfer surfaces. The significant features of this receiver are shown in Figure 6. Two helical tube coils form the interior cavity walls. The preheat-boiling coil, located adjacent to the aperture, is a 1.11-cm (0.4375-in.) tube with a coil diameter of 0.43 m (17 in.) and a coil length of 0.371 m (14.6 in.). The reheat coil is a 1.8-cm (0.75-in.) tube with a coil diameter of 0.43 m (17 in.) and a length of 0.175 m (6.9 in.). Both coils are manufactured from Inconel 625 or type 347 stainless steel. These coils are brazed separately and mechanically joined together. The aperture assembly is the same as the Brayton receiver. The top of the receiver cavity is an uncooled ceramic plate, which is adjustable in the axial direction through the use of an adjustment screw located on the exterior case.

Thermal Design

The optical and thermal design procedures used for the Rankine receiver are similar to those of the Brayton receiver. However, a distinct difference affects this design as the fluid changes phase in the preheat-boiling section when single-phase heat transfer and basic flow friction data were used to predict the design heat transfer coefficients for liquid and steam. The correlations of Chen (1), below 70-percent quality, and Lockhart/Martinelli (2), two-phase flow above 70-percent quality, were used to establish coefficients of performance in the boiling region.
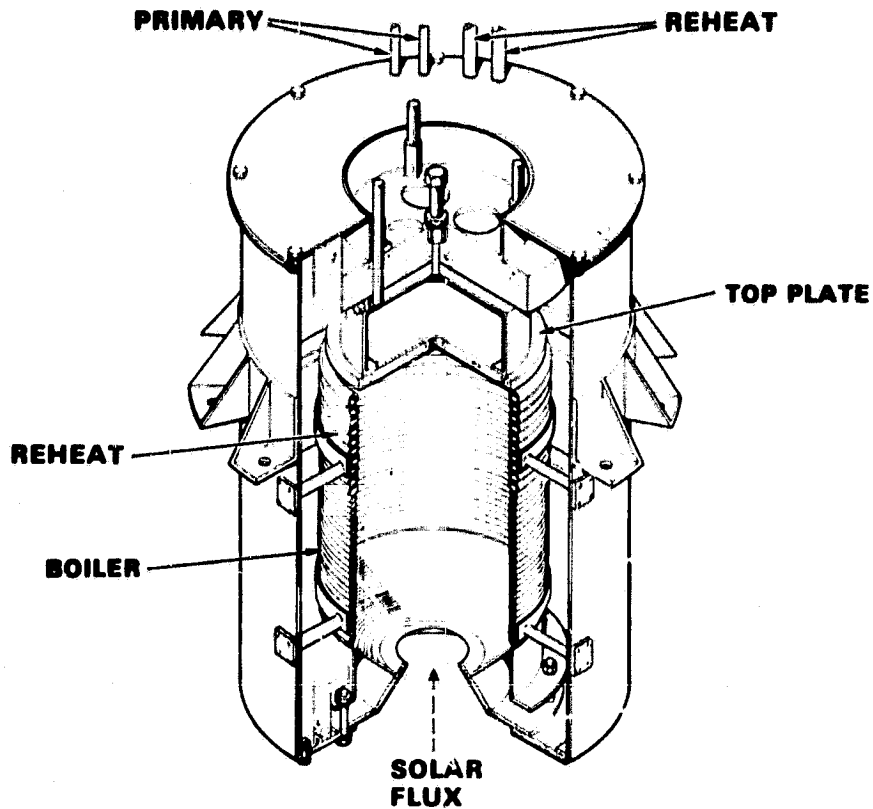
FIG. 6. PROTOTYPE STEAM RANKINE SOLAR RECEIVER

The cavity wall and fluid temperature distribution for a steady-state thermal analysis of the boiling and reheat application is shown in Figure 7. The steam outlet temperatures from the boiling and reheating sections are matched. The slope of the temperature curve at this location indicates that the match is highly dependent on flux distribution. Consequently, a sensitivity analysis was conducted. This was based on relocating the peak flux 7.62 cm (3 in.) toward the top and of the cavity and altering the distribution by reducing the peak flux 20 percent and distributing the energy toward the top of the cavity. The resulting temperature profile is shown in Figure 8. Since distribution variations of this magnitude were considered possible, a movable top end plate was included within the design. Repositioning the plate toward the aperture 4 cm (1.6 in.) rebalances the fluid temperature at 704°C (1300°F). This is accomplished by a combination of shielding of the reheat section and reradiation from the top plate to the remainder of the cavity. The energy bookkeeping summary and cavity efficiency for the boiling-reheat design requirement is shown in Table 2.
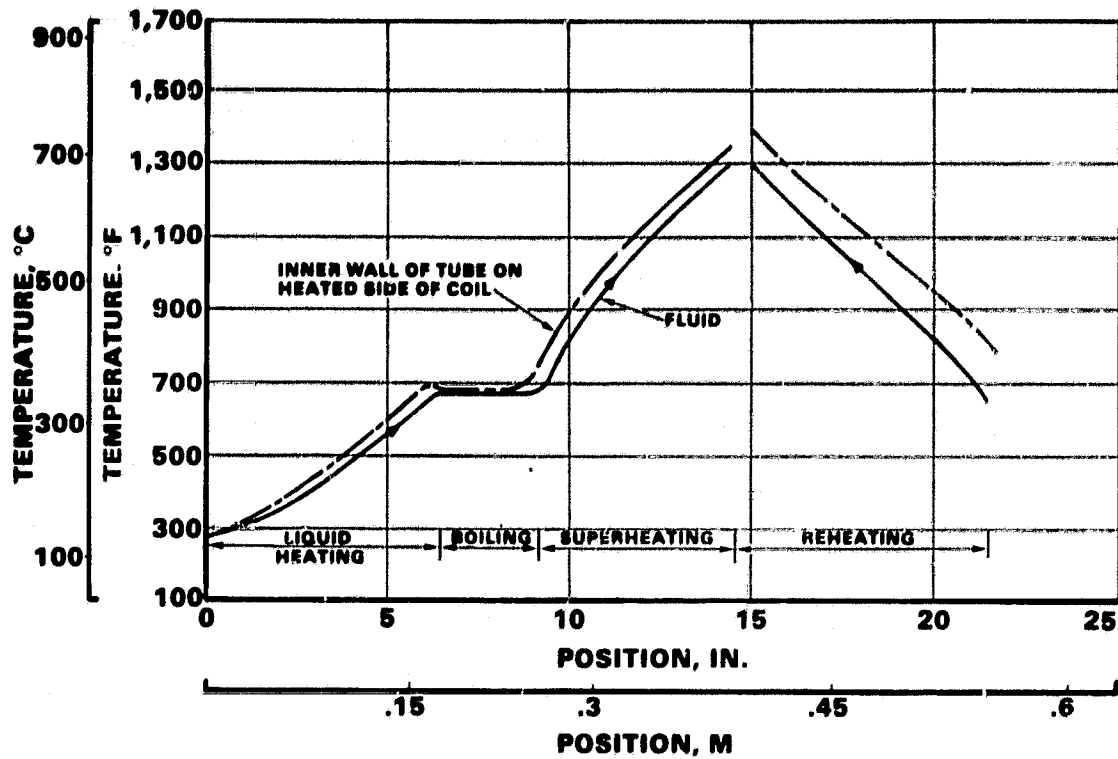
FIG. 7.   AXIAL TEMPERATURE DISTRIBUTION WITH DESIGN FLUX
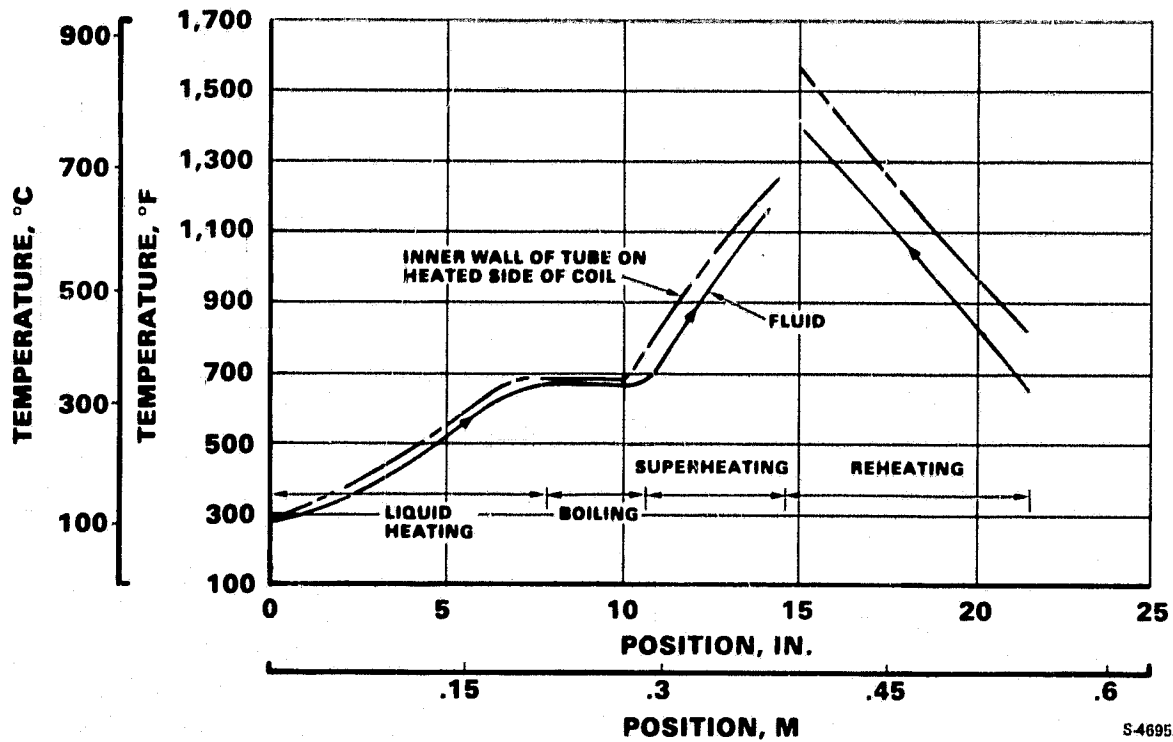
FIG. 8.   AXIAL TEMPERATURE DISTRIBUTION WITH REDISTRIBUTED FLUX

TABLE 2

STEAM RANKINE SOLAR RECEIVER THERMAL PERFORMANCE SUMMARY

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Solar input ............................. 85 kwth
Aperture radiation loss................. 1.3
Insulation loss ........................ 1.2
Assumed aperture assembly convection
   and radiation loss .................. 2.5
Thermal power to fluid ................. 80
Receiver efficiency .................... 94 percent
Flow rate .............................. 71 kg/hr (157 lb/hr)
Pressure drop
        Boiler ......................... 2 percent
        Reheat ......................... 10 percent
Without reheat
        Flow rate ...................... 89 kg/hr (196 lb/hr)
        Pressure drop .................. 3 percent
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Structural Design

The receiver is designed to operate at a maximum pressure of 17.57 MPa (2550 psi) at 704°C (1300°F) and to withstand a proof pressure of 37.2 MPa (5400 psi) at room temperature.

By uncoupling the boiling and reheat coils the axial coil bending loads that would have occurred at this junction were avoided. The remaining stresses are the result of pressure and temperature differences acting on the tube cross section. A computer-aided stress analysis was used to determine the peak combined stresses occurring in a tube section operating at 371°C (700°F). The peak combined stress is 154 MPa (22.34 kpsi). Based on Inconel 625 mechanical properties, the projected life is greater than 1.10^5 cycles.

Test Program

A test program that is comparable to the one conducted on the Brayton receiver will be computed on a prototype unit. Operation at the design point will be verified and a cyclic thermal pressure test will be conducted.

ACKNOWLEDGEMENTS

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2. Lockhart, R. W., and R. C. Martinelli, "Proposed Correlation of Data for Isothermal Two-Phase Two-Component Flow in Pipes," Chem. Eng. Progress, 45:39, 1974.

AN ORGANIC RANKINE RECEIVER FOR THE SCSTPE PROGRAM

by

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ABSTRACT

This paper presents a brief description of an Organic Rankine Cycle (ORC) Receiver which is presently being developed for the SCSTPE Phase II program. The receiver employs an integrated cavity/pool boiler* which permits the design of a small, lightweight, low cost and efficient moderate temperature receiver for use in a dish-Rankine PFDR system.

INTRODUCTION

Under the SCSTPE (EE#1) Phase II Program, FACC will develop a PFDR solar thermal electric system employing Rankine-cycle Power Conversion Assemblies (PCAs) mounted at the focus of Parabolic dish concentrators. The PCA consists of a receiver, organic Rankine cycle (ORC) engine and high-speed AC generator (Figure 1). The design of the receiver is a major technical challenge in the development of this PFDR system. Cavity-type receivers are generally most efficient for moderate and high-temperature systems. There are, in general, two types of cavity receivers:

- Direct heated, where the engine working fluid is heated within the receiver.

- Indirect heated, where a secondary fluid is heated in the receiver and the primary (engine working) fluid is heated in a separate heat exchanger.

Each approach has advantages and disadvantages, strongly influenced by system considerations. For the SCSTPE Phase II Program, FACC has chosen to try an indirect heated design, based on a concept studied in depth during the Phase I part of the program. The most important difference between the Phase I and Phase II efforts, however, is the operating temperature range. The high temperature (800°C) Stirling engine studied during Phase I resulted in the selection of sodium for the receiver fluid. The moderate operating temperature (427°C) of the Phase II ORC requires the search for a more applicable fluid.

SUBSYSTEM DESCRIPTION

A sketch of the baseline receiver configuration is presented in Figure 2. The cavity receiver is a simple structure consisting of two cylindrical shells, one cantilevered inside the other from a connecting toroidal shell. The two ends are capped with spherical heads forming a

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*Patent applied for

design with minimal modifications. For example, canisters of high thermal capacity materials (i.e., eutectic salts) can be inserted within the receiver annulus, with energy transfer facilitated by the high boiling heat transfer coefficients of the secondary fluid. The fully insulated receiver (12.7 cm of insulation) can accommodate a maximum 100 kW_t energy within a 1 x 1 x 1.2 m envelope at a gross weight of 180 kg including 20 kg of a typical fluid. Based on Phase I vendor quotations, the complete receiver/thermal transport package can be manufactured for under $2500 when built in production quantities. The operational life of the optimized, lowest life cycle cost receiver is selected at 15 years, based on design tradeoffs between material corrosion rate and material creep-rupture limitations.

BENEFITS OF POOL BOILING RECEIVER

The heat transfer coefficients associated with pool boiling are very high and generally result in:

- Reduced cavity area (thus, a lighter and lower cost receiver)

- Reduced receiver-to-engine temperature differential (reduces thermal losses and thus increases system efficiency)

- Reduced sensitivity to the incident flux levels (thus a large safety factor against temperature overshoot or burnthrough).

Other benefits include a simplified design that does not require tubes, fins, flux adjusters, pumps or special controls. By selecting the right fluid, the vapor pressure at the steady-state operating temperature can be about 1 atmosphere. This virtually eliminates any pressure differential, hence reduces the cavity wall thickness which in turn reduces the temperature gradients, weight and cost of the receiver. The thermal inertial of the receiver cavity walls and boiling pool provide an inherent buffer storage capability during short inclement operating conditions such as those associated with a cloud passage. The thermosyphon also operates at a nearly constant temperature.

The condenser/heat exchanger also has very high film coefficients. This permits a heat exchanger configuration and surface geometry to yield a small compact unit without concern about the solar flux distribution and levels.

PRELIMINARY FLUID SELECTION

Some of the more important characteristics of the receiver fluid are listed below.

- Critical point above the maximum operating conditions of the engine working fluid.
- High boiling heat transfer coefficients.
- High burnout heat flux.

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- Stable pool boiling for a range of operating conditions.
- Low vapor pressure at operating temperature.
- Non-corrosive, non-toxic, non-flammable and chemically stable.
- Easy to handle and fill/drain receiver.
- Freeze point below ambient conditions.
- High heat capacity.
- Low cost.

As previously mentioned, sodium was selected for use in the high temperature (~800°C) receiver. At the lower operating temperatures of ORC engines (~350-425°C), several candidate fluids exist subject to further investigation. These fluids include the various terphenyls, sulfur, aluminum bromide, etc.

PERFORMANCE

Figure 3 presents a comparison of typical boiling and gas-in-tube heat transfer rates. As shown, the boiling systems have much higher heat transfer rates than those for forced gas convection; also less heat transfer surface area is required and lower temperature differentials between the surface and the working fluid are experienced. Reference 1 indicates that sulfur (with a small amount of iodine to reduce the high viscosity at lower temperatures) has comparable performance to water in a heat pipe application. In addition, the burnout heat flux for sulfur is approximately 1000 kW/m^2 at a pressure of 1 atm (Reference 2). This gives a safety factor of approximately 3 over the predicted worst case flux deposition for a typical cavity receiver configuration.

Figure 4 shows the vapor pressures of various heat transfer fluids as a function of temperature. The vapor pressures of the terphenyls and sulfur are approximately 1 atm at the upper operating temperature (~427°C) of ORC engines. The vapor pressure of aluminum bromide is slightly higher. In the case of the terphenyls and sulfur, the net pressure loading on the receiver is very low, with obvious structural and safety advantages.

The temperature gradients throughout the receiver subsystem are presented in Figure 5. The largest temperature drop occurs through the receiver wall. The backface wall-to-pool temperature differential is typically quite small due to the high heat transfer coefficients characteristic of the pool boiling phenomena. The temperature drop through the vapor pipe is predicted to be on the order of a few degrees centigrade, due to the pressure difference between the pool and heat exchanger. A very small temperature drop is also predicted for the condensation heat transfer to the secondary heat exchanger. The temperature drops through the secondary heat exchanger will be minimized by utilizing a high performance plate-fin configuration.

Transient Operating Characteristics

An in-depth transient analysis of the receiver/thermal transport subsystem is necessary in view of the inherent non-steady nature of the

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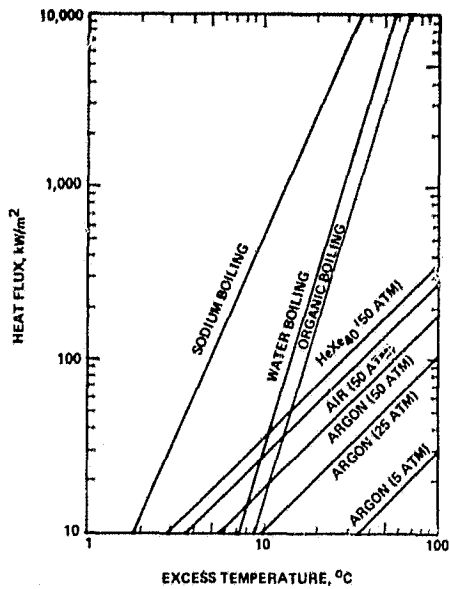
FIG. 3.   BOILING AND GAS-IN-TUBE
          HEAT TRANSFER
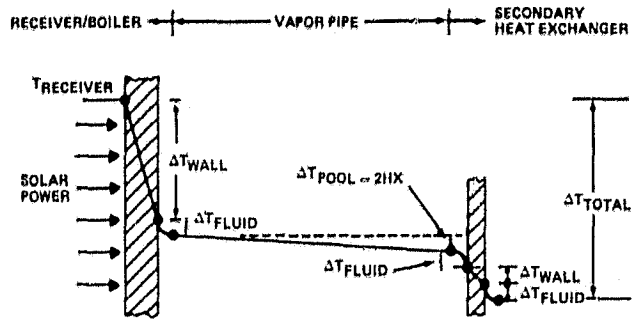
FIG. 5.   SUBSYSTEM TEMPERATURE GRADIENTS
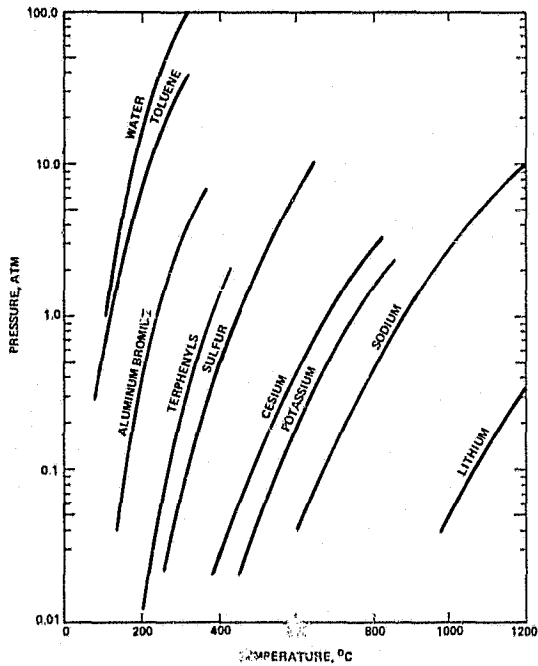
FIG. 4.   VAPOR PRESSURES FOR SEVERAL
          HEAT TRANSFER FLUIDS
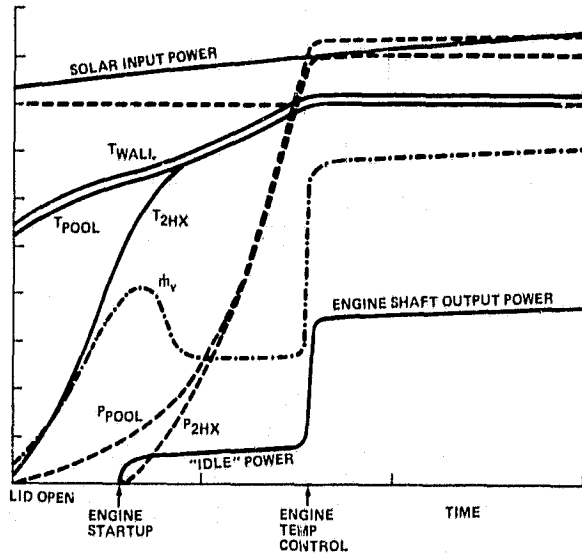
FIG. 6.   SUBSYSTEM RESPONSE DURING
          NORMAL STARTUP

solar flux. The objective is to characterize the behavior of the subsystem for all operational modes encountered in a solar application. During Phase I, a transient thermal model was developed from the basic equations for conservation of mass, conservation of energy, the equation of state for vapor, and the vapor pressure equation. It is assumed that the vapor is saturated (vapor and liquid in quasiequilibrium), the vapor volume is approximately constant and that the receiver orientation effects are negligible. The energy balance considered the incoming solar power, the thermal power to the engine, and the thermal losses from the subsystem. Pressure drops throughout the entire transport subsystem were also included. Typical results of the transient analysis are discussed below.

NORMAL START-UP. Figure 6 presents the subsystem temperature response and engine output power during a normal start-up condition. The solar input power profile is based on the 15 minute Barstow, California solar insolation data for a typical uncloudy day and includes the effects of both concentrator size and efficiency, thus representing the total power entering the receiver. In the morning, after normal operation from the previous day and nighttime cool down, the receiver pool is still warm. The receiver lid is opened prior to focusing on the sun. Once the sun is "on", the pool and heat exchanger temperatures rapidly increase towards the steady-state operating level. The pool and heat exchanger temperatures correspond to the saturated vapor pressure at the respective temperatures. The temperatures, pressures, and vapor mass flow rate increase as the solar energy continues to enter the system. After several minutes the engine head temperature has reached the predetermined start temperature. The engine is then started and operated at a low or "idle" power level consistent with a previously selected condition. After several more minutes, the engine working fluid reaches the steady-state operating temperature (427°C) and the engine temperature control mode is activated. At this point the temperature controller is modulated to maintain the engine temperature within the control band as the solar flux varies during the day.
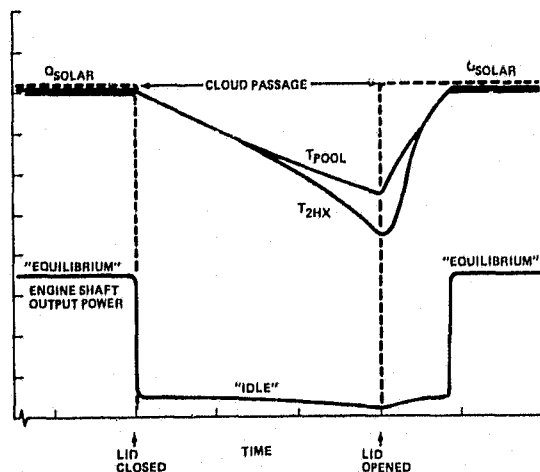
FIG. 7. SUBSYSTEM TEMPERATURE RESPONSE DURING CLOUD PASSAGE

CLOUD PASSAGE. Figure 7 presents the subsystem temperature response during a typical cloud passage. As the cloud passage starts its passage, the solar input power goes to zero, the receiver lid closes and the subsystem temperatures start to decrease. The engine output power will decrease until operation is at a low or "idle" power level. During cloud passage the receiver pool and engine fluid temperature decrease while the engine "idle" power remains relatively constant. When the cloud has passed, the solar power returns and the receiver lid is opened allowing the subsystem temperatures to increase. Several minutes are

required to heat the subsystem back up to the steady-state operating temperature.

The results of all of the cases investigated during Phase I of the program demonstrate that the performance of the subsystem is stable, well-behaved, and has long thermal time constants which facilitate engine control.

CONCLUSIONS

An ORC receiver utilizing an integrated cavity/pool boiler is technically feasible at the present time and uses state-of-the-art materials. The use of a pool boiler permits the design of a small, lightweight, low cost and efficient, moderate temperature receiver for use in a dish-Rankine PFDR system.

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NON-HEAT PIPE/P-40 STIRLING ENGINE

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ABSTRACT

This project will demonstrate the technology for a full-up Hybrid Point-Focus Distributed Dish Stirling Solar Thermal Power system by the fall of 1980 at JPL's Desert Solar Test Facility near Lancaster, California. Hybrid operation is provided by fossil fuel combustion augmentation, which enables the Stirling engine to operate continuously at constant speed and power, regardless of insolation level, thus providing the capability to operate on cloudy days and at night.

The Non-Heat-Pipe Receiver/P-40 Stirling Engine system will be installed and operated on the JPL Test Bed Concentrator. A 25-kW direct-driven induction-type alternator will be mounted directly to the P-40 engine to produce to a 60-Hz, 115/230-volt output.

NON-HEAT PIPE RECEIVER DESIGN

The Non-Heat-Pipe Receiver design is a cavity-type receiver, as illustrated in Figure 1. The primary receiver surface is a conical plate with integral passages for the helium working fluid. The passages are formed by Inconel 617 tubes imbedded in a copper matrix, which in turn in incapsulated in an Inconel 617 sheet. The cone is heated by solar insolation on the exposed surface and by combustion gas on the back surface and the regenerator tubes. The receiver is attached directly to the Stirling engine cylinders and regenerator housings. Simplicity in design has been emphasized, along with extensive use of parts and assemblies proven in other applications but under similar operating conditions, such as normally found in industrial boilers and gas turbines. Where expensive cobalt alloys are required, their use has been minimized.

The combustion system design is based on heavy duty industrial burner technology, scaled to the size and configuration required to assure reliable cold start, stable combustion over the full operating range and uniform heating of the heater tubes extending from the underside of the cone to the engine regenerator manifolds. The combustion air, provided by an electric-motor-driven constant speed blower, is directed through a preheater into the combustion chamber, which contains eight integrally cast venturies, oriented to produce a swirling flow field inside the
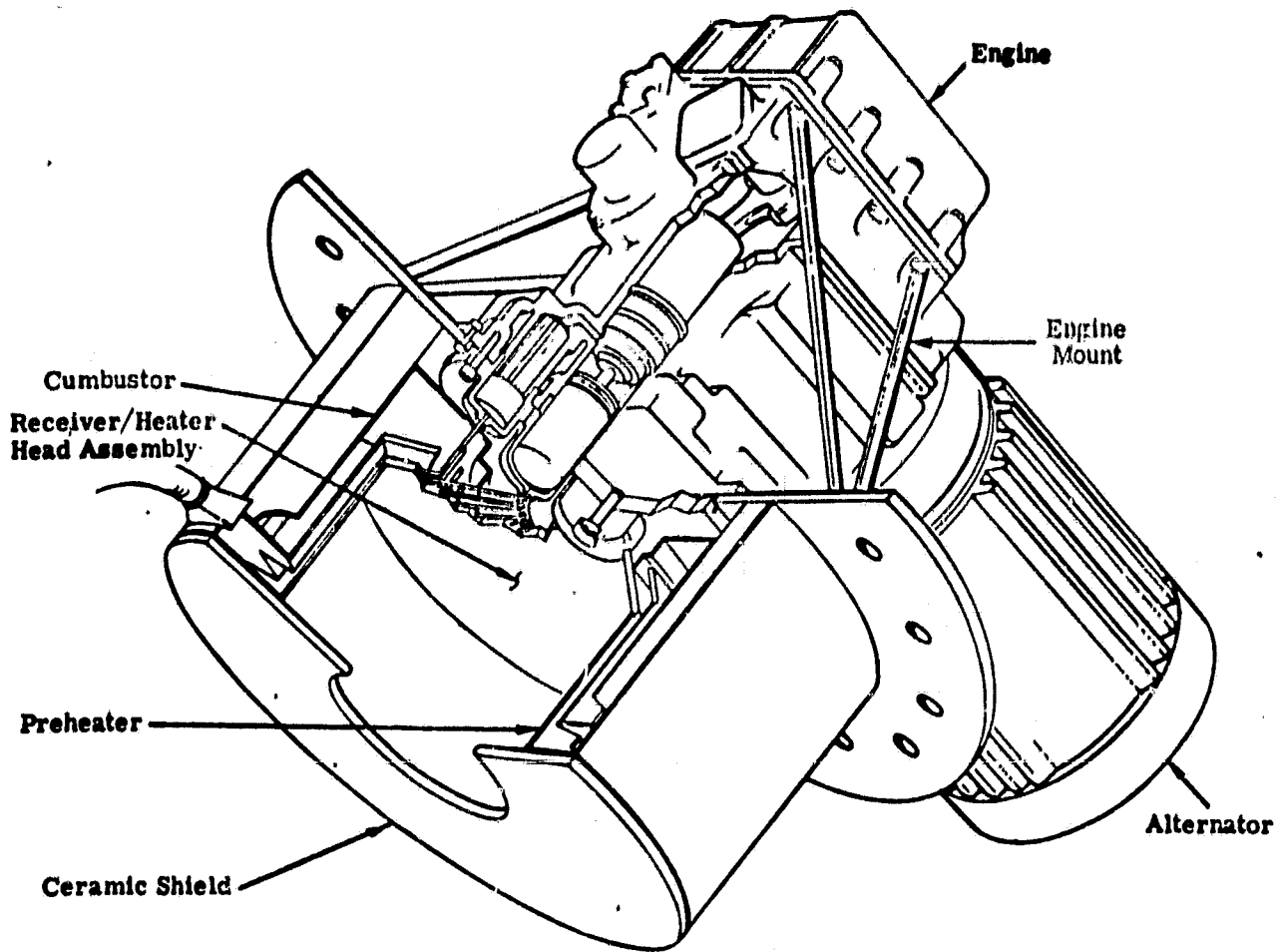
FIGURE 1. NON-HEAT PIPE/P-40 STIRLING ENGINE

combustion chamber. Fuel is introduced through a jet located
inside each venture. Electric spark igniters are provided di-
rectly in front of two of the venturies; the igniters also pro-
vide flame sensing, so that the main fuel valve closes auto-
matically in the event of flame-out. Automatic restart is pro-
vided.

Performance Goals

The following performance goals have been identified by JPL for
the Non-Heat-Pipe Receiver design:

Concentrator diameter (active)	10 m
Geometric concentration ratio	2000
Peak insolation (1 kW.m^2)	76.5 kW
Concentrator efficiency (clean)	0.83
Total error (slope plus pointing)	3 mr
Fossil fuel combustor peak input to helium	70.0 kW$_c$
Combustor turndown ratio	10:1
Working fluid temperature (helium)	1200° to 1500°F
Peak engine pressure (helium)	2500 to 3000 psi

Expected Receiver Performance (24-cm Aperture Diameter)

Losses (kW)		
Radiation	2.8	5.2
Reflectance	0.9	0.7
Convection	3.6	4.4
Efficiency (%)	0.875	0.827
Maximum Cavity Temperature (°F)		
Center Plug	1966	2053
Cone	1561	1836

Program Status

The receiver design effort has been completed and a Detailed Design Review was held on September 27, 1979. As shown by the schedule in Figure 2, combustion and heat transfer tests are being conducted at Fairchild Stratos Division in Manhattan Beach, California and are carried out jointly by JPL, Fairchild and the Institute of Gas Technology. Test objectives include evaluation and demonstration of cold start, combustion stability and energy release at various power levels, combustion air preheat, pressure drop, fuel/air ratios and heat transfer. Reliable cold start performance, full design output power and turndown capability have been demonstrated. The general arrangement of the combustion test rig is illustrated in Figure 3.

FIGURE 2.   MAJOR TECHNICAL MILESTONES CONTRACT 955400
30 November 1979
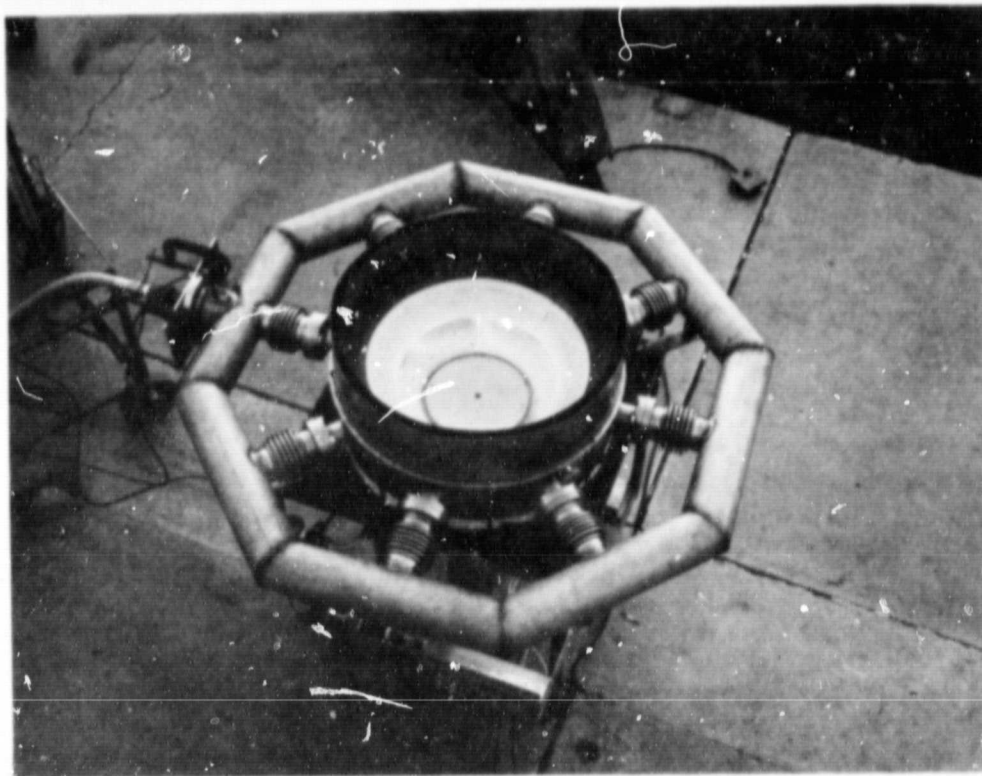
FIGURE 3.   PHOTO OF TEST RIG

SESSION III
POWER CONVERSION DEVELOPMENT

THE SCSTPE ORGANIC RANKINE ENGINE

BY

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ABSTRACT

This paper describes the Organic Rankine cycle (ORC) engine under consideration for the PFDR solar thermal system being developed for JPL/DOE by FACC under Contract 955637. Design parameters, method of control, performance and cost data are provided for engine power levels up to 80 kWe; efficiency is shown as a function of turbine inlet temperature in the range of $149^{\circ}C$ ($300^{\circ}F$) to $427^{\circ}C$ ($800^{\circ}F$).

INTRODUCTION

Under the SCSTPE Program, FACC will develop a solar thermal PFDR, distributed generation system employing small Rankine-cycle Power Conversion Units (PCUs) mounted at the focus of parabolic dish concentrators. The baseline PCU is comprised of an organic Rankine cycle (ORC) engine, high speed AC generator and a ground-mounted AC/DC converter (rectifier). The Rankine cycle was selected for the SCSTPE Program on the basis of highest performance for least program risk (compared with other heat engine cycles). The ORC engine was selected over a steam Rankine engine on the basis of programmatic and technical factors, although a steam system is currently under consideration for a parallel development effort.

The PCU has not yet been selected; proposals are currently being solicited from a number of engine manufacturers, including Sundstrand, Garrett/AiResearch, Barber-Nichols, Thermo-Electron and General Electric. During the Phase I Small Power Systems study, however, FACC contracted with Sundstrand to provide a preliminary high performance ORC design (Ref 1). The design is an outgrowth of Rankine engine studies carried out by Sundstrand for NASA (Ref 2); it currently serves as the baseline SCSTPE engine until final ORC engine selection and is described below.

SYSTEM DESCRIPTION

The prototype ORC engine is a regenerative, hermetically-sealed 22 kW_e unit with a single-stage axial-flow turbine; supercritical toluene is the working fluid, with a turbine inlet temperature (TIT) of $427^{\circ}C$ ($800^{\circ}F$) and a maximum system pressure of 4.52 MPa (656 psia). A high-speed, 4-pole homopolar inductor alternator is direct-coupled to the turbine and cooled by the working fluid; variable-frequency AC power is converted to DC output by means of the solid state rectifier. Figure 1
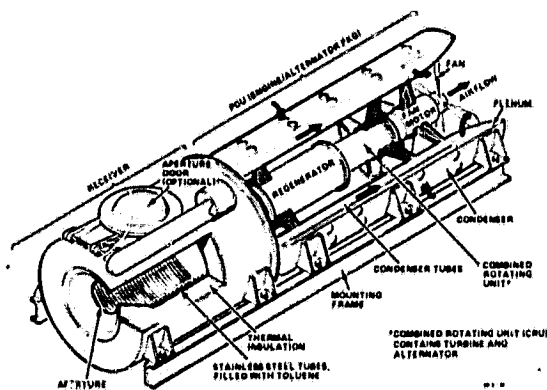
FIG. 1. ORC POWER CONVERSION ASSEMBLY
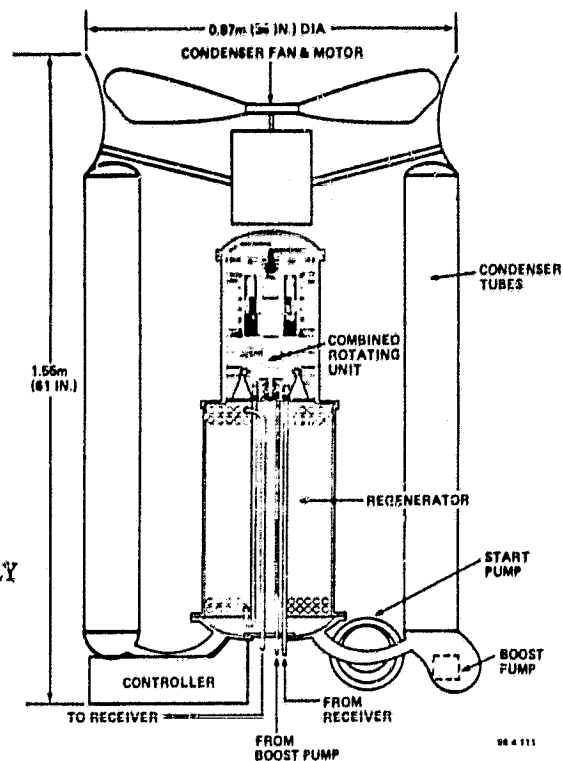
FIG. 2. BASELINE (22 KW_e) ORC POWER CONVERSION UNIT

is a cutaway view of the power conversion assembly, i.e., the PCU and the receiver*, showing the arrangement of the major engine components; the assembly is pallet-mounted for ease of installation/removal. A cross-section of the PCU is shown in Figure 2; the condenser is configured in a cylindrical shape surrounding the regenerator and the combined rotating unit (CRU), i.e., the hermetically-sealed turbine/alternator/feed pump components. This makes for a very compact PCU, measuring 0.87m (34 in.) in diameter by 1.55m (61 in.) in length. Forced draft cooling of the condenser is accomplished with an electrically-driven fan whose speed is varied (in 3 steps) as a function of cooling load and ambient air temperature to minimize parasitic losses. A dry-cooling arrangement was selected because of the lack of water in the high-insolation regions of the U.S. A PCU system schematic diagram is shown in Figure 3; note that the working fluid is used to cool the bearings and the controller as well as the alternator. The pertinent thermodynamic state points are identified on the figure and specified in Table 1. A pressure-enthalpy diagram for toluene is given in Figure 4,

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*The receiver shown is an alternate Garrett/AiResearch-designed unit of the direct-heated type, based on a steam receiver design currently under development for JPL/DOE; in the companion systems paper by Pons and Grigsby the baseline receiver is shown as the indirect-heated type, designed by FACC.

TABLE 1. PCU THERMODYNAMIC STATE POINTS

	STATE POINT	PRESSURE		TEMP.	
		MPa	(PSIA)	^{o}C	(^{o}F)
1	TURBINE INLET	3.96	(574)	427	(800)
2	REGENERATOR VAPOR INLET	0.014	(2.07)	308	(587)
3	CONDENSER VAPOR INLET	0.013	(1.92)	76	(168)
4	FEED PUMP INLET	0.069	(10)	52	(125)
5	ALTERNATOR COOLING INLET	4.52	(656)	58	(136)
6	REGENERATOR LIQUID INLET	4.51	(654)	63	(146)
7	VAPORIZER LIQUID INLET	4.45	(646)	248	(478)
8	VAPORIZER OUTLET	4.06	(589)	427	(800)
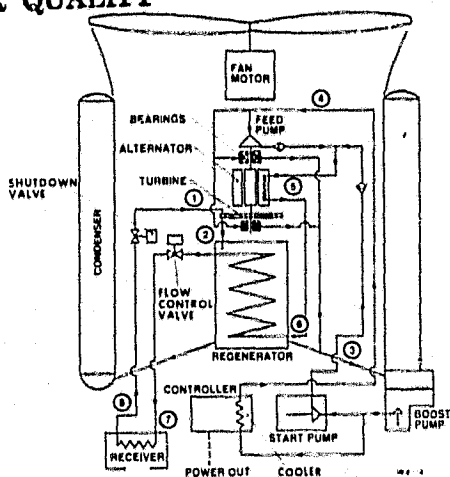
FIG. 3. BASELINE PCU SYSTEM SCHEMATIC
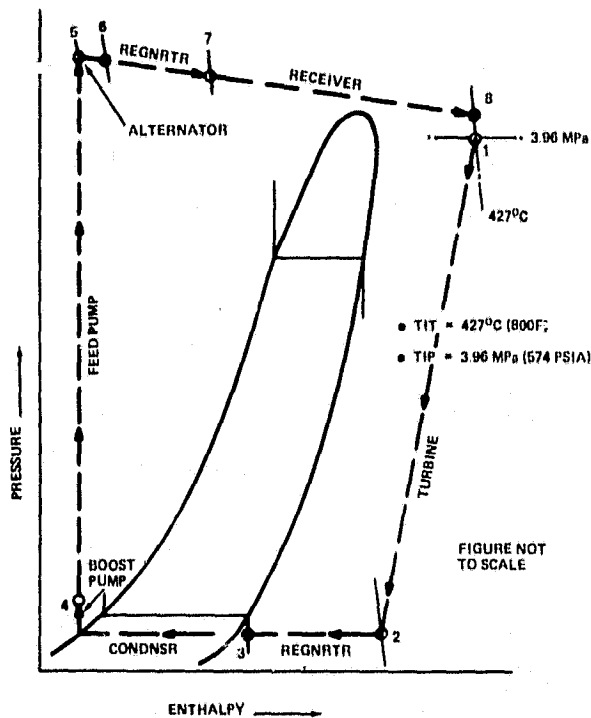
FIG. 4. PRESSURE-ENTHALPY DIAGRAM FOR TOLUENE SHOWING ORC STATEPOINTS

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also showing the cycle operating path and the aforementioned state points. Gross weight of the PCU is estimated at 296 kg (653 lb); a weight breakdown of the 22 kW$_e$ unit is given in Table 2.

TABLE 2. BASELINE (22 kW$_e$) PCU WEIGHT BREAKDOWN

COMPONENT	WEIGHT	
	kg	(lb)
CONDENSER	96	(16)
FAN/MOTOR	44	(212)
COMBINED ROTATING UNIT	85	(96)
REGENERATOR	17	(37)
START PUMP	16	(35)
ELECTRONIC CONTROLLER	9	(20)
FLUID (INVENTORY)	15	(33)
BOOST PUMP, VALVES, MISC	14	(32)
TOTAL	296	(653)

CONTROL

The PCU control scheme is designed both for stable operation under varying solar input and for high part-load efficiency, a highly desirable feature in a solar power system. As the solar input to the receiver varies, the turbine inlet temperature is held constant by varying the toluene flow rate; this is achieved by slaving an electro-mechanical flow control valve (which controls the output of the shaft-driven toluene feed pump) to a turbine inlet temperature sensor. In addition, a controller located at the power module provides turbine speed (and power) control by varying the alternator field excitation, thereby regulating output voltage and delivering variable amounts of power into the grid in direct proportion to the solar input. The local controller is under supervisory control by the plant central microprocessor, which contains command look-up functions to permit operation at the optimum turbine speed for each load value. As mentioned earlier, condenser fan speed is also varied with load (under central control) to maximize system efficiency.

PERFORMANCE

427°C (800°F) is generally considered to be the upper limit for operating with toluene and was picked as the baseline TIT to maximize PCU efficiency and reduce overall system energy cost. At the (rated) ambient temperature of 27°C (80°F), overall PCU efficiency, i.e., from thermal input to DC electrical output, is 28.5%. In consideration of the possibility of

toluene breakdown at elevated temperature, PCU performance was also
determined for lower values of TIT; Table 3 summarizes design point
characteristics for TIT values of 371°C (700°F) and 399°C (750°F) as
well as for the baseline design. Note that the penalty for operation
at 371°C is two points in efficiency, i.e., 26.5% compared with 28.5%
baseline value; as shown in the comparison systems paper by Pons and
Grigsby, this corresponds to about a 7% increase in (operational) system
energy cost. Operation at reduced temperature may, of course, not be
necessary. For example, it is projected that the rate of toluene
degradation will actually be quite low, since the bulk of the inventory
is not at peak temperature most of time. Sundstrand estimates that
the toluene will have to be changed only about every 30,000 hours, or
about twice in the 30 year life of the solar plant. Note further that

TABLE 3. PCU DESIGN POINT CHARACTERISTICS

PARAMETER		371°C (700 F)	399°C (750 F)	427°C (800 F)
DC POWER OUT	kW	22	22	22
THERMAL POWER IN	kW	83	79.7	77.2
PCU EFFICIENCY*	%	26.5	27.6	28.5
FAN POWER	kW	1.7	1.8	1.9
PARASITIC POWER**	kW	0.12	0.12	0.12
RECTIFIER EFF'Y	%	97	97	97
ALTERNATOR EFF'Y	%	92	92	92
PUMP EFF'Y	%	54	53	52
TURBINE EFF'Y	%	74	73	73
REGENERATOR EFFY	%	95	95	95
BEARING LOSSES	kW	0.1	0.1	0.1
FLUID FLOW RATE	kg/hr	519	494	461
	(lb/hr)	(1144)	(1090)	(1021)

*TO DC OUTPUT

**INCLUDES CONTROLS AND BOOST PUMP

the use of a hermetic-sealed system minimizes oxide formation and attendant scale deposition on the plumbing. Figure 5 shows the general trend in efficiency for small (20-50 kW_e) ORC power conversion units, over the range $300^\circ F < TIT < 800^\circ F$.

Figure 6 shows the effect of engine size on PCU efficiency for the specified three values of TIT. There is a substantial drop in efficiency below about 20 kW_e. Figure 7 shows the efficiency of the 22 kW_e PCU as a function of thermal input and ambient air temperature. Note the excellent part-load performance, which is the major reason for the system's high annual capacity factor (ACF = 0.418) at the Barstow, CA site.

COST

For system economic projections, both capital and maintenance costs for the PCU are essential inputs. Figure 8 is an estimate of these PCU costs over the power output range of 5 to 80 kW_e, based on annual production rates of 100,000 units/year. At this stage in the development of the system, however, there is considerable uncertainty over the accuracy of these data; a possible error of $\pm40\%$ is not an unreasonable assumption at the present time.

CONCLUSIONS

A carefully-designed ORC power conversion unit can achieve good efficiency at relatively low temperature, i.e., compared with Brayton, Stirling or steam Rankine cycle engines. The low temperature assures high solar collection efficiency (which contributes to high overall system efficiency), lower risk and lower cost, since less critical materials and lower-stress equipment designs can be used.

Many thousands of operating hours exist on ORC systems/components, albeit at different sizes than for the components of the baseline system. Nevertheless, the ORC-PCU should be considered a state-of-the-art device. In addition, toluene is a fully characterized substance and its toxicity, flammability and other environmentally sensitive parameters are quite well known and safe handling procedures are well established.

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1) Anon, "Phase I of the First (Solar) Small Power System Experiment (Experimental System No. 1)" Final Report, No. V-6529, Ford Aerospace & Communications Corp., Aeronutronic Division, Newport Beach, CA, 5 May 1979.

2) Bland, T., "15 kW_e (Nominal) Solar Thermal Electric Power Conversion Concept Definition Study - Steam Rankine Turbine System," Sundstrand Corp., Report DOE/NASA/0061-79/1, NASA CR-159589, AER 1713.
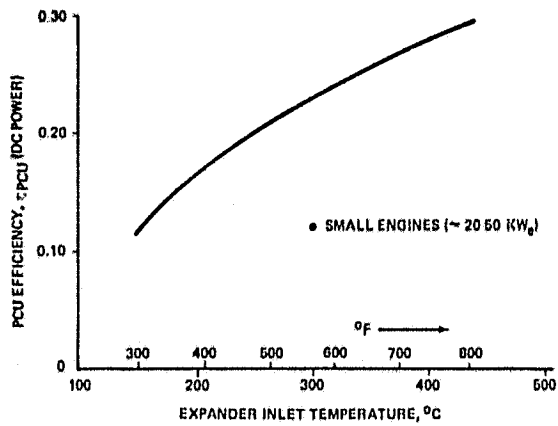
FIG. 5. INFLUENCE OF TEMPERATURE ON ORC POWER CONVERSION UNIT EFFICIENCY
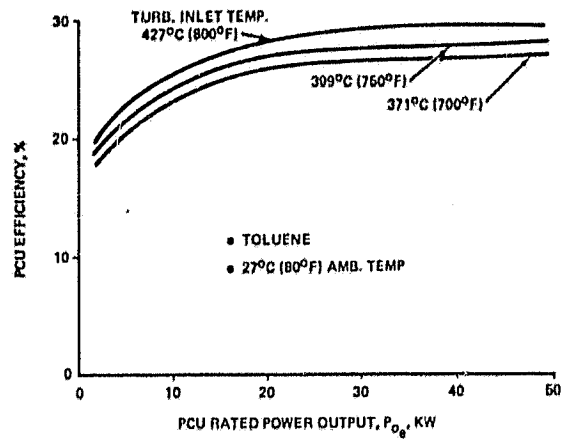
FIG. 6. EFFECT OF ENGINE SIZE ON PCU EFFICIENCY
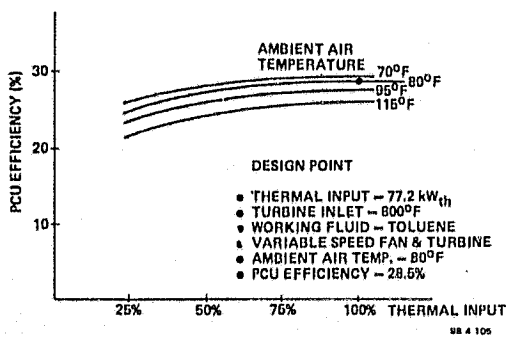
FIG. 7. PCU PART LOAD PERFORMANCE
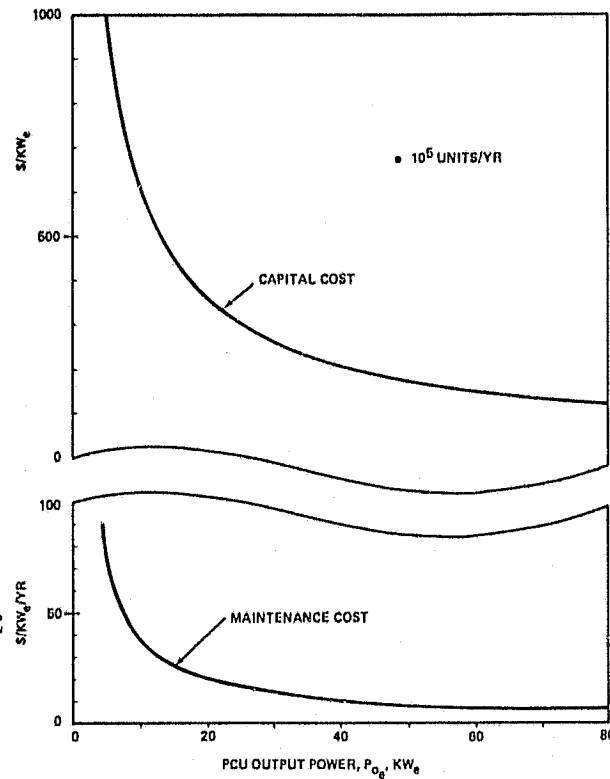
FIG. 8. PROJECTED PCU COSTS

A HYBRID BRAYTON ENGINE CONCEPT

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ABSTRACT

A first generation open cycle Brayton engine concept for use in full-scale solar module testing, was defined in NASA/JPL study contract DEN 3-69. This concept has been extended to include solar/fossil hybrid capability. The combustion system defined for hybrid operation consists of a wide range combustor liner, a single airblast atomizer, an ignitor and a high-voltage ignition unit. Wide range combustor operation would be achieved through combining pilot and primary zones.

The hybrid control mode and the solar only control mode are both based on the concept of maintaining constant turbine inlet temperature and varying the engine speed for part-power operation. In addition, the hybrid control concept will allow the operator to set a minimum thermal power input to the engine by setting a corresponding minimum engine speed. When the solar thermal power input falls below this minimum, fossil fuel would be utilized to augment the solar thermal power input.

INTRODUCTION

A concept definition study (NASA/JPL Contract Den 3-69) defined a first generation open cycle Brayton engine for use in full scale solar module testing originally scheduled to commence late in 1980. The engine concept has been presented at previous DOE review meetings. It is also described along with other engine concepts and supporting study results in a final report now being readied for release (1). This initial engine concept includes the use of an existing turbo-compressor from the Garrett/AiResearch (Phoenix) GTP36-51 gas turbine engine to minimize the procurement duration and costs. The engine concept was designed to operate with solar energy only, using the solar Brayton receiver being built at Garrett/AiResearch (Torrance) under JPL contract.

Subsequent to initiating the NASA/JPL study contract, a new requirement was added based on the fact that JPL's Second Engineering Experiment (EE2A) would be a hybrid system. This required adding a combustor to the engine concept to provide for solar/fossil hybrid capability. This presentation's purpose is to describe the combustor and corresponding controls formulated to convert the initial Brayton engine concept to the current MOD-0 Hybrid Brayton engine concept.

COMBUSTION SYSTEM

The combustion concept is presented in Figure 1 and consists of a wide range combustion liner, a single airblast atomizer, an ignitor and a high-voltage ignition unit. This system was chosen because it would provide simple low-cost design features and a proven wide operation range.
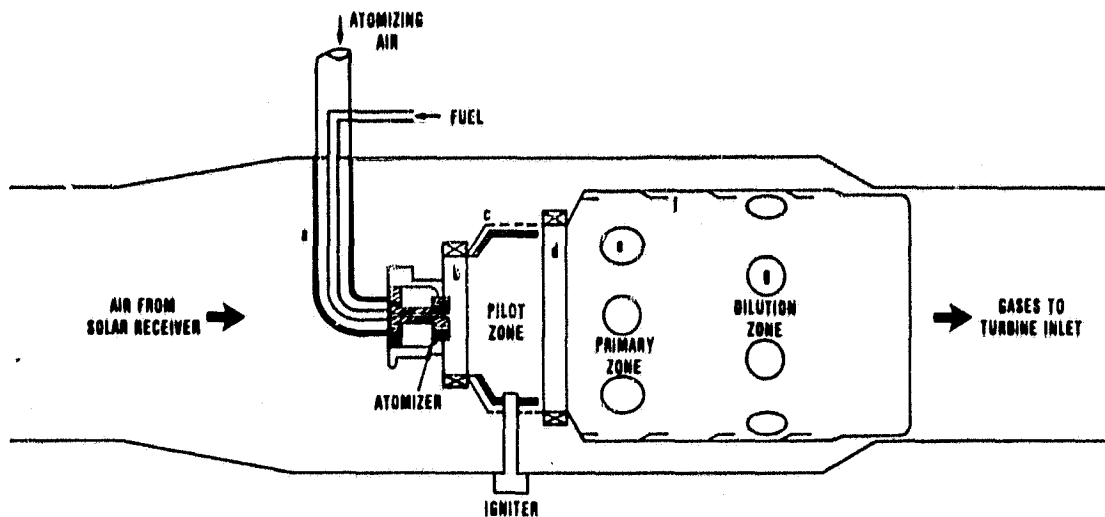
FIGURE 1.   COMBUSTOR CONCEPT

The wide range combustor system is considered a conventional type because it has neither fuel staging nor variable geometry. The wide range would be achieved through a combination of pilot and primary zones. The system would rely on strong recirculation in the pilot zone for flame stabilization. At low fuel flow rates, the flame front would be confined to the pilot zone. The flame front would expand into the primary zone for operation at the higher fuel flow rates. This burner would also take advantage of the airblast atomizer characteristics to obtain satisfactory spray quality over an estimated eight to one fuel flow range. Atomization would be achieved through the use of a high velocity air stream to shear the fuel film into small droplets. This type of atomizer is currently in use on several AiResearch gas turbines. Cooling to keep the maximum liner skin temperature levels below operating limits would be accomplished by using conventional film cooling skirts in the primary and dilution zones, and a combination of impingement cooling and a thermal barrier in the pilot zone.

Fuel system design must also address the possibility of fuel thermal decomposition in both the manifold and the atomizer due to the high inlet air temperature to the burner. Operating temperature of these parts would be minimized by routing the fuel in the inner of the two concentric passages leading to the fuel atomizer. Low temperature air bled from the compressor discharge for use by the airblast atomizer would be ducted through the outer concentric passage. The outer surface of the outer concentric passage which is exposed to the hot air from the solar receiver would be treated with a thermal barrier coating similar to that used in the combustor pilot zone.

The system can be designed to operate on a variety of fuels including unleaded gasoline, jet-type kerosenes, diesel fuels and natural gas. It is currently planned to design the first units to use JP-4 fuel.

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CONTROL CONSIDERATIONS

Addition of a fossil fuel combustor will significantly increase the flexibility of, and the opportunities for utilizing the solar Brayton module. For instance, prior to installing the module on the concentrator, fuel could be used to start and check out hybrid power conversion module operation without requiring a solar receiver and the attendant radiant energy source to supply the input thermal power. Also, when little or no insolation is available such as for night-time maintenance or for night-time and cloudy day power generation, the combustor would allow the module to be fully operable. Again, the combustor could be used to prevent module shutdown during cloud passage on an otherwise sunny day, or the combustor could also be used to provide makeup input energy during periods of low or intermittent insolation to maintain some pre-selected power delivery rate. For example, the combustor could be used to supplement the energy from insolation and provide rated power.

The control and power conditioning concept is shown in Figure 2. Dashed lines indicate the additions to the solar only control concept required to describe the hybrid control concept. The control concept will maintain the turbine inlet temperature T_7 at a constant value and increase or decrease the engine speed N_T as the insolation to the receiver increases or decreases respectively. The engine speed will be varied by commanding the control rectifier to change the electrical load on the engine generator. The desired engine speed is that speed at which the engine air flow will be heated to a pre-selected value (1500°F) at the outlet of the receiver. For this control concept to function, the 60 Hz utility grid or bus bar must be prepared to accept all of the electrical power generated. If it cannot, excess power wasting must be accomplished until the grid load can be increased, or the solar power module deactivated. A concept for accomplishing this function is presented in the left side of Figure 2.

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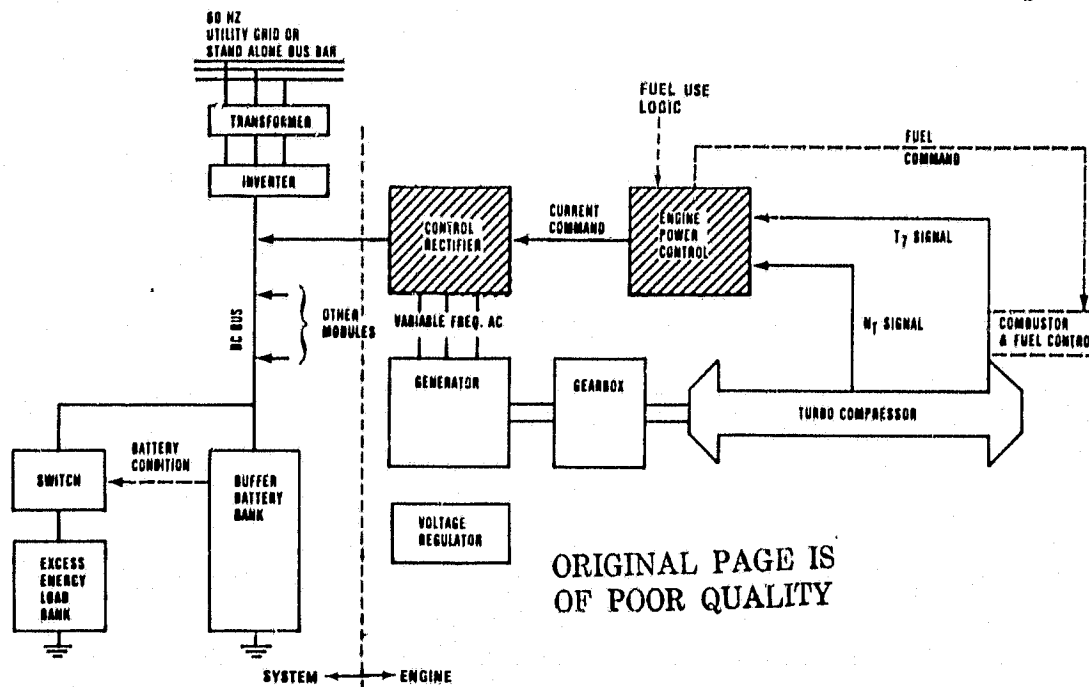
FIGURE 2. CONTROL AND POWER CONDITIONING CONCEPT

In the hybrid control system concept, fossil fuel would be utilized to augment solar thermal input. Figure 3 shows an approximate representation of how the engine rotor speed and pertinent temperatures would behave if subjected to a simplified insolation schedule shown in Figure 3(a). In this case fossil fuel is used to complement the insolation during certain periods of the day identified along the abscissa by the terms "fossil only", "hybrid" and "solar only". The fuel use logic input picked for illustration is one in which the solar module would be adjusted to operate continuously at rated output power starting before sunrise and continuing at rated power until after sunset except when the insolation exceeds rated intensity. This selected power level at which the module would be required to operate when using fossil fuel would be established by setting an adjustable speed reference called N_{set} shown in Figure 3(b). N_{set} in turn would be bounded by a small speed tolerance band in the control module identified by N_{high} and N_{low}. When increased insolation would be experienced during hybrid operation it would first tend to cause the receiver outlet temperature to increase and this would cause a fuel flow reduction until some previously established fuel flow would be reached, as at "d" in Figure 3. The engine speed would then increase until it reached N_{high} as at "e" which would shut off the fuel flow. The control would then behave in the same manner as a solar only control in the region between "f" and "g".

When the engine speed falls to N_{low} because of decreasing insolation, fuel flow would be resumed as at "h" in Figure 3. The control would be designed to avoid a requirement for the fuel atomizer to operate over an excessively large fuel flow range by appropriate choice of a minimum fuel flow. The effect of this minimum fuel flow value is shown on the three curves of Figure 3 by small perturbations in the regions identified by "d-e-f", "h", "i", and "k-l". Figure 3(c) shows that the turbine inlet temperature stays constant throughout the assumed daily schedule of input thermal power as a result of the complementary action of the receiver temperature rise and the combustor temperature rise. Through the action of N_{set}, the engine can be adjusted to operate at rated power as shown in Figure 3, or it can be set at other values higher or lower, depending on the application requirements and the fuel consumption economics. Choosing N_{set} at a value corresponding to maximum power level would involve the use of larger fuel quantities. Setting N_{set} at a value slightly above self-sustaining would minimize fuel consumption and still avoid restarts following cloud passage.
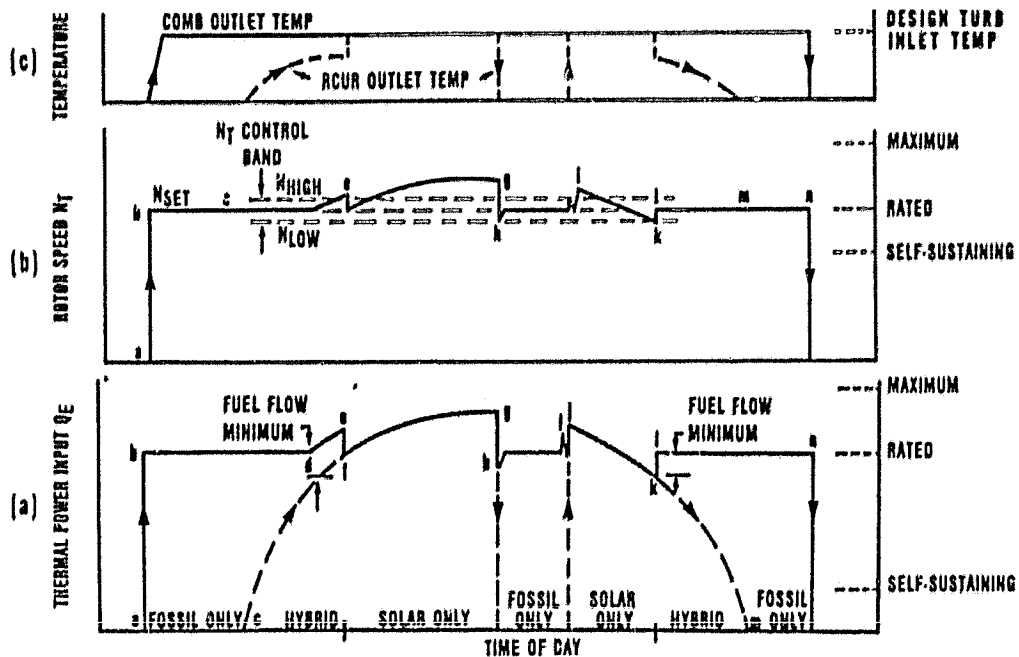
FIGURE 3.   HYBRID CONTROL CONCEPT-TYPICAL DAY

SUMMARY

An isometric view of the hybrid MOD-O engine is presented in Figure 4 which shows the combustor assembly installed between the receiver outlet and the turbine inlet. The combustor addition will cause thermodynamic performance to drop by about 1.3 efficiency points at the engine shaft because of added pressure drop, and a small percentage of bleed flow which bypasses the recuperator in order to provide fuel line cooling and fuel atomization.

Features or advantages of adding hybrid capability to the Brayton engine concept are identified as follows:

o   Retains constant turbine inlet temperature control for good part load efficiency

o   Adds option for continuous operation at rated power independent of insolation

o   Adds option for operation at turbine inlet temperature higher than the receiver's capability

o   Provides operation during cloud passage

o   Adds option for operation at night for power generation or maintenance

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The combustion system and control concept described will be subjected to analysis and design in the NASA/JPL contract for the MOD-O engine.
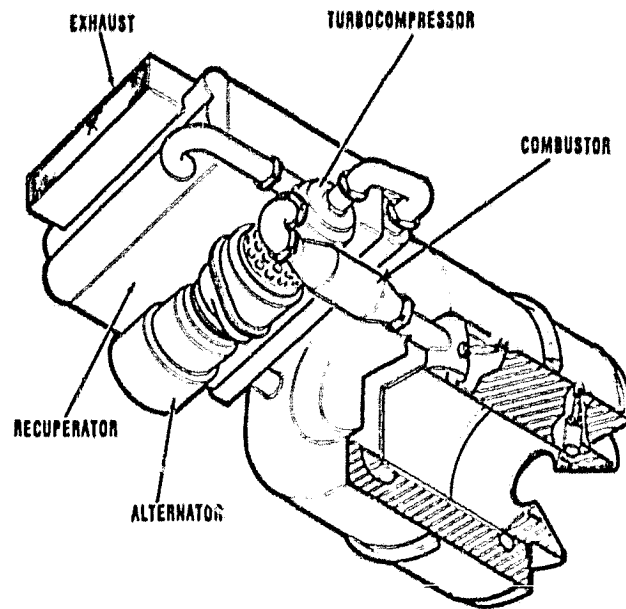
FIGURE 4. BRAYTON ENGINE GENERATOR AND CAVITY RECEIVER ASSEMBLY

REFERENCES

1. L. D. Six, et. al., Concept Definition Study of Small Brayton Cycle Engines for Dispersed Solar Electric Power Systems, NASA CR 159592, (January 1980.)

THE UNITED STIRLING P40 ENGINE FOR SOLAR DISH CONCENTRATOR APPLICATION

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ABSTRACT

The United Stirling P40 engine is a key component in a solar concentrator based energy conversion system, to be demonstrated and tested during 1980-81. This paper reviews the inherent characteristics of modern Stirling engines and focuses on the baseline P40 double-acting engine. This four cylinder engine is the result of extensive component development work at United Stirling in Sweden, and is also playing key roles in other application programs, notably the DOE/NASA Automotive Stirling Engine program. The extent of modifications required for the solar application is reviewed and performance data are predicted. Finally, the potential of an advanced solar Stirling engine is briefly dealt with.

INTRODUCTION

Stirling engines distinguish themselves from most other heat engines by utilizing external heat supply to an internal, closed cycle with gas -- normally helium or hydrogen -- as the working medium. The external heat supply concept and the inherent high thermal efficiency of Stirling engines, facilitating a smaller and thus less expensive concentrator, make them a prime candidate for integration into solar thermal electric power systems.

United Stirling is involved as a contracting partner in the JPL Dish Stirling Solar Receiver technology demonstration project. The objective of that project is to demonstrate, at the JPL Edwards Test Station, a first generation prototype system within one year. The United Stirling contribution to this early demonstration will be to provide a modified version of an existing prototype double-acting Stirling engine. The focus of this paper will be on presenting the P40 engine background and experience.

P 40 Stirling engine

Alternator   Receiver / burner
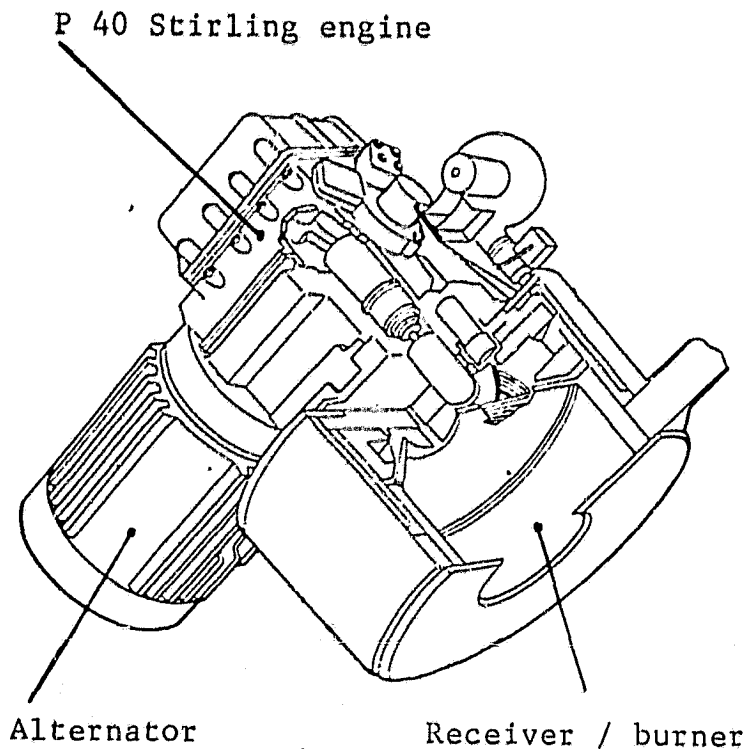
Figure 1.   The JPL energy conversion module, to
be tested at Edwards.

THE DISH-STIRLING-ALTERNATOR SYSTEM

The concept selected for the Edwards demonstration project
is based on utilizing a JPL test bed parabolic concentrator in
conjunction with an energy conversion system as shown in Fig-
ure 1. A solar receiver and gas combustor unit, to be supplied
by the Fairchild Stratos Division, will provide for heat supply
to the P40 engine in a hybrid mode, allowing the system to be
operated with a constant power output. The P40 engine inter-
faces with a General Electric induction type alternator, that
will deliver 60 Hz, 230/460 volt output to the grid.

The P40 engine was selected for this project primarily be-
cause it is a readily available and well proven prototype engine
that has a near-term potential for production and that requires
only limited modifications for integration into the JPL system.
The basic needs for modifications comprise:

-- provision of dry sump lubrication system to allow the
   engine to be operated in an inverted position;

-- adaptation of the cooling system to the test site external facilities;

-- provision of interfaces with concentrator, receiver, alternator and system controls.

THE BASELINE P40 ENGINE

United Stirling (Sweden) is a research and development company that was established in 1968 for the sole purpose of developing Stirling cycle engines, and to realize their potential as reliable, economical, energy efficient and environmentally acceptable means of energy conversion. The corporate objective is commercial production of Stirling engines.

Early experience at United Stirling included development of a four cylinder, single-acting, rhombic drive type of engine. It turned out, however, that this type of engine was too heavy and complex for most of its intended applications. Subsequently, basically all efforts at United Stirling has been concentrated on development of double-acting engines. This category of Stirling machines have only one piston per cylinder which reduces bulk, weight and number of parts without sacrifice in performance. After a thorough analysis of alternative configurations, a decision was made, four years ago, to concentrate the development on a U-configuration engine, employing parallell cylinders and twin, interconnected crankshafts. The U-configuration represents several advantages, affecting the overall cost and serviceability of the engine:

-- two crankshafts, geared to a common output shaft reduce installation height in a vehicle;

-- parallell cylinders facilitate the machining of cylinder faces in one horizontal set of operations;

-- the parallell cylinders and their straight-forward interfaces with the heater head component, makes inspection and servicing of reciprocating parts easy;

-- a symmetrical arrangement of key components of the hot part of the engine is facilitated by the parallell cylinders and results in improved fluid dynamic conditions.

In its baseline form, and with state-of-the-art gas mean pressure and temperature, the maximum shaft power of the P40 engine is 40 kW at 4000 rpm. The peak point efficiency (measured) is 32%. Both these data refer to hydrogen as the working

medium and with automotive type auxiliaries driven.
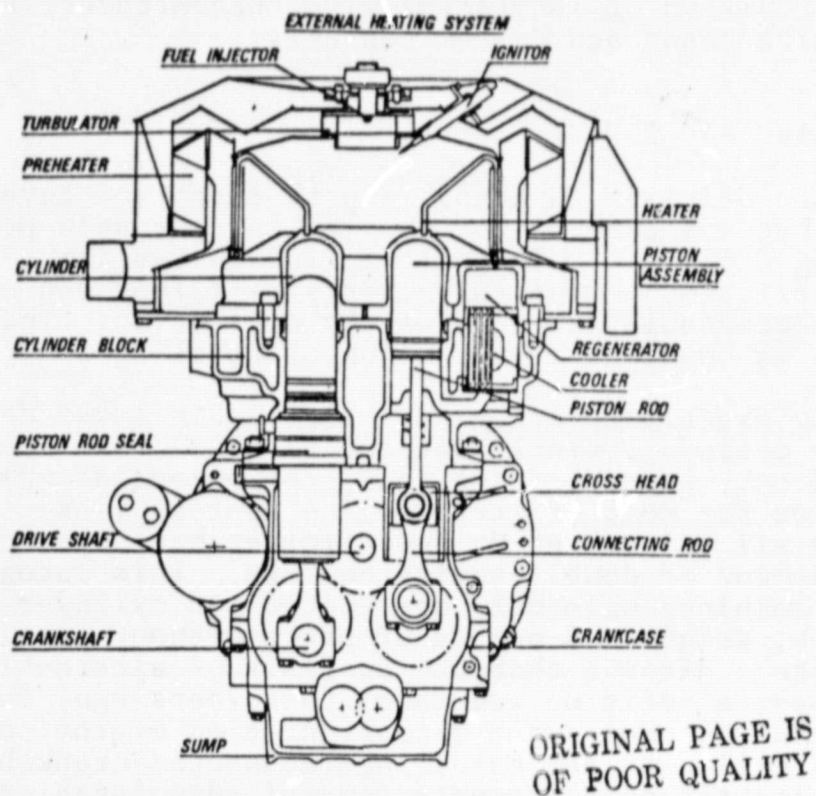
Figure 2. Cross-section of United Stirling's
baseline P40 engine.

A cross-section of the baseline, external combustion type
P40 engine is shown in Figure 2. In this case, heat is sup-
plied to the closed cycle from continuous combustion of a li-
quid or gaseous fuel via the engine heater head, which is a
tube-type heat exchanger. Air is being preheated to some
700°C in a metal plate recuperator.

Several conceptual and design features give the P40 engine
a potential for a very long time between overhauls. Such unique
features are for instance:

-- inherent low vibration level;

-- absence of a valve gear;

-- insignificant deterioration of lubricant due to low
   temperature and separation of combustion products from
   the oil.

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P40 engines have been subject to extensive tests for about three years, by now. Predominantly, these engines have been used for successive refinement of key components and subsystems like heater heads, piston rod seals, power controls and low emission combustors. More than 5,000 engine hours have been accumulated on the dynamometer so far. Additionally, about 150,000 hours of separate component testing contribute to making the P40 engine a well proven and reliable prototype that is now rapidly approaching the point where extensive field tests is the next logical phase.

The P40 engine is playing a key role as a baseline engine in the DOE/NASA Automotive Stirling Engine (ASE) program. Six P40 engines are hitherto planned for test cell and vehicle evaluation within the ASE program, and an additional twelve P40 engine derivatives will be forth coming in that program. Another current role of a P40 engine is to form the basis for an underwater propulsion system using liquid oxygen combustion of diesel fuel.

PREDICTED PERFORMANCE IN THE DISH SOLAR SYSTEM

Experience from testing baseline P40 engines show an unusually good correlation between calculated and measured performance. Based on that experience, and on recer er inner wall temperatures given below, the following engine performance at 1800 rpm is predicted:

	700°C		800°C	
	He	H_2	He	H_2
Max. power, kW	22.5	24.5	26.0	27.0
Max. efficiency, %	35	37	39	40

POTENTIAL OF AN ADVANCED SOLAR STIRLING ENGINE

Although only few modifications are planned for this first solar power demonstration, performance is predicted to be already competive. The solar application, however, introduces some new operating parameters and system requirements for the P40 operation and time between overhaul, for instance, justifies further development work aiming at prolonging the life of certain components, notably the piston rings and the piston rod seals. The introduction of a ceramic receiver/heater head -- although not regarded as essential for achieving competive performance -- has the potential of substantially reducing the life cycle cost of the engine.

Thus, based on a relatively low-risk development program, an engine time between major overhauls of 30,000 hours seems achievable as a result of a modest advancement program.

SESSION IV
HARDWARE TEST AND EVALUATION

JPL'S PARABOLIC DISH TEST SITE*

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ABSTRACT

A Parabolic Dish Test Site (PDTS) has been established at the Jet Propulsion Laboratory (JPL) California Institute of Technology's Edwards Test Station (ETS) in the California Mojave Desert to carry out Department of Energy (DOE) sponsored work in testing solar point focusing concentrator systems and related hardware. The site was chosen because of its high solar insolation level and year around clear sky conditions. A description of the Parabolic Dish Test Site objectives and capabilities is contained herein. Also described are the various facilities and equipment at the PDTS, and the concentrator experiments being performed.

INTRODUCTION

The PDTS is located approximately seventy airline miles north of Los Angeles, in the California high desert (elevation of 2300 feet) with an average rainfall of four inches per year. The site occupies approximately ten acres of the 600 acre Edwards Test Station. Ample adjoining acreage has been set aside for future growth. The primary purpose of the PDTS is to provide a site for the testing and evaluation of:

1. Concentrator-receiver-power conversion systems
2. Concentrators
3. High flux density receivers
4. Thermal transport
5. Power conversion systems
6. Hybrid systems using point focusing solar concentrators and fossil fuels

OBJECTIVES

The objectives of this task are threefold. First, the PDTS will be utilized to support solar thermal development activities, primarily to test and evaluate DOE developed hardware. Second, acceptance testing of prototype solar thermal power systems will be accomplished at the PDTS before committing to fullscale production. Third, test and evaluation of industry developed point-focusing systems will be accomplished at the PDTS as time and funding permit and feedback will be provided to industry on the integrity of these systems.

CAPABILITIES

The JPL ETS was selected as a prime location to perform testing and evaluation of Point-Focusing Distributed Receivers, at the subsystem and system level, at temperatures between 600 F and 3,000 F for the following reasons:

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* Sponsored by DOE through an agreement with NASA

1. ETS based personnel have a large amount of experience in working with high temperature, high pressure fluids, since ETS is JPL's rocket engine test facility. This experience is directly applicable to thermal power system (TPS) projects.
2. A high insolation level exists at ETS which is considered one of the best in the United States.
3. Excellent meteorological conditions exist at ETS - thus minimal down time because of bad weather.
4. Supporting services include: instrumentation and calibration laboratories; electric, machine, and weld shops with personnel; office space; and a cafeteria.
5. All required utilities are readily available.
6. Security as well as easy access for visitors is provided at all times.
7. An Emergency Rescue Crew and Vehicle is available to provide emergency medical treatment at ETS.

SAFETY

Safety is a first order consideration at the PDTS. As testing progressed from Precursor Concentrator to the Test Bed Concentrator test phase, the safety aspects for the PDTS became more involved. Initially, fairly simple safety requirements were needed, but as solar flux densities increased, stricter safety requirements were required. The key point of the PDTS safety practices are:

1. Written test procedures are required prior to the start of any testing activity.
2. Safe operating limits of critical parameters (temperature, pressure, etc.) are remotely monitored during subsystem and system testing, and displayed in the Control Room. Upper and Lower limits are predetermined and set into the Data Logger so that an alarm will alert the operator in the control room.
3. An emergency override procedure is implemented should a safe operating limit be exceeded or anticipated.
4. Safety glasses (gas welding goggles) and hard hats are required for operating personnel in the test area during "on sun" operation of solar concentrators.
5. Operating personnel are not permitted to work closer than two focal lengths from the concentrator while tracking the sun.
6. The "buddy system" is used by personnel in the test area during operation of the solar concentrators.

DATA ACQUISITION AND REDUCTION

To obtain the required data formatted for efficient analysis, during performance testing of the subsystem and system tests, a computer automated Data Gathering and Processing (DGAP) system was designed and implemented at the PDTS. DGAP equipment is required to periodically make parametric measurements, display the data in real time, monitor and record data on mass storage. The necessity of a computer processor system is dictated by the large volume of data to be processed, the need for real-time analysis of critical parameters, the requirement for graphical representation and off-line data analysis with higher mathematical functions, and the requirement for efficient system flexibility to support a wide range of testing. Operational experience to date has pointed up the value of real-time printout of data as well as real-time displays of critical parameters.

The computerized data acquisition system at the PDTS includes a Digital Equipment Corporation PDP 11/10 minicomputer with two RK05 disk drives, one half inch, nine track magnetic tape transport, high-speed multiplexers, A/D converters, three Acurex autodata nine data loggers, CRT terminals, alphanumeric and graphic video monitor, and a printer-plotter. The interface between the computer and its peripherals is provided by RS 232-C serial data lines.

Each of the three data loggers has the capability of accepting up to 1,000 channels of data. Input cards are provided for type "K" and "T" thermocouples, voltages up to 120V DC, 4-10 ma and 10-50 ma current transmitters and RTD's. Programming of the data loggers may be accomplished manually or by the computer. The data loggers scan up to 24 channels per second with resolution to 0.01 percent of full scale. Resolution to 0.001 percent is available at reduced scan rates. The high speed multiplexers and A/D converter can scan low levels (10mV-500mV full scale) at rates up to 200 channels or samples per second. A data logger with high common mode rejection is essential because signals being measured are in the millivolt range.

All data is stored on one half inch magnetic tape for retrieval. Final data reduction is performed at the JPL Pasadena facility using a Digital Equipment Corporation PDP 1134A computer. This Pasadena facility also develops the software used at the PDTS.

WEATHER STATION

Insolation measurements were begun in October 1977 at ETS, Building E-22. This facility is approximately 500 feet from the PDTS. The following measurements are being taken and recorded:

1. Direct component of radiation, using two pyrheliometers
2. Total sky radiation, using a pyranometer
3. Wind speed and direction
4. Temperature and dew point
5. Barometric pressure
6. Circumsolar telescope data

The pyrheliometers and the pyranometer, Kendall model Mark III and Kendall model Mark VII, respectively, were developed by JPL utilizing the absolute radiometer concept. These instruments have a range of 0 to well over 1000 watts/m^2.

The wind speed instrument, model 1022S, was manufactured by Meteorology Research, Incorporated. This instrument has a range of 0 to 75 MPH.

The wind direction instrument, model 1022D, was manufactured by Meteorology Research, Incorporated. This instrument has a range of 0 to 540°.

The ambient temperature and dew point measuring instruments are each designated as model 892-1, manufactured by Meteorology Research, Incorporated. These instruments each have a range of -30 to +50° C. Humidity is derived from these measurements.

The barometric pressure measuring instrument, model 751, was manufactured by Meteorology Research, Incorporated. This instrument has a range of 24.6 to 31.5 in Hg.

The circumsolar telescope was developed by Lawrence Berkeley Laboratory to obtain solar radiation measurements for accurate prediction of performance of solar thermal systems utilizing focusing collectors. The instrument measures the effects of atmospheric conditions on the direct and circumsolar components of solar flux. In operation the solar guider aligns the instrument platform at the center of the sun. The telescope body scans back and forth across the image of the sun and circumsolar region to an angle of $\pm$3 (the solar diameter is about 32 minutes of arc).

A small aperture located in the image plane restricts the angular view of the telescope to solar disc. The light passing through this aperture is chopped, filtered, detected, digitized and written on a magnetic tape as a function of the angular position.

Weather Station data is taken at 1 minute intervals, 24 hours a day. One month's worth of data can be acquired on a single reel of magnetic tape. A small uninterruptible power system is included to prevent data drop-outs during commercial power outages.

CONCENTRATORS

Concentrators constructed at the PDTS for the Point-Focusing Distributed Receiver Technology (PFDRT) Project are described briefly below.

Precursor Concentrator

The precursor concentrator consists of a backing structure simulating a portion of a parabolic concentrator together with an hour angle declination mount. Six mirror facets, (24" x 28") such as used on the Test Bed Concentrator, are mounted on the structure. The Precursor was used primarily as a tool to measure mirror performance and to evaluate alignment techniques.

Omnium-G Module

An Omnium-G (Heliodyne Model MTC-25) solar powered electric generating plant, an early product of industry, was purchased from the Omnium-G Company and installed at the PDTS. The Omnium-G characteristics are as follows:

CONCENTRATOR

6 meter diameter (19.7')
18 petals (mirrors)
25.9 square meter useable reflective area
Electro polished aluminum mirror surface;
Trade name is ALZAC, made by ALCOA
Reflectivity is 81-85%
4 meter focal length (13.1')

TRACKER

2 axes sun tracker
1.9° /sec. slew rate (down to up)
    at 24 volts

0.45°/sec. slew rate in azimuth
    at 24 volts

Test Bed Concentrator (TBC)

Two eleven meter parabolic TBCs supplied by E-Systems, Incorporated, Dallas, Texas, are installed at the PDTS. The mirror facets, based on a JPL development effort, for these TBC's are made by bonding a second surface mirror to a spherically contoured block of Foamglas (Pittsburgh Corning Corporation) and coating the substrate with a protective sealer and painting it white. Supports for the facets are bonded to the edges. The TBC characteristics are as follows:

NOMINAL 11M DIA REFLECTOR
70 kWth @ 800 W/M^2 INSOLATION
228 FACETS
    - 2ND SURFACE SILVERED GLASS
    - 24" x 28" NOMINAL SIZE
    - 3 REGIONS OF NOMINALLY DIFFERENT RADII OF CURVATURE
      520", 620", 634"
    - INITIAL REFLECTIVITY 95% MAX
    - SLOPE ERROR 1 MR
6.6 M FOCAL LENGTH
PARABOLOIDAL MOUNTING STRUCTURE f/d = 0.6
DESIGN WT AT FOCUS = 1100#

(STUDYING CONSTRAINTS ON OPERATION TO
 ACCEPT 3000°)
TRACKING ERROR 1 MR
SLEW RATES
    - AZIMUTH 2,000° /Hr.
    - ELEVATION 200° /Hr.
8" DIAMETER CONCENTRATED BEAM
1,000 W/CM^2 peak flux
3,600° K PEAK EQUILIBRIUM TEMPERATURE

EXPERIMENTS AND EXPERIMENTATION EQUIPMENT

Types of Tests

The test and evaluation phase of systems and subsystems at the PDTS includes, but is not limited to, the following tests:

TRACKER MECHANICAL CHECKOUT	FLUX MAPPER
CONCENTRATOR MECHANICAL CHECKOUT	COLD WATER CALORIMETER TESTS
MIRROR SEGMENT ALIGNMENT	RECEIVER THERMAL PERFORMANCE
SOLAR TRACKING ERROR	SYSTEM PROOF AND LEAK TEST
REFLECTIVITY (18 PANELS)	POWER CONVERSION PERFORMANCE
MOONLIGHT FOCAL POINT LOCATION	

A dish-Stirling solar experiment is being planned on one TBC to test the feasibility of the advanced receiver and Stirling engine-alternator subsystem designed by Fairchild Stratos Division of Fairchild Industries, Inc., and United Stirling of Sweden. When mounted on the TBC the test module will be capable of generating 20 kilowatts of electricity. Testing will begin in early 1981.

Test Equipment

Three different cold water calorimeters have been designed and built by JPL:

1. Coil tubing calorimeter
2. Flat plate calorimeter
3. Cavity calorimeter

The calorimeters are used to measure the integrated thermal flux at the concentrator's focal point. The coil tubing calorimeter used on the precursor concentrator is for thermal flux loads up to 2KWth. The flat plate calorimeter used on the Omnium-G is for thermal flux loads up to 25KWth. The Cavity calorimeter which will be used on the TBC's is for thermal flux loads up thru 95 KWth.

A flux mapper was fabricated for use in characterizing concentrator flux pattern and intensity. The flux mapper is a three-axis scan system for measurement of high radiant flux levels as might be expected near the focal plane of a high concentration ratio solar concentrator.

The flux mapper has three modes of operation: 1) pin diode relative, 2) cone radiometer relative, and 3) cone radiometer absolute. In the pin diode relative mode, a pin diode probe scans through the concentrated sun beam while a reference diode is pointed at the sun. The two readings are combined to arrive at a concentration ratio. Similarly, a cone radiometer probe can be used in conjunction with the reference diode for a concentration ratio. The cone radiometer probe may also be used alone to measure flux by calibrating the probe with a small eletrical resistive type heater which is built into the probe.

OMNIUM-G CONCENTRATOR TEST RESULTS*

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ABSTRACT

The Jet Propulsion Laboratory Solar Thermal Power Systems Project, Module Development, conducted a performance evaluation on a commercially available point-focus solar concentrator manufactured by the Omnium-G Company. Thermal power test results indicate that slightly more than six kilowatts of thermal energy is available from a system of this configuration using a 10 cm aperture under the conditions outlined in this paper.

INTRODUCTION

Preliminary results of evaluation testing conducted to determine the thermal performance of a Heliodyne[TM] model HTC-25s tracker/concentrator manufactured by the the Omnium-G Company of Anaheim, California are summarized in this paper. The concentrator is part of the OG-7500 module purchased by JPL in 1978.

This system consists of a two-axis, sun-tracking parabolic dish concentrator six meters in diameter with a four meter focal length. The dish structure has 18 pie-shaped elements, or petals, surfaced with anodized aluminum (Alzak [R]).

All tests were conducted with petals that were new, clean, and in an "as received" condition. Sun-tracking was done in the manual override mode, i.e., automatic sun-tracking was not employed. More detailed results of these tests will appear in an external report.

TESTING

The chronological order of the tests performed on the system is shown in Table 1. These thermal power tests are part of a more extended series.

A concentrator retrofit is indicated in Table 1. Within that time interval the Omnium-G Company recovered the original "A"-mold petals and replaced them with "C"-mold petals; only results for the latter are presented here.

The system checkout testing was conducted to determine an operational ready-state and to establish remote control capability of the system on the Parabolic Dish Test Site (PDTS) at the JPL Edwards Test Station.

Table 1. Chronological Order of Significant Tests
Performed on the Omnium-G System

12-21-78 System Checkout	04-12-79 Convertor (Cold)
01-27-79 Reflectivity Tests	04-20-79 Fluxmapper
02-06-79 Alignment	04-23-79 Concentrator Retrofit
02-06-79 Calorimeter	thru
02-22-79 Alignment	05-10-79
02-27-79 Calorimeter	05-15-79 Alignment
03-12-79 Moonlight Focal Plane Evaluation	05-25-79 Fluxmapper
Plane Evaluation	06-06-79 Calorimeter
03-13-79 "Stop Testing" Memo	06-22-79 Convertor (Cold)
	08-20-79 Convertor (Hot)

The concentrator is positioned in the azimuth and elevation axes by a null-seeking sun-tracker system consisting of a sun-sensor photocell box and tracker electronics module. The sun-sensor photocell determines the error and the tracker electronics module controls the tracker DC drive motors. The diagram shown in Figure 1 illustrates the concentrator with the convertor (receiver) mounted at the focal point. A hemispherical reflectivity test series was performed before the first set of concentrator petals was installed. In this test a light source was used to illuminate a small area of a concentrator petal and the reflected light intensity was measured. Twenty-two concentrator petals were measured at nine locations and the average reflectivity was eighty-four percent.

The concentrator petals were aligned at night to assure that all reflected images were superimposed at the focal plane. Three different alignment methods were used. Figure 2 illustrates the method used for the "C"-type petal concentrator installation. After positioning the concentrator toward the light source, an observer views the reflecting surface through the wire hoop eyepiece. Technicians then adjusted each individual petal manually until full illumination of the reflective surface was observed. The manufacturer selected the mirror elements for installation prior to delivery, and no further provision was made to refocus the petals after delivery to the test site.

Boresighting, the final alignment operation, requires the manual repositioning of the sun-sensor photocell box relative to the concentrator support structure. Repositioning assures that the aggregate group of solar images is centered on the receiver aperture. This operation, or its verification, must take place following each changeout of an experiment to compensate for mass changes at the focal-point end of the support structure.

EXPERIMENTAL APPARATUS AND METHODS

The thermal performance output of the concentrator was determined by three different tests. The flat-plate cold-water calorimeter, the fluxmapper, and the Omnium-G receiver were the devices used in testing. The flat-plate calorimeter and the fluxmapper yield data as a function of aperture diameter. There was special interest in the results of the 10 cm (4 inch) dimension because it was the cavity entrance diameter for the receiver supplied by Omnium-G.
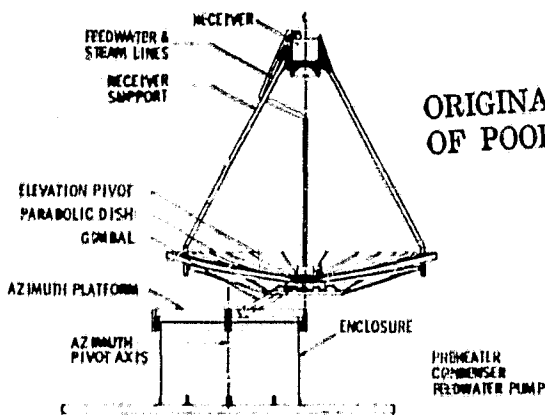
Figure 1. Omnium-G Heliodyne tracking concentrator/collector
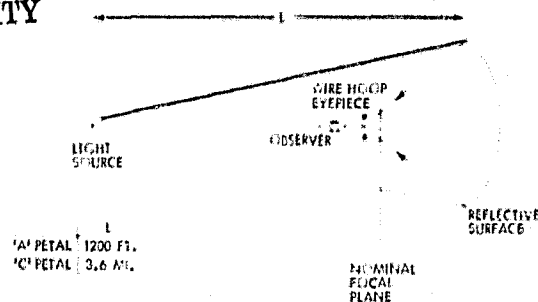
Figure 2. Nighttime alignment technique

The flat-plate calorimeter was fabricated from two 36 cm by 36 cm square copper plates. The plates were furnace-brazed together after cooling water passages were machined into one of them. These parallel passages were connected to inlet and outlet passages forming manifolds. The calorimeter was designed to permit a low water temperature rise and a hot-side surface temperature of less than 38°C. The front surface of the calorimeter was painted with 3M Velvet Black spray paint providing a 0.97 solar absorptivity.

The water temperature rise across the calorimeter was controlled in the range 3°C to 6°C by adjusting flow rate. If the temperature rise is too low there will be a high degree of uncertainty in the measurement results and if the temperature rise is too high it will cause an excessive calorimeter operating temperature.

The calorimeter water flow rate was measured using a turbine- type flow meter. The absolute inlet temperature of the feed water was measured with a thermocouple probe near the flow meter. The rise in water temperature was measured with thermocouples arranged in series (a thermopile) so that a larger output voltage for the small temperature difference could be measured. Nominal water flow rate was 38 liter/min.

The calorimeter was mounted approximately 10 cm behind the focal plane location supplied by the Omnium-G Company. Separate aperture plates (with various size apertures) were mounted at the focal plane. These plates were fabricated from 1.9 cm-thick sheets of transite (asbestos), and had a lifetime of about two hours, sufficient to acquire test information. Aperture size (diameter) was varied in the range of approximately 8 to 18 cm.

Initial calorimetric data indicated that a problem existed in the original concentrator petals. As a result of this data, the concentrator system was realigned so that thermal performance could be improved. Some improvement was noted but further information was required to evaluate the optical image near the focal plane.

Visual evaluation of focal length and focusing quality of each concentrator petal was accomplished by using the moon as a light source and viewing the reflected lunar image on a moveable target located at, and near, the focal plane. Representatives of Omnium-G Company were present for these tests and they determined that the concentrator petals were not properly focused individually or collectively. The recommendation of the manufacturer was to terminate the evaluation on the original "A" type petals and replace them with the "C" type. After the concentrator petals were replaced, the final alignment was performed by Omnium-G personnel.

The fluxmapper was then installed and the first thermal performance data obtained for the "C"-type concentrator assembly. The fluxmapper is a device that utilizes a water cooled probe that moves in an X-Y plane perpendicular to the focal axis, or Z-axis. Motion on the Z-axis, ahead and behind of the focal plane, facilitates a three-dimensional mapping of the vicinity of the focal plane. (See paper by W. Owen in these Proceedings.) Figure 3 illustrates the mounting of the open ring support structure and electronics package.
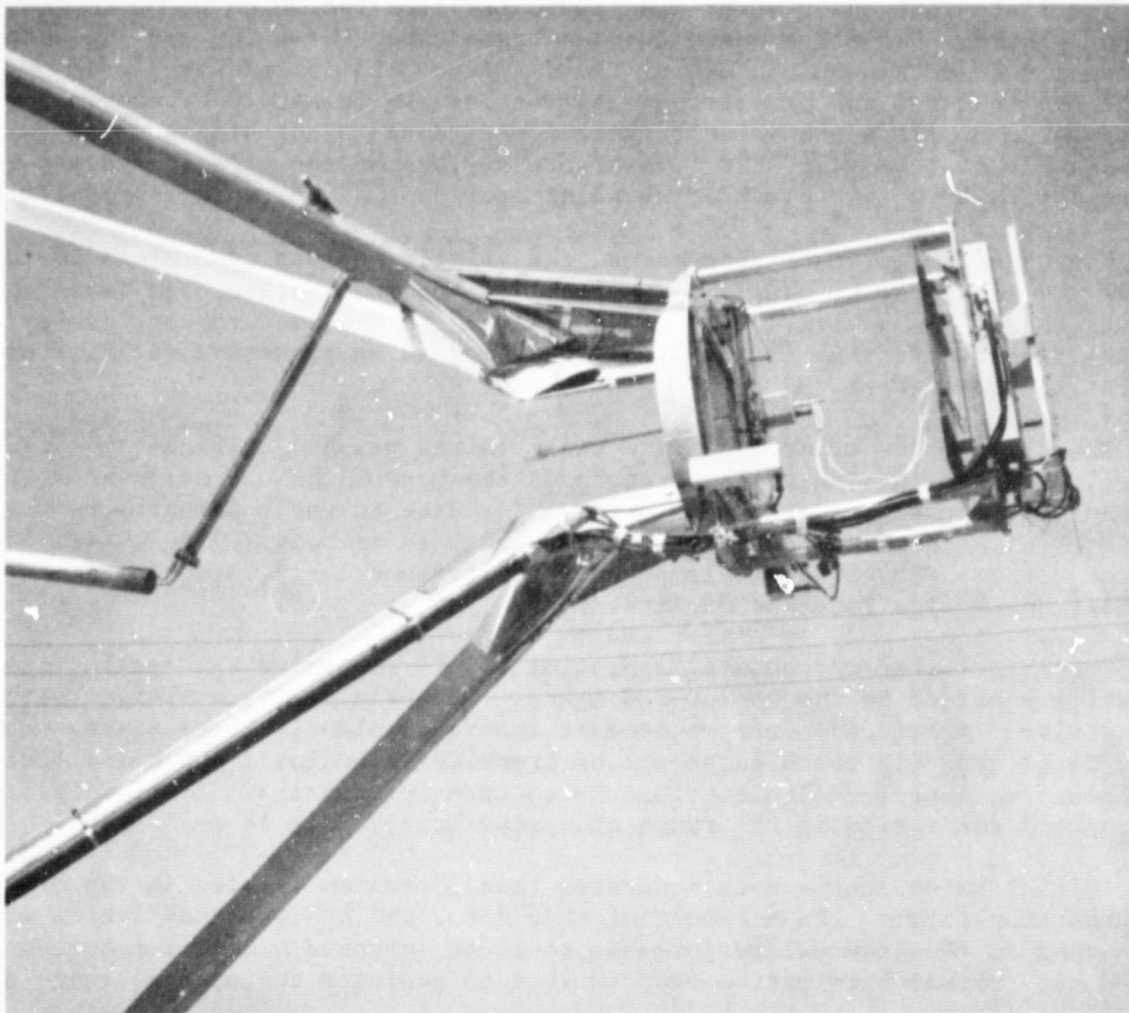
Figure 3. Fluxmapper mounted at the nominal focal plane

All controls for the fluxmapper were programmed into a microprocessor that was also used to gather, store, and process the data acquired by the probe. Output from the processor was displayed on an X-Y plotter or line printer for real-time evaluation of concentrator focal plane shape, and flux intensity.

The third device used to determine thermal performance of the concentrator was the convertor (receiver) manufactured by the Omnium-G Company. This receiver, an early design, incorporated a 10 cm diameter aperture and a steam coil buried in an aluminum block. Originally this aluminum was to have been heated to a molten state, but present design limits the aluminum mass temperature to 638°C (1180°F).

The receiver was tested at two temperature levels: 93°C (200°F), called a "cold" test, and at 204°C (400°F), called a "hot" test. In the first test series facility tap water was used and no steam was produced. The second series utilized the arrangement shown in Figure 4; sufficient back pressure was applied to maintain a saturated water condition at the receiver exit. Steam formed across the expansion valve was condensed and returned to the feedwater reservoir. During this test, the receiver outlet water temperature was maintained for an hour to allow the receiver to achieve thermal equilibrium.

TESTING CONDITIONS

The flatplate calorimeter data and the fluxmapper data were obtained with new, clean petals. Some of the receiver data were obtained with petals that were dirty. In all cases, a manual override tracking mode was employed to assure a continuous on-sun condition, and automatic tracking was not utilized because of occasional tracker drift.

Data was recovered continuously for each test run but only data taken at insolation levels greater than 800 W/M^2 was analyzed. All data was normalized to a solar insolation value of 1000 W/M^2. Solar insolation data was acquired by using three Kendell Mark III, and one Eppley, Pyroheliometers. Wind speed and direction also were recorded.

Omnium-G personnel were invited and encouraged to observe all tests at the PDTS. In addition, JPL furnished the Omnium-G Company with various test data and other results.

THERMAL PERFORMANCE TEST RESULTS

A typical flux contour plot obtained for the "C"-type petals is shown in Figure 5. Superimposed is a hypothetical aperture diameter of 10 cm (4 inches). The peak flux near the center of 700 W/in^2 corresponds approximately to 110 W/cm^2. Fluxmapper data corresponding to various aperture sizes as well as flatplate, coldwater calorimeter data is shown in Figure 6.

Flatplate and coldwater calorimeter data had an uncertainty of ±400 watts, which is indicated by bound-bars in Figure 6. Agreement between fluxmapper data and calorimetric data is excellent.
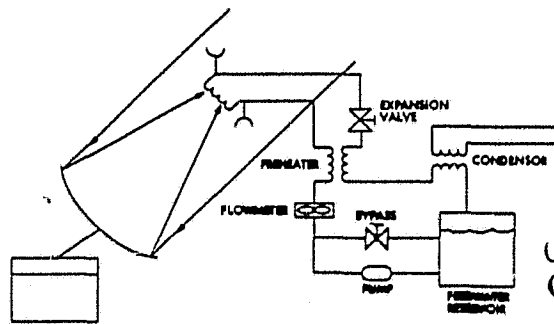
Figure 4.   Receiver Thermal Performance
            Test Schematic Diagram
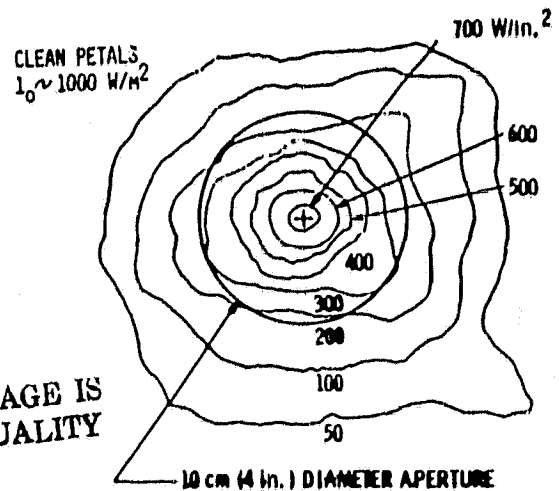
Figure 5.   Typical flux map at
            the focal plane

"Cold" and "hot" receiver test data are shown in Figure 7 relative to the previous data, which is represented in Figure 7 by the cross-hatched region. Of course, the receiver test results apply only for a 10 cm aperture. The cold receiver test data agrees well with the previous data.

For the cold receiver tests, the receiver outlet temperature was maintained at less than 93°C (200°F) to prevent two-phase flow. A comparison series of tests was performed during the cold water receiver series to determine the effect of dirt and dust accumulation on the concentrator. A 16% improvement in thermal performance was obtained following a mirror cleaning operation recommended by Omnium-G.

The data plotted for the hot receiver test series was obtained while the petals were dirty, but assuming the same 16% improvement could be achieved, thermal performance very close to the calorimetric, fluxmapper, and cold convertor data might be expected. However, the difference in the cold and hot
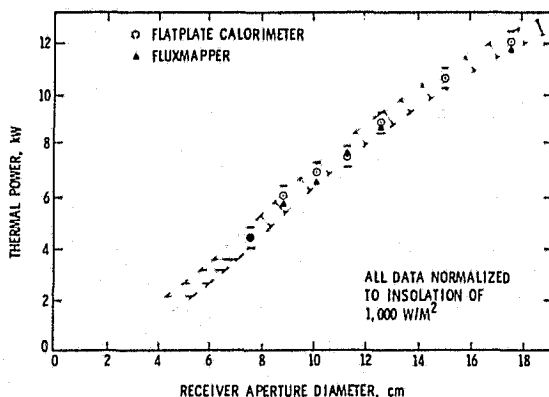
Figure 6.   Preliminary thermal power
            test results
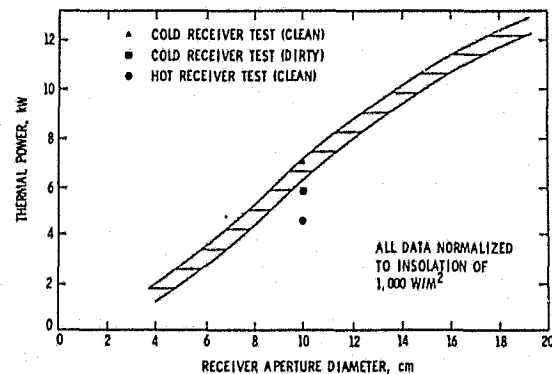
Figure 7.   Receiver (converter)
            test results

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receiver data (Figure 7, dirty petals) cannot be explained solely on the basis of differences in thermal reradiation.

Uncertainty in data, including the statistical variation of calorimetric data of +400 watts (approximately 6% of the energy through a 10 cm diameter aperture), has been estimated. Thermal reradiation received by the flatplate calorimeter from the heated aperture plates was estimated to be about 420 watts for an aperture plate temperature of 325°C. This effect, now being investigated experimentally, is expected to decrease with increasing aperture size. Estimates of thermal losses from forced convection, due to winds of the magnitude seen during test data acquisition (20 mph), indicate about 1 to 2% wind effect.

CONCLUSIONS

Thermal power test results on an Omnium-G tracking concentrator, purchased by JPL in the fall of 1978, have been presented. This includes coldwater calorimeter and fluxmapper data, and some preliminary data using the early Omnium-G receiver design. The measured thermal power was in the range 6 to 7 thermal kilowatts for new, clean petals, and a 10 cm aperture. Design changes to increase the receiver aperture diameter to 20 cm have been completed by the Omnium-G Company in accordance with their continuing development program. A new receiver design has been delivered to JPL and plans are to test it by the summer of 1980.

ACKNOWLEDGEMENTS

THE JPL FLUX MAPPER*

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Pasadena, California

ABSTRACT

The JPL Flux Mapper is a device that can map the intensity distribution in three dimensions of concentrated solar energy at the focus of a concentrator. Intensities to 10,000 solar constants can be measured. Constructed to assist in concentrator and receiver development, it consists of a radiometer which is moved through the concentrated sunlight in a series of planes perpendicular to the optical axis by means of a mechanical rastering device. Various radiometer probes can be utilized depending on the time and accuracy requirements of the program. Energy levels are recorded as a function of location. Reduction of this data can be in various formats, e.g., contour maps, digital arrays, isometric visualizations and other displays as the user requires.

THE FLUX MAPPER

Purpose

While optical theory is quite exact, real optical systems have many non-idealities that make their precise performance difficult to predict. This proves to be particularly evident where very large solar energy collection systems are designed to be produced at low cost. To help overcome this difficulty, JPL has designed and built a Flux Mapper to gather empirical data about the concentrated energy at the focal zone of a solar concentrator. This data is essential to understanding optimum solar receiver design, helps characterize solar concentrators, provides a means for comparing analysis with actual hardware, and provides a tool for comparing various systems in the field.

System

The principal components of the Flux Mapper system (Figure 1) are a radiometer probe, a mechanical locating device, a data and control processor, and a data acquisition system.

Probes

Two radiometer probes are currently in use at JPL. The high speed probe (Figure 2) consists of a highly reflective, water cooled body and heat shield. A 0.006 inch diameter aperture limits the amount of energy falling on the PIN diode detector whose voltage output provides a signal proportional to the incoming energy. This system has an extremely short time constant

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(nanoseconds) and when carefully calibrated can provide data with about ± 10%
accuracy. The second probe (Figure 3) is a Kendall absolute cavity
radiometer. This probe is a ruggedized version of the absolute standard
laboratory instrument. Where the longer time constant of 4 to 6 seconds can
be tolerated, this instrument can provide accuracies of less than ± 2%.

Mechanism

The traversing mechanism (Figure 4) consists of a mounting frame from which
the probe mounting carriage travels in an x-y plane. This carriage contains a
stepping motor which allows the probe to be indexed in the z direction.
Normal scanning sequence is horizontally (x) from the lower left corner,
stepping upward (y) at the end of each line until an entire x-y plane is
measured. The probe then moves to a new plane (z) and the x-y process is
repeated. Scanning rates are variable but a typical 1250 data point plane
takes about 90 seconds to scan.

Data Acquisition

Data is acquired simultaneously in both a hard copy "quick look" mode and on
magnetic tape. For "quick look" needs, an x-y-y plotter is utilized giving an
intensity trace as a function of position with system parameters displayed or
printed from the CRT. This same data can also be stored on magnetic tape for
later computer reduction.

Data Reduction

Data display can be either full digital, semi-reduced digital (Figure 5) for
rapid utilization or in a variety of graphical displays such as contour plots
of each plane (Figure 6) or isometric displays for visual examination
(Figure 7).
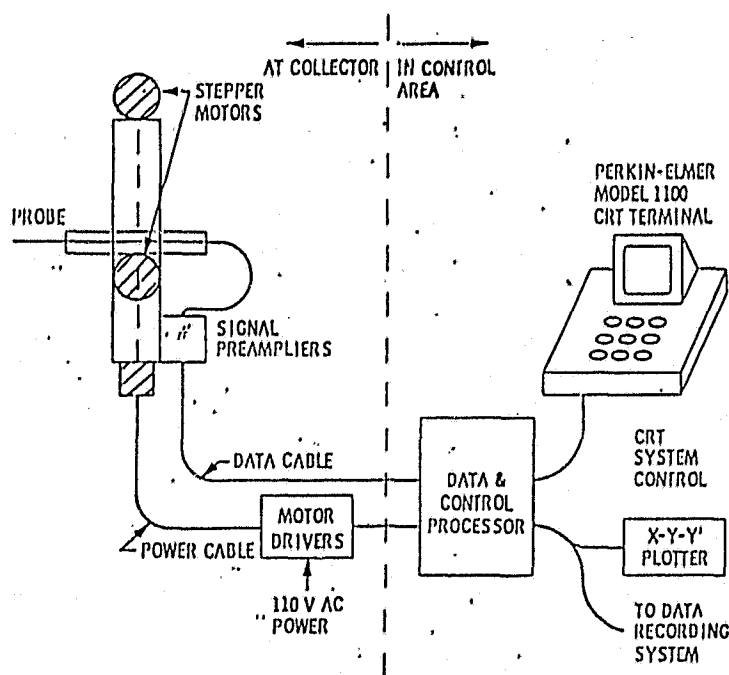
FIGURE 1.   FLUX MAPPER LAYOUT

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HIGH INTENSITY SENSOR
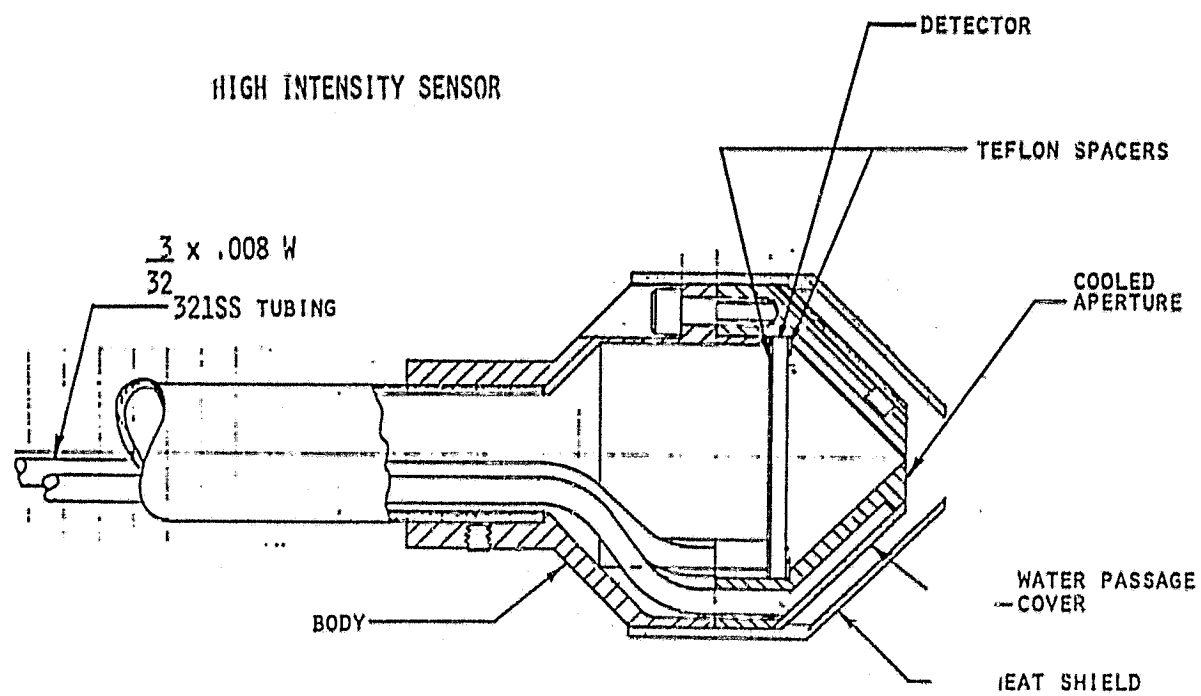
FIGURE 2.   HIGH INTENSITY PIN SENSOR
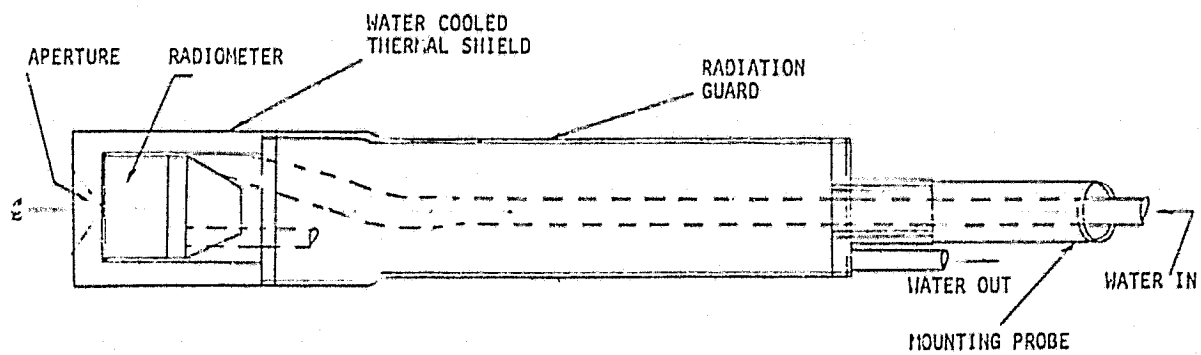
FIGURE 3.   ABSOLUTE CAVITY RADIOMETER

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FIGURE 4. FLUX MAPPER MECHANISM

	1	2	3	4	5	6	7
1	1	3	10	16	15	9	1
2	5	13	19	60	63	39	17
3	9	29	73	169	180	85	36
4	7	37	139	320	275	102	29
5	3	28	106	218	174	93	36
6	2	12	38	57	58	45	15
7	0	0	2	4	6	6	1

$$\frac{Watts}{in^2}$$

2"

2"

TOTAL =   10,660 Watts
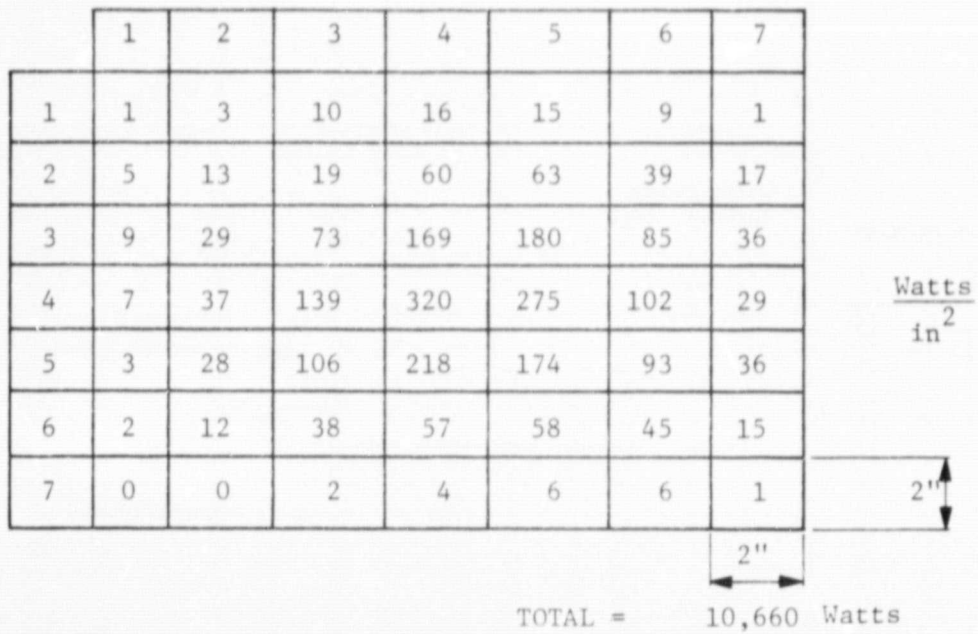
FIGURE 5.   MATRIX DATA DISPLAY

136
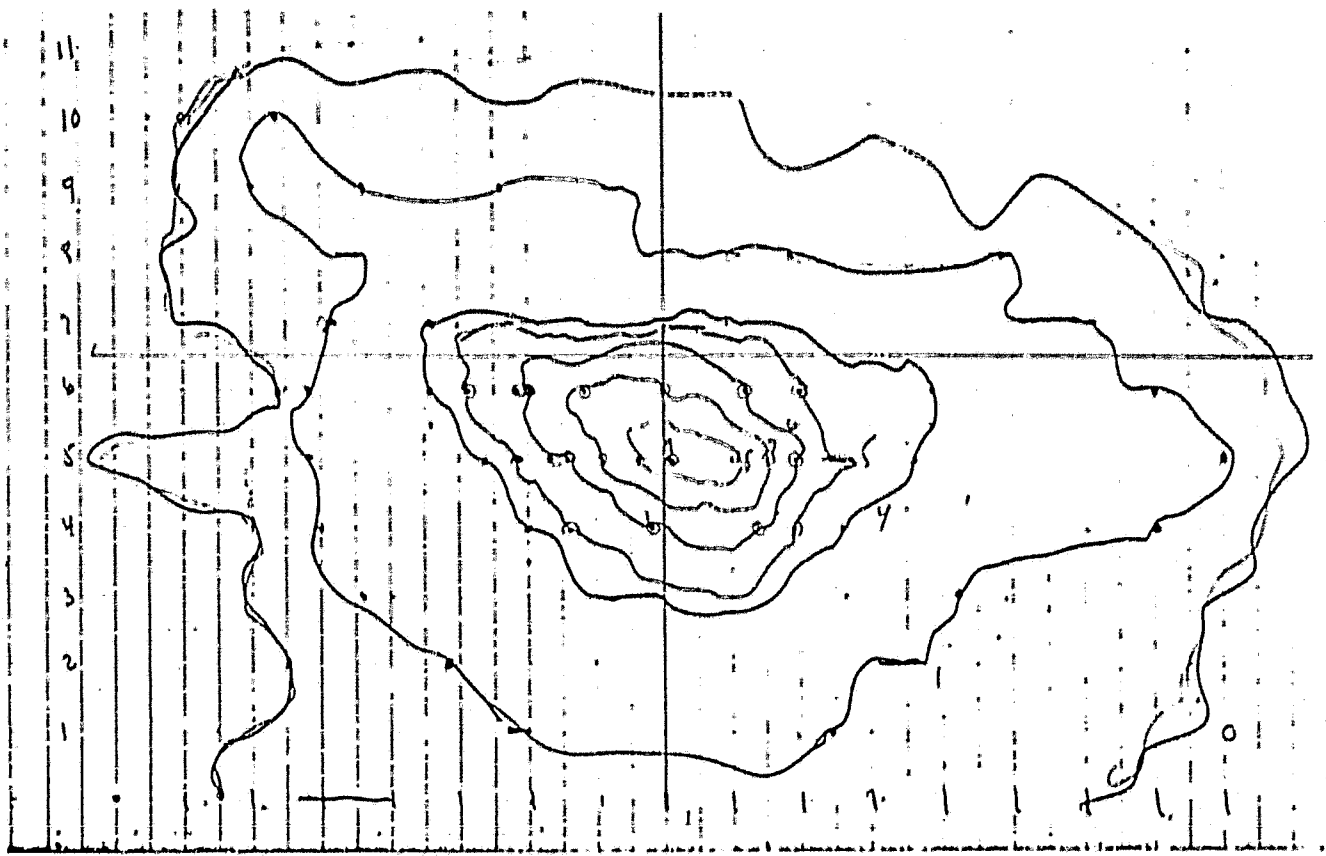
FIGURE 6.   CONTOUR PLOT DISPLAY

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☐ 0.6   BTU/sec. in^2
▧ 0.4
⬚ 0.25
▨ 0.1

⊢─┘◄─1 INCH
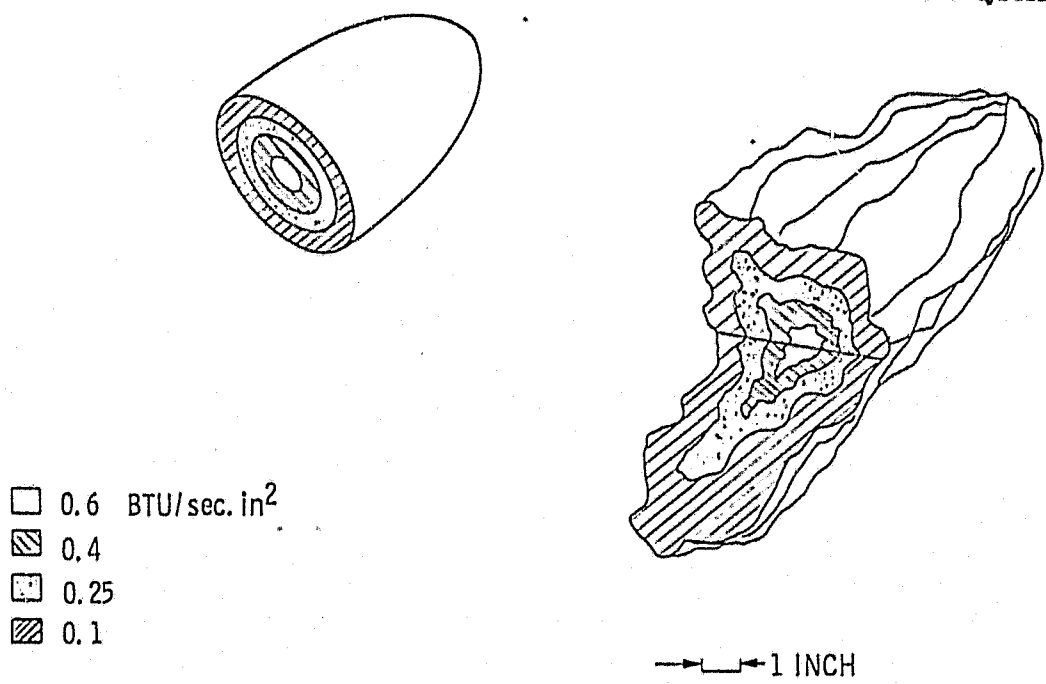
FIGURE 7.   ISOMETRIC DATA DISPLAY

SESSION V
MASS PRODUCTION COSTING

COSTING THE OMNIUM-G SYSTEM 7500

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Abstract

A complete Omnium-G System 7500 was cost analyzed for annual production quantities ranging from 25 to 100,000 units per year. Parts and components were subjected to in-depth scrutiny to determine optimum manufacturing processes, coupled with make or buy decisions on materials and small parts. When production quantities increase -- both labor and material costs reduce substantially. A redesign of the system that was analyzed could result in lower costs when annual production runs approach 100,000 units/year.

Objective/Purpose

The principal objective of this study was to determine the production cost of the complete Omnium-G System 7500 solar collector for various annual production volumes of 25, 100, 25,000 and 100,000. The purpose of this study by JPL was to establish a "baseline" to which other designs of point focusing distributed receiver components, subsystems and systems could be compared for cost and performance.

Introduction

The Omnium-G System 7500 Parabolic Concentrator (Figure I) is a parabolic dish, six meters in diameter, composed of 18 reflector petal segments. This assembly is articulated in both elevation and azimuth, thus enabling it to track the sun from horizon to horizon. The reflector segments are fabricated from electrochemically polished (Alzak) aluminum which is bonded to a polyurethane substrate.

The concentrator focuses the rays of the sun onto a receiver that is 3.9 meters in front of the mirror center. This receiver acts as a heat exchanger, boiling water which is contained in a helical tube and thereby producing steam. The steam in turn powers a steam engine which turns a generator producing electricy.

This study estimated the cost of direct labor and material which results in a cost number. No attempt was made to estimate the selling price of the system or its components.

No capital equipment costs were considered. A figure of $10.00/hr was applied for direct labor.

OMNIUM-G SYSTEM-7500

FIGURE NO. 1

ALTITUDE DRIVE

RECEIVER

RECEIVER STRUT

PETAL

AZIMUTH DRIVE (TROLLEY)

ENCLOSURE

CONCRETE CURB

BACKUP STRUCTURE

CANTILEVER SUPPORT

SKIRT

FOUNDATION ANCHOR

140
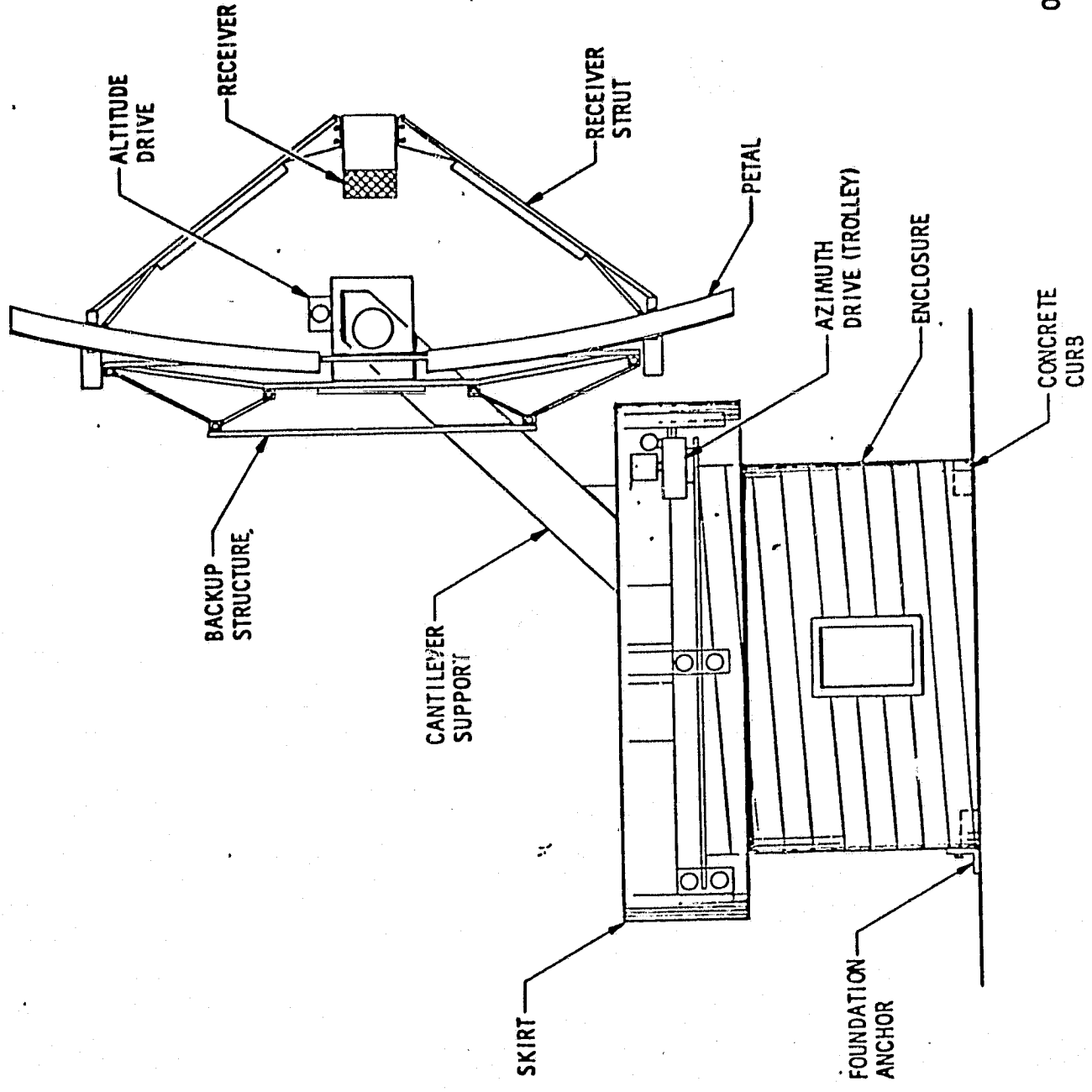
Methodology

Each part, component, assembly (major and minor) and the final assembly was examined and evaluated as to its material cost and method of manufacture based on the particular annual production volume under review.

The evaluation was performed primarily by carefully examining actual parts and the manufacturing procedures as performed at the Omnium-G facilities in Anaheim, California. The original evaluation was based on a production rate of less than fifty (50) units during the calendar year 1979.

For very low production volumes of 25 to 100 units per year the manufacturing costs of this Omnium-G 7500 System are extremely labor intensive and expensive. At the higher annual productionl volumes, the labor content is reduced with an increase in capital equipment.

The JPL cost analysis of the Omnium-G 7500 System required the preparation of the following:

a. Engineering parts lists
b. Detail drawings
c. Raw material costs
d. Part manufacturing process
e. Labor hours to produce each part estimate
f. Assembly labor hours estimate

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It was assumed that for small production runs of 25 to 100 units per year, most of the items would be purchased and assembled in an in-house facility. However, it is important to note that the steam engine is presently being made by Omnium-G in their own facility.

When production increases to 25,000/year, it was assumed that a make or buy decision would be made to obtain the lowest cost based on a tradeoff of capital investment versus direct labor cost. Again the assembly would be in-house. At this production level, a complete system must be produced every four (4) minutes with a single shift of 8 hours/day.

As production increases to 100,000/year, it was assumed that most items would be made in-house with an investment in the necessary tooling and capital equipment. Assembly would be in-house and would require a complete system every minute based on an eight hour working day.

Results

The cost estimates for the complete Omnium-G System 7500 are shown in Table 1. The table has complete costs for labor and material for each of the four annual production volumes studied. Figure 2 is a bar chart that graphically illustrates the System 7500 reduction in cost as the production volume increases.

As quantity production increases, both labor and material show significant cost reductions.

SUMMARY
PRODUCTION QUANTITIES AND COSTS PER UNIT

SUB-ASSEMBLY	25 UNITS		100 UNITS		25,000 UNITS		100,000 UNITS	
	MATL	LABOR	MATL	LABOR	MATL	LABOR	MATL	LABOR
Receiver Assembly	391.27	120.50	378.57	114.50	291.20	80.15	213.55	45.80
Backup Structure	476.57	171.10	379.17	162.50	270.63	113.80	155.56	65.00
Petal Assembly	3,066.84	78.00	2,877.63	75.00	2,100.60	30.00	1,540.29	13.40
Receiver Strut	169.24	17.90	166.00	17.00	126.46	12.00	93.08	6.80
Cantilever Support	842.78	151.60	743.98	144.00	565.24	100.80	420.38	57.60
Elevation Mechanism	601.37	44.70	586.14	42.50	451.03	29.75	330.35	17.00
Azimuth & Trolley Assy	746.18	93.20	642.96	88.50	494.69	62.00	362.70	35.40
Yoke Assembly	175.34	73.70	170.95	70.00	119.67	49.00	70.14	28.00
Base Assembly	336.61	82.60	326.29	78.50	252.46	55.00	198.89	31.40
Electrical	288.50	85.80	288.50	81.50	216.38	57.10	156.68	32.60
Foundation	550.05	766.20	550.05	727.85	385.04	673.25	220.02	545.89
Steam Engine	123.13	335.50	123.13	318.70	92.34	218.30	73.88	127.50
Condenser	41.85	23.00	41.95	21.80	31.39	15.26	25.11	8.70
Circulation	20.40	11.60	20.40	11.00	15.30	7.70	12.24	4.40
Flatwall	797.96	30.50	797.96	29.00	638.37	20.40	478.77	11.60
Power Cont	2,396.89	73.70	2,396.89	70.00	1,797.66	49.00	958.75	28.00
Transport	438.77	39.30	438.77	37.33	329.08	13.63	223.77	5.98
TOTALS	11,463.75	2,199.90	10,929.24	2,089.68	8,177.54	1,587.14	5,534.16	1,065.67
GRAND TOTALS (MATL + LABOR)	$13,663.65		$13,018.92		$9,764.68		$6,599.23	

TABLE 1

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OMNIUM-G SYSTEM 7500

COST AS A FUNCTION OF PRODUCTION VOLUME

25/YEAR — $13,663.65

100/YEAR — $13,018.92

25,000/YEAR — $9764.68

100,000/YEAR — $6599.23

FIGURE 2

The Omnium-G System 7500 that JPL evaluated was an existing design. No attempt was made to modify the design with an eye to reducing cost, however, significant cost reductions could possibly be obtained if the system were redesigned to take advantage of high volume manufacturing techniques.

ACKNOWLEDGEMENT

TBC COSTING

H. L. Kaminski, P. E.
Pioneer Engineering & Manufacturing Co.
Warren, Michigan

ABSTRACT

The primary task under this contract is to determine the cost of producing
and installing a Parabolic Dish Concentrator in annual production volumes of
10,000, 50,000, 100,000 and 1,000,000 units. Each individual part will be
evaluated for material cost, the type and number of operations required to work
the raw material into the finished part. Each operation will be costed for
labor, burden, tooling, gaging, machinery and equipment. Facilities require-
ments will be estimated for each production volume. Suggestions will be made
for design and material alterations that could result in cost reduction.

MANUFACTURING COST ANALYSIS METHODOLOGY

The cost estimating methodology consists of two primary phases, the "Cost
Procedure" and the "Fabrication Analysis", each of which is explained below.

Cost Procedure

This is the technique for handling the numbers in the estimating process.
The flow of pertinent cost factors is illustrated in Fig. 1. The management
of these factors is greatly assisted by an "Estimating Operation Sheet".

Estimating Operation Sheet

The vehicle for tabulating and processing the cost of each component is the
"Operation Estimating Sheet" (Fig. 2). Each element of the cost data is
shown on this sheet.

Operation Description

The first column is used to define the specific work to be done on each
component, operation by operation.

Type of Equipment

Here a general listing is made of the type of machine used to perform the work.

M/P

The third column heading is an abbreviation for "Manpower" meaning the number
of men required to perform the operation.

PCS/HR
MIN/PC

Here is listed the estimated work standard for the operation performed, the
floor to floor time factored by productivity. The pieces per hour is a function
of the standard time.

COST ANALYSIS FLOW

Variable
Burden

Variable
Cost

Direct
Material

Direct
Labor

Mfg.
Cost

Fixed
Cost

Indirect
Material

Indirect
Labor

Tooling
Cost

Machinery
Cost

Fixed Burden
Includes
Capital Equipment
and
Other Fixed Expenses

Facilities
Cost

Fig. 1

OPERATION DESCRIPTION	TYPE OF EQUIPMENT	M/P	PCS/HR. MINS.	LABOR COST / LABOR RATE	OCC HOURS	BURDEN RATE	BURDEN COST	VAR COST / MFG COST	DIE MODEL $(000)	TOOLING $(000)
						V				
						M				
						V				
						M				
						V				
						M				
						V				
						M				
						V				
						M				
						V				
						M				
						V				
						M				
						V				
						M				
						V				
						M				

TOTAL VAR LABOR & BURD
TOTAL MFG LABOR & BURD

MATERIAL
SCRAP
SET UP
OTHER
MARK UP %

TOTAL VAR. COST
TOTAL TRANS. COST

KEY ☐
NON KEY ☐
VOL. _____
UPC _____

PART NO

SKETCH – REMARKS

SHT | COIL | GAGE | QUAL | MAT'L | PCS | ROUGH WT

COST PER LB. _____   MAT'L. COST _____

PART NAME

Fig. (2)

Pioneer Engineering & Manufacturing (1-79)

Labor Cost
Labor Rates

Labor Rate, here in dollars per minute, is the wage paid to the operator for the skill classification and equipment represented. The Labor Cost is a product of minutes per piece and the labor rate.

OCC. HRS.

This is an abbreviation for "Occupied Hours". This represents the time during which a given piece of equipment is occupied to perform its function on the component under consideration. This may include the time during which the machine is being loaded and unloaded and is not itself working.

Burden Rate-V

This represents Variable Burden Rate and is given in dollars per hour for a specific operation and a specific machine. It represents the hourly cost of all expense directly associated with the production of the component being considered. If one unit of production is withdrawn this cost is eliminated for that unit. It is given in dollars per hour.

Burden Rate-M

This represents Manufacturing Burden Rate. It includes the variable rate plus indirect labor, indirect material, capital amortization, taxes, insurance and other fixed costs. It is given in dollars per hour.

Variable Cost

This is a product of the "Variable Burden Rate" and the "Occupied Hours".

Manufacturing Cost

This is a product of "Manufacturing Burden Rate" and "Occupied Hours".

Die Model

This is the estimated cost of models required for the production of forming dies.

Tooling Cost

This is the cost of tools required to perform the operation using the selected equipment.

Cost Per Lb.

This number is obtained from the material source; when volume justifies, directly from a mill.

Total Variable Labor & Burden/Mfg Labor & Burden

Each of these is the sum of these costs as they appear in the column above.

Material

This number is transferred from the left side of the sheet.

Scrap

This factor represents the scrap to be expected from the operations listed above, based on the material, the equipment, and the tolerances required.

Set-Up

This represents the cost per unit of product to set up the above listed equipment to perform the function for which it was installed.

Other

This is a catch-all line to be used for special costs not included in other areas.

Mark-Up

This line is used to include profit when the objective is to obtain a cost including this factor. This factor will vary with the industry and the product being evaluated.

Total Variable Cost

This is the sum of Variable Costs listed in the column above, including Material, Scrap. It does not include Set-Up, Other and Mark-up.

Total Transfer Cost

This is the sum of Manufacturing Costs listed in the column above, plus Material, Scrap, Set-Up, Other and Mark-Up.

Vol.

This is actually "Volume" and used to show the annual production for which the cost estimate is being produced.

"Key", "Non-Key", "UPC"

These items represent part identification characteristics peculiar to the automotive industry and are used only when such estimates are made.

Fabrication Analysis

The application of cost factors as illustrated in "Cost Procedure" above is

149

17"

7"

43.4#

2 ½"

64.7#

4.5#

28.8#

2 ¼"

1 ¼"
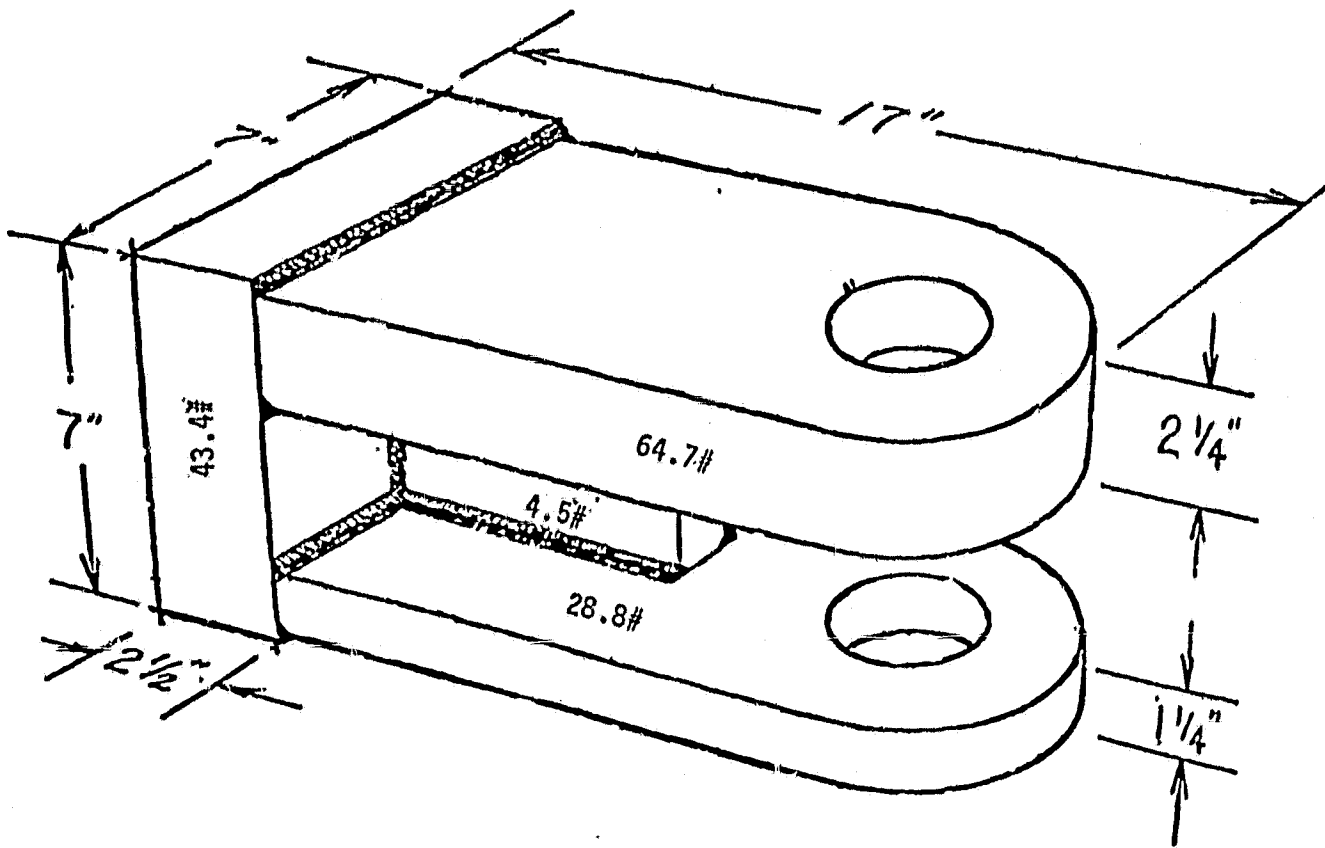
Total Weight 141 lbs.

Clevis-Weldment
Present Design

(Fig. 3)

150
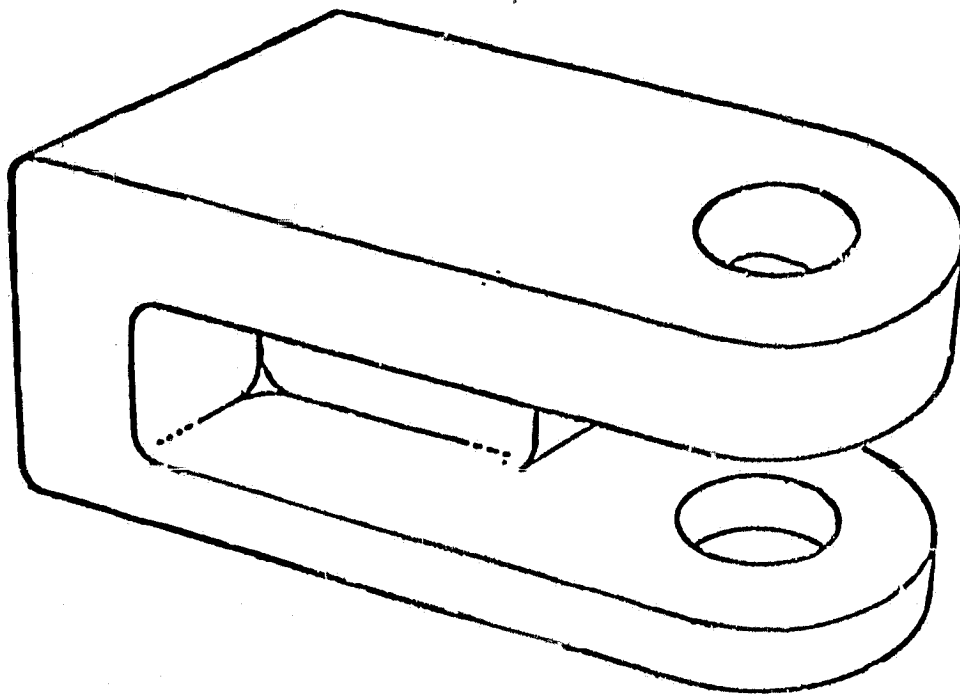
Clevis-Casting
Proposed Design

(Fig. 4)

essential in the derivation of product cost. However, the basis for product cost is the analysis of the part to be produced and the decision of how it will be produced; the kind and size of machinery, tooling and material handling equipment.

In the case of the Test Bed Concentrator, every piece in each of the 23 concentrator sub-assemblies must be analyzed for its production system for each of the four volumes under consideration. In all, some 12,864 items must be costed. For the purpose of this discussion we will illustrate one element of these sub-assemblies, the clevis (Fig. 3) used to join the parabolic dish to the alidade. There are two such clevises, one on each side of the dish at the 90° and 270° positions.

As shown in the sketch the clevis is a welded assembly of four parts, having a total weight of 141 pounds. It is part of a major sub-assembly consisting of 39 different parts. To produce this major sub-assembly it is necessary to divide it into minor sub-assemblies for the sake of handling and accessibility. The clevis is one such sub-assembly.

In low volumes the elements of the clevis are manually loaded into a fixture and hand welded. In high volume, the parts are manually loaded into a fixture and automatically welded. The fixture could be on a continuous line with automatic clamping. Automatic loading and unloading could be accomplished by evaluating the cost effectiveness of the design.

Each operation required to produce the clevis, by component part, is listed on the Estimating Operation Sheet, after which the cost procedure is used.

COST REDUCTION ANALYSIS

As an element of the costing contract, Pioneer is to make suggestions for the cost reduction of the production of the TBC. An illustration of such an idea can be made of the clevis (Fig. 4).

As a weldment of the clevis would require twelve distinct operations from raw stock to completed sub-assembly.

As a casting the clevis could be completed in as little as three operations, with its attendant reduction in manpower and equipment cost.

COST ESTIMATING BRAYTON AND STIRLING ENGINES

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Abstract

Brayton and Stirling engines were analyzed for cost and selling price for production quantities ranging from 1000 to 400,000 units per year. Parts and components were subjected to indepth scrutiny to determine optimum manufacturing processes coupled with make or buy decisions on materials and small parts. Tooling and capital equipment costs were estimated for each detail and/or assembly. For low annual production volumes, the Brayton engine appears to have a lower cost and selling price than the Stirling engine. As annual production quantities increase, the Stirling becomes a lower cost engine than the Brayton. Both engines could benefit -- cost wise -- if changes were made in materials, design and manufacturing process as annual production quantities increase.

Objective/Purpose

The principal objective of this study by JPL was to determine production costs and selling prices for both Brayton and Stirling engines to be used in solar energy applications for annual production volumes of 1,000, 25,000, 100,000, and 400,000. The purpose of the study was to use the generated numbers to compare the relative cost and selling price of different engines when they are used in solar power conversion units.

Introduction

The engines evaluated in this study were the following:

Brayton Engine - As designed by AiResearch Manufacturing Company of California. The engine was updated to 20 KW from a basic subatmospheric design of 10 KW.

Stirling Engine - As designed by United Stirling (USS) of Malmo, Sweden. The engine was a P-40 design modified for solar energy application and was rated at 30 KW.

This study estimated the cost of direct labor and material which results in a cost number. A figure of $10.00/hr. was applied for direct labor. Estimates were made of the tooling, capital equipment and factory area required to assist in determining the selling price of the engines.

The engines evaluated by JPL were existing designs. No attempt was made to modify the design with an eye to reducing the cost.

Each of the companies involved - both AiResearch and United Stirling have indicated that modifications could be made to their engine designs to reduce the estimated costs.

Methodology

Each engine part, component, assembly (major and minor), and its final assembly was examined and evaluated as to the cost of its material and method of manufacture based on the particular annual production volume under review. When estimating the costs of engines produced at the rate of 1000/year, it was assumed that most of the items would be purchased from small shops and assembled in an in-house facility.

When the production run increases to 25,000/year, it was assumed that a make or buy decision would be made to obtain the lowest cost based on a tradeoff of capital investment versus labor cost. Again, the assembly would be performed in-house. It should be noted that a production of 25,000 engines per year requires an engine every four (4) minutes with an eight (8) hour working day.

As the production increases to 100,000 units/year, it was assumed that most items would be made in-house with the necessary investment in tooling and capital equipment. Assembly would be in-house and would require an engine every minute based on an eight hour working day. With production at 400,000 units per year, multiple and duplicate facilities would be required and they would have to operate two eight (8) hour working shifts per day.

The evaluation was performed by examining either detailed drawings or actual parts and in some cases both drawings and parts were available for examination. The study evaluated the costs of direct labor and direct material only. Costs were determined for annual production volumes of 1000, 25,000, 100,000 and 400,000.

For low production volumes of 1000 and 25,000 units/year the engine manufacturing costs are considered to be labor intensive, whereas the manufacture of engines at higher production volumes would be capital intensive which can result in lower unit costs for materials and labor.

Estimates were also made for the probable cost of both the tooling, the capital equipment and the factory area that would be required for each of the production volumes under consideration.

Selling prices were determined by using a modified "Interim Price Estimation Guidelines" (IPEG) which was developed by JPL for use in the LSA program. The modified IPEG provides for indirect labor and material, factory area, amortization of tooling and capital equipment, financing, taxes, inflation, profit, etc.

Restrictions

In order for JPL to obtain detailed information (drawings, specifications, etc.), from which cost estimates of engines could be made, manufacturers of Brayton and Stirling engines were contacted and requested to supply the

required information. The manufacturers agreed to supply the necessary information provided JPL would execute an Agreement of Confidentiality and/or a Secrecy Agreement that would preserve the proprietary rights of the companies involved.

The result of these agreements means that JPL cannot publish detailed cost information on parts, components or assemblies. The only information that can be published are the final estimates of cost numbers for a complete engine.

Representatives from both United Stirling (USS) and AiResearch Manufacturing Company of California have reviewed and concurred with the JPL approach to the manufacturing process selected for each component, etc. Additionally, these representatives reviewed the costing analysis and the cost numbers generated by JPL for material, direct labor, tooling and capital equipment.

Results

The cost estimate for the engines in an annual production of 100,000 is shown in Table 1. A chart showing the cost reductions obtained wih increases in annual production volumes is illustrated in Figure 1. A chart showing the selling price of the engines at various annual production quantities is illustrated in Figure 2.

ENGINE COST ESTIMATE
100,000 UNITS/YEAR

	BRAYTON	STIRLING
RAW MATERIAL AND/OR PURCHASED PARTS	$1,317.78	$1,055.77
LABOR HOURS	12.53	12.12
LABOR COST @ $10.00/HOUR	$125.30	$121.20
MISCELLANEOUS	--	$30.00
TOTAL ENGINE COST (LABOR & MATERIAL)	$1,504.08	$1,206.97
CAPITAL EQUIPMENT	$20,775,575	$70,565,000
TOOLING	$9,081,800	$22,229,000
TOTAL CAPITAL EQUIPMENT & TOOLING	$29,857,375	$92,794,000

TABLE 1

STIRLING ENGINE

1,000	25,000	100,000	400,000

$5269 $2209 $1207 $1132

BRAYTON ENGINE

1,000	25,000	100,000	400,000

$1750 $1601 $1504 $1366
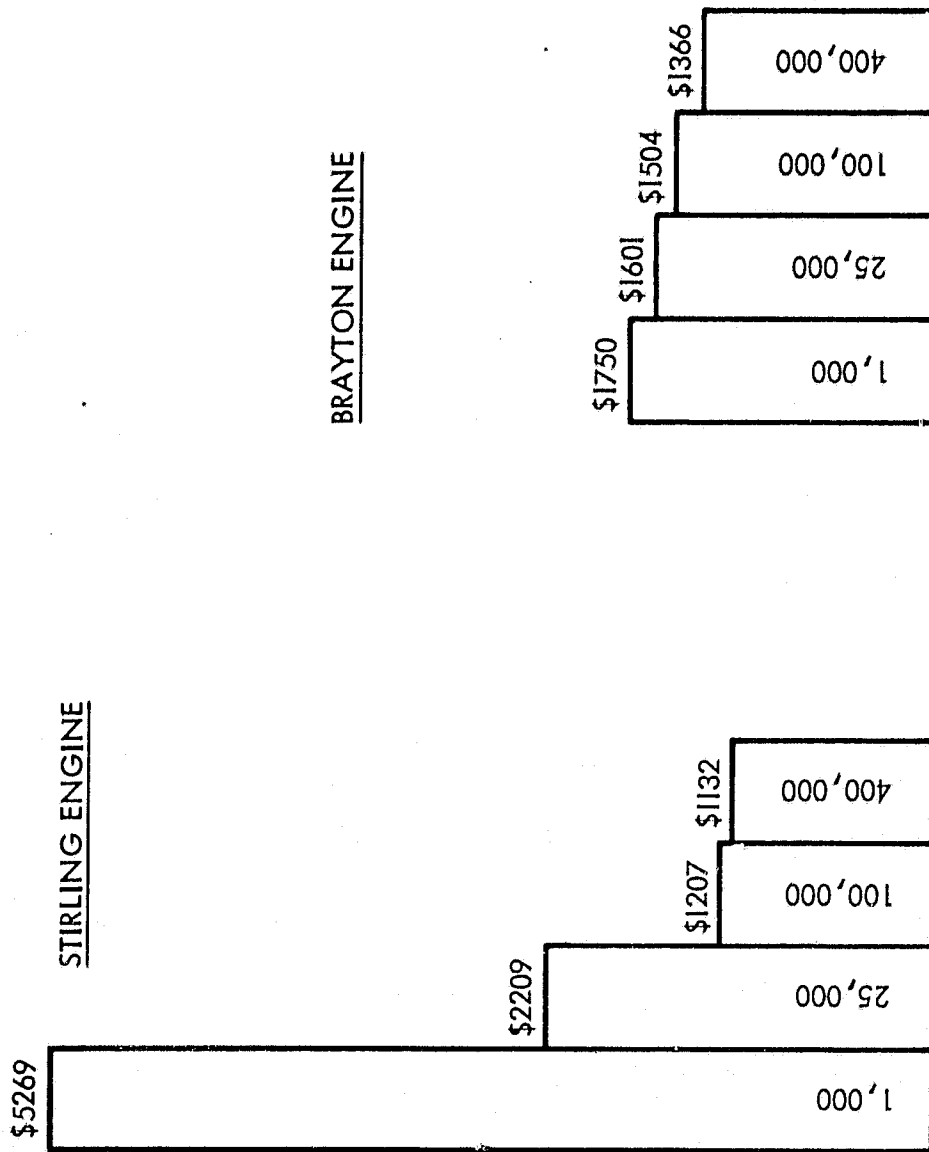
ENGINE COST VS ANNUAL VOLUME

FIGURE 1

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STIRLING ENGINE

$12915			
1,000	25,000	100,000	400,000
	$4145	$2165	$1866

BRAYTON ENGINE

$5328			
1,000	25,000	100,000	400,000
	$2440	$2069	$1865
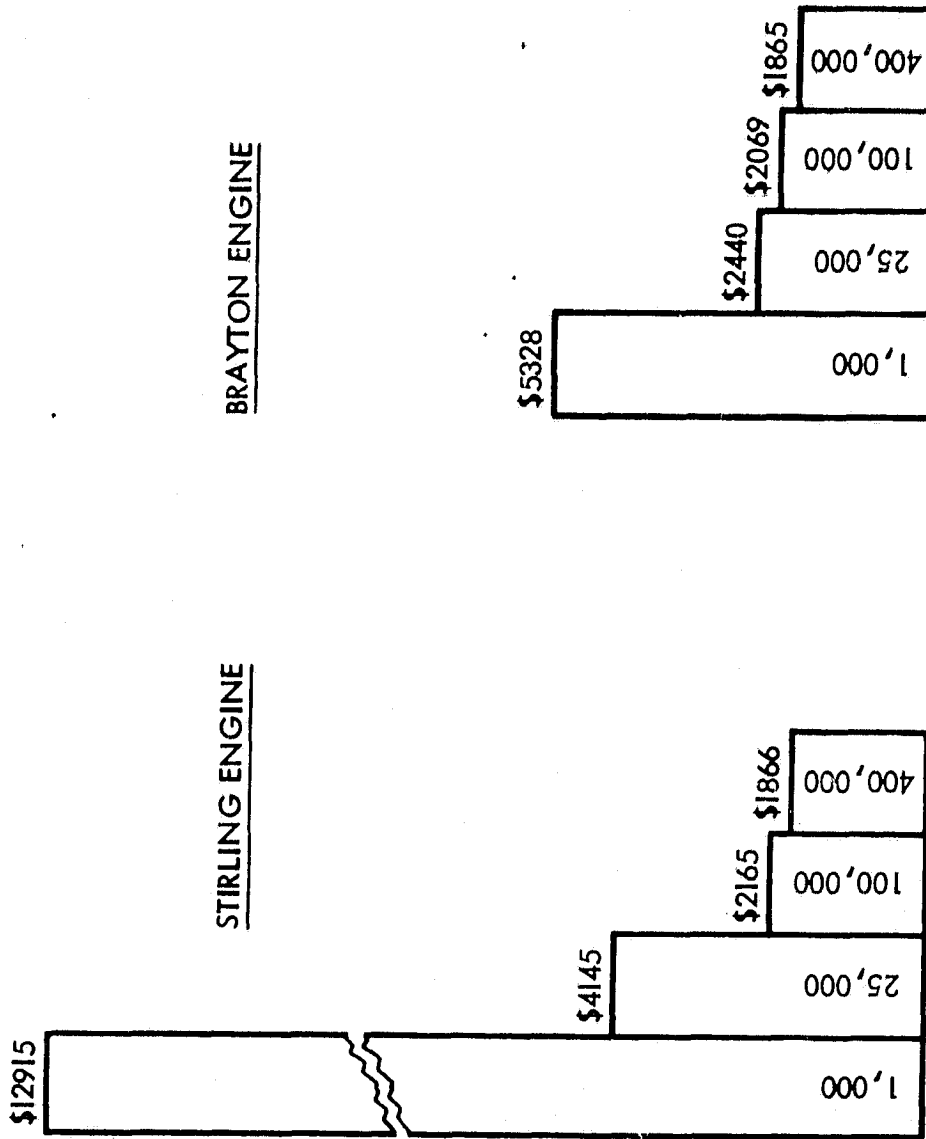
ENGINE PRICE VS ANNUAL VOLUME

FIGURE 2

SESSION VI
PARABOLIC DISH APPLICATIONS

THE DISH-RANKINE SCSTPE PROGRAM
(Engineering Experiment No. 1)

by

R. L. Pons and C. E. Grigsby
Ford Aerospace & Communications Corporation (FACC)
Aeronutronic Division
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ABSTRACT

Paper summarizes the activities planned for Phase II of the Small Community Solar Thermal Power Experiment (SCSTPE) program. A Dish-Rankine Point Focusing Distributed Receiver (PFDR) solar thermal electric system will be designed and developed and a single power module tested at the JPL Solar Thermal Test Facility, Edwards AFB, California. Major design efforts will include: development of an advanced concept indirect-heated receiver; development of hardware and software for a totally unmanned power plant control system; implementation of a hybrid digital simulator which will validate plant operation prior to field testing; and the acquisition of an efficient organic Rankine cycle (ORC) power conversion unit (PCU). Preliminary performance analyses indicate that a mass-produced Dish-Rankine PFDR system is potentially capable of producing electricity at a levelized busbar energy cost of 60 to 70 mills per KWh and with a capital cost of about $1300 per KW.

INTRODUCTION

FACC will be the Systems Contractor for Phase II of the SCSTPE program, under contract to JPL. The Phase III effort, as currently envisioned, will consist of the fabrication, installation and test of multiple power modules comprising a complete power plant - in the range of 1/4 to 1 MW_e - at a site to be selected by DOE.

The Phase I studies carried out by FACC considered PFDR solar thermal electric systems employing Stirling, Brayton and Rankine cycle engines. Given the benefits of mass production, all of these concepts were shown potentially capable of producing electricity at a cost competitive with the energy cost projected for fossil- and nuclear-fueled plants in the near future. The Dish/Rankine PFDR concept was chosen for the Phase II SCSTPE program primarily because it offered the best performance for the lowest program risk. In general, Rankine cycle engines represent a well-developed technology and should prove to be very reliable equipment. At the module power levels of interest (~20 KW_e) to the SCSTPE program, however, there is a lack of data on representative hardware, and an experimental program is necessary to obtain operating experience and provide a valid data base for accurate projections of performance, reliability and (maintenance) cost of the ultimate commercial systems.

The overall milestone schedule for the SCSTPE program is shown in Figure 1. The major constraint is the customer requirement to have the

MILESTONES	FY 79		FY 80		FY 81		FY 82		FY 83		FY 84	
	CY 79		CY 80		CY 81		CY 82		CY 83		CY 84	
PHASE I												
DOE CONTROL POINTS					START DET DES △ PD		FAB & INSTALL △ PD		BEGIN OPERATION △ PD			
PHASE II												
PRELIMINARY DESIGN				PDR								
SUBSYSTEM DES & DEV					COMPLETE							
DETAILED DESIGN				START	FAB COMPL	DDR						
SYSTEM VERIFICATION TESTS		START MOC		FAB	START TEST	COMPLETE TEST						
PHASE III												
SITE PREPARATION				SITE RFP SELECTION								
FAB PLANT HARDWARE												
SUBSYS INSTALL & CHECKOUT												
SYSTEM LEVEL CHECKOUT									◇			
PLANT ON LINE									◇			
PLANT TEST & OPERATION									◇			
PFDRT SUBSYSTEMS												
CONCENTRATOR - LCC				DESIGN	FAB & INSTALL TEST							
- TBC		FAB INSTALL TEST										

FIG. 1. OVERALL MILESTONE SCHEDULE FOR SCSTPE PROGRAM

plant "on-line" by mid-FY83. The critical path for Phase II is acquisition of the organic Rankine PCU during month 15 for integration with the FACC receiver and subsequent installation into the power module at the JPL Solar Thermal Test Facility. This schedule assumes a 12-month development cycle for the organic Rankine PCU.

The Preliminary Design Review will be held after 4 months; the Systems Design Review after 12 months; and completion of the Phase II program after 23 months. In addition to program schedule and cost considerations, subsystem and component selection will be based on economics of a commercial, mass-produced PFDR system (circa 1990) designed for 1 MW_e rated power without storage. The remote (unmanned) plant will interconnect with a utility grid network. The Barstow, California, site will be employed for preliminary design computation. Subsequent analyses will use the Phase III site currently under source selection.

Effort during design of the major subsystems will address the following key issues:

Concentrator - The General Electric prototype 12-meter Low Cost Concentrator (LCC) will be provided by JPL as the baseline. The JPL/E-System Test Bed Concentrator (TBC) will remain as backup for the System Verification Tests at the JPL Solar-Thermal Test Facility.

Power Conversion Unit -- A detailed presentation of this subsystem has been given previously by Mr. Boda. Among the key issues to be addressed are the rather tight development schedule discussed previously and the lack of operating experience on toluene at the desired operating temperature range of 700-800°F. The baseline PCU will be hermetically sealed to avoid leakage, oxide contamination, etc. A parallel steam Rankine engine system is under consideration as program backup.

Receiver - Details of this subsystem were given previously by Mr. Osborn. Key issues relate to the selection of an acceptable secondary working fluid within the relatively short time available prior to the scheduled decision date at PDR. The direct-heated receiver concepts currently under development as a part of the JPL PFDR program remain as backups.

Plant Control - FACC will design the plant control subsystem for remote, unmanned operation. The detailed design of the hardware and software for complete control of a multi-module plant is a major task of the Phase II program. A complete hardware-in-loop system simulator will be constructed so that complete dynamic simulation of plant operation can be achieved; varying solar insolation, start-up, shut-down, transient cloud cover, forced outages and the like will be simulated and thoroughly examined. An additional benefit of this simulator is its applicability to other PFDR systems, regardless of the type of engine employed.

Energy Transport - The Energy Transport subsystem is a conventional DC electrical network. The program decision to go DC is based on extensive studies which show no significant difference in system efficiency between the AC or DC design, whereas the DC network permits an easier interface (one point) with the utility grid, and, if storage were desired, permits a more efficient interface with batteries since the DC-DC interconnection does not require additional conversions.

BASELINE SYSTEM

The baseline system for SCSTPE has been established consisting of the collector subsystem, the energy transport subsystem and a central plant control subsystem. Details of these subsystems are given in the following paragraphs.

Collector Subsystem

The collector subsystem consists of multiple power modules. Each power module contains a 2-axis tracking parabolic dish concentrator, a cavity receiver and an ORC Power Conversion Unit (ORC engine and electrical generator). The control rectifier is also part of the PCU, but is mounted at ground level near the base of the dish concentrator. Figure 2 shows the prototype power module which uses the 12-meter General Electric Co. Low Cost Concentrator (LCC) currently under development as a part of the JPL PFDR program. The LCC is a lightweight, advanced design unit which employs injection-molded plastic dish segments,

integral reflector surface, front structural bracing and a wheel/track type of azimuth/elevation mount with the unique capability to achieve an inverted stow position in order to reduce survival wind loads and provide easy access to the power conversion assembly and the reflecting surface. The prototype LCC will use an aluminized plastic reflecting surface; later designs may use silvered glass mirror elements with substantially higher reflectivity and longer life. Sun tracking is accomplished by a combination open loop/closed loop system. A more detailed discussion of the LCC has been given by Mr. Zimmerman of the General Electric Company.

A cutaway view of the power conversion assembly consisting of the receiver, ORC engine, alternator and plumbing is shown in Figure 3. Complete weight of the assembly is 490 Kg (1078 lb); it is 2.60m (8.52 ft) long and fits within a 1-meter-diameter circle. The receiver* is an indirect-heated design based on the pool-boiling or thermosyphon concept thoroughly studied by FACC during the Phase I program. It is essentially a double-walled cylindrical container with a secondary fluid boiling in the annulus. (The leading candidates for the secondary fluid are sulphur mixed with 10-15 percent iodine and a terphenyl organic compound.) The cylindrical container is connected by a short pipe to a heat exchanger which contains the circulating toluene. The vaporized secondary fluid is transported up the pipe by natural convection, condenses on the toluene heat exchanger surfaces and returns to the boiler by gravity.

The PCU has not been selected although preliminary designs have been submitted by a number of firms including Sundstrand, Barber-Nichols, Garrett/AiResearch, Thermo-Electron and General Electric. Both Sundstrand and Barber-Nichols have had contracts from FACC to provide high-performance ORC engine designs. The Barber-Nichols design (Figure 3) has an electrical output of about 16 KW$_e$ at rated power conditions.
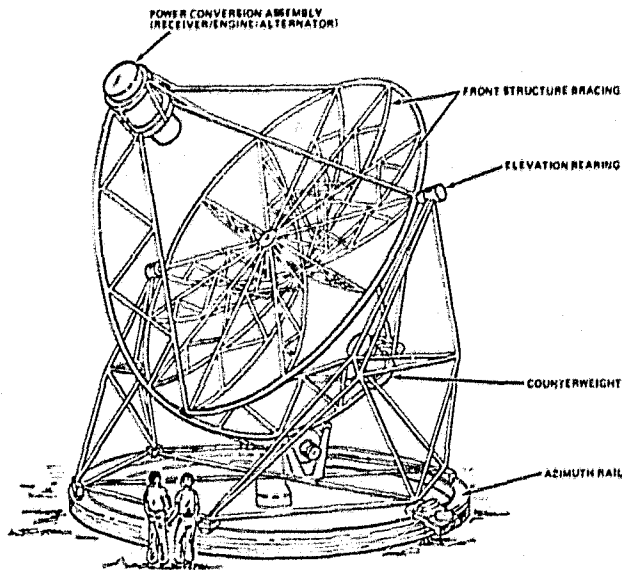
FIG. 2.   POWER MODULE INCORPORATING LOW COST CONCENTRATOR AND ORC POWER CONVERSION ASSEMBLY
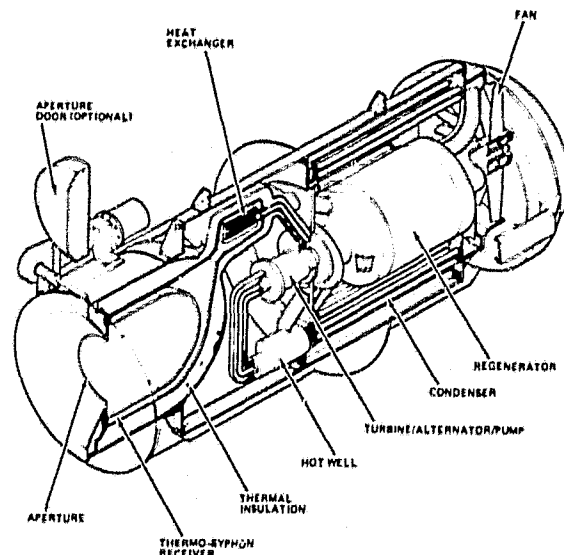
FIG. 3.   ORC POWER CONVERSION ASSEMBLY

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*Patent Applied For

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An air-cooled condenser is packaged concentrically about its turbine/
alternator/regenerator components as shown in Figure 3. Toluene opera-
ting supercritically is the working fluid with a maximum temperature of
427°C (800°F). Consideration has been given to the effect of the 427°C
maximum operating temperature on the long-term stability of toluene.
Estimates have been made which indicate that the working fluid will
have to be changed only about every 30,000 hours or twice during the
30-year life of the plant. It should be noted that the rate of fluid
degradation is low since the bulk of the toluene fluid inventory is at
much lower average temperature than the 427°C maximum operating tempera-
ture. Note further that the use of a hermetically sealed system mini-
mizes oxide formation and attendant scale deposition on the plumbing.

Energy Transport Subsystem

The overall SCSTPE system schematic shown on Figure 4 illustrates the
major elements of the Energy Transport Subsystem. A DC electrical sys-
tem interconnects the individual power modules and converts the collec-
ted energy into AC power by a central inverter. Standard interface
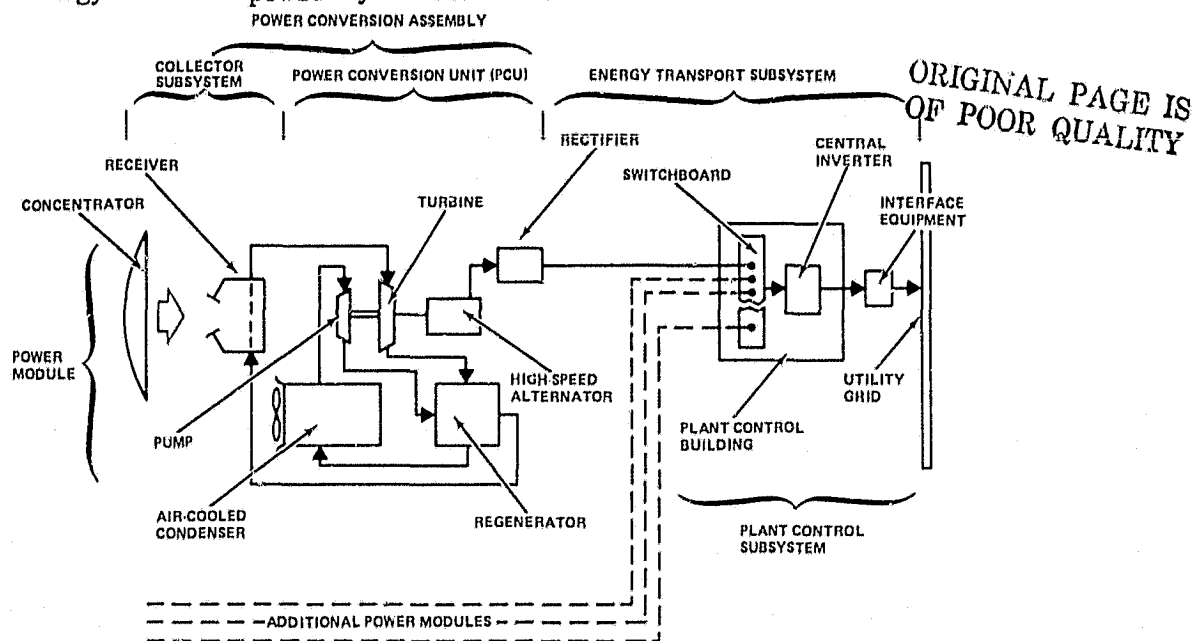
FIG. 4.   SCSTPE SYSTEM SCHEMATIC

equipment is used to connect to a utility grid. Overall efficiency of
the SCSTPE Energy Transport Subsystem from PCU output to the utility
grid is estimated at 93.4 percent. All components are off-the-shelf
items with demonstrated performance and minimum risk.

Plant Control Subsystem

The Plant Control Subsystem is designed to permit remote, unmanned
operation of the SCSTPE. A central microprocessor serves as the
supervisory-level controller and centralized interface for communica-
tions among all plant subsystems and the central plant control room.
The general functions performed by the control subsystem include

(1) Automatic/Manual control of all plant subsystems.

(2) Coordinated sequencing of plant subsystems for its various operating modes such as: start-up, shutdown, normal operation, intermittent operation and emergency operation.

(3) Plant system protection against failures (grid faults, environmental conditions, etc.) by means of monitoring key measurement variables and commanding automatic emergency sequencing.

(4) Status monitoring of relevant plant variables for control room terminal display and recording.

Most control functions will be implemented as algorithms in the microprocessor software; however, in certain cases local analog electronic control loops may be used and only supervisory level control will be provided. The microprocessor speed and memory have been sized to permit sequential communication with each power module through a serial-multiplexed data bus.

SYSTEM PERFORMANCE

A major variable in the ORC system is the working fluid temperature at the inlet to the engine expander (turbine). Figure 5 shows the influence of turbine inlet temperature (TIT) on the pertinent component efficiencies. Note that overall system efficiency (from sun to electric grid) is maximum ($\sim$21%) at 427°C (800°F), which is the upper limit for the data, corresponding to an upper limit estimated for reliable operation with toluene. As shown later, it is possible to operate at somewhat lower temperature, if an added safety factor is desired, with only a small increase in energy cost. The performance data presented herein, however, have been computed at a temperature of 427°C.

System annual output was determined by calculating performance in 15-minute intervals for a Barstow, CA, site during CY1976; all plant parasitic losses are included. Figure 6 shows the power budget for an individual module as a function of time for a typical Barstow day. Figure 7 shows power delivered to the grid, per module, for three representative days of the year. For a 1 MW$_e$ system, nominally rated at a solar insolation of 800 W/m^2 and an ambient temperature of 27°C (80°F), approximately 68 power modules are required and annual energy output is 54.5 MWH/Dish, for a total system output of 3706 MWh/year. This corresponds to an Annualized Capacity Factor (ACF) of 0.418 without storage and adjusted for computed System Availability.

These computations were carried out for a spatial arrangement of modules corresponding to 25 percent packing fraction, i.e., the ratio of concentrator aperture area to land area. At 25 percent packing fraction, the annual energy loss due to mutual shading/screening of concentrators is negligible (Reference 1) and total system cost, including electrical cabling and land (at $5000/acre) is minimum. Corresponding
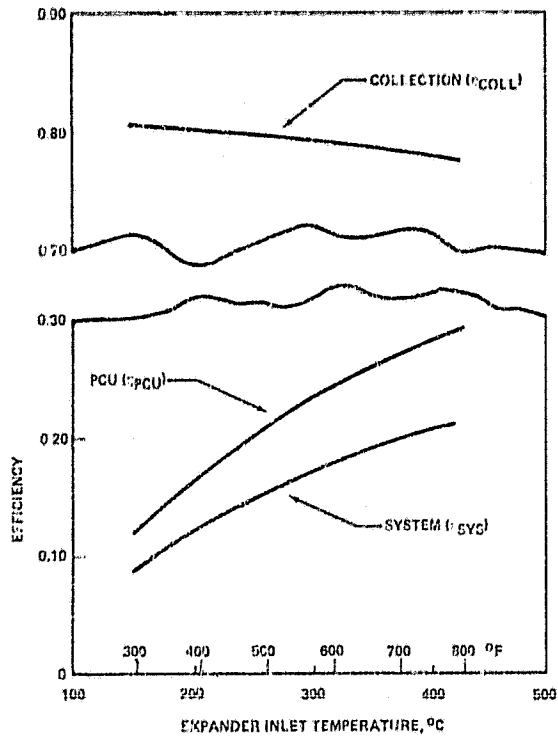
FIGURE. 5. EFFECTS OF TEMPERATURE ON COMPONENT EFFICIENCY (OPTIMIZED 1 MW$_e$ - ORC SYSTEM)

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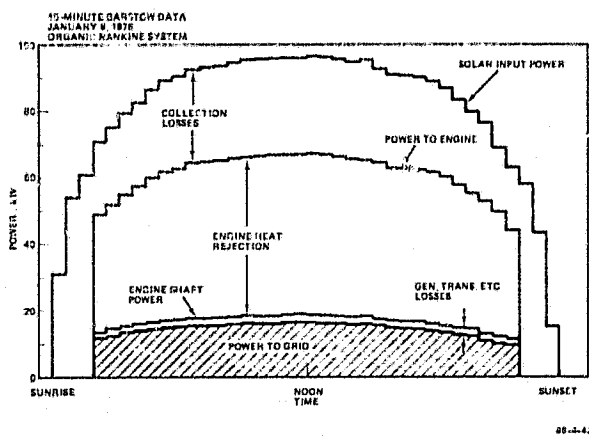
FIGURE. 6. INDIVIDUAL POWER MODULE SYSTEM PERFORMANCE FOR A TYPICAL DAY
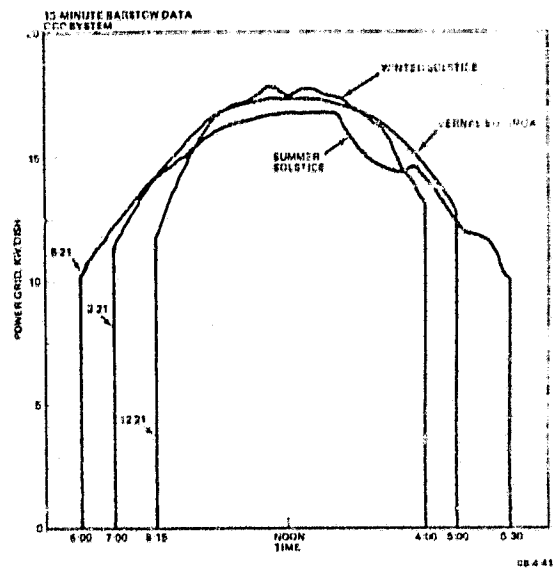
FIGURE. 7. SYSTEM PERFORMANCE BY SEASON (INDIVIDUAL POWER MODULE)
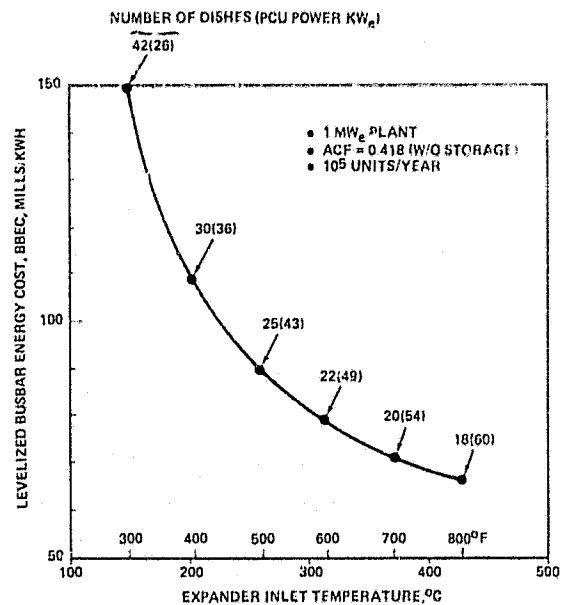
FIGURE. 8. OPTIMIZED ORC SYSTEM PERFORMANCE

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land area for a prototype 1 MW$_e$ plant is 7.6 acres. Higher packing fractions are achievable, but with some loss in energy. For example, at 50 percent packing, annual energy loss is about 6 percent, but land costs would have to exceed about \$30,000/acre to achieve minimum system cost at this density.

SYSTEM ECONOMICS

A generalized economic analysis was carried out for the Dish-Rankine concept, assuming optimized components* and the benefit of mass production/installation techniques. Life cycle cost analysis techniques (Reference 2) were employed to determine System Levelized Busbar Energy Cost ($\overline{BBEC}$), which is used as the sole comparative parameter. Figure 8 shows the influence of TIT on $\overline{BBEC}$ for a production rate of 100,000 modules/year. The benefits of higher temperature are obvious, but very non-linear since the reduction in $\overline{BBEC}$ for the last 55°C (100°F) difference in TIT is only about 5 mills/kWh (~7%). Note that lowest $\overline{BBEC}$ is on the order of 70 mills/kWh despite use of the relatively conventional FACC concentrator design. Use of more advanced concentrators currently in the design stage could reduce $\overline{BBEC}$ below 50 mills/kWh.

Figure 9 shows the effect of power module production rate on BBEC. Note that modest production rates (~1000/year) result in energy costs low enough to be attractive at the present time for certain special applications, e.g., islands, military facilities and remote sites.

Figure 10 shows the sensitivity of $\overline{BBEC}$ to plant size. For plant rated power on the order of 1/2 MW$_e$ and above, the maximum variation in $\overline{BBEC}$ is only about 10 mills/kWh (~15%). Below 1/2 MW$_e$ there is a substantial increase in energy cost - due primarily to the influence of the fixed cost elements.

CONCLUSION

The Dish-Rankine PFDR concept projects excellent performance; an ACF of 0.418 without storage reflects the very good part-load performance of the ORC engine. The concept also projects very good economic potential, given the benefit of mass-production and the use of optimized components. The SCSTPE program is a challenge, particularly with regard to schedule, but will offer many benefits toward development of the ultimate, operational PFDR small community power system.

REFERENCES

1. Osborn, D. B., "Generalized Shading Analysis for Parabolic Concentrator Fields," ASME Paper 80-RET-33, 1980 Energy Source Technology Conference, New Orleans, 3-7 February 1980.

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*An FACC concentrator design was employed since it is the only design for which suitable parametric performance/cost data are currently available.
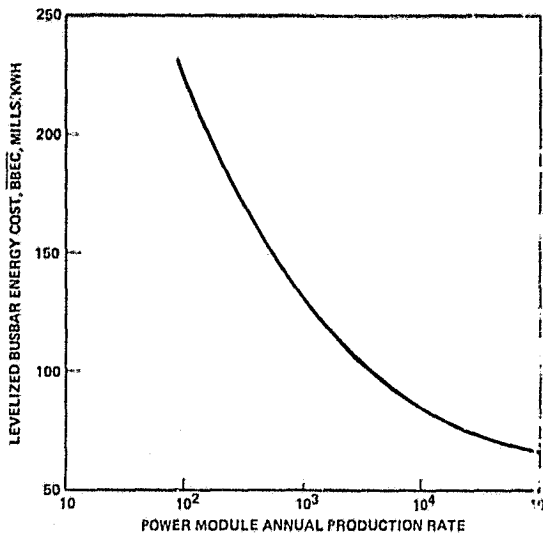
FIGURE. 9.   EFFECT OF POWER MODULE
              ANNUAL PRODUCTION RATE
              ON (MIN) ENERGY COST
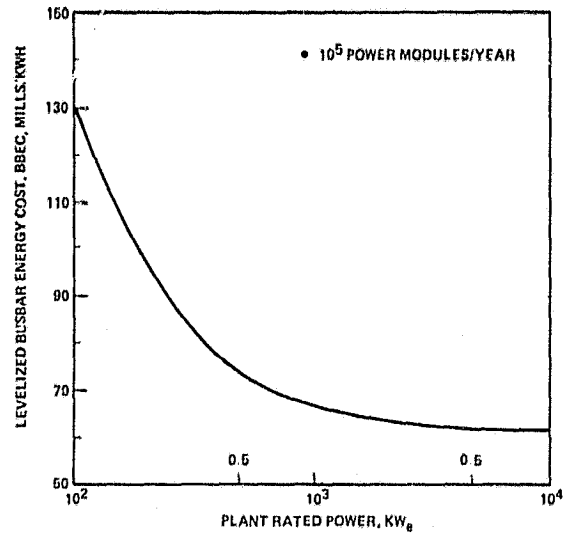
FIGURE. 10.   EFFECT OF PLANT SIZE
               ON SYSTEM ENERGY COST

2.   Doane, J. W., et al, "The Cost of Energy from Utility-Owned Solar Thermal
     Electric Systems" JPL Report 5040-79 ERDA/JEL 1012-76/3, June 1976.

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SITING SOLAR THERMAL POWER EXPERIMENTS

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ABSTRACT

Solar thermal power experiments will provide experimental operation data bases leading to later full-scale demonstrations. The Small Community Solar Thermal Power Experiment will test a point-focusing, distributed receiver system in a small community, electric utility application. Site participation and system development for this experiment are being pursued in separate, coordinated efforts.

Site planning is becoming increasingly important for solar experiments as well as all kinds of development due to increased competition for desirable sites and increased complexity of regulatory requirements. Siting issues can be categorized as:
1) Resources and physical environment at this site
2) Acquisition, permits and regulations
3) Development requirements and costs.
In this paper these issues are addressed with respect to the unique requirements of solar thermal power experiments.

INTRODUCTION

Solar Thermal Power Applications Experiments

Purpose of Applications Experiments

Point-focusing distributed receiver system technologies and applications are being developed as part of a program to provide solar thermal power alternatives for future energy needs. Key elements in this development are system experiments which test technologies in representative user environments. These experiments provide realistic data bases for design modifications, user interfaces and extrapolations of experimental operation which will lead to full-scale demonstrations and then to commercial applications.

Application Experiment Plans

Applications for point-focusing distributed receiver systems include electric utilities, isolated loads and industrial thermal and electric power. Two applications experiments have been defined. The Small Community Solar Thermal Power Experiment will be on-line in 1983. Preliminary system design is underway, and site participation proposals are being evaluated by DOE. The Military Module Power Experiment is a cooperative project with the Navy and will also be on-line in 1983. The system development procurement is in process for a 100 KWe experiment at the Yuma Marine Air Station. Additional experiments are planned.

DIRECT AND TOTAL INSOLATION
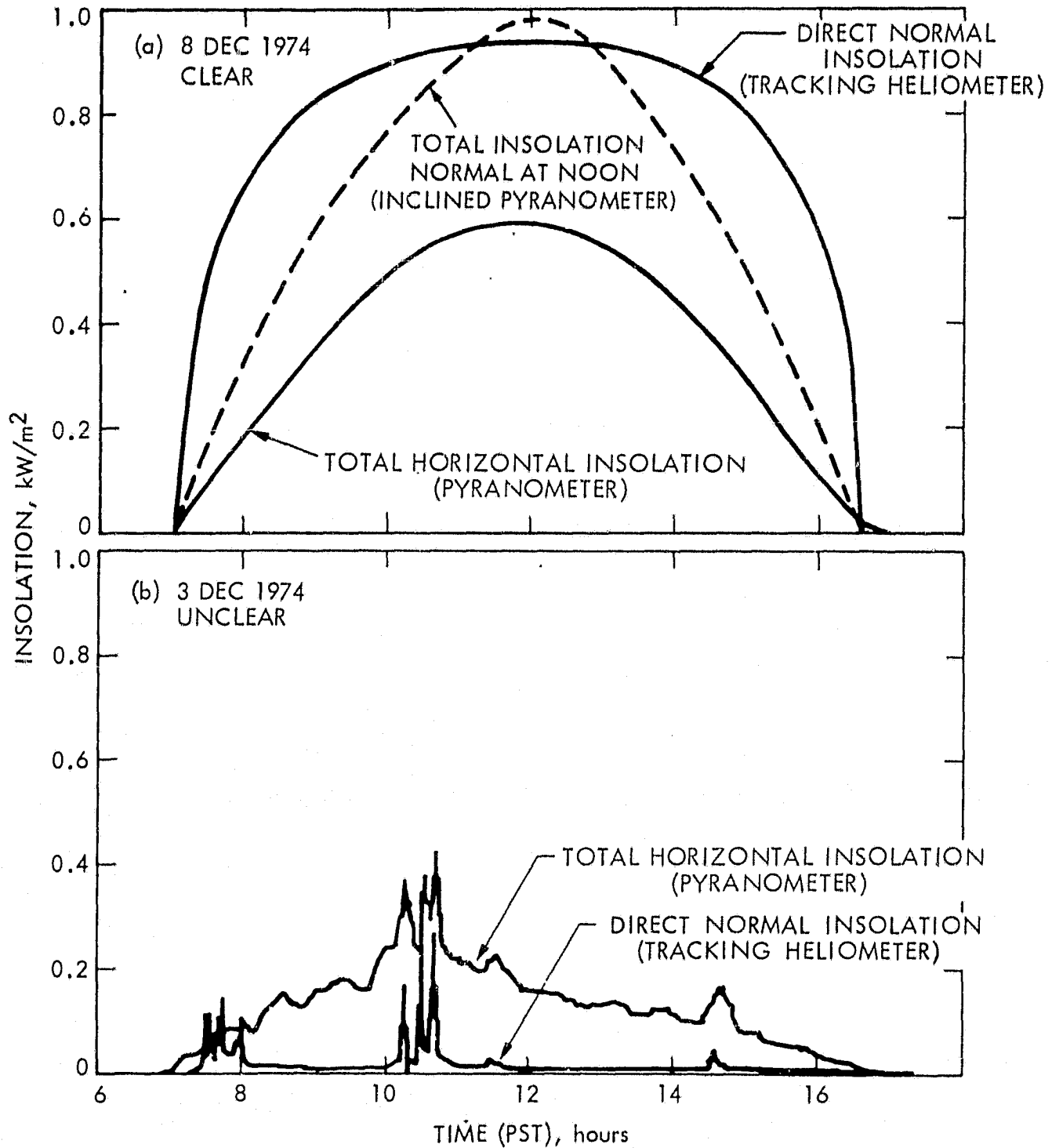
Small Community Solar Thermal Power Experiment

The first experiment in the electric utility application area will use near-term point-focusing distributed receiver technologies. The experiment will be located in a distinct urban or rural community, preferably, with a peak electric power requirement of less than 20 MWe served by an electric distribution system owned and operated by its own utility. The construction of the experimental solar thermal power plant will be accomplished by a system contractor in a parallel but separate action to site participation. The site participant as a cooperative partner will provide support including:
1. A suitable 10 acre site with appropriate zoning and permits for experimental plant activities.
2. Access roads and utility service to the site.
3. An electrical interface to the participant's distributional network.
4. Various data, maintenance and operational support services.

Site Development Trends

Increased competition for the most desirable sites is resulting in higher costs and the use of marginal sites. Regulatory requirements are also increasing, and the involvement of more agencies is leading to increased permit acquisition time. At the same time construction costs are rising more rapidly than general inflation. Further, local authorities are imposing additional development requirements including peripheral and off-site development. These trends increase the importance of site planning.

SITING FACTORS

Factors for any kind of site development can be considered within three categories. Resource availability includes not only the resources important to the development, but also those environmental factors which mitigate the effectiveness of the resources. Site availability includes the actual acquisition of the site together with the regulatory environment which affects the timely availability of the site for the intended development. The remainder of this paper addresses these siting categories as they affect an experimental solar thermal power plant.

Site Resources

Solar Thermal System Requirements

The most important resource required by a solar thermal power plant is direct normal insolation. While this is primarily a regional resource it also varies with local atmospheric shading conditions. Environmental factors such as wind impact the effective utilization of the solar resource while dust and pollutants can degrade the ability of the system to utilize the solar resource.

Direct Normal Insolation

The solar resource includes direct and diffuse components. Flat plate, low temperature technologies utilize both components, and most solar data is

measured as total insolation on a horizontal surface. Point-focusing solar thermal systems track the sun and concentrate the solar energy to produce high temperatures. Since the diffuse insolation component cannot be effectively concentrated, these systems utilize only the direct normal insolation component.

Figure 1 illustrates the difference between direct and total insolation for two winter days in the California desert. On a clear day the direct normal insolation exceeds the total horizontal insolation because of the cosine of the sun's inclination angle. On the unclear day the situation reverses. The total horizontal insolation remains at about half of the clear day levels, consisting primarily of the diffuse component. However, there is little effective direct normal insolation. This difference between direct and total insolation results in different regional distributions. There is a dominant latitudinal variation in total horizontal insolation while there is a dominant longitudinal variation in direct normal insolation, primarily due to cloud cover.

Local Obscuration and Shading

Local available direct insolation may differ significantly from the indicated regional values. Fog or clouds can reduce the indicated regional insolation while regional insolation may be understated if there are local cloud conditions at the nearby measuring station. The local insolation resource can also be reduced by shading from nearby topographic features or buildings which interrupt the solar view in southerly directions above a 10 degree angle from the horizontal. North facing slopes on the site require greater spacing between concentrators to preclude shading from adjacent concentrators. Future land uses adjacent to the site must be considered, and this may involve easements for solar access.

Environmental Factors

The effective availability of the insolation resource may be mitigated by various environmental factors. Concentrator structures are designed to withstand 100 mph winds when stowed, but they will not operate at full efficiency in winds exceeding 30 mph. Dust and air pollution require more frequent concentrator cleaning and may lower the efficiency of concentrator surfaces.

Site Availability

Site and Permit Acquisition

Competition for land has led to the increased use of sites with some kind of development problem. Indeed, some land may not be available for development at any reasonable cost or effort. Additionally, the acquisition of title is no guarantee that the land will be available for the intended development. Zoning and land use plans are becoming increasingly important factors, and proposed developments proceed more smoothly if they are compatible with these plans rather than in opposition. This can mean the difference between a minimum permitting effort and costly, time-consuming public hearings.

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Environmental Impact

One of the advantages of solar thermal power is the renewable, clean nature of the solar energy resource. Hence, solar thermal power will have less environmental impact than fossil or nuclear power plants. In addition solar power is perceived by the public to be environmentally desirable. However, potential environmental impacts cannot be ignored. Any development project disrupts the env ironment on and around its site. Washing of collectors and potential spills of heat transfer fluids could affect nearby aquifers. The visual impact of collectors may be offensive to some. These potential impacts and alternative land uses need to be considered not only with respect to the permitting of the experimental plant, but also with respect to public perception of eventual large-scale solar thermal development.

Site Development

Solar Thermal Land Requirements

The dispersed nature of the solar resource leads to rather large land area requirements for solar thermal power plants. Land requirements for near term technologies are approximately 10 acres for a plant with a peak power output of 1 MWe. As system efficiency increases it is expected that this will be reduced to about 3 acres per MWe, still a large area compared to direct fossil plant requirements.

Site Preparation Costs

Because of the large area requirements, site preparation is an important part of the total cost of a solar thermal power plant. Site preparation includes clearing, grading, drainage, access and perimeter improvement. These activities are part of a mature construction technology with little opportunity for cost reduction through technology improvement.

Site preparation costs are also significantly affected by size. The land requirements for a plant are non-linear because of the unused area around the plant perimeter. Unit costs for clearing and grading are fairly constant with size but perimeter costs vary with the square root of area because of the geometric relationship. Perimeter development requirements for architectural walls, landscaping, et cetera cannot be overlooked, particularly when the plant is located in or near town close to the end user.

Potential Reduction of Site Preparation Costs

As solar thermal system costs are reduced, site preparation and construction becomes proportionally a more important cost factor. Several approaches to cost reduction have been considered. Higher system efficiency with the resulting lower area requirement has an obvious effect as does the selection of sites with minimum development requirements. Beyond this, collector foundation construction similar to that for transmission towers is being considered to reduce the grading at each collector location and to minimize access requirements to construction equipment. Field layouts can be considered which utilize a site primarily in situ. This may increase collector spacing but could still considerably reduce site preparation efforts.

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THE JPL ISOLATED APPLICATION EXPERIMENT SERIES

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ABSTRACT

The goal of the Thermal Power System Project's Applications Development element
is to establish the technical, operational, and economic readiness of small power
systems for a variety of applications in the power range below 10 MWe. Power
Systems are being developed and tested to the point where commercialization efforts
can lead to successful market penetration. A key element in this strategy is the
use of experiments to test hardware and assess operational readiness. The JPL
Isolated Application Experiments are described and their objectives discussed.

BACKGROUND

The three successive milestones required in the development of a new
technology to the point of commercial readiness are: 1) demonstrating
technical feasibility, 2) verifying readiness of the technology, and 3)
meeting cost goals required for commercial readiness. The three phases in the
evolution of a new technology can be described as creation, development, and
commercialization. Participation by both government and the private sector
may be necessary, with increasing activity by the latter as the commercial
readiness phase is approached. Potential users are involved early in the
design phase, and to the maximum extent possible.

A key element of the program strategy is first the identification, and later
the penetration, of near-term markets that will provide a stimulus for
establishing a manufacturing industry. This, in turn, will lead to cost
reductions as a result of improved manufacturing methods, coupled with an
increasing volume of production as lower cost markets are penetrated. The
importance of this program element lies in the belief that design improvement
alone will not result in a sufficiently low price to penetrate the utility
market. A combination of mature technologies and mass production, however,
offers the potential for economically competitive power systems with a
significant environmental advantage.

Potential users will be sought that fall into two broad market categories: 1)
the near-to-mid-term market, which is smaller, and for which costs are higher;
and 2) the far-term market which largely corresponds to the utility sector for
which a mature solar thermal technology is needed before penetration can be
expected. Application studies and system analyses are being conducted to
develop candidate system configurations best matched to the users in each
category. Selected system design concepts will be developed through contracts
let to private industry.

THE ISOLATED APPLICATION EXPERIMENTS

The Isolated Applications Experiment Series is the second major activity within the Applications Development area. The Series will be a set of small (approximately 60-150 kWe) solar thermal power experiments, each of which is meant to address a separate isolated load application.

These experiments will employ point focusing distributed receiver technology with emphasis on electric and possibly some thermal power applications. The program will be closely integrated with the Technology Development element of the Thermal Power Systems Project with the objective of utilizing the technologies being developed under that program.

The first experiment in the Series has been initiated and is co-sponsored by the U.S. Navy under the auspices of the Civil Engineering Laboratory (CEL). CEL and JPL have worked together to develop system requirements. The experiment, designated as the Military Module Power Experiment, will be a modular system using a hybrid fired Brayton cycle energy conversion. Subsequent experiments will test different versions of similar hardware in different applications which are now being selected.

Primary considerations in implementing the series are to:

o   Test the readiness of suitable solar power technologies at the system level in a number of different applications.

o   Economically provide testing of both technologies and markets, thus meeting principal program objectives without large expenditures.

o   Involve a large consituency of industrial suppliers and users.

o   Address the potential for near-to-mid-term market for small power systems that is needed to provide the initial incentive to manufacture these systems.

o   Increase programmatic flexibility by employing a number of small and varied experiments.

Emphasis will be on:

o   High reliability and safety.

o   Early plant deployment.

o   Low program cost.

o   Complete test and evaluation.

The engineering experiments will be designed, installed, and operated to permit JPL to better understand solar thermal plant applications and technical feasibility.

The objective of the engineering experimentsd is not to maximize the kWh of
energy generated by the solar plant or to lower the electric power costs of
the site participants. Rather the objectives are to:

1.   Verify that the solar thermal plant can produce power from solar
     radiation supplemented by fossil fuel to meet energy requirements for
     this application during designated test periods.

2.   Verify that the solar hybrid plant concept can be considered as a firm
     power resource for this application during designated test periods.

3.   Characterize the total performance of the plant (site preparation,
     components, subsystems, modules, and plant) as a function of load
     characteristics, insolation, weather, operations and maintenance
     activities, safety regulations, environmental regulations, seismic
     factors, and legal and socio-technical factors.

4.   Identify and understand plant failure modes.

5.   Identify and quantify the impact of solar hybrid plant operations on the
     daily operations activities of user personnel and on user manning
     requirements.

6.   Identify and quantify the impact of solar hybrid plant installation and
     operations on the local environment.

7.   Identify and quantify the impact of solar hybrid plant installation and
     operation on the acceptance of solar power plants by local public
     officials, local power system officials, and the local public.

Schedule

Tentative schedules have been developed for the series. The MMPE will begin
operation during FY83 with a test and evaluation period of 2 years duration.
Subsequent experiments in the series will begin at approximately 12 month
intervals.

THE MILITARY MODULE POWER EXPERIMENT

The hardware to be employed in the MMPE consists of the General Electric Co.
Low Cost Concentrator plus engine and receiver design by the Garrett Corp.
Control and display systems plus auxilliary equipment will be defined during
plant detail design. A brief description of the major components follows.

The Low Cost Concentrator (LCC) currently being designed by the General
Electric Company is a twelve meter diameter point focus parabolic reflector
which tracks the sun with two-degrees-of-freedom. The reflector is composed
of 24 injection molded plastic panels arranged in three concentric rows,
supported on twelve radial trusswork ribs located inside the reflector dish.

C-3

All panels have the same frontal surface area. The reflective surface is a second surface metallized plastic film which is integrally bonded onto the panel when the panel is injection molded.

The reflector is supported on trunnions at the rim of the reflector to provide motion in elevation, allowing a stowage orientation pointing to the ground. This orientation reduces the wind loads and aids in keeping the reflective surface clean. The pivots are supported on tripods mounted on the base, which provides azimuth rotation about a pintle bearing by six wheels running on a steel circular track. Windless-driven cables are used to provide rotation, the azimuth cable lying in a groove on the circumference of the base and the elevation cable on an arch running from the receiver/engine at the focus to the counterweight at the rear.

The internal radial trusses are precisely positioned by tooling during the reflector buildup. The individual reflective panels are mounted directly on the trusses with no provisions for focusing adjustments. No field welding during LCC site assembly is envisioned.

An ephemeris generated by a central computer provides $\pm1^\circ$ coarse solar tracking and each LCC has an active solar tracker for $\pm1/8^\circ$ fine solar tracking. Each prototype concentrator, with a clean plastic film surface, is projected to provide 66 kWth into a .283 meter diamter aperture under an insolation of 0.8 kW/m^2.

Glass second surface mirrors as the reflective surface will also be investigated.

The Brayton cycle solar receiver is currently being designed by the AiResearch Manufacturing Company of California. The active cavity is 0.5m in diamter and 0.86m in overall height. The aperture is 0.2m in diamter. The plate fin matrix is 1.3cm in depth and 0.71m long. The matrix and headers are fabricated of Inconel 625. The reflector skirt/aperture assembly is fabricated of silicon carbide as is the cavity back plate. Inside the carbon steel shell is 13cm of Johns-Manville Cerablanket insulation. The entire assembly weighs about 193 kg.

This size receiver is designed to accept about 85 kWth through the aperture. It is designed for use with an open cycle air Brayton power conversion unit. Maximum operating pressure is about 354 kPA (50 psia) when operating with a 815°C (1500°C) outlet temperature and a 565°C (1050°F) inlet temperature. Mass flow is about 0.25 kg/sec of air at these conditions. Pressure drop is about 3% of the inlet pressure. The receiver has been designed for a 30 year lifetime.

Hybridization of the solar-powered hybrid power conversion unit (PCU) that is being evaluated for use with point focus distributed receiver electric power systems permit operation on solar radiation, combustion of liquid fuels or on combinations of both. The PCU consists of:

1. A radial turbine and compressor assembly running on oil bearings which is the power section of AiResearch Model GTP36-engine.

2. A 400 Hz, 8000 rpm generator.

3. A gearbox from an AiResearch production engine to reduce turbine shaft speed to the required range of generation speeds.

4. A high-effectiveness recuperator using plate-fin construction in a pure counterflow arrangement.

5. A liquid fuel combustor designed to be compatible with the PCU's solar thermal configuration and in series with the solar receiver.

6. An engine control system which holds turbine inlet temperature constant at 815°C (1500°F) over a range of thermal energy input to the cycle of 30 to 72.7 KW. Inputs below 30 KW require the unit to run at constant speed and at a reduced turbine inlet temperature to avoid recuperator over-temperature.

The degree of MMPE module self-containment will be driven by both economics and reliability. Each module will contain (at a minimum) concentrator, receiver, hybrid combustor, turbine, recuperator, compressor, alternator, module controls, starter, concentrator drives, tracking devices and sensors, some fuel storage and necessary exhaust hardware. A completely self-contained module is desired with only the true plant functions located centrally. These will be power combination and conditioning equipment, module and plant performance indicators, grid interconnection equipment, computing and data recording facilities, instrumentation, plant safety and control equipment. The normal mode of module operation will be unattended, however each module will be equipped for safety or emergency shutdown, both manual and automatic. Although a fixed installation is expected, individual modules must be transportable, field erectable and field serviceable.

Long term thermal storage will not be included in the plant. No thermal buffering will be provided except by the heat capacity of the installed components and working fluid. The hybrid combustor control system will provide the desired transient response characteristics.

SITE SELECTION

Site selection for MMPE has been a U.S. Navy responsibility. It will be conducted in parallel with the system integration control activities and basically independent of the technical tasks. The Marine Corps Air Station at Yuma, Arizona, has been tentatively selected as the site for the experiment. The plant will be operated by the system integrator for the first three months of its evaluation. The following 21 months will see operation by MCAS Yuma personnel.

INDUSTRIAL APPLICATION EXPERIMENT SERIES

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ABSTRACT

This paper presents the objectives and implementation plan for the Industrial Application Experiment Series of the Applications Development element of the Thermal Power Systems Project. The first experiment in the series will be the Industrial Thermal Module Experiment. The approach to implementing the experiment is presented and an implementation schedule is provided.

INTRODUCTION

The Industrial Application Experiment Series will accomplish the deployment of experimental parabolic dish systems into the industrial sector for the purpose of providing user, supplier, sponsor, and developer with a realistic assessment of system feasibility in selected near-term industrial applications. System feasibility, step three in a five step model of the commercialization process,* is the deployment of technologically-ready components, properly integrated into working, experimental modules, for evaluation in user environments. The modules are not mass-produced. However, the design of the module and components may be compatible with mass production techniques.

OBJECTIVES

The objectives of the Industrial Application Experiment Series are:

1. Verify that selected parabolic dish systems can produce energy from solar radiation to meet the energy requirements of selected industrial applications during designated test periods.

2. Determine to what extent the parabolic dish systems can be considered firm energy resources for the selected industrial applications during designated test periods.

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* An adaptation of the commercialization process of the National Photovoltaic Program, the five step process suggested here consists of technical feasibility of components, technical readiness of components, system feasibility, system readiness, and commercial readiness.

3. Characterize the total performance of the plant (site preparation, components, subsystems, modules, and plant) as a function of load characteristics, industrial activities at the site, insolation, weather, operations and maintenance activities, safety regulations, environmental regulations, seismic factors, and legal and socio-technical factors.

4. Identify and understand the failure modes of the selected parabolic dish systems.

5. Identify and quantify the impact of operating the parabolic dish systems on the daily operations activities of user personnel and on user manning requirements.

6. Identify and quantify the impact of the installation and operation of the selected parabolic dish systems on the local environment.

7. Identify and quantify the impact of the installation and operation of the selected dish systems on potential acceptance of commercial units by local industrial officials representing labor and management, local public officials, and the local public.

8. Provide accurate input data to life-cycle energy cost models, based on required O&M activities and energy displacement.

9. Provide feedback to the component and system-level hardware and software design processes.

IMPLEMENTATION

The implementation of the Industrial Application Experiment Series will be accomplished initially through the Industrial Thermal Module Experiment and later through additional experiments involving thermal, electric, and combined thermal and electric systems. The approach is to progress through a series of steps, from single-module to multi-module systems, from thermal-only applications to more complex combined thermal and electric applications. The experience of other solar thermal experiments, particularly those involving parabolic dish hardware, will be utilized to the fullest extent possible in experiment planning and implementation.

INDUSTRIAL THERMAL MODULE EXPERIMENT

The Industrial Thermal Module Experiment will accomplish the objectives of the Industrial Application Experiment Series within the limited scope of near-term thermal applications, small systems size and existing developed hardware. The experiment will also provide an early stimulus to the collector industry, primarily through the reduction of risk to potential users and, secondarily, through the purchasing of hardware by the Government.

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The key elements of the approach to the Industrial Thermal Module Experiment are:

o   Rapid deployment of existing technology

o   Small, low cost, low risk experiments

o   Near-term thermal applications

o   Industrial user and system supplier on contractor team

o   Industrial sites

o   Developed hardware

o   Verification testing of systems required prior to deployment

o   Involvement of small business

To accomplish the rapid deployment required for this Experiment, implementation is accelerated in each of the five phases of the plan. In the first phase, proposal preparation, developed hardware is selected by a prospective Contractor team for a thermal application at a particular industrial site. The second phase, contractor selection, involves identification of site, system, user, and supplier; the level of verification testing required at the JPL Parabolic Dish Test Site at Edwards Air Force Base, California, is negotiated. During the design phase, plant design is completed very soon after contract award in order to permit the placement of orders for hardware in FY1980. During the fourth phase, verification testing is accomplished at the Parabolic Dish Test Site, if required. Three levels of testing at the Parabolic Dish Test Site may be required:

1.   None: System-level testing has already been completed.

2.   Minimum: A short (two month) test period is needed. No modification to the hardware is necessary. The hardware is then qualified for system feasibility evaluation at the user's site.

3.   Maximum: Two short test periods are required, the second following modifications to the hardware to correct problems identified as solvable through minor modifications (requiring two months of downtime).

At the end of verification testing, a go/no-go decision is made by JPL on deployment of hardware, based on test findings and the recommendation of the Contractor. During the fifth phase, the system is installed, checked-out, tested and evaluated at the user's site. Plant installation during FY1981 is highly desirable.

Early events in the implementation of the Industrial Thermal Module Experiment are scheduled as follows:

1. CBD Announcement   February 1980

2. RFP Release   Second Quarter 1980

Organizations interested in receiving an RFP should contact:

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4800 Oak Grove Dr., M/S 506-401
Pasadena, Ca   91103

SPS MARKET ANALYSIS

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ABSTRACT

Advanced Energy Department of General Electric is performing a study for JPL on the Effects of System Factors on the Economics of and Demand for Small Solar Thermal Power Systems (SPS). Study goals are to estimate market penetration as a function of time, SPS performance factors, and market/economic considerations, and to formulate commercialization strategies. A market analysis task has included personal interviews by GE personnel and supplemental mail surveys to acquire statistical data and to identify and measure attitudes, reactions and intentions of prospective SPS users. Over 500 firms were contacted, including three ownership classes of electric utilities, industrial firms in the top SIC codes for energy consumption, and design engineering firms. A market demand model was developed which utilizes the data base developed by personal interviews and surveys, and projected energy price and consumption data to perform sensitivity analyses and estimate potential markets for SPS.

INTRODUCTION

This presentation reviews the on-going GE Advanced Energy Department study of Effects of System Factors on the Economics of and Demand for Small (1-10 MWe) Solar Thermal Power Systems (SPS). The study goals are to estimate market penetration rates for these systems as a function of time, SPS performance factors and market/economic considerations, and to develop cost effective strategies for accelerating the market penetration rate for promising near-term applications. Three major tasks comprising this study include: market analysis, market penetration sensitivity analysis, and commercialization strategy formulation. This review summarizes the market analysis tasks, with emphasis on results obtained from the personal interviews and mail survey conducted. The market demand model is also presented.

STUDY APPROACH

A nationwide study was conducted among three major classes of utility ownership, i.e., investor-owned utilities, rural electric cooperatives, and municipal systems, among the top eight energy consuming classifications of industrial firms, and among selected design engineering firms. Types of industrials contacted in the study included chemicals, paper, food, transportation equipment, textiles, stone, clay, glass, petroleum refining, and others. Firms in all fifty states were included in the study sample. The selection of industrial firms included an equal number of firms with and without in-plant generation equipment to help remove bias caused by this variable. Similarly, the electric utility firms contacted included both firms which generated all or part of their power requirements as well as non-generators which function as distributors and resellers of electric power.

Over 240 industrial, 200 utility and 70 design engineering firms were contacted. Although there were some firms which declined to participate in the study for a variety of reasons, the overall response rate has been high and is currently about 60%.

Personal interviews were conducted by project personnel and members of GE Industrial Sales and Electric Utility Sales Divisions. In addition to the market study information provided by the firms being interviewed, many of the GE field sales engineers provided their views and comments on the SPS and potential for applications of solar electric systems. Confidentiality of data provided was stressed with all respondents and was a key factor in their study participation, particularly in providing financial and investment criteria information.

In addition to personal interviews, a supplemental mail survey activity was conducted. A list of firms was carefully compiled to assure that it was as representative as possible and with minimum biases. All firms were contacted in advance to verify name, title, and address of the survey respondent. Each individual was sent a personal letter from the GE Program Manager soliciting participation in the sutdy, material describing the SPS and a comprehensive questionnaire. After a reasonable period of time, all who had not responded were contacted to verify receipt of the survey package. Duplicate mailings were sent to anyone who had not received the original mailing. Telephone interivews were conducted by professional interviewers in those cases in which the survey package had been received, and the respondent preferred such an interview rather than returning the completed questionnaire. To reduce bias resulting from a detailed technical evaluation of systems concepts by study participants, only a broad overview of the solar systems being considered by JPL was given. System configuration data and cost estimates were derived from data provided by JPL. Both the distributed collection central generation and distributed generation concepts were presented to encompass systems with and without process steam output. Sufficient detail was given to enable respondents to answer questions regarding the possibility that they would consider an SPS as a possible power plant option in the 1990 time frame. SPS land area requirements for three representative solar regions of the country were developed, as well as projected system and busbar energy costs for each region. SPS capacity factor of forty percent was used in the system descriptions.

INITIAL FINDINGS

Industrial Firm Responses

Primary reasons for in-plant generation were determined from responses of industrial firms which now generate all or some of their electric power requirements. Reasons stated in descending order of importance include; the fact that generation is a by-product of steam production, that is is less expensive than purchased power, that it provides a non-interruptible power source, or that the firm has an inexpensive fuel source.

Information on plans for dealing with future energy requirements was also solicited, and provided data on plans for conversion to other fuel types, adding or replacing existing in-plant generation equipment, or purchasing of greater proportions of electrical needs.

Among the factors which would have the most influence in consideration of purchase of a SPS in the 1990 time frame, the list included: meeting the company's financial criteria for capital investments, lower operating costs than conventional systems, tax credits, delivered energy costs (¢/kWh), and ability to fossil fire the SPS to achieve higher capacity factor. The least influential factors included: appearance or aesthetics of the systems, modularity and relocatability, loan guarantees, and the exchange of excess power with local utilities.

Fifty-six percent of the industrial firms contacted stated that they would consider the SPS as an option in the 1990-time frame. Of these positive responses, 59% felt that the SPS would most likely be considered as an addition to their present generating equipment, 27% as a replacement for the generation equipment now on-line, and 21% as a system to repower existing power plants. Due to multiple answers by some firms, these total over 100%. Major SPS benefits perceived included fuel availability, energy price protection, clean non-polluting system, and availability of steam or process heat. Major drawbacks were cited as land cost and availability, busbar energy cost, system capital cost, and low capacity factor.

The mean after tax rate of return on investment (ROI) required was 19 percent. The average price of industrial land suitable for installation of the SPS was $20,600 per acre. Land prices varied from a few hundred dollars to over $100,000 per acre.

Electric Utility Responses

An overall positive response rate of fifty-five percent was expressed by utility firms with regard to whether they would consider an SPS as a power plant option in the 1990-time frame. Among those responding in the affirmative, 76% perceived the SPS as an addition to present generating capacity, 14% as a system for repowering existing power plants, and 16% as a replacement for generating equipment now on-line.

The most influential factors considered by utilities in the purchase of an SPS were meeting the firms' capital investment requirements, busbar cost of electricity, lower operating costs than conventional systems, initial system price ($ per kilowatt) and demonstrations of SPS in the local area. The least influential were availability of process steam, usability to power existing plants, and tax credits. Major benefits perceived included transmission savings, price protection, fuel availability, and clean non-polluting system. Major drawbacks to SPS perceived by utilities were low capacity factor, land cost and availability, system capital costs, and non-proven technology.

The average fixed charge rate for utility firms was approximately twenty percent, while the required ROI was about twelve percent. The price of suitable land for SPS utility installations averaged $8,700 per acre.

Design Engineering Responses

The seventy design engineering firms were contacted for qualitative data and to

obtain their views and reactions to the two system configurations presented. The SPS configuration option featuring central generation was preferred 2:1 by the design engineering firms responding. Most were concerned about solar energy variability and felt that supplemental fossil fuel firing for added capacity factor was important. The availability of process steam as an output was a desirable feature. In general, these firms were not as concerned about land cost and availability as industrial and electrical firms contacted, perhaps reflecting the fact that they may be somewhat insulated from the effects of land costs.

MARKET DEMAND MODEL

A schematic diagram of the SPS demand model is shown below.

DEMAND MODEL FLOW CHART
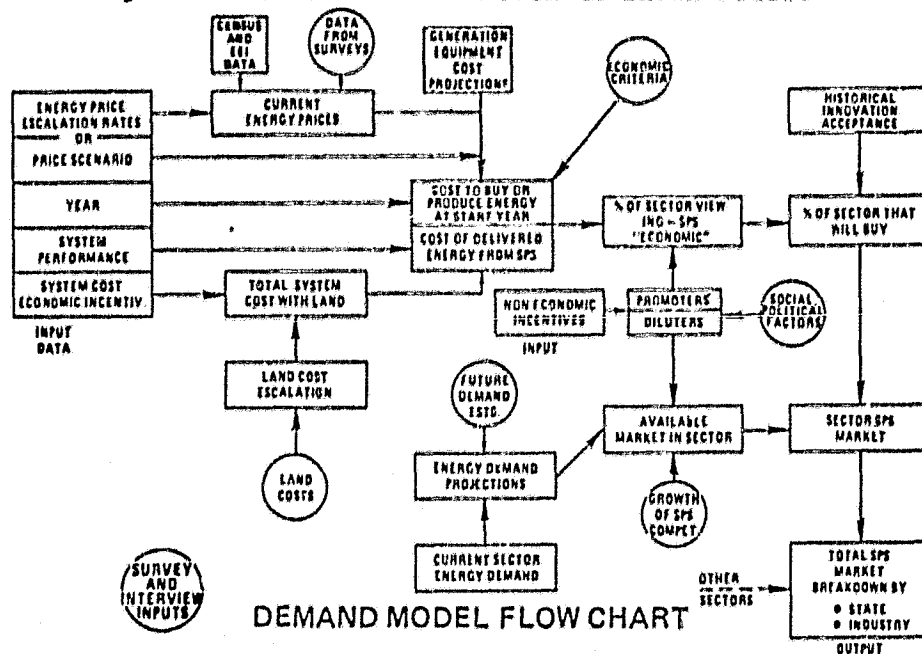
Principal user inputs to the model include: year for which SPS market estimate is desired, SPS cost estimate at that time, SPS performance – electrical and thermal output (including variation with insolation level), applicable economic incentives such as tax credits, either a future energy price scenario or, alternatively, price escalation rates which the model can apply to current price levels.

Model output is an estimate of SPS total industrial market at the year of interest and a breakdown by individual sectors – industries and states. Exercise of the model for a series of years and corresponding system costs will yield a market penetration scenario. Input parameters can be varied to test the sensitivity of each on the rate of penetration.

The data model input includes Edison Electric Institute data on energy prices and Survey of Manufacturers data on energy prices and energy consumption. Price and consumption data are augmented with data from the personal interviews and mail survey.

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Principal interview and survey inputs to the model include (in approximate order of importance): economic criteria applicable to investment in equipment such as SPS, land availability and cost, non-economic influences (such as pollution problems, energy curtailment protection, etc.), strategies to meet future energy requirements, and desirable SPS system characteristics.

Actual treatment of these inputs in the model depends on the type and quality of interview responses. Items such as land costs and economic criteria are found to be statistically distributed so as to be representable by standard distribution curves in most sectors. Where this is not the case, tabular data is utilized.

Within a sector, given land cost distribution and the input system cost, a total cost distribution is first computed. Energy price for the sector at the reference year is obtained either from the input price scenario or from current prices and the input escalation rates. The economic criteria distribution is then employed to determine, based on energy price versus SPS performance and cost, what portion of the sector will view SPS as economic or cost effective.

Once economic viability is reached, SPS penetration rate will be assumed to follow historical patterns typified by the Fisher-Pry substitution model. The available market within a sector will be established from current sector energy requirements and future projections. Interviews and surveys have identified market diluters, such as land non-availability, that reduce the available SPS market size. Combining the available sector market with the above determined penetration rates yields the estimated SPS market at the particular point in time of interest. Combining all sectors yields total SPS market. Data on product technology substitutions experienced by the General Electric Company in various power generation equipment fields will be used in establishing a historical trend data base for the model. The SPS demand model is easily expandable to more sectors either to enlarge the scope of the market assessment or to "fine tune" the results.

CONCLUSIONS AND COMMENTS

The high response rate from industrial, utility and design engineering firms achieved during the market analysis task is a strong indication of a high level of interest in SPS. Data obtained from the personal interviews and mail survey activities is now on computer files. There are approximately 140 variables associated with each industrial questionnaire and 100 with each utility questionnaire completed. The data base contains information on present and future electrical requirements, electricity purchases and in-plant generation, process steam use, options for dealing with future energy requirements, land costs, investment criteria, and factors which would influence SPS purchase considerations by industrial and utility firms and other such information. The demand model and this data base provide a means for performing market penetration rate sensitivity analyses using actual industrial and electric utility data, and in helping to identify potential SPS demonstration sites and applications.. Formulation of commercialization strategies will benefit from and rely heavily on these market analysis results.

MILITARY MARKETS FOR SOLAR THERMAL ELECTRIC POWER SYSTEMS

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ABSTRACT

The Department of Defense (DOD) is the single largest consumer of engine driven generators. Its procurement is responsive to factors other than first cost. Its non-combat applications are similar to the general market for non-grid power systems which is estimated to be over 2,000 MW/year in the U.S. and 28,000 MW/year worldwide.

The DOD maintains an inventory of over 1,800 MW of engine-generators 15 KW and larger, with an estimated procurement rate of over 140 MW/year. Most current systems are diesel driven, but nearly the entire requirement could be met by advanced heat engines of the types being developed as point-focussing, distributed receiver power plants. A conceptual system consisting of a heat engine which efficiently burns liquid fossil or synthetic fuels, with a "solarization kit" for conversion to hybrid solar operation could meet existing DOD requirements for new systems which are quieter, lighter, and multi-fueled. An estimated 24 per cent (33 MW/year) or more could operationally benefit from the solar option.

Baseline cost projections indicate levellized energy cost goals of 210 to 120 mills/KWh (15 to 1000 KW systems). Fuel cost escalation is the major factor affecting the value of the solar option. A baseline calculation for fuel at $0.59/gal in spring, 1979, escalating at 8 per cent above general inflation indicates a value of $2700/KWe for a solarization kit.

INTRODUCTION

The military power market is of interest in and of itself. The Department of Defense (DOD) is the single largest purchaser of engine driven generators. Its purchase decisions are based on factors other than first cost, and can be responsive to national energy goals. Current systems demonstrate recognized operational deficiencies, providing motives for conversion to a new technology. The services can provide controlled test beds with the support of the military laboratories where even secondary impacts such as parts stockage, training, and reduced fuel transportation can be studied.

The military market is also important because it is a readily defined and relatively centralized segment of the general market for non-grid power systems. According to information developed at the JPL workshop for Potential Military and Related Civil Users of Small Solar Thermal Technologies, civil applications resemble military requirements in duty cycle, environment, and service needs. The plant requirements imposed by non-combat military power applications can, as a first approximation, stand for non-grid electric power applications as a whole. According to a General Motors study, this amounts to over 2000 MW/year in the U.S. and 28,000 MW/year worldwide for systems larger than 35 KW.

MILITARY POWER APPLICATIONS

Application Categories

Military electric power requirements fall into six operational categories. One
of these, electric generators permanently mounted on vehicles, was not considered.
Space limitations would tend to prohibit the use of a solar collector for such
systems. Four operational categories. tactical, theater, isolated, and
emergency power requirements, are now met by diesel or gas turbine driven
generators. Installation power needs are virtually all met with purchased power.
The following table summarizes information by category for systems 15 KW and
larger:

TABLE: INVENTORIES AND PROCUREMENT POTENTIAL

	INVENTORY	PROCUREMENT	SOLAR POTENTIAL	CRITICAL RQTS
TACTICAL	650 MW	81 MW/yr	16 MW/yr	size, weight, RAM*
THEATER	330 MW	17 MW/yr	7 MW/yr	fuel supply, size
ISOLATED	230 MW	11 MW/yr	10 MW/yr	RAM, fuel supply
EMERGENCY	600 MW	30 MW/yr	-----	1st cost, start up
INSTALLATION	**	**	**	life cycle cost

*RAM = reliability, availability, maintainability.
**Installations purchase the approximate equivalent of 5,000 MW generating
capability. A theoretical potential of 250 MW/yr follows. If self
sufficiency for critical requirements were sought, 30 MW/yr market
potential would result based on emergency inventories.

Tactical Power Systems

Tactical power systems are mobile electric power systems which are assigned to
troop units, both combat and rear area. They range in size from 0.5 to 750 KW.
Most systems are smaller than 100 KW. Their standardization, requirements
definition, DOD development, and product improvement are centrally managed by
the DOD Project Manager for Mobile Electric Power. Standard sizes are 15, 30,
60, 100, 200 and 500 KW. Requirements are for utility and precise power at
50/60 or 400 hertz. All are three phase, four wire systems with voltage connections
for 120/208 and 240/416 volts. They are skid mounted, and designed to operate
at temperatures from -65°F to 125 F. Most are diesel driven. A growing
number are gas turbine driven. Fuel cells are under development for sizes
smaller than those dealt with here (0.5 - 5 KW).

DOD is interested in developing power systems that are lighter and more reliable
than current generators. Lower noise and infrared emissions and a multi-fuel
capability are also desired. Advanced Stiling or Brayton engines could meet
these requirements and also be designed to utilize a point focussing solar heat
source, when operationally feasible.

Based on Army holdings, no more than 15 per cent of current inventories (in MW)
are held by units which would operate in the combat area. 22 per cent belong to
non-combat support units or to air defense artillery. 7 per cent are used to
supply power to remote areas in garrison. 16 per cent are estimated to be in

garrison storage. 48 per cent are not specifically accounted for. These include units stored in depots and non-standard items. These estimates are rough, based on incomplete data. Marine Corps usage probably parallels the Army's. The Air Force and Navy should have much higher proportions of non-combat generators.

The average annual DOD procurement for 1979 - 1984 is projected to be 81 MW/yr. Given the available information, it is a reasonable estimate that not fewer than 20 per cent of military tactical generators could use solar concentrators as part of a hybrid solar/multifuel power system. A conceptual system would burn liquid fuel in its standard configuration. A standard "solarization kit" would be issued for integration with the standard engine-generator when fuel saving operation was feasible. The conceptual operational feasibility of such a system was confirmed by DOD engineers at the JPL workshop. There exists therefore a potential market of 81 MW/yr for a standard family of heat engine-generators and perhaps 16 MW/yr for a standard solariztion package.

Theater Power Systems

Theater power systems are large, prime power plants which are transported to a theater of operations for use in a semi-permanent location. Most systems in this category are air mobile. All three major services operate theater systems. They are "owned" by engineer units and are operated for the user under their control or supervision.

The theater-sized power plants are not standardized. Current holdings include 500, 700, 750, 1500, 2000, 2500 and 4500 KW diesel driven systems and 750 and 2000 KW gas turbine driven generators. Output power for all systems is 2400/4160 volts at 60 hertz with a 5o hertz capability. Approximately 40 per cent of Army and Navy systems are in peacetime use. These service inventories total 310 MW. Air Force bare base systems which total 20 MW are not used except when deployed. When in use, these prime power plants have a 24 hour duty cycle.

Transport is the critical requirement for theater power systems. Generators must be mobile and they must be supplied with fuel. The former characteristic tends to inhibit the use of solar collectors. The latter favors it. A conceptual system would consist of hybrid liquid fuel/solar heat engine generators which could be centrally located or dispersed. If the transportability of the engine generators are compatible with current systems' size and weight, the solar collection subsystem can legitimately be compared with the logistic fuel burden. Assuming a 20 per cent fuel displacement, current 750 KW systems would logistically justify solar conversion if deployment is anticipated for more than 120 days.

Current inventories are 330 MW. A 20 year life cycle implies a replacement rate of 17 MW/yr. Peacetime usage rates would justify a solar subsystem stockage of 40 per cent. A reasonable market potential estimate therefore is 7 MW/yr.

Isolated Power Systems

Military isolated power systems are remote permanent facilities which generate their own power. They are typically small (15-1000 KW), and include radar stations, communications sites, island installations and remote test facilities.

A survey was able to identify 88 MW in Air Force installations, 100 MW at Naval facilities and 40 MW at Army communication sites. The USAF total is most nearly complete. The Navy survey included only systems larger than 1 MW. The Army total is incomplete. Possibly twice the tabulated total of 230 MW is in the field.

Military remote facilities may use standard mobile systems or non-standardized generators to meet power needs. Generators are usually diesel engine driven with multiple redundant back up. The key operational requirements for isolated systems are availability and reliability. The Defense Communications Agency, for example, requires 99.99 per cent availability, allowing no more than 53 minutes down-time per year. Reliability requirements drive capital costs for uninteruptible power systems (UPS) as high as $1400/KW. A second important factor is the cost of fuel delivery. This is quite variable. It may involve no more than a 10 mile trip by tank truck or it may involve long distance supply by helicopter or tanker.

The higher cost of fueling isolated power systems and their requirement for multiple back up combine to make them attractive candidates for solar thermal powering. Unlike tactical and theater operations, isolated applications pose few requirements which would inhibit solar powering. Only rarely would the display of a solar concentrator enhance vulnerability. Duty cycles are often continuous and use rates are high.

A hybrid solar thermal power system used in a fuel displacing mode would be operationally valid in all but special cases. A representative conceptual system would include a buffer storage subsystem fed by a solar/liquid fueled heat engine-generator and one or more diesel or heat engine driven back ups. Such a UPS would have close to 100 per cent operational validity, and the potential market approximates the estimated procurement rate. Actual market penetration would be a function of array cost versus annual mean direct insolation.

Based on a twenty year life cycle and tabulated inventories, the estimated minimum procurement rate is 11 MW/yr. This implies a solar potential of 10 MW/yr. Because of the known gaps in the survey, the actual potential market is probably higher.

Emergency Power Systems

The duty cycle requirements imposed by back-up generators are incompatible with solar conversion. A large storage subsystem capable of meeting any short term demand would be required. The storage capacity might as well be operated off the prime power plant. Heat engines burning liquid fuels could be used to meet emergency power needs, but start-up times for such systems would likely be slower than for diesels.

Military emergency/back-up power inventories are estimated to be some 600 MW. A twenty year system lifetime would imply an annual replacement rate of 30 MW/yr. Although the potential market for solar thermal powering is nil, emergency power system inventories may be taken as a first approximation of mission critical power requirements at fixed installations. If self sufficiency of critical military power requirements is sought, both currently purchased power and existing

back-up units could be replaced by solar thermal power systems with modular back up capacity.

Installation Power Systems

U.S. military installations purchase electricity equivalent to approximately 5000 MW generating capacity. Using current DOD guidelines to project costs over 20 years, the equivalent uniform annual cost of power is 86 mills/KWh in 1979 dollars. Critical power needs constitute about twelve per cent of total consumption. A small cost bonus can be realized by replacing both purchased power and back-up.

The question of providing on-site power systems for military installations is primarily a political one. Congress would have to appropriate the capital funds required. Two policy questions will be of importance: 1) Will base self-sufficiency add to the ability of the armed forces to function in time of national emergency? 2) Is the national commitment to replace fossil fuel consumption with alternate energy sources one which warrants using the DOD as a market leader to achieve this goal? Once a political decision is made, the technical requirements are no different than those of civil small communities. Power systems being developed by JPL for the civil sector will meet military needs as well. The total potential market is approximately 30 MW/yr for critical requirements and 250 MW/yr overall.

COST GOALS

There are two measures of interest in determining cost goals for military solar thermal power systems. One is the cost of existing systems. The other is the value of the solar option for a hybrid heat engine. The first value can be calculated using a standard equivalent uniform annual cost equation, with measured data for inputs. The latter is calculated by determining the present value of fuel saved and subtracting out all solarization costs but the first cost of the solar subsystem. The standards of comparison are existing systems for the first value and an advanced heat engine burning liquid fuel for the second.

Cost calculations and sensitivity analyses show that the differential fuel price escalation rate is the critical variable driving costs. The value of the solar option is also a linear function of mean annual insolation as a first approximation.

Cost goals vary with the assumptions underlying projections. In spring 1979, an 11% discount rate, 10% general inflation rate, and 8% differential fuel escalation rate were chosen. The base cost of diesel fuel was $0.59/gal. The resulting base-line cost goals range asymptopically from 210 mills/KWh for 15 KW systems to 120 mills/KWh for systems larger than 1000 KW. The value of the solar option is then $2700/KWe at 1875 hours of annual direct insolation.

It should be noted that the market potentials estimated above are based strictly on operational considerations. Penetration will be a function of system costs compared to local insolation and of the costs of competing alternative systems.

SOLAR THERMAL PLANT IMPACT ANALYSIS
AND
REQUIREMENTS DEFINITION

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ABSTRACT

This paper summarizes progress on a continuing study comprising of ten tasks
directed at defining impact and requirements for solar thermal power systems
(SPS), 1 to 10 MWe each in capacity, installed during 1985 through year 2000
in a utility or a non-utility load in the United States. The prime emphasis
is on the Point Focus Distributed Receiver (PFDR) solar power systems.
Tasks 1 through 4, completed to-date, include the development of a comprehen-
sive data base on SPS configurations—their performance, cost, availability,
and potential applications; user loads; regional characteristics; and an
analytic methodology that incorporates the generally accepted utility
financial planning methods and several unique modifications to treat the
significant and specific characteristics of solar power systems deployed in
either central or distributed power generation modes.

INTRODUCTION

Solar thermal electric power systems have the potential to supply power for
industrial, commercial, institutional, and utility applications and to
reduce consumption of non-renewable fossil fuels. An analysis of the user
impacts and resulting system requirements is essential prior to commercial
acceptability of solar electric systems by both the user and the manufactur-
ing communities. Even for a single application, this is a complex task when
long range financial decisions must be made while the technology is still
evolving and the uncertainty of economic and related environments faces the
power production industry. As a result, several key steps are essential for
the findings of such a study to be meaningful. It is first necessary to
evaluate the current and the future status of solar thermal electric tech-
nology, to identify promising applications, and characterize important site/
region variables. Moreover, these interrelated data must be developed quan-
titatively with appropriate sensitivity limits in terms of system cost/
performance models, load models and characterization of user energy and
financial needs, and models for site/region characteristics including hourly
weather tapes. Then it requires the development of a methodology that is
not only currently fully accepted for system planning by the user community,
but with appropriate modifications it also takes into account the signifi-
cant and unique features of solar power systems and the changing economic,
policy, and user environment. Finally, reliance on achieving these objectives
on the basis of system point designs requiring continual change to fit a class
of applications needs to be minimized because it often involves defining

a priori the system requirements and configuration. The latter, in turn, imposes a lack of consideration of the complex interaction between solar plant, application characteristics, and the overall user system. Some key steps of the study approach by SAI are reflected in Figure 1. This approach incorporates the essential requirements stated earlier and is based on the use of a financial methodology recognized by the utilities but modified appropriately to make it equally applicable to non-utility applications. Thus the optimal system requirements are anticipated to result at the completion of this study—around the second and thrid semi-annual reviews.

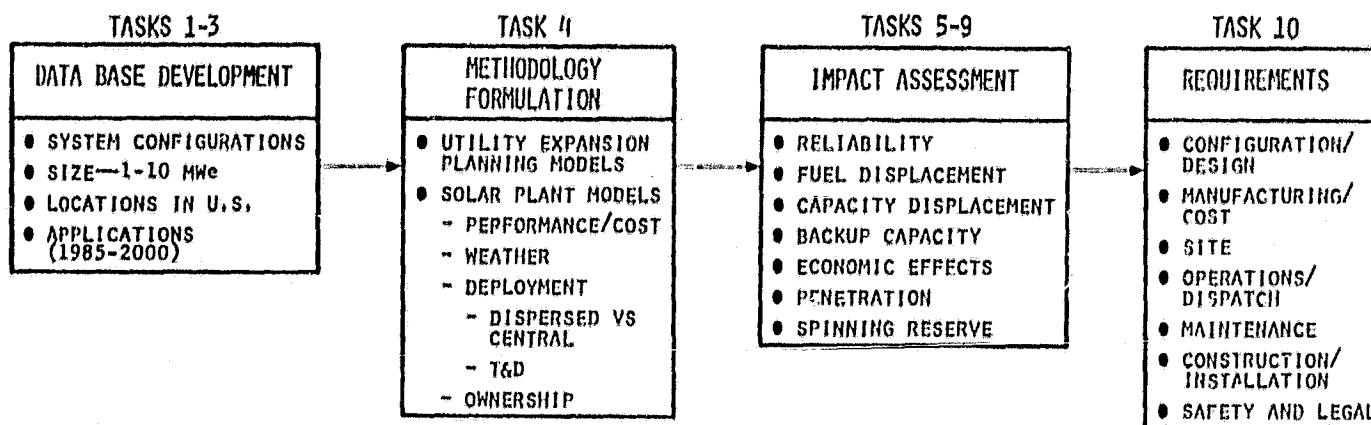| TASKS 1-3	TASK 4	TASKS 5-9	TASK 10
DATA BASE DEVELOPMENT	**METHODOLOGY FORMULATION**	**IMPACT ASSESSMENT**	**REQUIREMENTS**

• SYSTEM CONFIGURATIONS
• SIZE—1-10 MWe
• LOCATIONS IN U.S.
• APPLICATIONS (1985-2000)
	• UTILITY EXPANSION PLANNING MODELS
	• SOLAR PLANT MODELS
	  - PEPFORMANCE/COST
	  - WEATHER
	  - DEPLOYMENT
	    - DISPERSED VS CENTRAL
	    - T&D
	  - OWNERSHIP
		• RELIABILITY
		• FUEL DISPLACEMENT
		• CAPACITY DISPLACEMENT
		• BACKUP CAPACITY
		• ECONOMIC EFFECTS
		• PENETRATION
		• SPINNING RESERVE
			• CONFIGURATION/ DESIGN
			• MANUFACTURING/ COST
			• SITE
			• OPERATIONS/ DISPATCH
			• MAINTENANCE
			• CONSTRUCTION/ INSTALLATION
			• SAFETY AND LEGAL

FIGURE 1.   KEY STEPS OF STUDY APPROACH

To date, the effort has resulted in the development of a data base and a methodology relevant to SPS plant impact analysis and requirements definition. The results of these activities are summarized here.

SOLAR THERMAL ELECTRIC PLANT DATA BASE

The principal elements include collection, analysis, and screening of SPS conceputal designs, subsystems, components, and interfaces on the basis of their technical feasibility and commercial viability; selection of SPS systems with the potential to produce competitive electric power in the 1985-1989 and the 1990-2000 time frame; and development of parametric models for performance, cost, and dispatch strategies.

The emphasis of effort was a priori neither on defining the relative merits of the different SPS configurations nor on defining optimum systems. Rather, it was on providing parametric cost and performance models to be used as inputs to the overall requirements definition methodology. Such an approach is germane to execution of parametric sensitivity analyses deemed to be essential to definition of the optimum system requirements.

Much of the data on SPS parametric performance was derived from information provided by the manufacturers of specific subsystems and related components, from in-house files of Black and Veatch (B&V) and SAI, and from compilations developed by the Jet Propulsion Laboratory (JPL) and project reports completed under JPL, DOE/ERDA, EPRI, and private industry sponsorships. Certain contradictions that exist due to the diversity of objectives that these data were intended to serve were not resolved. Their resolution will require further analysis, design, development, and testing studies.

The SPS systems are characterized by several key subsystems. These include collector (concentrator, receiver), energy conversion, energy transport, and storage/hybrid subsystems. A variety of technologies, currently under investigation for each of these subsystems, and each with its own set of design parameters and cost/performance characteristics, were examined. Moreover, an SPS plant either consisted of multiple SPS modules, each generating about 15-25 kWe (distributed generation), or a relatively larger heat engine powered by thermal energy from a single large collector or a field of interconnected solar collector modules (central generation). Either mode of generation may have a dedicated storage, a dedicated hybrid power source, or a utility hookup.

Specifically, the subsystem alternatives evaluated in this study consisted of collector (concentrator/receiver) subsystem—point focusing distributed receiver (parabolic concentrator, circular Fresnel lens); energy conversion subsystem/thermodynamic cycle—Rankine, Rankine through storage, Brayton (open and closed), Stirling, and combined cycles; storage/hybrid configurations—no hybrid, no storage to both hybrid and storage; and energy transport —thermal/chemical (central generation), electrical (distributed generation). For these subsystem options, there were possible 24 SPS configurations for distributed generation and 48 for central generation. To reduce the number of potential systems, a set of selection criteria were established, which included an analysis of the technical feasibility and "component availability" during the 1985-2000 period for systems in the 1 to 10 MWe range.

Technical Feasibility

The principal considerations for the technical feasibility evaluation of SPS configurations involved interfacing of the inherent performance characteristics and limitations of the subsystems and components comprising the system. For example, a given thermodynamic cycle or heat engine has a specific range of temperature within which it can operate with an acceptable efficiency. Similarly, temperatures in the relevant range of operation of a given thermodynamic cycle may be obtained in a practical sense with only a specific type of solar collector. While, in theory, one has various options available in the energy transport, turbine, storage, and related electric generator and switchgear to be all centralized or dispersed, the inherent requirements of a thermodynamic cycle make one or the other mode of generation impractical. For example, high temperature thermodynamic cycles, such as Brayton and Stirling, could make centralized generation a more costly alternative with

the distributed collector systems when the heat losses, material require-
ments, pumping, and piping for energy transport to a central turbine are con-
sidered. Similarly, certain options, such as thermal storage for an open
Brayton system, are not feasible. The high temperature receiver outlet air
is not a good heat transfer medium. Any attempt to transfer the heat to
another medium, and to subsequently extract that heat into compressor dis-
charge air would tend to result in a large loss in available energy and a
greatly reduced cycle efficiency.

Component Availability

The component availability involved many considerations such as commercial
availability, cost/performance, engineering aspects, reliability, potential
performance improvements and market penetration, and system lifetime. Of
these, three significant factors were commercial availability, cost, and
engineering aspects that involved potential for future performance
improvements.

Commercial availability for different subsystems had to be flexible. Some
systems were commercially available today (1-10 MWe range), while others were
at a stage of development, where commercialization with available vendors,
was clear cut. Finally, certain systems were considered available if commer-
cial prototypes could be produced under fixed-price contracts. This flexi-
bility in component availability was essential to permit answers to the "what
if" questions for technologies that in theory offerred significant potential
for performance and cost improvements in the future. The major subsystems,
where commercial availability considerations were dominant, are the heat
engines and solar collectors.

Commercial availability for solar collector subsystems has a slightly differ-
ent meaning than for heat engine availability insofar as no large-scale com-
mercial production presently exists. Data on these elements were obtained
from published reports and established performance/cost goals of the DOE for
Solar Systems Components. These were considered available since related
hardwares (i.e., the ground based satellite communications antennas) are
commercial items.

Selected SPS System Configurations

A systematic application of the stated selection criteria to the data base
generated resulted in a reduced but yet substantial number of potential SPS
configurations as shown in Figure 2. Use of data developed for application
and regional classification was then made to arrive at recommended SPS con-
figurations for initial detailed analyses.

	BRAYTON OPEN	BRAYTON CLOSED	STIRLING	RANKINE	RANKINE THROUGH STORAGE	COMBINED
DISTRIBUTED GENERATION MODE	● ●	● ●	● ●	● ●		● ●
CENTRAL GENERATION MODE	○	○	○	⊗ X	⊗ X	○

	HYBRID	NO HYBRID
STORAGE	●	●
NO STORAGE	●	●

● ELECTRICAL TRANSPORT
X THERMAL TRANSPORT
○ CHEMICAL TRANSPORT

FIGURE 2. SELECTED SOLAR THERMAL ELECTRIC SYSTEM CONFIGURATIONS

System Performance Simulation/Cost Models

A computerized model, QAG, was developed by SAI and its subcontractor, B&V. The model simulates the performance of solar thermal power plants using hourly meteorological data and subsystem parameters as inputs. The performance of each subsystem is specified by its efficiency defined as the ratio of the output energy to the input energy to the subsystem. The interface between two interacting subsystems is characterized by linking factors which generally depend on the characteristics of the interacting subsystems. The off-design efficiency of each subsystem is expressed as a function of the energy input to it. The product of subsystem efficiencies and linking factors define the performance of the whole power plant.

Since the model performs an hour-by-hour performance simulation, hourly meteorological data are required as provided on SOLMET tapes. The necessary data includes hourly values of sun elevation, sun azimuth, direct normal radiation, barometric pressure, dry bulb and wet bulb temperatures, wind speed, and others. Additional inputs consist of system specification parameters associated with each plant type.

The outputs of the model include hour-by-hour and annual totals of the plant energy distribution, including energy from concentrator, receiver turbine generator, and total plant; energy from and to thermal or electrical storage; fossil fuel consumption for hybrid operation; and efficiencies of the various subsystems. These results are stored on file for subsequent analysis by various expansion planning and/or user load models.

The cost model includes the capital cost and the operations and maintenance (O&M) cost. The capital cost is the sum of the installed cost of each

subsystem and interface components. The direct capital cost is multiplied by a factor which accounts for spares, contingencies, siting, and indirect costs. O&M consist of costs associated with regular maintenance, forced maintenance, and component or unit replacement overhaul.


SELECTION AND FORMULATION OF APPLICATION MODELS

Because of the broad range of potential applications for an on-site, inherently modular, electric source of power such as solar thermal electric power (SPS) systems, it was necessary to quickly screen, rank and select potential applications of 1-10 MWe solar thermal electric power (SPS) systems and formulate a data base characterizing the selected applications in terms of energy requirements, load models, energy costs, geographic distribution, and other factors which affect the use of solar thermal electric power. A broad range of potential applications were investigated in detail, including manufacturing and industrial business, military installations, large and small utility systems, agricultural and irrigation applications, national parks, and minerals and mining industries. In addition, a comprehensive data base was developed which provides electrical load profiles, electrical consumption and cost data, and geographic distribution data required for the impacts analysis of SPS systems.

Total electrical energy consumption in the US was about 2.10^{12} kWh in 1977 for approximately 90 million grid-connected customers. From the average use per customer, it is clear that potential grid-connected applications of 1-10 MWe systems are primarily large commercial/industrial/institutional customers. However, various classes of applications have quite different energy requirements based on their key mission requirements. The profitability orientation of manufacturing establishments, for example, stands in sharp contrast to the defense mission of military installations, or the concern of utilities for reliable power generation. These differing mission requirements imply different concerns and issues for solar thermal electric power systems and dictated different approaches for analyzing the various application categories. An analysis of a range of applications and user types was completed to identify key variables affecting the system requirements definition and to develop representative load profiles. Figure 3 shows an example of a typical load profile for a generic class of applications.

Utilities provide a majority of US electric energy demands and hence represent the largest single potential market for SPS systems. Several recent studies have developed a number of synthetic utility models with typical load profiles, generation mixes, and transmission networks. These models form the baseline utility systems used in subsequent analysis.

Industrial applications represent a favorable SPS market because of large size and energy consumption, familiarity with large equipment characteristics, availability of maintenance and operating personnel, and access to the large capital funds required for SPS investment. The key factor determining the viability of SPS is expected to be cost effectiveness.

NORMALIZED CUSTOMER DEMAND

TIME OF DAY
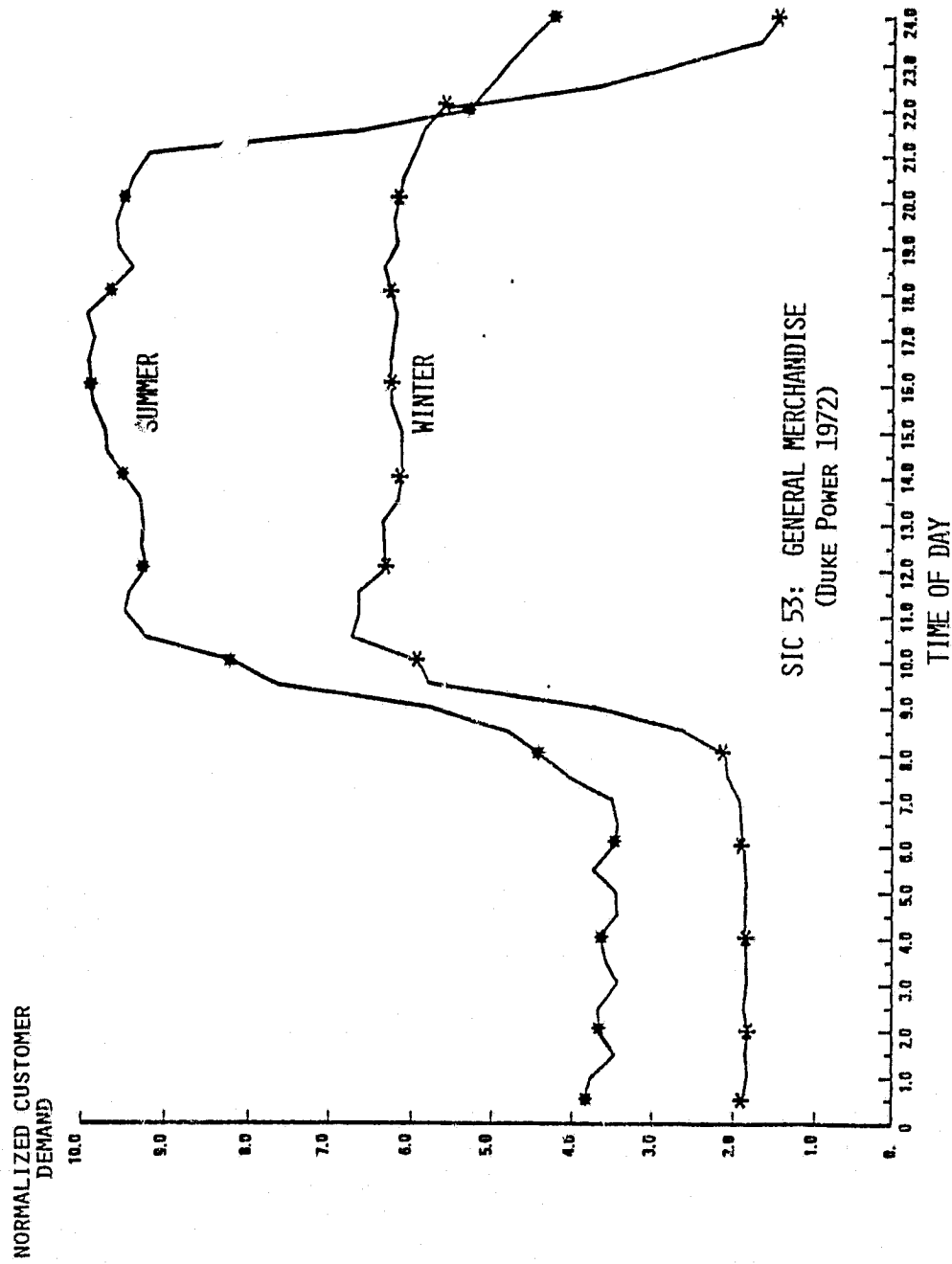
SIC 53: GENERAL MERCHANDISE
(Duke Power 1972)

FIGURE 3. EXAMPLE OF SINGLE-DAY DEMAND PROFILE

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A detailed analysis of industrial applications was performed based on energy consumption, electricity costs, load shapes, insolation, and representative solar system performance and costs. For each 3-digit SIC code and state, the profitability of solar investment was calculated, and the resulting energy displaced was estimated based on user load shapes and conservative system sizing (turbine/generator output no more than average daytime demand). Specific industry-state combinations looked attractive because of high electricity costs and/or high insolation, with total market size also playing an important role. Land availability, also a key factor, was not addressed because of insufficient data; nominal land costs were used.

Military installations have large potential for application of SPS because of the availability of funding if mission requirements are met, the orientation towards long-term economics, the desire to be independent of utility outages, and the availability of manpower for operation and maintenance. In addition, military installations provide requirements that are quite different from the profitability orientation of industries.

Other applications which were investigated included national parks, agriculture and irrigation in particular, and various other potential applications of 1-10 MWe SPS systems.

REGIONAL CHARACTERIZATION

The desired properties of a useful regional characterization are homogeneity among important physical and demographic parameters and ease of use in applying the categorizations to an assessment of the suitability of generic SPS types and loads. The diversity of climatology and demography required some compromises. The dominant parameters were direct insolation and the cost of electrical energy to industrial users. The basic regional divisions were structured within the constraint of geographical contiguity of states and yet providing the maximum degree of homogeneity for a cost/effectiveness index defined as the product of the average annual insolation and the industrial electrical utility cost per kWh. Seven regions were defined to characterize the United States. In certain of these regions geographically non-contiguous states had to be included.

Water resources, wet and dry bulb temperatures, and wind velocity were characterized for the regions, and were found to be reasonably homogeneous within the boundaries determined by the dominant parameters. Many of the characterizations in the western states were site-specific because of the irregular topography, but no scheme limited by a small number of regions can accommodate such irregularities. The characterizations are presented in three forms—graphic presentation of contours for first order assessments, tabulations of monthly averages by regions and subregions for use in approximation of system performance, and hourly typical meteorological year (TMY) records for detailed simulation. The hourly records are SOLMET-TMY tapes for 25 US sites plus two synthetic tapes developed by SAI to represent major portions of regions not adequately covered by SOLMET records. Figure 4 shows recommended system configuration/application/site combinations for subsequent analyses.

PFDR PLANT CONFIGURATION	APPLICATIONS	UTILITIES				INDUSTRIES		
		EPRI SYSTEM F	EPRI SYSTEM B	EPRI SYSTEM E	35 MW COOPERATIVE	3 SHIFT PRIMARY METALS	1 SHIFT WOOD PRODUCTS	MILITARY BASES
DISTRIBUTED GENERATION	BRAYTON	BOSTON	SANTA MARIA FRESNO ALBUQUERQUE	FORT WORTH	FORT WORTH*▲ BOSTON	BOSTON SANTA MARIA		YUMA*
	STIRLING	BOSTON	ALBUQUERQUE SANTA MARIA FRESNO	FORT WORTH	FORT WORTH	BOSTON SANTA MARIA	BOSTON SANTA MARIA	BOSTON SANTA MARIA
	COMBINED	BOSTON	SANTA MARIA					
	BRAYTON WITH HYBRID	BOSTON	SANTA MARIA					YUMA*
	RANKINE WITH STORAGE	BOSTON	SANTA MARIA			BOSTON SANTA MARIA		
CENTRAL GENERATION	RANKINE WITH HYBRID							
	ORGANIC RANKINE NO HYBRID NO STORAGE				FORT WORTH*			

*ECONOMIC AND BACK-UP IMPACTS TO BE COMPLETED BY 1 APRIL 1980

▲NO HYBRID, NO STORAGE

FIGURE 4. RECOMMENDED SYSTEM CONFIGURATION/APPLICATION/SITE COMBINATIONS

SOLAR ELECTRIC POWER SYSTEMS IMPACT ANALYSIS METHODOLOGY

SAI has developed a methodology which evaluates the impacts and economics of grid-connected solar electric technologies within the overall utility context. The model provides a comprehensive analysis of the impacts of different solar electric technologies on the utility, and estimates the economic value of the solar plants to the utility, dispersed user, and/or third-party investor. The final output of the model is a set of estimates of the break-even cost for solar electric technologies under different assumptions about ownership, payback period, and return on investment. An overview of the model is shown in Figure 5. The overall assessment methodology involves five separate model segments—hourly simulation of solar electric system performance; utility load projection and adjustment for the output of the solar plants; capacity expansion and mix adjustment for conventional utility generation; production costing for the resulting conventional utility mix; and finally, economic analysis of the solar plant value under different ownership alternatives. Because of the extensive calculations that are involved, the models have been implemented with a modular structure so that analysis runs can be made independently of the others. The various model segments are described as follows.

Solar Electric System Performance Models

The solar electric performance models, briefly described earlier, simulate the hourly output of various solar technologies. Separate models are available for photovoltaic, solar thermal electric, and wind systems. The simulation model used for solar thermal electric power systems is QAG. At each hour, QAG computes steady-state energy balances; tracking losses; cosine losses; blocking and shading; reflectivity (or transmissivity); surface error losses; receiver intercept factors; receiver absorptivity, re-radiation, and convection losses; thermal transport losses; storage or hybrid energy flows; and part-load turbine generator efficiencies. Outputs consist of the annual energy flows to/from various subsystems, overall plant performance summaries, thermal energy credits (where applicable), and hourly electric output files for total generation and energy consumed on-site. The model outputs can be used directly for systems analysis and design trade studies, or the hourly output files can be attached for input to subsequent analysis models.

Load Adjustment Model

The load adjustment model estimates the impact of the solar electric generation on the overall utility loads. The original loads for the utility are first projected to the time span of interest, and then the outputs of the solar electric plants are subtracted on an hourly basis, taking into account the transmission and distribution benefits of on-site generation. Solar plant outputs are scaled by the number of units and capacities of the
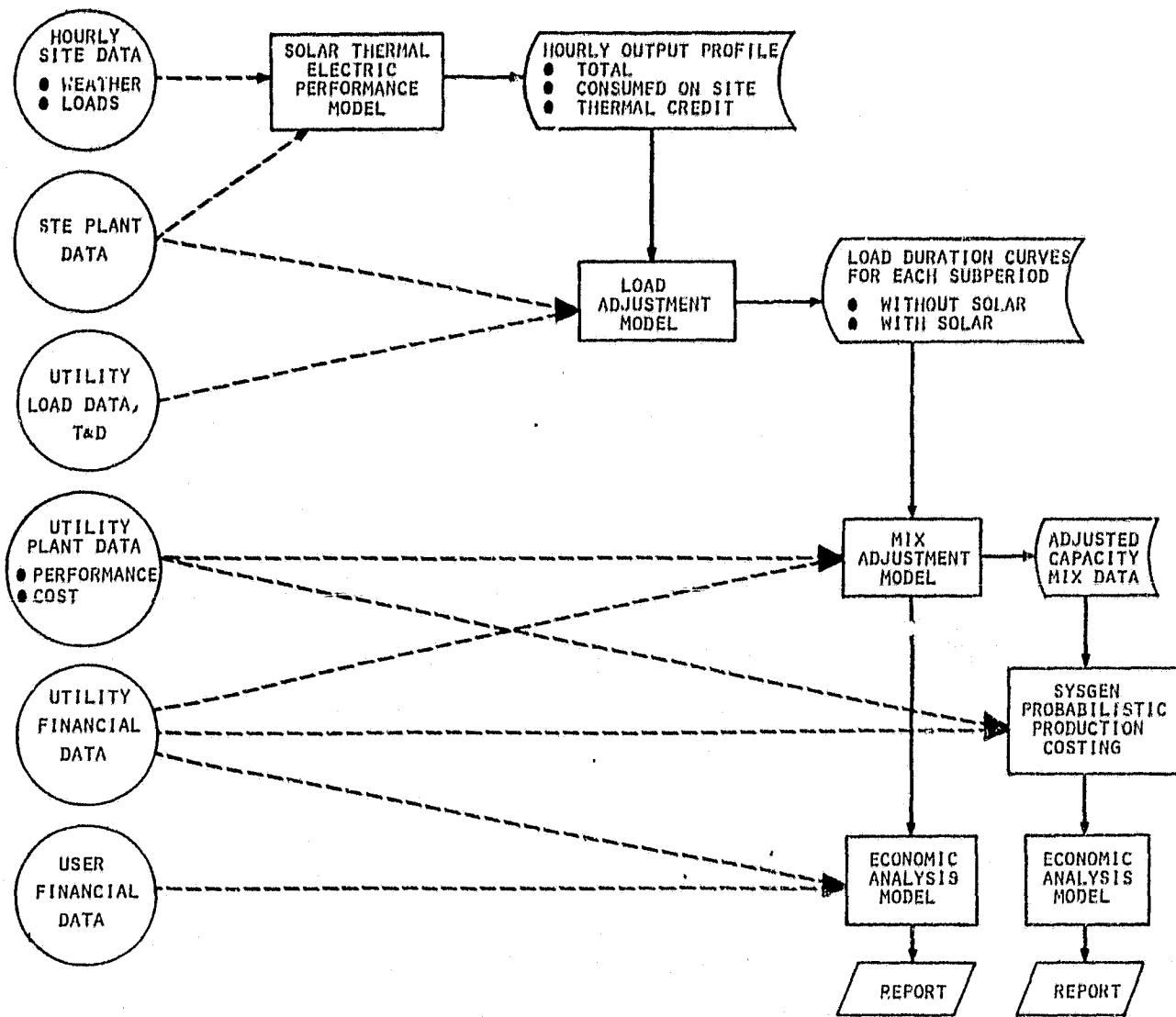
FIGURE 5. SOLAR ELECTRIC POWER SYSTEMS IMPACTS AND INTERACTIONS

various solar systems, and then their hourly outputs are subtracted proba-
bilistically in the sense that various combinations of solar plant outages
are considered at each hour in accordance with the forced outage probabilities.
The hourly results are then accumulated in the form of load duration curves
for each month or season. These load duration curves are stored for both the
original load projection (without solar) as well as for the solar-subtracted
loads. This provides a non-solar reference case which is carried along with
the solar case throughout the remaining analysis, so that the differential
impacts of the solar generation can be accurately measured.

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Mix Adjustment Model

The mix adjustment model performs a capacity expansion analysis to determine the type and number of conventional generating units which should be added to the existing utility mix to meet projected electric demands at minimum total cost. This analysis is performed for both the solar case and the non-solar reference case. Inputs for the analysis include the existing utility system generating plants; the available plants for capacity expansion; characteristics of each plant type, including rated capacity, minimum operating levels, fuel type, heat rates, forced outage probabilities, maintenance requirements, fixed capital costs, and variable O&M costs; utility economic data, such as fuel costs, escalation rates, taxes, discount rate, insurance, etc.; and projected utility load data in the form of seasonal or monthly load duration curves both with the without solar.

The usual approach to utility mix optimization is to use a screening curve analysis which does not account for the previously existing plant mix of the utility, the discrete sizes of the available plants, the minimum operating levels of the plants, the spinning reserve requirements to maintain available capacity for meeting sudden load increases, or the probabilistic forced outage characteristics of the various plants. SAI has formulated the basic capacity expansion problem as a mixed-integer linear programming problem which is solved using a standard linear programming package with branch and bound techniques for the integer variables. The objective function of the linear program is to minimize the present worth of total fixed plus variable plant costs. The solution of the linear program provides the basic capacity expansion plan; however, it assumes de-rated plant capacities without accounting explicitly for the probabilistic nature of plant forced outages. This is performed in a subsequent analysis step, which estimates loss of load probability (LOLP) using a Gram Charlier-Fourier transform series expansion technique to rapidly evaluate convolutions of the demand and plant outage random variables. Peaking capacity is then added or subtracted from the generation mix to meet the required LOLP reliability criterion. Finally, a maintenance schedule is estimated by removing plants according to maintenance requirements so as to levelize the reserve margin defined as total available plant capacity (minus peak demand) over all months. The final output of the mix adjustment model is the adjusted capacity mix (both with the without solar), the estimated annual production costs for each generator type and fuel type, and an estimate of the present worth of revenue requirements for the utility.

Detailed Utility Production Costing Model

A detailed probabilistic production costing model, SYSGEN, is used if necessary to provide a refined estimate of production costs based on the modified load duration curves and the optimized conventional capacity mix for both the system with solar generation and the reference system with no solar generation. SYSGEN uses the standard Booth-Baleriaux algorithm to account for plant outages, in which the effective load duration curve seen

by each generator (or valve point) is expressed as the original load duration curve plus the random outages of previous generators in the loading order. The successive load duration curves are computed using a recursive technique to perform the required convolutions.

Economic Analysis Model

The outputs of either the mix adjustment model and/or the detailed production cost model are then used to provide estimates of the breakeven costs of the solar plants for utility, on-site user, and third-party investor/ownership alternatives. Additionally, the economic analysis can calculate the net present worth of the solar systems for various solar plant cost assumptions. The key assumption of the economic analysis is that the rate structure applied to solar system investors will reflect the difference in cost of electric service to this customer class, so that the overall savings provided by the solar plants are passed on to the investor.

ACKNOWLEDGEMENT

A STUDY OF MASS PRODUCTION AND INSTALLATION
OF SMALL SOLAR THERMAL ELECTRIC POWER SYSTEMS

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ABSTRACT

This study of concentrating collector industrialization included
technological constraints, materials availability, production capacity,
and manufacturing and installations plans and costs at different
production levels. Several constraints were identified.

Cobalt, for the engine and receiver, is supply limited. Alternative
lower temperature alloys and higher temperature materials (ceramics) are
discussed. Economics and production efficiency favor co-location of
cellular and thin glass production for reflectors. Assembly and
installation are expensive for small sites and few alternatives exist to
apply mass production techniques to lower these costs for the selected
design. Stepping motors in the size and quantities required are not
commercially available today but could be in the future.

The study concluded that additional development should be concentrated on
design modification to permit industrialization of the assembly and
installation process, the use of alternative materials in the
engine/receiver subsystem, the design of motors and gearboxes matched to
concentrator requirements, and development of an integrated process for
reflector production.

PROJECT DESCRIPTION

This project is based on a conceptual design of a concentrating solar
collector system developed by Jet Propulsion Laboratories. The hardware
elements of the system were divided into four basic component packages:

- Power Conversion Component -- including the
  receiver, engine, and generator units.

- Reflector Component -- including second surface
  "thin" glass mirrors, cellular glass support gores,
  and mounting hardware.

- Structure and Foundations Component -- including
  receiver and engine support structure, reflector
  support ring structure, ballast support structure,
  intermediate structure, pedestal, pedestal
  foundation, and intermediate structure track and
  foundation.

●   <u>Drive and Control Component</u> -- including the
elevation actuator, azimuth drive, two-axis shadow
band sun sensor, on-board controller, and power
communication connections.

Each component was described in terms of the process steps and materials
and equipment needed for the manufacture of 5,000, 50,000, and 500,000
concentrators per year. The transportation requirements from points of
manufacture to installation sites and the on-site assembly and
installation processes and techniques were also developed. Based on the
criteria established for concentrating collector systems, the maximum
size of any one site would be 500 collectors or approximately 10
megawatts electric.

INDUSTRIALIZATION ISSUES

<u>Materials-related Issues</u>

In the course of the analysis two components of the system were found to
be resource limited -- the receiver and buffer storage units of the power
conversion package and the stepping motors and generator of both the
drive and control and power conversion components. In both instances
cobalt was the material in short supply that would tend to limit
industrialization.

The receiver and buffer storage units use cobalt in a high-temperature
superalloy called Haynes 188. At the intermediate volume level, 50,000
units per year, the concentrator manufacturer would use 27% of domestic
cobalt consumption; at 500,000 units per year the requirement would be
83% of the world's annual use. Since the dedication of these quantities
of cobalt for concentrator systems is unrealistic in view of the current
priority uses of cobalt, two other high-temperature alloys were
investigated and found to be practical if the design temperature were
lowered by 100°F. These alloys are Inconel 601 and Incoloy 800H.

In addition to being commercially available in the necessary quantities,
these alloys possess two other advantages; they are considerably less
expensive and more workable than the cobalt alloy. In the longer term,
ceramics -- particularly sintered silicon carbide and hot pressed silicon
nitride -- offer both cost and higher operating temperature advantages.
However, 10-20 years of research and development will be needed to
develop the strength requirements necessary for solar applications and
the processing technology to obtain net or near net shapes in ceramic
products.

The generator in the power conversion component and both of the stepping
motor drives use cobalt in their permanent magnets. Although the
quantity of cobalt in any one unit is relatively small, at the higher
volume levels the total material requirement is significant. However,
alternative designs using wound coil units have been designed and

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produced commercially. Although such units carry a premium cost, they have an offsetting advantage of being capable of higher torque than units currently produced with permanent magnets. Higher torque drives, in turn, permit simplification of the gear drive units without significant degradation in the pointing accuracy of the drives.

Process Technology Issues

Although the manufacturing technology for all of the components of a concentrating collector system exists in industry today, two important developments must still be made. In the case of the power conversion component, the majority of the elements, although similar to automotive, aircraft, or gas turbine technology, contain one or two differences which will limit volume production. The first is industrial capacity. For the cellular glass gores, the thin glass reflector, the engine recuperator, receiver, and buffer storage units and stepping motors, industrial capacity exists to fabricate the units needed for the collector system at the 5000 unit annual volume but not at the 50,000 unit per year level. In some instances, such as for reflectors, it can be argued that the separate locations of existing industrial production are inappropriate for the process needs of solar collectors. Nevertheless, in virtually every instance the potential fabricators of the units or subsystems would be drawn into plant and equipment investments based on the growth of viable collector system business.

A separate problem exists for components such as structures and foundations. The components of a collector system are by design high bulk-low value elements. As a result, it is highly desirable, indeed necessary, to subcontract or otherwise locate the production facilities for these components on a regional basis to minimize transport costs. At higher volumes of production this poses little if any problem but at the lower end of the volume scale, transportation costs represent an impediment to industrialization.

Site-specific Issues

The conceptual design of the concentrating collector employs an 11-meter diameter dish, long and heavy structural components, and components such as reinforced precast concrete foundations and drive, control, and power conversion packages that are unlikely to be fabricated in the same production plants. As a result large concentrator systems are not transportable when fully assembled; therefore, a site assembly process is required. In addition, since alignment of the reflector panels, engine, and sun sensing mechanism is critical, a portion of the assembly process on site must be conducted in a protected environment. When this factor is combined with the relatively small number of units to be located at any one site, the result is not only a relatively costly assembly and installation charge but also an essentially flat cost curve relative to increasing annual production volumes.

Concentrator Costs

A summary of the costs associated with an installed collector is contained in Table 1 below.

TABLE 1

SUMMARY OF COMPONENT AND PROCESS COSTS FOR
THE CONCEPTUAL DESIGN OF A CONCENTRATING SOLAR COLLECTOR

	Per Unit Costs in Third Quarter 1979 Dollars		
	5,000 Concentrator Units/Yr	50,000 Concentrator Units/Yr	500,000 Concentrator Units/Yr
Power Conversion Component	$25,250	$12,300	$ 6,925
Reflector Component	2,136	1,747	1,747
Structure, Foundation, Assembly, and Installation	16,080	12,706	12,592
Drives and Controls	5,366	4,174	3,656
Installed Cost/Concentrator	$48,832	$30,927	$24,920

As can be seen, the components which are produced in traditional
manufacturing plants such as the power conversion package, drives and
controls, and reflectors demonstrate cost reductions with increasing
volume. Costs for the structures, foundation, assembly, and
installation, however, are relatively constant at high and intermediate
volumes and are sharply increased at low volumes due to the higher costs
of fabricated structural elements and transportation and limited
applicability of "mass production" techniques.

AREAS FOR FURTHER RESEARCH

Since the conceptual design for a concentrating collector system is but
the first in a series of designs, the costs estimated in this study
should be utilized as an indication of where effort should be expended to
achieve cost reductions rather than as absolute or immutable values.
Based on these costs the primary benefits of redesign efforts or of
alternative designs may be experienced by increasing the
industrialization associated with structures, foundations, assembly, and
installation. Three possibilities suggest themselves:

- Smaller concentrators which require less field
  assembly and installation processing may permit
  reductions in cost with increasing volume.

- Larger sites of up to and over 50 megawatts electric
  will favor mechanization and automation of site
  processes and tend to drive costs lower.

- Alternative designs that permit subassembly of
  component parts of a collector system in the
  fabrication plants will permit reductions in
  site-related activities and, more importantly, will
  tend to retain collector costs on an experience
  curve related to volumes produced.

In addition to the points indicated above, other components of the
collector system will either require or benefit from further development
activity. These include:

- Directed development of ceramics for the receiver
  and buffer storage units.

- The involvement in the engine development program of
  alternative suppliers to increase the source
  availability.

- Co-development of drive motor and gearbox packages
  matched to meet both the torque and accuracy
  requirements of a collector system.

- Integrated process development for complete
  reflector panels. This would include gore
  fabrication and shaping, "thin" glass fabrication
  and mirroring, lamination of the two components,
  sealing, hardware installation, and environmental
  testing.

SESSION VII
TROUGH AND BOWL SYSTEMS

THE CROSBYTON PROJECT

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ABSTRACT

The occasion of this meeting was a Big Event for the Crosbyton Solar Power Project. The project both hosted the meeting and used the occasion for the first test of the ADVS, the largest single solar collector ever built. This project represents the only American work on the Bowl Concept, which Texas Tech refers to as the Solar Gridiron Concept. The concept is unique among the concentrating/tracking concepts in that it employs a stationary mirror to reduce cost. Tracking is accomplished by moving the receiver/boiler. The ADVS gridiron mirror forms a 120° arc of a sphere, surfaced with 430 curved panels, each about 1 m x 1 m. The aperture diameter of the dish is 65-ft. The preliminary system performance agrees with predictions and expectations. The mission of the project is to determine the feasibility and utility of building a 5 MWe solar-fossil fuel hybrid electric power plant employing the Solar Gridiron Concept, and, should the technical basis warrant construction, then to establish such a power plant at Crosbyton, Texas.

The Crosbyton Solar Power Project has hosted this meeting for Texas Tech and the U. S. Department of Energy. This has been a great privilege for several reasons. In particular, it offered us the opportunity to exhibit our Analog Design Verification System (ADVS), including the largest single solar collector ever built. The only problem with the exhibit was that it was not complete! In parallel with our efforts to make this a meeting that you would enjoy, we were trying very hard to complete the system and ready it for a demonstration. Intensive effort went into the site, particularly during the thirty days immediately preceeding the meeting. Frankly, we wanted to try the system out in private, before a public demonstration-particularly in front of a "public" like you fellows.

By nightfall last Thursday, January 17, 1980 the ADVS had finally reached the point where it could be tested to see if it could make steam. The sun passed into clouds at sunset. There was no sunlight Friday, only clouds. There was no sunlight Saturday, . . . or Sunday, . . . or Monday. Time had essentially run out; this meeting would begin Tuesday morning. The meeting, targeted as an opportunity to show off the world's largest single solar collector, had come, and the ADVS was untested!

The crowning blow, after the four long days of waiting for the sun, came at 3:30 a.m. Tuesday, January 22: the snowfall began. I know well when it started to snow; I was driving through Crosby County on the way home from the

site. Tuesday morning and the USDOE meeting began with 6 inches of snow on the ground and a totally overcast sky.

Several USDOE officials, who could only be away from Washington for the one day, Tuesday, were driven to the Crosbyton site on Tuesday afternoon to, at least, see the hardware that they had funded: the largest single solar collector ever built. At that time it had collected only snow, never any solar power. As the van pulled into the site parking lot, a pale disk of the sun glimmered through the clouds. There might be an opportunity to test the system! Should an untested system be tried under such poor weather conditions, so late in the day (about 3:30 p.m.), in front of such distinguished visitors? Who knows what should have been -- it was! Following steps, rehearsed only mentally, the work force set up to try, not just for the first hot water ever produced, but to try for steam.

By 4:15 p.m. the system was ready for the attempt. The sun was doing much better, but was hazy and low in the sky. A foot of snow covered the bottom of the giant bowl. Upper mirror panels were caked to a lesser degree with snow and glittered with ice. Sixteen mirror panels were covered with plastic, frozen to the glass. The receiver had to be swung up two feet above the rim of the dish to acquire the sun. [Sometimes, your self-confidence has to be tested.] At 4:20 p.m. January 22, 1980, the system produced 500°F, 500 psi steam. The first scrimmage had taken place at the Solar Gridiron. Texas Tech and its subcontractor E-Systems had done it, had at least brought the system to operational status.

A second decision was required: should the demonstration, long pre-scheduled for 3:30 p.m. Wednesday, January 23, be attempted in front of the entire USDOE meeting attendance? [Your self-confidence will be tested more than once.] The two Greyhound buses and four vans, bringing you fellows, arrived at the site a little late. One bus had missed a turn, had gotten stuck in roadside mud, had been pulled out by former Crosbyton Mayor Snodgrass' son with a tractor, and arrived somewhat after 3:30 p.m. Somehow the word of a "first test" had spread through Crosbyton and Crosby County. The longest parade of pick-up trucks, vans, cars, ambulances, and school buses in memory, appeared, as if by magic, and covered every parking place for a quarter of a mile. Two separate, but well-mixed audiences were present. A crowd of approximately 300 people had come to the Solar Gridiron.

All was ready, the sun was bright in a crystal clear sky. [One lady from Crosbyton has prayed all night for a clear sky so we could have our chance. She was there, and there were tears in her eyes.] The receiver was swung to the correct position, the focal region of the dish. The receiver lit up with incredible brightness for the first time ever and steam came forth. Without any doubt, steam was produced. Santa Fe Railroad had loaned a steam whistle to the project. Before 300 witnesses the whistle began to spit and sputter; then it sounded and released its cloud of steam into the clear air. [At least it looked like a cloud to us, remember?] The first game had been played at the Solar Gridiron and you had Complimentary Tickets.

DANGER
DO NOT
ENTER

[Since this is the kind of paper that obviously could not have been written before my talk was given on Thursday morning, January 24, I will admit writing it later by inserting some anachronisms and describing what may appear to be future history.] Two days later, on Friday, January 25, the project work force made its first effort at "design condition steam": 1000°F at 1000 psi. Design condition was easily achieved! The week in review: Tuesday morning, it might work; Wednesday morning, it will work; Thursday morning, it does work.

Following the week of the meeting in late January, sixteen of the next eighteen days brought no useful sun. You fellows were here at the "right" time, as it turned out. Although our work force was under considerable pressure, it was a "right" time for us, too. You fellows had a rare experience that you may never have again: you got to watch somebody else's system being born in public. Sure, we were nervous, but you should have been also. You were the first to stand by those lines bearing live steam!

The ADVS is a scaled down (65-ft) version of the ten 200-ft mirror paneled dishes planned for an electric power plant at Crosbyton. Construction of the 65-ft dish was begun in July of 1979, but the project has been in the works since 1974. When the City Council of Crosbyton, Texas became alarmed with the high, and rising, prices of fossil fuels, T. J. Taylor (then mayor pro-tem) and Norton Barrett (City Secretary), and Bob Rhodes, Chamber of Commerce President, came to Texas Tech University to find someone interested in Solar Research. They were directed to me, a Professor of Electrical Engineering. Several ideas were discussed, and we finally decided on the Solar Gridiron Concept. The next step was Washington, D. C. Mr. Taylor, Mr. Barrett, Mr. Rhodes, and Dr. Stan Liberty (also a Professor in E.E.) and I went to Washington to talk with the ERDA, now USDOE. The project received $2.5 million in 1976 to begin the necessary research to bring this dream to a reality. I have served as Project Director since the beginning and Dr. Herb J. Carper of the Department of Mechanical Engineering has been Project Manager since 1977, replacing Dr. Liberty. The Administrative Coordinator is Travis L. Simpson, whom you should all remember.

What makes the Solar Gridiron or Bowl Concept different from most concentrating/tracking solar concepts is that the mirror panels are fixed in place, and the receiver tracks the sun. The ADVS receiver, which is cylindrical in shape is wrapped with 2 black tubes. Through these tubes flows water, which because of the sun's concentration on the receiver, is heated to 1000°F steam. In a full scale system, the steam would then turn a turbine to produce electricity. If data from the ADVS proves, as expected, that the design is sound, then construction of the 200-ft dishes could begin as early as 1981. The preliminary optical to thermal conversion efficiency measure is coming in right on the expected levels. The dream is still there, and you were there!

IEA/SPS 500 kW DISTRIBUTED COLLECTOR SYSTEM
by

Temple W. Neumann and Creighton D. Hartman

ABSTRACT

This paper reviews the results of engineering studies for an International Energy Agency (IEA) project for the design and construction of a 500 kWe (net) solar thermal-electric power generation system of the Distributed Collector System (DCS) type. The project is part of the IEA Small Solar Power System (SSPS) Project, and is being constructed as a demonstration plant in the province of Almeria in Southern Spain.

The DCS system design was completed by a 10 nation team headed by Acurex Corporation, a U.S. firm. Construction is presently underway. The design consists of a mixed field of parbolic trough-type solar collectors of both German and U.S. design which are used to heat a thermal heat transfer oil. Heated oil is delivered to a thermocline storage tank from which heat is extracted and delivered to a boiler by a second heat transfer loop using the same heat transfer oil. Steam is generated in the boiler, expanded through a steam turbine, and recirculated through a condenser system cooled by a wet cooling tower.

NOMENCLATURE

Symbols:

A_c = net collector area, m^2

c_p = heat transfer oil specific heat at average temperature

Δt_i = difference between the inlet and outlet temperatures of collector heat transfer oil

ΔT = mean fluid temperature in collector minus ambient temperature ($260°C - 15.8°C = 244.2°C$)

$\eta_{p.G.}$ = efficiency of power generation system

$\dot{m}$ = mass flow rate, kg/second

η = efficiency

ω = hour angle (solar noon is zero)

ϕ = latitude (north positive)

Q = rate of heat absorption by receiver tube

q_i = incident insolation, watts/m^2 collector

R_B = ratio of beam radiation on the reflector aperature to that on a surface normal to the beam

δ = declination (north positive)

INTRODUCTION -- THE IEA-SSPS-DCS PROJECT

The Small Solar Power Systems (SSPS) project is a program of the International Energy Agency (IEA). The program is intended to provide a solar-electric design suitable for both industrialized and developing countries in the range from 50 kW to 5 MW through a modular approach. The demonstration plant is presently under construction in the province of Almeria in Southern Spain. The Operating Agent for the IEA on the project is the Deutsche Forschungs- und Versuchsanstalt fur Luft- und Raumfahrt e.V. (DFVLR) a scientific and research agency of the German government. A consortium of Acurex Corporation and Tecnicas Reunidas (Spain), supported by subcontractors from eight other participating countries, conducted the detail design studies which are presented in this paper. The construction phase is being performed by a consortium of Acurex Corporation, M.A.N. Neue Technologie (Germany) and Tecnicas Reunidas with the support of firms from other participating countries.

The essential requirements for the design were:

1. Net output of 500 kW electrical at an insolation of 920 watts/m^2
2. Energy storage capacity of 0.8 MWh
3. Variable output from 10 percent to 100 percent of capacity whether grid-connected or operating independently of the electrical power grid
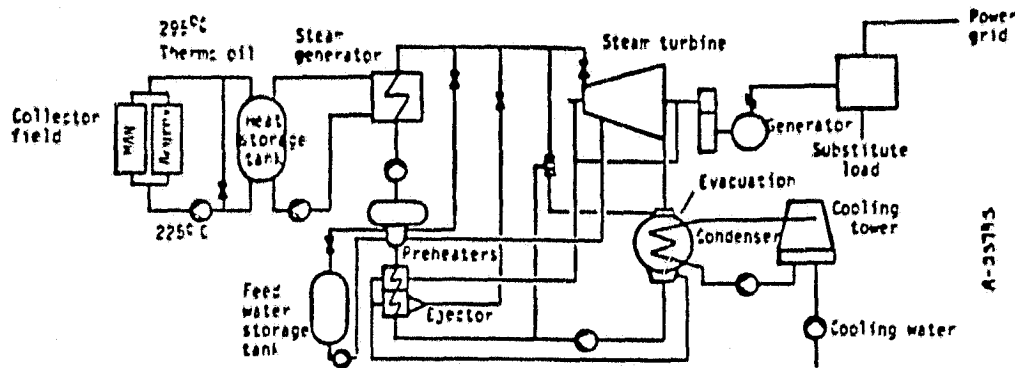4. 2000 hours of operation annually at rated output

Figure 1. 500 kWe solar electric power generation
system.

GENERAL ARRANGEMENT

The major subsystems for the DCS consist of the following, collector field, energy storage system, power conversion system, master control/data system, electrical system, roads and buildings, auxiliary equipment.

Two collector fields of approximately equal size are planned, with a total collector area of 4904 m². One field is made up of 10 loops of 48 collectors of U.S. design manufactured by Acurex Corporation and the other field is made up of 14 loops of six collectors of German design manufactured by M.A.N. Neue Technologie. The Acurex collector is single-axis tracking with the rotational axis oriented east-west. The M.A.N. collector employs two-axis tracking. The entire plant is fitted into an area 210 m east-west by 168 m north-south, including thermal storage and equipment. The system has been designed with three heat transfer loops. The first loop extracts low-temperature heat transfer oil from the bottom of the thermal storage tank, circulates it through the collector fields and returns it to the top of the storage tank. This decouples the solar fields from the power generation cycle but the power generation equipment can also be run directly from the collector fields if desired. (This connection is not shown on Figure 1.) The second loop extracts hot oil from the top of the storage tank, circulates it through the boiler and returns it to the bottom of the storage tank. The third loop circulates water through the boiler and then expands the steam through the turbine to extract energy for electrical power generation. The cycle is completed by condensing the expanded low-enthalpy steam and pumping the condensate back to the boiler. The thermal energy is converted to electrical energy by means of the steam turbine power conversion module (PCM). The process flow diagram, Figure 1, illustrates these loops.

The thermal energy is stored in an insulated tank 4.2 m inside diameter and approximately 15 m high, located near the power generation building. Various pumps, valves and auxiliary tanks are also located in this mechanical equipment area.

DESIGN ANALYSIS

System Sizing

The system design emphasized minimum capital cost; life-cycle costing has been performed but was not the primary criterion for equipment selection. Because of the high installed cost of solar equipment, the difference in optimization between a system based on life-cycle costs and one based on minimum capital cost is minimal.

The collector field size was calculated on the basis of parabolic trough concentrating collectors with glass reflective surfaces. The collector efficiency parametric equations used were as follows:

Acurex Collectors: $\eta = 0.756 - 0.57 \frac{\Delta T}{q_i}$

M.A.N. Collectors: $\eta = 0.685 - 0.435 \frac{\Delta T}{q_i}$

The design point was taken as the equinox noon condition, when the insolation is 920 watts/m². The incidence factor for both the Acurex and M.A.N. collectors is unity at the equinox noon design point. The calculated efficiencies are:

Acurex $\eta = 60.5$ percent
M.A.N. $\eta = 57.0$ percent

From these efficiencies, the field flowrate per loop is calculated so that the outlet temperature will be the desired 295°C.

$$\dot{m} = \frac{\eta q_i A_c}{\eta c_p \Delta t_i}$$

Acurex area = 267.7 square meters per loop
M.A.N. area = 192 square meters per loop
The loop flowrates are:
Acurex   0.778 kg/sec.
M.A.N.   0.523 kg/sec.

The flow requirement for the entire field is determined by the power generation cycle efficiency. With an efficiency of 0.2275 and a gross electrical output of 570 KW to allow for

parasitic power, input to the power generation system must be 2507 KW. This is assumed to be accomplished in the steam generator at an efficiency of 99 percent. Since the temperature drop from the field to the steam generator is negligible (less than 0.5 degrees), the required output of the field is 2532 Mw. The total flow requirement is computed as

$$\dot{m} = \frac{Q}{C_p \, \Delta T} = \frac{2532 \times 1000}{2729 \,(295-225)} = 13.3 \text{ kg/second}$$

This requires 9 Acurex loops and 13 M.A.N. loops when the field is equally divided on an aperture area basis. The total flow is then 13.8 kg/second owing to the necessity to install discrete loops. To ensure adequate design margin, 10 Acurex loops and 14 M.A.N. loops will be installed.

Investigations were made of the effect of orienting the Acurex collector loop axes in various directions to peak their performance during different times of the year and thus equalize the field output over the year. The direct normal insolation that each collector orientation receives daily for the specified performance days is shown in Figures 2, 3 and 4 and illustrates the effect.

To determine the effect of various field orientations on the energy collected throughout the year, a tracking correction factor was derived. The tracking correction factor, R_b, is the ratio of beam radiation on the reflector aperture to that on a surface normal to the beam. Since Acurex collectors are one-axis tracking, the R_b factor is less than one. This factor is obtained from the following relations:

North-south orientation:

$$R_b \div \left[(\sin\phi \, \sin\delta + \cos\phi \, \cos\delta \cos\omega)^2 + \cos^2\delta \, \sin^2\omega \right]^{1/2}$$

East-west orientation:

$$R_b = (1 - \cos^2\delta \sin\omega)^{1/2}$$

The optimum collector orientation is based on energy collected and compatibility of the collected energy and annual load distribution. In general, north-south tracking gives an advantage for summer peaked-load profiles and east-west tracking favors the winter. An E-W field orientation was chosen to provide a more even output over the year. However, a reduction in total annual operation time results.

Spacings and field arrangement (number of rows) of collectors determines their mutual shading and field pipe losses which in turn also affect the required collector field size. The shading losses for the parabolic trough Acurex collectors consists of the mutual shading of the adjacent collector and the shading due to the end supports for the receiver tube or self shading contribution due to mutual shading.
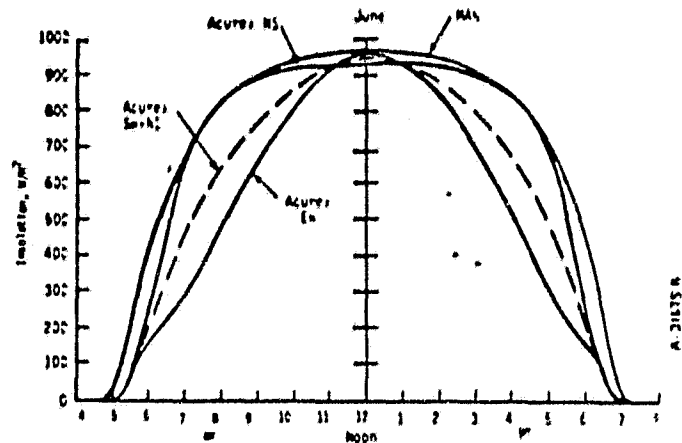

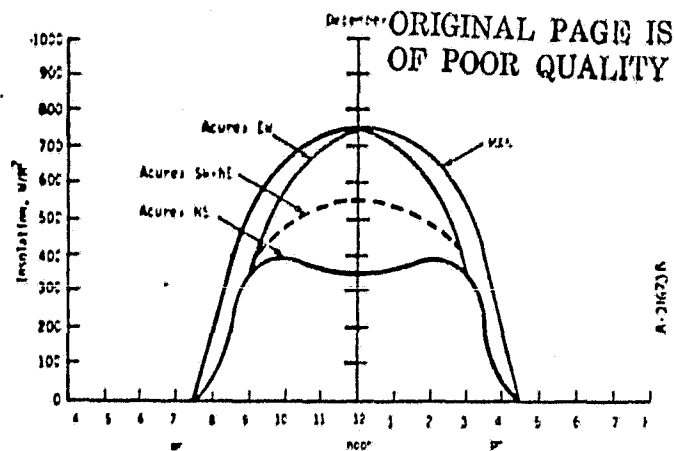Figure 2. Effect of collector orientation.
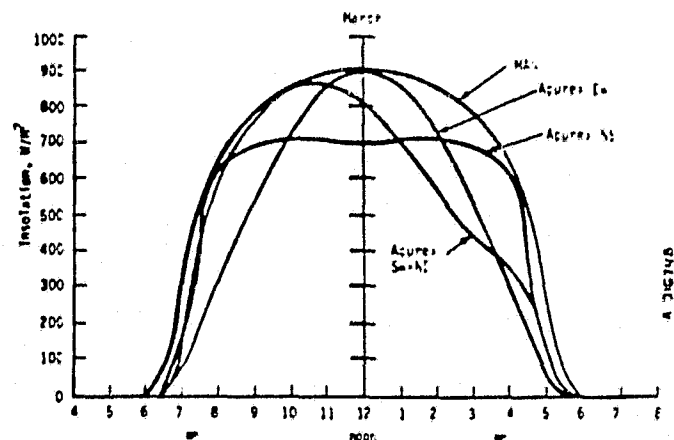
Figure 3. Effect of collector orientation.

Figure 4. Effect of collector orientation.

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The shading of the M.A.N collectors consists only of the mutual shading of adjacent collectors. The shading losses are tabulated below and shown by month in Figure 5.

POWER LOSS DUE TO SPACING (SHADING)

Month	A:NS	A:EW	MAN
Equinox	2.4%	0%	3.4%
Summer	0.98%	0%	2.2%
Winter	0.94%	0.76%	6.3%
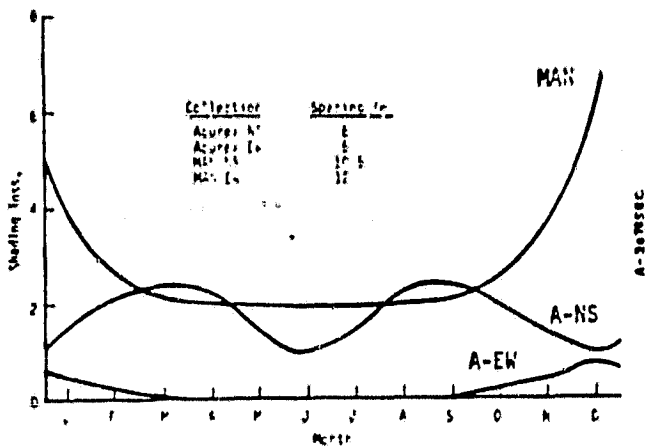
Figure 5. Monthly shading losses for the IEA collector fields.

System Performance

Analysis Methods. In evaluating the system, the SOLTAN code was utilized. In this code, a computation scheme making use of the collector thermal performance curve was the basis for the steady-state performance calculations. The SOLTAN code also calculated the transient performance of the stratified storage tank. The approach was Lagrangian.

Before the simulation of the final design configuration was performed, the insolation data file used in the SOLTAN calculation was modified to make use of the weather data for the actual site and the specified insolation levels. Making use of the data required selecting hourly data for 3-day intervals for each of the three months used in the simulation and interpolating these data to establish monthly insolation values for calculation of annual performance. The hourly system dynamic response was predicted for representative 3-day intervals during the year. This approach was adopted because: (1) hourly integration of the system response is required to represent the system transients properly; (2) calculations of system response for all 365 days of the year are prohibitively costly and unnecessary; and (3) three consecutive days were found to be long enough for the system to undergo many cycles of operation and provide results independent of the initial conditions for the calculations

The final task was that of defining the parameters which provide the system specification and corresponding performance. This involved utilizing the parameters for the power generation unit to establish the final collector field size and layout which necessarily resulted in the predicted performance of the final design.

To compute the transient behavior of the system, a different computer code was written. In this code, a separate subroutine exists for each component and, in some cases for the different functions of a component. The system components modeled were the collector field, consisting of the receiver tubes, manifold pipes, and connectors lines, the inlet buffer tank, and finally the flowrate control system.

Steady State Performance. The choice of operating temperature is closely tied to the availability of the working fluid and the overall system efficiency. System efficiency can be defined as:

$$\eta_{system} = \eta_{collector} \times \eta_{P.G.}$$

Although the efficiency of the power generation cycle increases as a function of the cycle peak temperature, the collector efficiency drops significantly because of larger energy losses at higher temperatures. Therefore, a rather flat optimum operating temperature curve exists where the system efficiency is at its peak, in the range of operating temperatures from 280°C to 316°C. The determining factor is the availability of a suitable working fluid and the influence of temperature on the receiver tube coating. Both of these favor the lowest possible temperature consistent with power generation efficiency. A midrange temperature of 295°C was selected as the best compromise.

The daily operating hours were calculated by numerical methods using the diurnal variation in insolation and the incidence factor appropriate to the relative sun position. The three given days were used to construct a curve of annual variation in daily operating hours at 500 kW electrical. This curve is shown in Figure 6. The annual operating time is 2144 hours. Only at the equinox design condition does the system operate entirely from solar insolation. At all other times, the system operates from a combination of storage and solar insolation, using the storage tank as a buffer. The study assumes sufficient storage is available to avoid collector desteering and is only an estimate of system output.

The system estimated performance is listed below. Figure 7 shows the power stair steps and subsystem efficiencies.
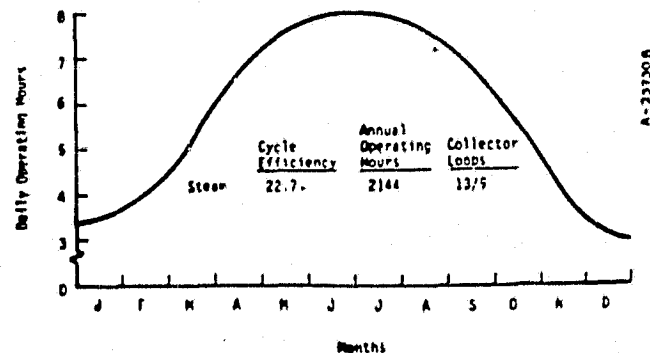

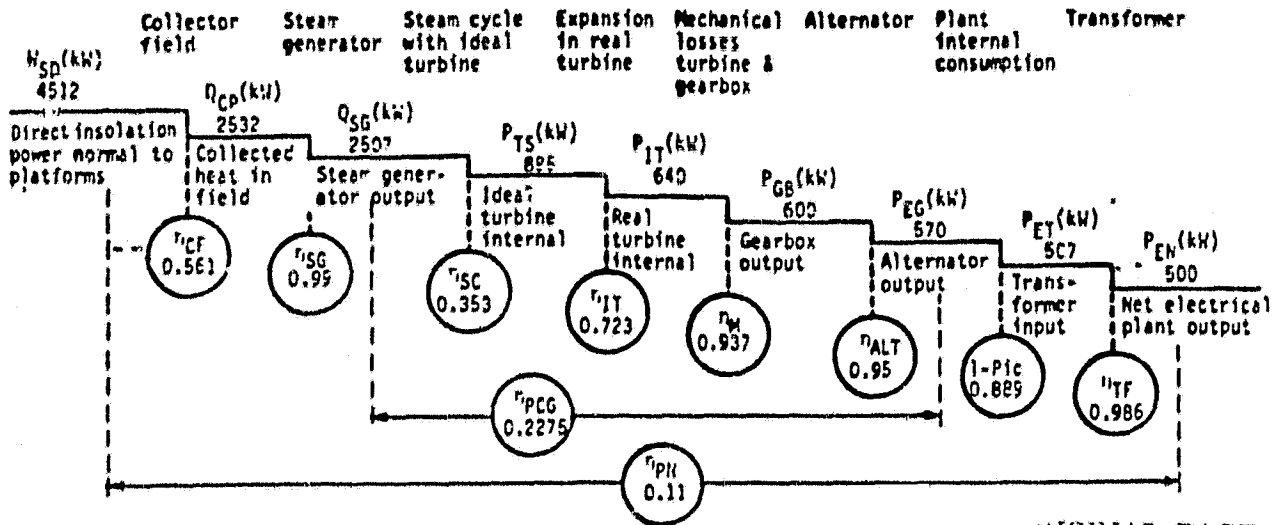Figure 6. Annual variation in daily operating hours.

Figure 7. Power stair steps and efficiencies of the IEA-Solarfarm Almeria.

DESIGN PERFORMANCE

Collector field flow rate	13.8 kg/sec
Collector inlet temperature	225°C
Collector outlet temperature	295°C
Design insolation	920 Watts/m² at equinox noon
Minimum operating insolation	300 Watts/m²
Nominal storage capacity	0.8 MWH
Steam generator outlet conditions	278°C at 25 BAR
Power conversion cycle efficiency	22.75 percent
System overall efficiency	11 percent
Net electrical output	500 KW
Annual operating hours at 500 kWe	2144 HR

Transient Analysis. In consideration of the thermal lag in the collector field, studies were conducted of various strategies for anticipating the lag so that over- or undershoots of outlet temperature can be avoided. Figure 8 shows a case when the insolation drops and is then restored, such as a cloud passage. If only the field outlet temperature is measured there is first a loss in outlet temperature and a cutback in field flowrate and then later a temperature overshoot and steady state error if a slow response control is used. The same thing occurs with a fast response control but outlet temperature oscillations are more pronounced and longer lasting. When the insolation is sensed and used to control the field flowrate, then the initial temperature drop is nearly eliminated but some oscillations in outlet temperature remain. When both the outlet temperature (feedback) and the insolation (feedforward) are sensed, then the system oscillations are better controlled. It has been demonstrated at the USDOE/Sandia Solar Total Energy facility that feedforward alone does not give adequate control, so the feedback element appears essential. The control system for the IEA-SSPS-DCS program incorporates the feedforward-feedback concept. Subsequent analyses of system transient response were calculated on the basis of a feedforward-feedback control strategy.
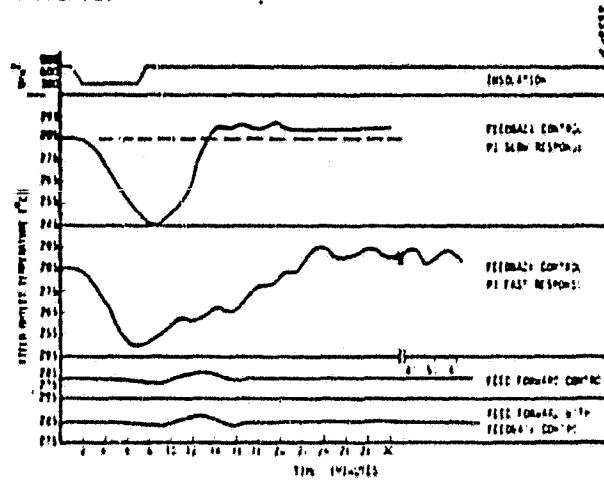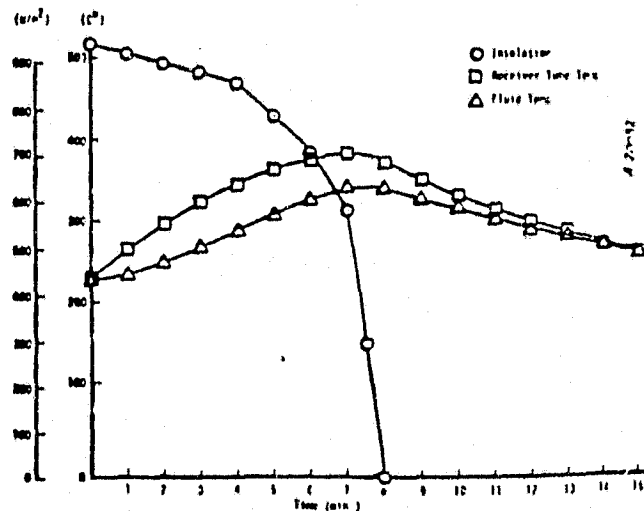

Figure 8. System transient response.

Figure 9. Power loss temperature profiles (while tracking).

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A number of transient analyses were conducted in addition to the basic studies described above:

- Transient thermal response of the Acurex collector to a loss of power, Figure 9
- Temperature rise in the Acurex collector receiver during the ten-second startup time of the emergency generator assuming loss of pump power during the transient, Figure 10
- Temperature rise in the Acurex collector receiver for a static collector after loss of tracker power if the sun crosses the focal plane, Figure 11

- Analysis of the temperature rise in an Acurex collector field loop when fully shaded after operation at 631 W/m² insolation, Figure 12
- Analysis of the inlet and outlet temperature transient for a normal startup procedure for the Acurex fields, Figure 13
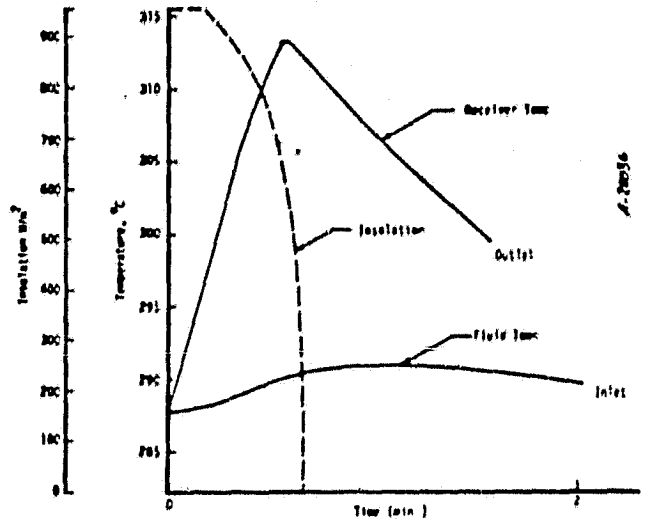- Analysis of the cold startup with 10°C fluid in the thermal storage tank, Figure 14

Figure 12. System transient response -- partial cloud cover.

Figure 10. Thermal effect of desteering delayed by 10 seconds.

Figure 13. System transient analysis -- normal startup.

Figure 11. Static collector temperature profiles.
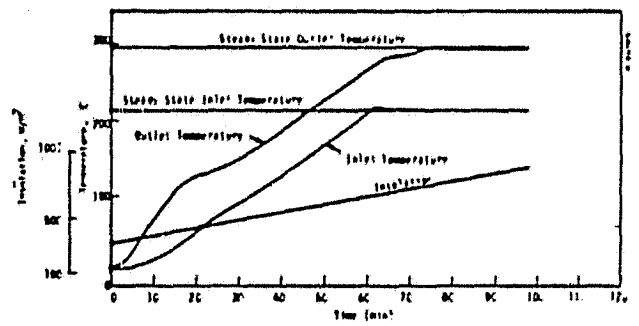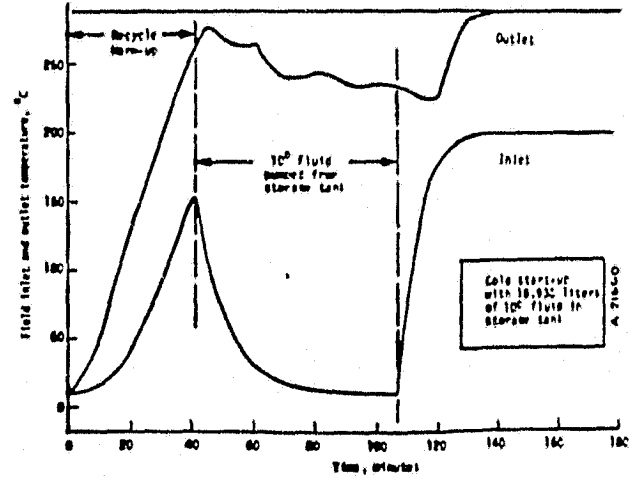

Figure 14. System transient response -- cold startup.

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SUMMARY AND CONCLUSIONS

The demonstration plant, when completed in 1981, will provide a working model for use of all participating nations in gathering practical experience in the operation of such systems in both grid-parallel and in stand-alone modes. Extrapolation to larger and smaller systems then can be made from the well established performance at the nominal 500 kW power level.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to all who have participated in, and contributed to the project up to the present time. These include many individuals from the International Energy Agency, the Executive Committee for the SSPS program and members of the technology and energy ministries of the governments involved, and in particular those from the U.S. Department of Energy.

In particular, we wish to express our appreciation to members of DFVLR, the Operating Agency's staff, especially to Herr W. Grasse, SSPS Project Director, Dr. W. von Kries, Deputy SSPS Project Director, and Dr. A. Kalt, DCS Project Director, for their cooperation and assistance.

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Members of Acurex's own technical staff who made significant technical contributions to this project include W. Kennedy, Chief Engineer, M. Matteo, Associate Project Engineer, Dr. A. Schraub, Stage 2 Project Manager and H. Dehne, Stage 2 Project Engineer.

COOLIDGE SOLAR POWERED IRRIGATION PUMPING PROJECT

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ABSTRACT

Construction of a 150 KW solar thermal-electric power plant on an
irrigated farm near Coolidge was completed in autumn, 1979. The plant,
designed by Acurex Corp., includes over 2100 m^2 of Acurex made parabolic
trough type collectors and an organic Rankine cycle turbine engine built by
Sundstrand Corp. The plant is interconnected with the electrical utility
grid. The installation is being operated by the University of Arizona with
Sandia Laboratories direction. Operation is providing an evaluation of equip-
ment performance and operating and maintenance requirements as well as the
desirability of an on-farm location.

BACKGROUND

Approximately 13 percent of the energy used on U.S. farms is used for
pumping to irrigate about 20 million hectares (50 million acres) or 13 percent
of the total cropland (5,9). About 85 percent of the irrigated cropland is
located in 17 western states. On farms with deep subsurface water sources,
70-90 percent of the crop production energy may be used for pumping (8). The
magnitude of irrigation energy requirements, potential natural gas shortages
and greatly increased energy costs motivated a request to examine the use of
solar energy to drive irrigation pumps by Arizona farmers after the oil em-
bargo of 1974.

A University of Arizona feasibility study in 1975-76 listed a number of
engineering and economic factors to be considered and conditions to be met for
successsful marketing and use of solar powered pumping plants (7). These included
development of lower cost solar devices, improved energy use management and
availability of capital at a modest price. During the past three years, four
known solar power plants have been constructed to evaluate the use of solar
energy to drive irrigation pumps. The first three units began operation in
1977; construction of the fourth was completed in autumn, 1979.

Photovoltaic cells are used to provide up to 25 kilowatts (KW) of elec-
trical energy to drive irrigation pumps at the University of Nebraska farm near
Meade (10). Parabolic trough type solar collectors and Rankine cycle turbine
engines are the principal components of the other earlier systems (1,3). The
two plants, a 50 KW installation located on a farm near Gila Bend, Arizona
and a 25 KW plant on a Willard, New Mexico farm, are directly coupled to
pumps with electric motor backups. The Willard installation includes consider-
able thermal energy storage capacity for nighttime operation while the Gila
Bend plant has none.

COOLIDGE PLANT

The fourth experiment encompasses design, construction, operation, and evaluation of a 150 KW solar power plant. Plant size was selected to meet the energy requirements of deep well pumping to provide irrigation water for a quarter section or 65 hectares (160 acres) of Arizona cropland. The plant generates electricity since existing pumps were electrically driven and the power can be readily used in other applications.

The 150 KW plant is located on the Dalton Cole farm southwest of Coolidge in central Arizona. The cooperator was selected from among a group of volunteer farmers by a governor-appointed committee. An important factor in site selection was cooperation of the local utility company. Backup energy is required to assure pump operation; full utilization of solar plant output is economically desirable. Electric District Number Two, the local utility company, is supplying or purchasing energy as required.

The Arizona experiment is funded by the U.S. Department of Energy and technically supervised by Sandia Laboratories. Additional funding and technical support have been furnished by the Arizona Solar Energy Commission and the University of Arizona, respectively. In the first phase of the project conducted in 1977, competing conceptual designs were developed by three firms: Honeywell, Black and Veatch, and Acurex. Honeywell proposed use of several large parabolic dish collectors. A Brayton cycle turbine engine and electrical generator set were to be mounted adjacent to each collector receiver. Black and Veatch proposed a field of heliostats or individually tracking reflectors, central receiver type collector, and Rankine cycle engine. Acurex proposed use of a field of single axis tracking, parabolic trough type collectors and Rankine cycle turbine engine.

The Acurex Corporation concept was selected for design and construction in late 1977, appearing to have the fewest technical unknowns and be most economical. The solar power plant plans consisted of collector, energy storage and energy conversion sub-systems, Figure 1.
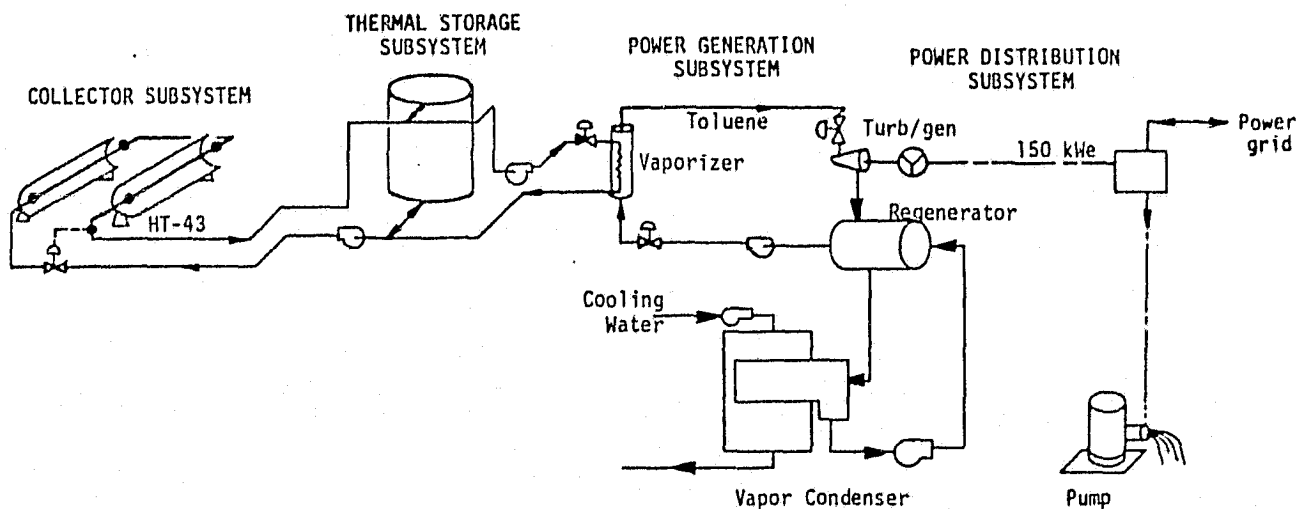

FIGURE 1. Schematic diagram of the 150 KWe solar
powered pumping facility (2).

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The collectors, 1.83m wide by 3.05m long (6 feet by 10 feet), have reflective parabolic surfaces of aluminum (Coilzak) and concentration ratios of about 36 to 1. Collector receiver tube is coated with a selective black chrome surface and surrounded by a pyrex tube. The collectors, manufactured by Acurex, are arranged in a series of north-south oriented rows. Solar collector area is greater than 2100 square meters (23,000 square feet). An addition is being planned which will nearly double the collector area.

A heat transfer oil, Caloria HT43, is being used as the collector fluid. This oil remains stable and in fluid state at the 288°C (550°F) temperature to which it will be heated permitting low pressure flow. Energy storage is a 113 cubic meter (30,000 gallon) tank of hot oil. Initial collector area permits only daytime operation. The planned collector addition will permit about 20 hours of operation on a sunny June day.

Energy conversion is accomplished by a Rankine cycle turbine engine through expansion of the organic fluid toluene. The engine, made by Sundstrand Corporation, is a scaled down version of one developed for other relatively low temperature applications such as conversion of power plant waste heat. Net engine efficiency is expected to be 17 percent; overall system energy collection and conversion efficiency is expected to average seven percent annually.

EVALUATION

The Arizona experiment is providing an evaluation of a relatively small sized power plant located on a farm in Arizona and interconnected with the electrical utility company grid. The economies of scale for solar power plants are not well known; different designs might be more appropriate with different sized plants. This experiment is evaluating a design using distributed, parabolic trough type, concentrating solar collectors and Rankine cycle, turbine engine to generate 150 KW of electrical energy.

Location on a farm in central Arizona provides an evaluation in that environment; some of the characteristics being sunny, hot, and dusty. Solar plant operating and maintenance requirements, competing land uses and energy use management all affect the desirability of an on-farm location. Land is available in agricultural areas in central Arizona. However, operation and maintenance of a power plant is a new and additional farm task. Minimum attention was a solar plant design objective; amount and type of attention will be determined.

Since solar power plants are capital intensive, complete utilization of output is desirable to minimize energy production costs. More complete solar powered pumping plant utilization may be obtained through energy or water storage or use of alternative energy sources during peak demand periods (7,11). Crop residues and animal wastes are two potential energy sources. However, pumping energy costs will not necessarily be reduced by the use of other energy sources or storage. Interconnection with the electrical utility system could require less management and perhaps be most cost effective. Mutually beneficial operation might involve purchase of off-peak supplemental energy from the utility company and controlled period generation and sale of energy to the utility.

The backup and utilization problem has been resolved in the Arizona experiment since the local utility company is providing energy when solar plant output is insufficient and purchasing energy not needed on the farm. Plant output and farm use will be recorded and conservation and load shifting measures will be examined to determine methods for improved matching of energy supply and demand.

The University of Arizona is operating the Coolidge solar plant with technical assistance from Sandia Laboratories and the manufacturers. This operation is evaluating new solar power plant components and determining operating and maintenance requirements. A number of experiments also are being conducted to evaluate solar collector, thermal storage and turbine generator operation. Performance and operating and maintenance requirements data will be used to suggest methods to improve performance, reduce servicing and increase reliability. To date, the solar plant has been operated almost daily for over two months and storage tank thermocline stability and winter solstice energy collection tests have been conducted.

Solar power plant production cost estimates are high, tentative and variable-from less than $3,000 to over $10,000 per kilowatt of output (2,4). Preliminary analyses have indicated some necessary conditions for cost competitiveness with alternative energy sources (6). These include low capital and operating costs and high utilization. This experiment will provide additional information on future capital and operating costs and plant utilization. Economic analyses will be updated as information becomes available.

CONCLUSIONS

The Arizona 150 KW solar powered pumping experiment is providing an evaluation of a medium sized solar power plant using distributed collectors and much new technology. The application appears appropriate since irrigation demand reaches a peak during the period of maximum insolation, a farm can provide a good environment for solar devices including adequate land area, and farmers are seeking alternative energy sources.

The experiment is expected to provide information on design, operation, and maintenance which will lead to equipment improvements. The experiment also is expected to indicate the practicality of locating a solar power plant on a farm and provide comparative cost data. Thus, the experiment is an important step in the development of solar power plants.

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THE 50-HORSEPOWER SOLAR-POWERED IRRIGATION
FACILITY LOCATED NEAR GILA BEND, ARIZONA

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ABSTRACT

The operation of the 50-horsepower solar-powered irrigation facility near Gila Bend, Arizona over three years demonstrates the technical feasibility of solar-powered pumping. The Rankine cycle facility was built using 1976 technology. The requirement now is to use the technology that has been developed over the last four years to design a facility specifically for the irrigation farmer. Considerations to meet his needs and to demonstrate whether solar thermal conversion is a potentially viable application for pumping irrigation water in the United States are suggested.

INTRODUCTION

The initial program to develop the 50-horsepower solar-powered irrigation facility was funded at Battelle Memorial Institute by The Northwestern Mutual Life Insurance Company as one of several programs undertaken to accelerate the development of practical applications of solar energy.

The installation is on a 76,000-acre ranch west of Gila Bend, Arizona. The ranch represents an agricultural investment in one of this country's most arid regions where intensive irrigation is required to produce crops on the 25,000 acres that are irrigated.

The solar irrigation pumping system serves to return tail water from a collection sump to concrete lined distribution ditches. Water supplied to the irrigation system from a number of deep wells is applied to the fields from the distribution ditches by siphons in an amount approximately 10 percent in excess of that required by the crop; the resulting 10 percent runoff is recovered from the graded fields in a network of tail water ditches. The solar irrigation pump returns the tail water, which collects in a sump, to irrigation ditches servicing an area of approximately 5000 acres. The lift from the tail water sump to the distribution ditches varies daily, ranging from 7 to 12 feet.

In 1975 when the design of the facility was initiated, the following were guidelines:

(1) Select off-the-shelf equipment or equipment that was as near to off-the-shelf as possible

(2) Take every advantage of available technical information with proper exercise of experience and judgment

(3) Design a system to produce 50 horsepower but include the potential for applying the same design practices to scale up to 250 horsepower

(4) Include in the design the potential for operating the system in remote locations with only minor modification.

The thrust of these guidelines was that our program was not to be a research effort; it was a development and application effort.

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System definition, design work, component selection, procurement, assembly, testing, and installation were completed in about 18 months; the system was dedicated in April, 1977. The basic components of the system are shown in Figure 1.
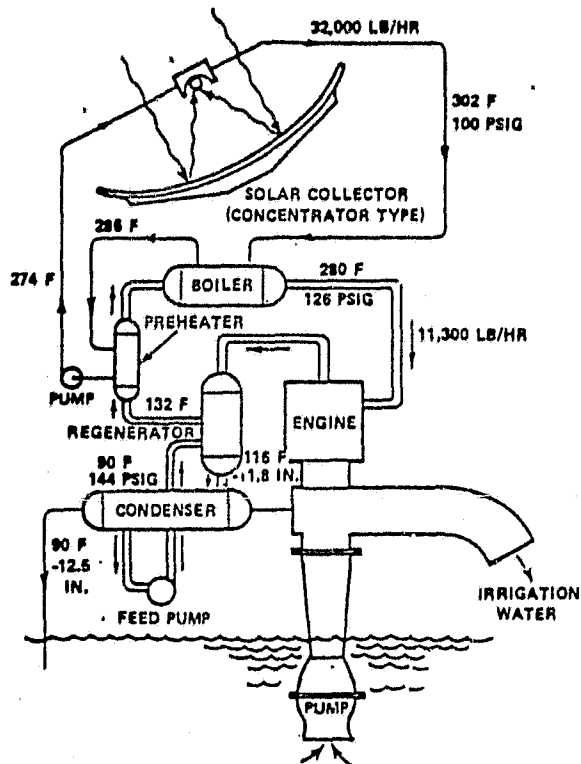

**FIGURE 1. A SCHEMATIC OF THE SOLAR-POWERED
IRRIGATION SYSTEM: 1977**

The figures are design values.

The collector field (5785 sq ft) heats the water, which in turn is used to flash the working fluid (R-113) to drive the Rankine cycle turbine at a maximum speed of 30,500 rpm; this is then geared down to 1755 rpm. The 50-horsepower system can deliver a maximum of 10,000 gpm.

In this paper, there is no attempt to cover all of the activities in the three years of operating the facility and making modifications to it. The purpose is to highlight some observations dealing with the pragmatic use of solar power in a particular agricultural application.

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OPERATIONS

The system was operated for a total of 800 hours during part of the 1977, 1978, and 1979 irrigation seasons. On several occasions the water pumped exceeded 9000 gpm over short periods and an average of 7000 gpm for several entire solar days.

Collectors

When the collectors were new, well-focused, and tracking under bright sun conditions, they regularly delivered 48-52 percent average efficiency (design was 55 percent). After several months, and several problems which included the overtemperaturing of two absorber tubes, typical efficiency dropped to 46 percent.

To reduce convection losses, the absorber tube/receiver assembly was originally fitted with half-round sections of glass set into a seal. Dirt and dust which built up on the outer surface, though serious on its effect on operations, could be readily removed. However, within one month, the dust buildup on the interior surface of the glass was such that the covers had to be removed to be cleaned. The attendant problems with cleaning the glass -- removal, replacement, seal alignment, breakage -- immediately created an incentive to operate without the glass. We ran some tests comparing adjacent rows with and without clean glass covers; we were not able to measure individual flow rates. On the basis of our tests we found there was actually an increase in ΔT without the glass covers. The results would have been even more significant if the glass covers had been just a little bit dirty on the inside or the outside. We discontinued the use of the glass because in our system -- operating around 300 F -- it was far from cost effective to operate with them.

Dust is a normal environmental feature in Gila Bend. The dust, whether from dust storms, dust devils, or agricultural operations will collect on reflector surfaces. From a practical viewpoint the dust -- at least our dust -- did not reduce performance nearly as much as one would think. In the first year of operation the reflecting surface appeared very dusty after about one month -- particularly when viewed from a flat angle. The reflectors were immediately washed. There was no noticeable difference in the energy output of the field before and after washing. The field was washed twice more during 1977 with the principal difference still being aesthetic. From August 1977 through the five months of operation in 1978 and until August 1979 the collectors were not washed again. By this time the dust accumulation was such that performance was improved by washing. It will be significant to the farmer to know what the washing requirements are for his application. Washing is expensive; "excess" dirt accumulation will affect output. The farmer will want a definition of "excess" that he can use.

During 1978 a number of changes were made in the receiver assemblies. Some of the coatings on the receiver tubes appeared to have degraded; powdering and flaking were evident. A new receiver assembly design was available which had overall system improvement as well as improved thermal features. Combinations of old coatings, new coatings, black chrome, old housing, and new housings were a part of the 1978 and 1979 system. The performance of the various combinations of components does not appear to be markedly different, but detailed examination would have to be made to evaluate the efficiencies of the individual rows. If, as we suspect, there are only modest differences in efficiencies, the long-term effect of this in terms of initial costs and maintenance costs is significant.

Generally, the collectors appear to be holding up fairly well. There is one place on the reflector side where the metal backing is breaking away from the honeycomb core material. The manufacturer has looked at the separation; it is his judgment it is the result of a manufacturing error rather than degradation. Additionally, there are several places where the aluminized reflector surface is not adhering to the substrate as it should. Most of this, which is new this year, is occurring at seams but there are several places where there is some delamination in the middle of a panel. This degradation does not represent a large percentage of the total surface area. It does, however, represent a potential maintenance cost either in terms of repair or replacement.

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The remaining components of the collectors do not appear to be degrading in any way that affect performance or require maintenance.

Tracking

The subsystem that has caused the greatest problem is row tracking. It was, and still is, difficult to maintain consistently accurate tracking in conditions of changing cloud cover and haze. We have made modifications to our On/Off switching to incorporate semiproportional control on the motor speed and have replaced the mechanical relays with solid-state switching devices. Other improvements can be made and systems newer than ours offer substantial improvements. One problem with the newer systems is that the costs are going in the wrong direction.

Heat Exchangers

There is one feature of the Gila Bend facility on which we have little information. Data is available to calculate the performance of the heat exchangers — boiler condensor, regenerator, and preheater; the calculations made in 1977 and for part of 1978 indicated design or near design performance. Information is not available, however, on what is happening to the inside surfaces of the heat exchangers. This information must be developed to determine the maintenance requirements and to provide a design for the components that will enable the maintenance to be carried out.

RECOMMENDATIONS

The Gila Bend facility is basically a 1976 design. It was designed to demonstrate an application using state-of-the-art equipment. It has demonstrated that application. What is required now is an update to use the current state of the art (which is significantly advanced over 1976) and design an overall facility which will best fit the needs of the irrigation farmer.

It has yet to be demonstrated for the United States market whether the use of solar thermal conversion is (or is not) a viable application when the principal use is for pumping water. To date, most, if not all, of the demonstration systems have been built by engineers to be run by engineers. The real world need will be to deliver a system that is acceptable to the farmer in terms of meeting his operating and maintenance requirements . . . and particularly because of today's interest rates — first cost. A demonstration unit should be built with the following in mind.

(A) Components used must have the potential for significant cost reduction.

(B) The farmer wants water "on demand" day or night. The primary pumping will be by electric motor (or gas or diesel engine). Solar power, when available, will be used to reduce other forms of power consumed. This approach is equally applicable to low lift, shallow well, and deep well requirements. Furthermore, the potential solar output does not need to match the power requirements of the pump motor; the solar power portion can be substantially smaller and still be effective.

(C) The collector operating temperature needs to be examined carefully. The pros and cons of temperatures requiring glass covers for absorber tubes need to be examined in terms of field use by the farmer, not laboratory use by the engineer.

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(D) A sump application, such as the one at Gila Bend, is less desirable than an application on a well. The water from a well which will be diverted for the condensor cooling water is better than the water from a sump for two reasons:

    (1) The temperature of the well water is lower and does not have the temperature variation over time that is characteristic of sump water.

    (2) The well water does not have the solid debris characteristic of sump water.

(E) Tracking systems must provide the capability to follow the sun accurately when it can provide thermal inputs to the system. As mentioned before, systems are improving but costs are not. There have been many advances in the last four years in control technology and timing devices. For this specific application, a detailed examination should be made of the relative advantages of tracking the sun on the basis of where it actually is and where it is calculated to be.

(F) The master control system needs not only to start and stop the system under normal conditions but also to provide diagnostic information to the user for causes of shutdown or preventable falloff in performance. This suggests a well-conceived instrumentation and signaling system.

(G) In the design process, consideration must be given to how the farmer wants to operate and maintain his water pumping system.

    (1) When the pump is running, the solar portion of the unit should start automatically when there is sufficient energy from the sun; conversely, it should shut itself off automatically.

    (2) The system should run automatically and reliably without the need for an operator in attendance. One or two checks a day by the farmer (similar to the checks he currently makes on his motor driven pumps) should be sufficient.

    (3) The levels of skills required to operate and maintain the system should be little different than those currently employed. It is reasonable to assume that one week or less of training would provide the level of skills required for maintenance.

The foregoing does not necessarily define a large-scale system. In fact, quite the opposite may be true. For demonstration purposes, a 25 to 50-horsepower system could be used, coupled with a well-head pump.

The two existing systems that have any similarity to the system suggested are circa 1976 technology. With the advances that have taken place since, then, not only in solar technology but also in control technology, there is now the opportunity to really test the viability of solar thermal conversion for pumping water in U.S. irrigation operations.

PRELIMINARY OPERATIONAL RESULTS FROM THE
WILLARD SOLAR POWER SYSTEM

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ABSTRACT

The solar-powered system located near Willard, New Mexico, generates mechanical or electrical power at a capacity of 19kw (25 HP). The solar collection system incorporates east/west tracking parabolic trough collectors with a total aperture area of $1275m^2$ (13720 ft^2). The hot oil type thermal energy storage is sufficient for approximately 20 hours of power system operation. The system utilizes a reaction-type turbine in conjunction with an organic Rankine cycle engine. Total collector field efficiency reaches a maximum of 20 percent near the winter solstice and about 50 percent during the summer. During the month of July, 1979, the system pumped 60 percent of the $35,300m^3$ (28.6 acre-feet) of water delivered. Operating efficiencies for the turbine component, organic Rankine cycle engine and the complete power system are respectively 65-75 percent, 12-15 percent and 5-6 percent. Significant maintenance time was expended on both the collector and power systems throughout the operational period.

INTRODUCTION

The Willard solar power system provides both mechanical and electrical power with a capacity of 19kw (25 HP). The major application of the power system is the operation of a shallow-well irrigation system and the production of electrical power when pumping is not required. The power system is located near Willard, New Mexico on a commercial farm in the Estancia Valley.

Estimates indicate that irrigation farmers in New Mexico use $430,000m^3$ (15 million ft^3) of natural gas per year for pumping water (1). Arizona uses an equal amount and Texas about four times as much. These three states also use large quantities of electrical power where a large portion is generated from natural gas. Although the short-term supply appears adequate, the cost has escalated fivefold in the past six years and has consequently imposed an extreme cost "squeeze" on irrigation farmers. In the near future, the supply of natural gas to farmers is expected to dwindle to the point that the fuel will undergo curtailment for power applications. With this event, solar power systems under development now will provide one of several available alternatives.

POWER SYSTEM DESCRIPTION

The Willard power system generates a power output (mechanical or electrical) of 19kw. A belt-driven induction generator provides electrical

power when mechanical power for irrigation is not required. Table 1 summarizes the basic specifications and Figure 1 is a schematic diagram of the system showing the major components.

Table 1

WILLARD POWER SYSTEM SPECIFICATIONS

Location: Estancia Valley, near Willard, New Mexico latitude, 34.2°; elevation, 1835m (6019 ft)

Irrigation: Well depth, 32 m (105 ft); holding pond capacity, 5,560m^3 (4.5 acre. ft); area, 150,000m^2 (120 acres).

Solar Energy Collection: Parabolic trough, north-south axis, east/west tracking; Solar Kinetics collector field area, 651m^2 (7000 ft^2); aperture width 2.1 m (7 ft); Accurex collector field area, 625m^2 (6720 ft^2; aperture width 1.8m (6 ft) heat transfer fluid, Caloria HT 43; maximum collector recirculation temperature, 216°C (420°F); storage tank volume, 51.9m^3 (13720 gal).

Power System: Working fluid, R113; peak boiler conditions, 163°C (325°F) and 1550 kPa (255 psia); condensing water, less than 16°C (60°F); condenser conditions, 30°C (86°F) and 55kPa (8 psia turbine); turbine, single-stage,radial-inflow, reaction-type, 99mm (3.9 in) diameter, 36,300 RPM rotational speed; gearbox, two-stage, 1800 RPM rotational speed.

The system can be operated in three modes:
   °Solar energy to storage
   °Solar energy to power system
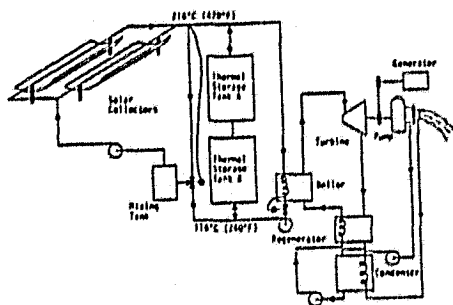   °Energy from storage to power system

FIGURE 1. SCHEMATIC DIAGRAM OF THE WILLARD SOLAR POWER SYSTEM
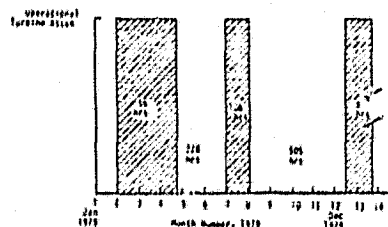

FIGURE 2. AVAILABILITY OF TURBINE ASSEMBLY FOR SYSTEM OPERATION

The greatest stability in power system operation occurs when drawing energy from storage -- the high temperature is relatively stable. Operating the power system from the solar collector field presents varying

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conditions in addition to the possibility of shut-down as a function of weather conditions. Automatic switching exists within the control system but requires refinement as significant temperature excursions occur at the boiler (pool-type) once a mode change is made. Power system shut-down is also automatic when energy (sufficiently high oil temperature) is unavailable.

OPERATIONAL PERFORMANCE

The Willard power system was operated during the 1979 growing season to provide irrigation water. Figure 2 shows the operational times to date of the turbine assembly and the complete power system. Those times when the turbine assembly is under repair, an orifice plate substitutes in place of the turbine. In this way, the remainder of the power system functions in the usual way. The times within the "bars" on Figure 2 are the system hours with the turbine assembly and those times outside the hours on the system without the turbine.

The solar fraction (pumped water divided by total water pumped) is given in Figure 3 for the operational period through July where the turbine was installed in the system. The thickness of the lines on the plot incorporate the experimental uncertainties associated with the calculation. Also, as the data is largely based on manually recorded data, the time intervals are resolved to the point where both water flow and power system data correspond. The average solar fraction for this time period is 0.6 relative to the total water pumped of $35,300m^3$ (28.6 acre-feet).

Reviewing the operation of specific components, the collection system will first be presented. Figure 4 shows the ratio of the actual time the collectors were in operation to that of the maximum time possible on an average monthly basis. These operational times are based on clocks installed within the electrical control system of the collectors. Therefore, the control pyranometer indicating when collection is possible yields the maximum time and the actual time is measured from the tracking circuitry. This ratio is less than unity for several reasons including abnormally high wind speeds and maintenance. The value calculated for August is based only on approximately 20 hours of operating time and thus not representative. The remaining months are based, however, on the total hours for that specific month. For the total hours of collector operation thus far, the time ratio is 0.73.

Figure 5 shows the normalized direct beam component of solar insolation resolved in the plane of the collector aperture as east/west tracking occurs. Separate curves are shown for the winter and summer solstice (2). Clear days are assumed in the calculation. Because of the collector orientation, the winter solar insolation collected decreases in the vicinity of solar noon. As the summer solstice is approached, the beam component of the solar insolation striking the collector becomes nearly uniform throughout the day as well as increasing in magnitude.

Typical operation of the Willard collector field results in efficiencies such as those given in Figure 6 for January 4, 1980. Between the times

1400 and 1410, the collector field changed from the re-circulation mode to the storage mode (introducing hot oil to storage). Note that during the re-circulation mode, the collector efficiencies are low while for storage, the efficiencies greatly increase. The cause of this increase is the relatively low temperature difference across the respective collector fields when in the re-circulation mode. The total field efficiency falls between the two extremes established by the Accurex and Solar Kinetics collector fields. During summer operation, the total field efficiency routinely approached 50 percent.

A partial explanation for the disparity in collector efficiency for the two collector fields is given in Figure 7. The total reflectivity of the
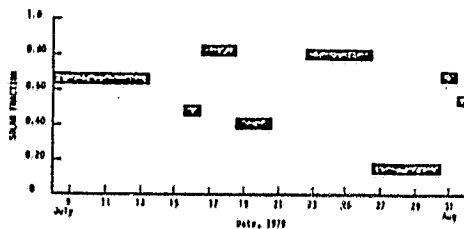

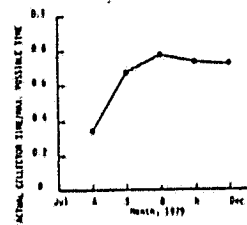FIGURE 3. SOLAR FRACTION FOR IRRIGATION PUMPING

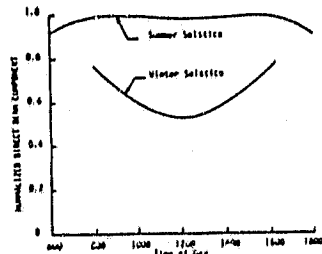FIGURE 4. OPERATIONAL SUMMARY OF WILLARD COLLECTOR FIELD

FIGURE 5. VARIATION OF NORMALIZED DIRECT BEAM COMPONENT OF SOLAR INSOLATION RESOLVED IN PLANE OF COLLECTOR APERTURE
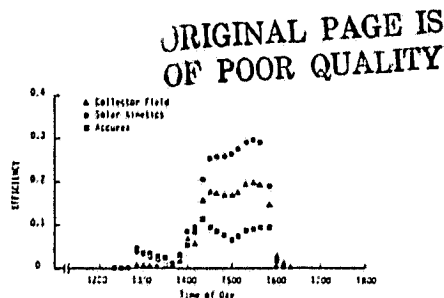

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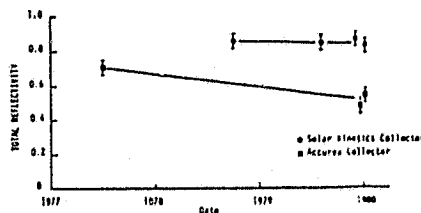FIGURE 6. VARIATION OF COLLECTOR EFFICIENCY ON JANUARY 4, 1980

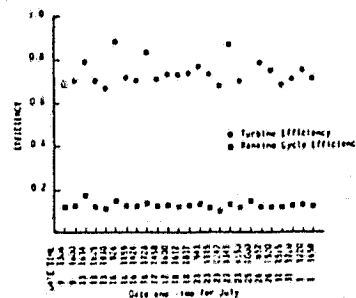FIGURE 7. COLLECTOR SURFACE TOTAL REFLECTIVITY

FIGURE 8. TURBINE AND RANKINE EFFICIENCIES FOR THE WILLARD POWER SYSTEM DURING JULY 1979

collector's reflective surface is shown as a a function of time. These measurements must be considered approximate and appropriate error limits

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are indicated on each of the measurement points (3). The actual measurement involves a portable instrument incorporating a light source varying between 350-750 nanometers where the illuminated portion is visually observed at an angle of 20°. The reduced reflectivity of the Accurex polished aluminum surface appears to account for part of the reduced performance of the collector.

For the July operational period, Figure 8 shows the turbine component and Rankine cycle efficiency. The turbine efficiency is based on the ideal case of isentropic flow while the Rankine cycle efficiency is based on the measured output power. While the turbine efficiency bounces in the lower 70's the Rankine efficiency varies between about 12 to 15 percent. The overall system efficiency for this time period is thus in the vicinity of 5 to 6 percent (output power is divided by direct beam solar insolation input).

A summary of the maintenance performed on the system is given in Figure 9. The major items are the non-routine activities associated with the collection system and the organic Rankine cycle engine. These activities include such things as: modification of collector control equipment, receiver tube and glass shroud replacement, removal and installation of turbine assembly, repair and replacement of the R-113 feed pump and the replenishment of the R-113 inventory subsequent to significant leaks. As improvements are made with the equipment, the non-routine maintenance will decrease.

The crops planted and harvested over the 1979 growing season were alfalfa and timothy hay approximately 50,000m^2 (40 acres) each. Yields were normal for the location and weather conditions.
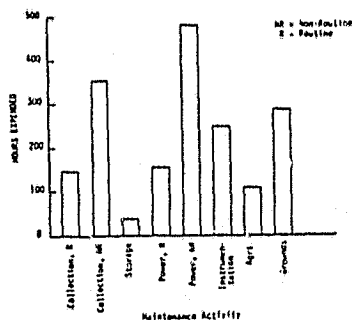

FIGURE 9. MAINTENANCE SUMMARY OF WILLARD POWER SYSTEM FOR 1979

Acknowledgments

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SOLAR TOTAL ENERGY—LARGE SCALE EXPERIMENT

SHENANDOAH, GEORGIA

Walter R. Hensley

ABSTRACT

The first industrial application of the Solar Total Energy concept has been initiated as a cooperative venture of the United States Department of Energy (DOE) and Georgia Power Company.

A part of the National Solar Total Energy Program (STEP), this large-scale experiment is the outgrowth of research started in 1972 by Sandia Laboratories. This effort seeks to evaluate a solar energy system which will provide electrical power and process heat, along with heating, cooling and domestic hot water supplies.

This "total energy" idea is not new, having been used commercially for years. Simply defined, it is a system which uses "waste heat" from electrical power generation to serve other useful functions. Combined with a solar energy system it offers these attractive features:

. Provides energy from a renewable resource
. Adaptable to applications in a wide range of types and sizes
. Makes maximum use of energy collected
. Has a closed loop system which does not pollute
. Compatible with existing utility systems

After research projects confirmed the feasibility of the solar total energy concept, an actual working system was designed and installed at Sandia Laboratories. Successful from the beginning, the Solar Total Energy Test Facility operation has provided the technology and operating experience which make the Shenandoah, Georgia large-scale experiment feasible.

The project objectives are to:

: Develop within industry, the engineering and development experience on large scale solar total energy systems as preparation for subsequent commercial size demonstrations.

: Acquire additional data to reduce the uncertainties of cost and performance predictions.

: Insure dissemination of technical data to provide a basis for expanded growth of solar total energy.

Progress to date covers activities through a final definitive design phase. Major accomplishments include the legal recording of a solar easement and development of a parabolic dish solar collector.

Now being completed is the Phase IV Definitive Design of a six-phase Project for conducting a Solar Total Energy Large Scale Experiment in late 1981. General Electric Company is designing the Solar Total Energy System (STES) with capacity to supply 60% of the total electric and thermal requirements of the 42,000 square foot Bleyle of America knitwear plant to be served at the Shenandoah Site. The system will provide 400 kilowatts electrical and 3.5 megawatts thermal energy.

The STES has a classical, cascaded total energy system configuration. It utilizes parabolic dish collectors, trickle oil thermal energy storage and a steam turbine-generator. The electrical load peak shaving system is being designed for interconnected operation with the Georgia Power system.

An account will be given of the technical considerations and interactions among the parties during the development of the Solar Easement Agreement applicable to the Solar Total Energy-Large Scale Experiment. Although the agreement is specifically tailored to the Shenandoah Project Site, the review of the key technical results and practical resolutions of the different interests of the several parties involved in the Shenandoah Project will be of benefit to anyone involved in present and future solar projects where the sun rights must be established and protected.

This paper also discusses the design and development of a 7-meter diameter parabolic dish solar collector. Each of the four main subsystems of the collector; (1) reflector, (2) mount and drives (3) receiver and (4) the controls is discussed briefly with the major emphasis on the receiver design.

To minimize development risks and production costs, a dish design based on use of stamped aluminum petals (sectors) was chosen. This design is similar to the design of a communication antenna already commercially produced. The reflective surface of the petals has a total reflectance of .86 and a specularity (dispersion) of 8 mrd. This performance is obtained by mechanical polishing and chemical brightening of the petal surface, followed by application of a clear RTV silicone protective coating. Selection of the material and weather proofing coating are discussed. Results from performance tests on an engineering development dish collector will be presented. Test results will be compared with pretest predictions.

At the completion of the preliminary design in September 1978, the engineering specifications for major equipment was as given in the following table 1. Final design now being completed, is only nominally different due to programmatic and technical considerations.

Table 1

Collector Field

Type	Paraboloidal Dish
Size	7M Diameter
Area	79,500 Ft^2
Fluid	Dow Corning Syltherm 800
Outlet Temperature Collector	750 F
Min. Inlet Temperature Collector	500 F
Maximum Fluid Flow Rate	387 GPM
Minimum Collectible Insolation	50 Btu/Hr-Ft^2

Turbine Generator Set

Cycle	Rankine Turbine
Working Fluid	Steam
Admission	Multi Valve
Stages	Multiple
Pressure Ratio	140
Inlet Condition	720 F/700 Psig
Extraction Steam Condition	105 Psig
Condensing Condition	5 Psig
Generator	Brushless Air Cooled
Maximum Rating	400 kW

High-Temperature Thermal Storage

Type	Trickle Oil
Volume	17,600 Ft^3
Size	13 Ft Dia, 12 Ft Ht (1 Tank) 20.6 Ft Dia, 16 Ft Ht (3 Tanks)
Storage Medium	Taconite
Void Fraction	45%
Temperature Change	250 F
Capacity	100 MMBTU
Max. Charge/ Discharge Rate	16/8.2 MMBTU/Hr
Insulation Thickness	12 In.
Oil Inventory	11,225 Gal

Low-Temperature Thermal Storage

Type	Stratified Water
Volume	120,000 Gal
Size	18 Ft Dia, 63 Ft Long
Storage Medium	Water
Temperature Range	210 F - 190 F
Capacity	20 MMBTU
Insulation Thickness	4 In

- - - - - Specifications for Major Items of Equipment

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SOLAR TOTAL ENERGY PROJECT AT SHENANDOAH, GEORGIA SYSTEM DESIGN

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ABSTRACT

The U.S. Department of Energy, with Sandia Laboratories providing technical support and management, is near completion of the Definitive Design Phase of the Solar Total Energy Project to be constructed at Shenandoah, Georgia. General Electric Company designed the Solar Total Energy System (STES) with the capacity to provide 50% of the total electrical and thermal energy requirements of the 25,000-square-foot Bleyle of America knitwear plant located at the Shenandoah Site. The system will provide 400 kilowatts electrical and 3 megawatts of thermal energy.

The STES has a classical, cascaded total energy system configuration. It utilizes one hundred twenty (120), parabolic dish collectors, high temperature (750°F) trickle oil thermal energy storage and a steam turbine-generator. The electrical load peak shaving system has been designed for interconnected operation with the Georgia Power system and for operation in a stand alone mode.

INTRODUCTION

The Solar Total Energy System at Shenandoah, Georgia, will be a large scale prototype of a classical cascaded system utilizing solar energy. Definitive performance and cost data for a solar system will be obtained during the operation of the system and an industrial solar total energy capability established.

Figure 1 is an illustration of the Project Site after installation of the STES. A high temperature silicone heat transfer fluid is used to transport solar energy from the parabolic dish collectors to thermal storage or a steam generator. Thermal energy storage is accomplished by use of a low cost, trickle oil system using an iron ore storage media. The power conversion system employs a steam Rankine cycle and high speed (42,500 rpm) turbine.

FIG. 1. SOLAR TOTAL ENERGY SYSTEM SHENANDOAH, GA

The STES has the flexibility to operate in either a stand alone or peak shaving mode while satisfying electrical power, process steam, heating and cooling requirements of the knitwear fabrication plant adjacent to the STES site.

Shenandoah is near Newman, Georgia and is an industrial-residential planned community. Sun right easements have been obtained on the land bounding the 5.74-acre STES site to prevent obstruction of the field insolation.

SYSTEM DESCRIPTION

Figure 2 depicts the three major loops of the STES: solar collection and storage, power conversion and thermal utilization.

A peak energy delivery rate of 10×10^6 Btu/hr is obtained from the solar collector field.

The solar collector field consists of twelve parallel branches with ten parabolic dish collectors in each branch. Energy is transported from the several collectors to thermal storage or the steam generator by a high temperature silicone (Syltherm^{TM} 800) heat transfer fluid, which is stable over the operating temperature range of the solar collector field (500°F inlet, 750°F outlet). During periods of low insolation or inclement weather, the system can be operating with energy from the thermal energy storage system or a fossil-fired heater.

The power conversion loop which includes the steam generator, turbine-generator and condensor is located in the mechanical building shown in Figure 1. Process steam (1380 lbs/hr) for the knitwear facility is extracted at an intermediate turbine stage. Thermal energy from the turbine exhaust steam is extracted via condensor and transferred to the thermal utilization loop for heating and cooling (by chilled water from an absorption unit) of the Bleyle Plant and the STES Mechanical Building. The major components of the thermal utilization loop (Figure 2) are the low temperature storage tank, cooling towers and the absorption air conditioner.

In the peak shaving mode, the STES operates with a 50 to 75 kW$_e$ baseload provided by the local utility. A summary of the system capabilities and load requirements is presented in Table 1. Fifty percent (50%) of the annual energy requirements of the Bleyle knitwear plant will be satisfied by solar energy conversion.

When operating in the automatic mode, start-up and operation of the STES will be based on a real time clock, as well as measurements of system status, demand and environmental conditions. A typical Operating Timeline for the system is shown in Figure 3.
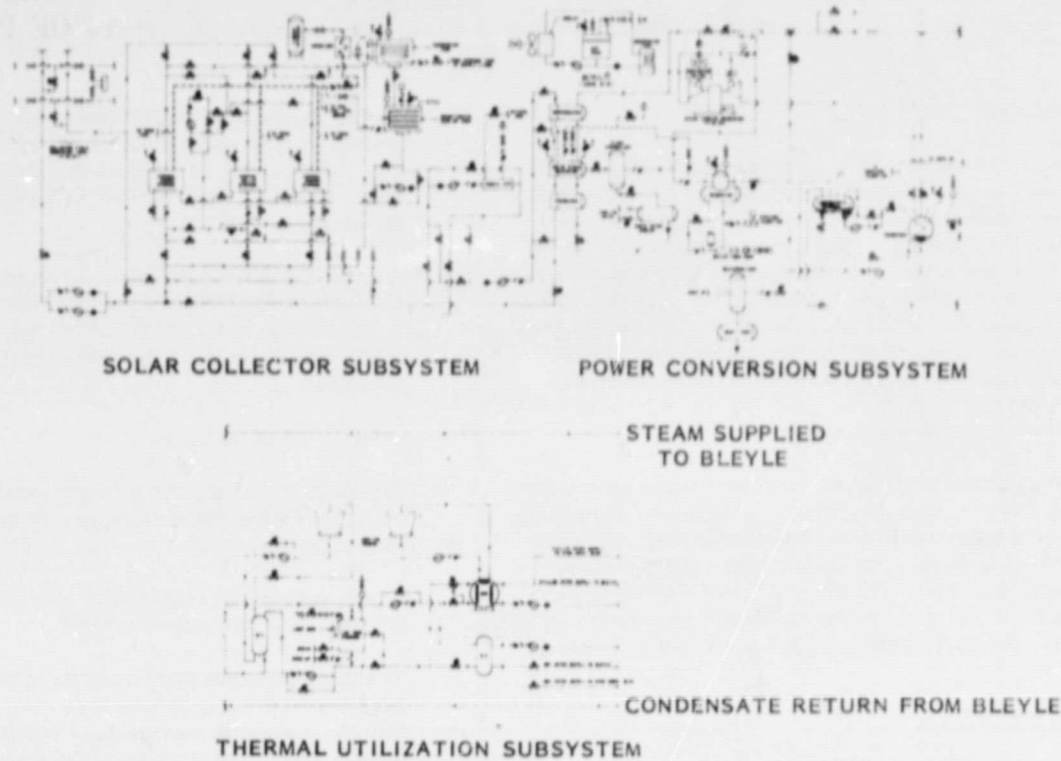
SOLAR COLLECTOR SUBSYSTEM   POWER CONVERSION SUBSYSTEM

STEAM SUPPLIED
TO BLEYLE

CONDENSATE RETURN FROM BLEYLE

THERMAL UTILIZATION SUBSYSTEM

FIG. 2. STES - THREE MAJOR LOOPS

TABLE 1. PEAK DEMANDS AND ANNUAL STES
ENERGY CONTRIBUTION

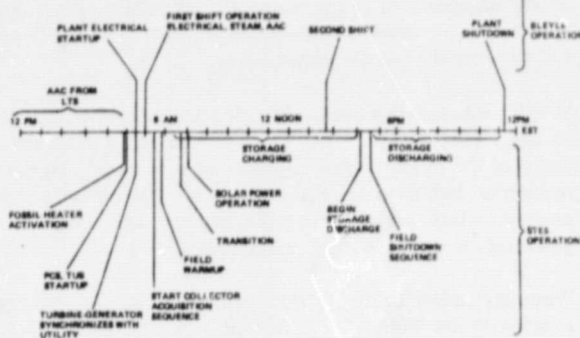| | LOAD REQUIREMENTS | | STES CAPABILITY | ANNUAL STES CONTRIBUTION |
	BLEYLE	STES		
ELECTRICAL	161 KW	137 KW	400 KW	34%
COOLING	113 TONS	20 TONS	133 TONS	78%
HEATING	324 KBTU/HR	32 KBTU/HR	356 KBTU/HR	98%
PROCESS STEAM	1.4×10^6 BTU/HR (1380 LBS/HR @ 114 PSIA, 337°F)	0	1380 LBS/HR	54%

FIG. 3. WEEKDAY STES OPERATING TIMELINE
CASE: APRIL 13TH SSMY

The solar collector field operates independently of the electrical and thermal load supply equipment. Operation is initiated by solar clock (with a measured isolation permissive) for startup, and operation continues through the day as long as sufficient insulation is available. Based on solar availability, thermal storage status, and demands, a backup fossil heater is activated, so that the Bleyle plant loads are always supplied.

For the case shown in Figure 3, which was abstracted from an annual system simulation using Shenandoah Solar Model Year climatology, the storage tanks were depleted in the early morning. The fossil heater was activated, the power conversion system and thermal utilization were started, and the turbine-generator synchronized with the utility. All this occurred prior to the Bleyle 1st shift startup. The collector field started up at approximately 6 o'clock and solar energy was provided to the system at 8 o'clock.

Solar Collector (SC)

The solar collector is a 7-meter diameter, paraboloidal dish with a cavity receiver. Reflected solar energy is focused onto a cylindrical coil of blackened stainless steel tubing (1/2-inch diameter) within the receiver. As the collectors are hydraulically connected in parallel, the total field temperature rise occurs in each receiver (250°F). The reflector assembly consists of 21 die-stamped aluminum petals with a highly reflective laminated surface (FEK 244).

Each collector tracks the sun through its daily and seasonal variations by use of a polar-declination gimbal arrangement. A hybrid sun tracking technique is em-

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ployed: course tracking of the sun ((± 0.6°) is computer controlled; and fine tracking of the sum (± 1/4°) is obtained by nulling the output of optical sensors. The optical tracker employs a pair of sensors on each axis. Sensors of each pair are located on opposite sides of the receiver aperture plate, and the collector is positioned by balancing the intensity of the "tails" on the reflected, focused image straddling the aperture. The use of a .6° computer limit prevents wandering of the collector because of extraneous reflections, i.e., cloud glint.

Four full size prototype solar collections (Figure 4) were built and tested in the Sandia Laboratories' Quadrant Facility to verify the performance and design adequacy of the Shenandoah Solar Collector. The test program established that excellent performance can be obtained from a high temperature (750°F fluid outlet temperature) parabolic dish collector fabricated with existing industrial processes. On a clear day, a collector thermal efficienty of 67% was realized, Figure 5.

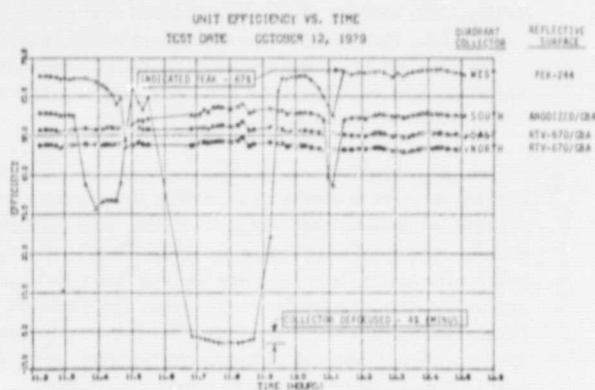

FIG. 4. QUANDRANT TEST OF SHENANDOAH SOLAR COLLECTOR

FIG. 5. QUADRANT TEST SOLAR COLLECTORS

Several required design modifications were identified and implemented during the test program. As a result of the high heating rate imposed on the receiver (concentration ratio of 234), it was necessary to add a quartz cloth covering to the receiver aperture plate. This layer reduced the stainless steel aperture plate temperature level sufficiently to eliminate plate warp-

ing. In addition, the epoxy used to stiffen the ends of the fiber optic sensor bundles degraded and distorted the sensor measurement. This was eliminated by replacing the optic bundle ends with a solid cane design that is compatible with the high temperatures occurring during acquisition and defocus of the collector. Subsequent tracking experimentation showed that the optical tracking system focused the receiver within the design tolerance (± 1/4°).

A major design concern was the slope error of the dish and its ability to concentrate the solar energy to satisfy the design intercept factor requirement (96%). A micro-densitometer evaluation was made of the reflected illumination from the dishes while tracking the moon and while focused on a boresight light. These measurements confirmed that the design intercept factor was satisfied.

High-Temperature Thermal Energy Storage Subsystem (HTS)

Excess collected energy will be stored for use during periods when the collector field cannot provide sufficient energy to operate the system. To minimize the capital investment in heat transfer fluid, the STES utilizes a trickle oil storage system, Figure 6.

TOP & BOTTOM MANIFOLDS BUILT IN FOR TRICKLE OR DUAL MEDIA OPERATION
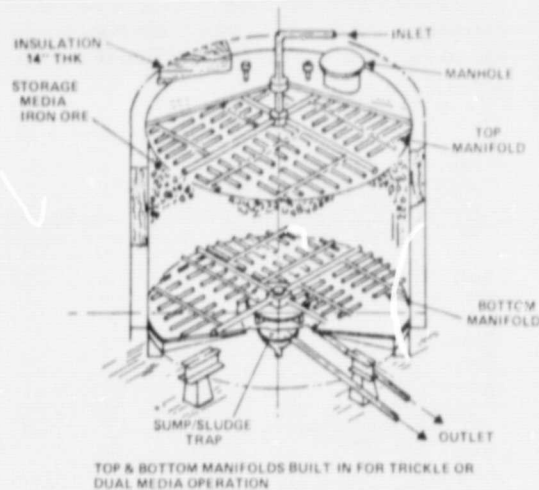
FIG. 6. TRICKLE OIL THERMAL ENERGY STORAGE

The heat transfer fluid is introduced at the top of the tank by a distribution manifold and allowed to trickle through a low cost, iron ore storage media. In both the charging mode and discharging mode, energy is transferred between the storage media and a thin film of the heat transfer fluid. For the STES, three storage tanks will be employed with a combined capacity of 60 million Btu. Maximum charge and discharge requirements for the thermal storage subsystems are 10 million Btu/hr.

To validate the trickle oil concept, a column test representative of the STES operational conditions was performed. It was shown that uniform heating and cooling of the bed, during charging and discharging , occurred

lt the fluid was distributed uniformly at the top of the tank, Figure 7, and that sharp thermoclines resulted.
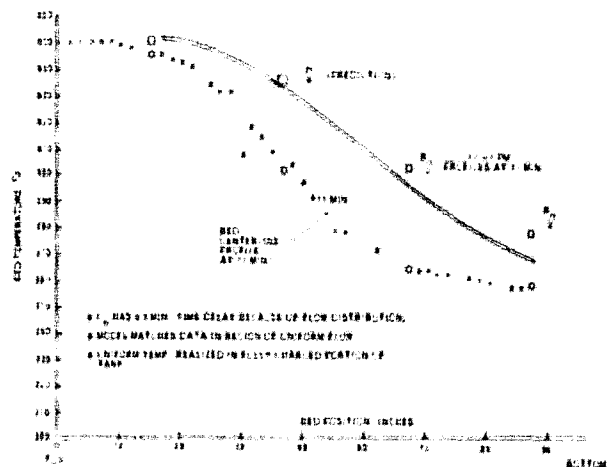

FIG. 7. TRICKLE OIL COLUMN TEST, CHARGING MODE

In addition, the test showed that the temperature gradient in a partially charged or discharged tank would not experience significant axial heat flow during normal operation, which would degrade the temperature of the stored energy in the charged portion of the tank, Figure 8.
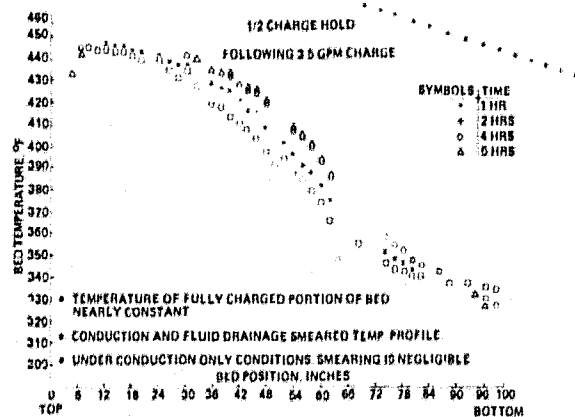

FIG. 8. TRICKLE OIL COLUMN TEST, HOLDING MODE

Power Conversion Subsystem (PCS)

Major elements of the power conversion subsystem are a drum-type steam generator with preheat and superheat sections, a high-speed steam turbine-generator set rated at 400 kW_e, a condenser, a condensate storage tank, a make-up demineralizer, a deaerator, required pumps and local controls.

The recirculating heat transfer fluid from the solar collector field can deliver 10 million Btu/hr to the steam generator and provide up to 10,500 lb/hr superheated steam at 700 psig/720°F to the steam turbine.

Alternately, in the event of turbine outage or no electric power demand, the steam turbine can provide saturated steam at 110 psig for process and other thermal uses. To avoid particulate erosion of the high-speed turbine blading (42,500 rpm), the steam flow is filtered to reduce the contaminate level to 0.1 ppm, with 95% of the particles less than 4 microns.

The steam turbine generator produces electric power in the range of 100-400 kW_e at 480 volts, 3 phase, 60 Hz. The steam turbine is a high specific speed/high efficiency design: high pressure stage efficiency is 66% and low pressure stage efficiency is 76%. Controlled extraction of superheated steam (110 psig) from the turbine provides process steam for the Bleyle plant and deaerator.

The turbine exhaust is condensed at 6 psig and the condenser cooling water (210°F) is used as the energy transport to the Thermal Utilization Subsystem.

Thermal Utilization Subsystem (TUS)

The thermal utilization subsystem consists of a 10 million Btu low temperature water (210°F) storage system, a 256-ton absorption air conditioner de-rated to 133 tons with inlet water at 210°F, and two cooling towers for heat rejection from the absorption air conditioner and excess energy from the PCS.

On an annual basis, the thermal utilization subsystem will provide 78% and 98% of the combined STES Mechanical Building and Bleyle Plant cooling and heating loads, respectively.

Controls and Instrumentation Subsystem (CAIS)

The control and instrumentation subsystem initiates, regulates and terminates collector tracking, energy storage, power generation and thermal utilization for heating and cooling of the Bleyle plant and the STES Mechanical Building. When operating in the peak shaving mode, the control and instrumentation subsystem monitors and regulates the generation of power to satisfy system requirements.

The control and instrumentation subsystem includes a central control console, a central minicomputer and remote microprocessor control units. The control system has the flexibility to be operated in a manual or automatic mode, and permits the operator to monitor or control the system functions from the control panel. Both mimics and color graphic CRT's are employed for data display. Data archiving is performed with magnetic storage tapes, and real time data in hard copy form is available via the computer line printer.

SUMMARY

A solar total energy system utilizing parabolic dish collectors has been designed that has the capability to provide greater than 50% of the energy requirements of a knitwear fabrication plant with 25,000 square feet of floor space.

The solar collector test program performed at the Sandia Laboratories test facility in Albuquerque has demonstrated that high thermal efficiencies (67% measured) can be obtained from a parabolic dish built with existing fabrication technology. Thermal efficiency and optical measurements have verified that the Shenandoah solar collector design will satisfy design criteria and performance requirements.

Column tests have demonstrated that the trickle oil thermal energy storage system will provide an efficient and cost-effective means of storing thermal energy.

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