SERI/TP-313-492
Solar Energy Research Institute

4th Semiannual Conference Advanced Solar Thermal Technology Program

Meeting Abstracts
Phoenix, Arizona
December 11-13, 1979

SERI

Prepared for
Solar Energy Research Institute
Golden, Colorado
and
U.S. Department of Energy
by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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ADVANCED SOLAR THERMAL TECHNOLOGY PROGRAM
SEMI-ANNUAL CONFERENCE

PHOENIX, ARIZONA
DECEMBER 11-13, 1979

AGENDA

TUESDAY, DECEMBER 11, 1979

8:30- 8:40 am	Meeting Announcements	SERI	W. Hunt
8:40- 9:00 am	Advanced Technology Meeting Introduction	SERI	B. Gupta
9:00- 9:45 am	Solar Thermal Program Overview	DOE	G. Braun
9:45-10:15 am	Advanced Technology Program	DOE	M. Gutstein
10:15-10:45 am	Break		

SYSTEMS APPLICATIONS OVERVIEWS

Session Chairman - J. Thornton

10:45-11:05 am	Systems Applications Overview	SERI	J. Thornton
11:05-11:25 am	Electrical Repowering Applications	SERI	R. Taylor
11:25-11:45 am	Fuels & Chemicals Applications	SERI	J. Finegold
11:45-12:05 pm	Industrial Process Heat Applications	SERI	D. Kearney
12:05- 1:30 pm	Lunch		

SYSTEMS DEVELOPMENT

Session Chariman - Floyd Livingston

1:30- 1:50 pm	Distributed Receiver Status	JPL	V. Truscello
1:50- 2:10 pm	Dish Brayton	JPL	T. Fujita
2:10- 2:30 pm	Dish Stirling	JPL	J. Stearns
2:30- 2:50 pm	Dish Rankine	Ford/Aerospace	R. Pons
2:50- 3:10 pm	Central Receiver Status	SLL	R. Wayne
3:10- 3:30 pm	Line Focus Systems	SLA	J. Banas
3:30- 3:50 pm	Break		

ADVANCED COMPONENTS AND SUBSYSTEMS

Session Chairman - J. Becker

3:50- 4:10 pm	Receiver Overview	JPL	A. Kudirka
4:10 4:30 pm	Engine Overview	LRC	R. Hyland
4:30- 4:50 pm	P-40 Stirling Engine Module	Fairchild/ U.S. Stirling	R. Haglund
4:50- 5:10 pm	Heat Pipe Solar Receiver for Stirling Engine	GE	W. Zimmerman
5:10- 5:30 pm	Receiver/Brayton Engine	Air Research	L. Six
6:00- 7:30 pm	Mixer - No Host Bar	ADAMS HOTEL	

WEDNESDAY, DECEMBER 12, 1979

8:30- 8:40 am	Meeting Announcements	SERI	W. Hunt

ADVANCED COMPONENTS AND SUBSYSTEMS (Cont'd)

8:40- 9:00 am	Ceramic Dome Receiver	MIT	P. Jarvinen
9:00- 9:20 am	High Temp Receiver	GE	C. Robertson
9:20- 9:40 am	High Temp Receiver	Sanders	S. Davis
9:40-10:00 am	High Temp Receiver	SERI	M. Bohn
10:00-10:30 am	Break		
10:30-10:50 am	$So_3/So_2-CO_2/CH_4$ Receivers	NRL	T. Chubb
10:50-11:10 am	Power Module	Sanders	A. Poirier
11:10-11:30 am	Free Piston Stirling	FRG	G. Benson
11:30-11:50 am	Free Piston Stirling	MTI	C. Dochat
11:50-12:10 pm	Advanced Concentrator Design	Accurex	R. Bedard

SUPPORT ACTIVITIES

Session Chairman - B. Gupta

1:30- 1:50 pm	Support Activities Overview	SERI	B. Gupta
1:50- 2:10 pm	Quality Assurance	SERI	H. Cobb
2:10- 2:50 pm	Technology Dissemination and TID Facilities Presentation	SERI	M. Cotton
2:50- 3:10 pm	STTFUA Activities & Experiments	SERI	P. Key
3:10- 3:40 pm	Break		
3:40- 4:00 pm	GIT ACTF Update and Activity	GIT	T. Brown

4:00- 4:20 pm	JPL Parabolic Dish Site	JPL	D. Ross
4:20- 4:40 pm	SERI Test Facilities	SERI	J. Castle
4:40- 5:00 pm	Storage Systems Overview	LRC	J. Calogeras

THURSDAY, DECEMBER 13, 1979

8:30- 8:40 am	Meeting Announcements	SERI	W. Hunt

SOLAR MATERIALS

Session Chairman - B. Butler

8:40- 9:00 am	Solar Materials Overview	SERI	H. Roberts
9:00- 9:20 am	Chemical Vapor Deposition	U. of Arizona	B. Seraphin
9:20- 9:40 am	High Temperature Paints	Exxon	A. Muenker
9:40-10:00 am	Polymer Protective Coatings	Dow Corning	W. Dennis
10:00-10:30 am	Break		
10:30-10:50 am	Materials Research at SERI	SERI	B. Butler
10:50-11:10 am	Thin Glass Development	Corning	A. Shoemaker
11:10-11:30 am	Cleanability of Reflectors	JPL	W. Carroll
11:30-11:50 am	Fluids/Containers Corrosion Monitoring	CSM	W. Averell
11:50-12:15 pm	Closing Remarks	DOE	M. Gutstein

SYSTEMS APPLICATIONS OVERVIEWS

REPOWERING APPLICATIONS

R. W. Taylor SERI Golden, CO

ABSTRACT

This paper discusses the utility value analysis performed in support of the SERI Repowering Strategy Analysis. Using standard electric utility models, the value of improved hybrid repowered and new 3-hour storage coupled improved stand alone plants are determined for a modified EPRI Synthetic Utility E. The value is determined by combining a dynamic (multi year) generation expansion analysis with a static (single year) production cost analysis. The analysis is performed for various levels and rates of solar thermal penetration. The results indicate that numerous situations exist where the value of heliostats is greater than the cost goals which have been proposed.

INTRODUCTION

The determination of a government response appropriate to the opportunities of repowering is an important policy question, and is the major reason for the Repowering Strategy Analysis. The study objective is:

> To define a government role in repowering that constitutes an efficient program investment in pursuit of viable private markets for heliostat-based energy systems.

In support of that objective, the study is designed to identify the scope and nature of the repowering opportunity within the larger context of its contributions to central receiver technology development and commercialization.

The Repowering Strategy Analysis was conducted in four tasks: Supply, Demand, Institutional and Integration. The major research area of the Supply Task covers the effects on heliostat selling price of changes in manufacturing process and/or scale. Emphasis was placed on heliostats because they represent a large fraction of total system cost, and because they are the solar thermal subsystem most amenable to cost reduction from volume production. Research in the Demand Task centered on the dynamic relationship between utility circumstances (system load, generation mix, prices of conventional fuels, percentage of penetration of solar capacity already on the system, etc.) and the value of an increment of solar capacity. This approach was considered essential to capture the effects on solar plant value to the efforts of Southwest utilities to reduce their reliance on oil and gas. The Institutional Task focused on the effects on the commercialization prospects of solar thermal plants from federal and state policies that impact fuel choice and power plant siting. Because demonstrated technical and economic feasibility do not guarantee commercial application, this assessment of nontechnical constraints on solar thermal applications was considered important. The Integration Task synthesized the results of the other three tasks.

The objective of the Demand Task portion of the Repowering Strategy Analysis is to determine and quantify the sources of the value of repowering (and of central receiver technology in general) to electric utilities. In order to accomplish this task with reasonable accuracy, it is necessary to determine the components of value as a function of solar penetration and time. This must be done on a dynamic basis by considering the initial conditions of the utility and comparing optimum generation expansion plans, through time, with and without solar penetration. These comparisons are then used along with a detailed look at certain individual years in order to assess the value of solar thermal capacity to the utility.

ASSUMPTIONS

The assessment of the viability of central receiver solar thermal power systems is based, to a large degree, on a variety of assumptions. While most of this paper discusses the results of the analysis, it is terribly important to understand the assumptions which were used in deriving the results.

The major assumptions used in this analysis are as follows:

- Modified EPRI Synthetic System E (a representative 1985 Southwestern electric utility)
- Moderately high Southwest insolation level, 2500 kWh/m^2-yr; typical year data
- Oil escalates at 12%/year starting from $5.50/MBtu in 1985 (roughly $33/bbl)
- High performance solar plants
- Only storage-buffered, repowered and three-hour storage coupled solar-thermal plants were considered; high capacity factor solar plants were not considered
- Three different penetration scenarios each with three different rates of penetration achieving a maximum of 8% of system capacity by 2009
- No special solar tax credits or other incentives were considered

In addition to the assumptions listed above, there were three important institutional assumptions. All of these have to do with conventional generation sources. First, for the utility system examined it was assumed that nuclear installations would be limited to one 1000 MW unit every five years. This assumption was based upon recent trends in the installation of nuclear facilities and a capital-constrained environment. The nominal utility size is 10,000 MW in 1985. Second it was assumed that there would be a sufficient supply of coal, at the price used, to fill the baseload generation gap left by the limitation on nuclear capacity. Third, the maximum rate of introduction of new baseload capacity is limited by restricting the maximum generation reserve to 25%, again due to capital constraints.

KEY FINDINGS

There are seven key findings which have been obtained from this analysis that have policy implications.

Numerous Situations Exist Where the Value of Heliostats is Greater Than the Cost Goal

While the value of heliostats obtained from the dynamic simulation of the synthetic utility is not a single number, the value in many cases is greater than the cost goals which have been proposed. Under certain circumstances where solar-thermal electricity competes primarily with expensive premium fuels, the value of heliostats is very high.

The Relatively High Value of Solar May Not Be Great Enough to Compete with New Baseload Coal and Nuclear Generation Sources

Although the cost/benefit ratio of solar-thermal systems is often less than unity, there are competing technologies for which investment dollars will return even greater benefits. The synthetic system studied is severely deficient in low-operating cost units (oil is being used for baseload capacity). Solar-thermal power systems, which operate in an "intermediate" to "peaking" mode, will therefore be in competition for capital investment dollars which the utilities can invest more profitably in baseload generation. The same characteristics which cause solar-thermal to be attractive from a one year production cost standpoint cause severe capital competition from a multi-year optimized expansion standpoint.

The Value of Solar-Thermal Electricity Is Not Constant with Time

Due to the highly nonoptimum initial generation mix with 60% of its capacity in oil-fired plants, the value of solar-thermal plants in the early years is very high. The system generation mix improves with time as large amounts of new low-operating cost capacity are added, causing a dramatic drop in the value of the electricity generated by solar. Then, in later years, the continually growing system requires new intermediate and peaking capacity. The combination of this requirement with ever increasing oil or substitute premium fuel prices makes the solar systems very valuable again after the year 2000.

Solar Thermal Value Trends are Consistent with a Program Plan Emphasizing Repowering Early Followed by the Later Implementation of New Stand-Alone Plants

The breakeven value of heliostats is a good way to compare the economic competitiveness of solar thermal technologies. Figure 1 shows the overall value trends from two of the scenarios used in the study. From this it is seen that repowering has a slightly higher value for heliostats in the period before 2000 and that stand-alone plants have a slightly higher value after this time. The period beyond 2000 has been drawn with dashed lines because of the great uncertainty of what will be the competing technologies and fuel prices in that time frame.

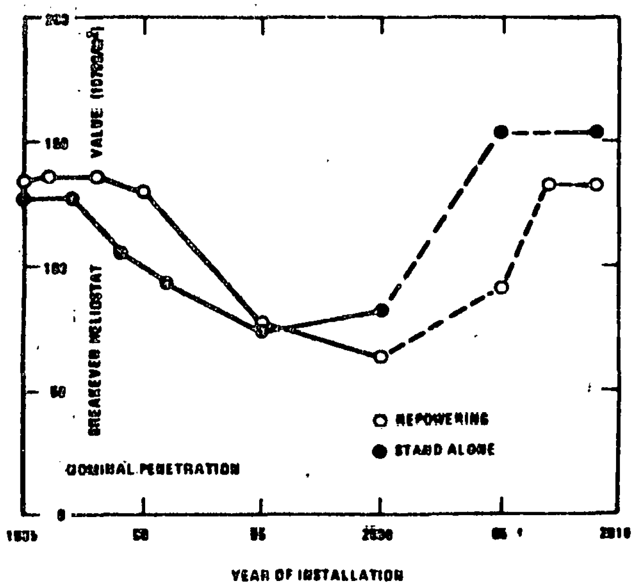

Figure 1. REPRESENTATIVE HELIOSTAT VALUE TRENDS

There Is a Near-Term Window for Repowering Not Based on Retirements Alone

Not only is there the longer term window which becomes closed due to plant retirements (all of the plants fired with #2 oil are retired on the synthetic utility system by the end of the study), but there is a near-term economic window due to the installation of large amounts of low operating cost capacity in the early years of the study.

The Dynamic Analysis Results Reveal Financial Problems Not Identified in the Static Analysis

The dynamic penetration of a utility by a capital intensive product such as solar-thermal plants can cause an ever-increasing net negative cash flow. This is caused by the added capital requirements of the new solar plants outweighing the current fuel savings of the solar units. Even though the static (plant lifetime) analysis may show a favorable cost/benefit ratio, the switch to solar thermal plants will cause a cash flow problem lasting much longer than the payback period of an individual solar-thermal unit.

The Institutional Constraints on Nuclear and Coal Generation Facilities Strongly Affect the Time Value of Solar

There are two institutional constraints which were applied which significantly influenced the value of solar. The first institutional constraint was to limit the amount of nuclear additions which could be made. The second institutional constraint applied was one which limited the percent reserve to a maximum of 25%. These limitations cause the value of solar-thermal plants to decrease more slowly in the early years than they otherwise would have.

IMPLEMENTATION OF SOLAR INDUSTRIAL PROCESS HEAT

D. W. Kearney
Solar Energy Research Institute
Golden, Colorado

SUMMARY

Process heat is used in such a diversity of industrial applications that it is misleading to categorize solar industrial process heat (SIPH) as a homogeneous entity. Various studies have been carried out in an attempt to identify the solar potential as a function of standard industrial classifications (SIC codes), quantified by energy use and maximum process temperature in each classification. However, it is becoming increasingly obvious that considerable detail is required for any given industrial use to accurately determine SIPH requirements.

For example, recent studies [1] at SERI have examined the potential for SIPH in such diverse applications as petroleum refining and fluid milk processing. Petroleum refining involves many different operations, and each of these can entail subprocesses over a wide range of process fluids and temperature levels. A careful examination of process needs show that about 22% of refinery process heat is delivered below 290°C (550°F), and almost 63% is delivered between 290°C (550°F) and 590°C (1100°F). While the higher temperature processes usually require fossil fuel combustion, the lower temperature needs could be supplied by solar energy. By contrast, fluid milk processes in dairies are entirely low temperature, generally requiring hot water or steam for cleanup at 60°C (140°F) and for pasteurization at about 77°C (170°F). An evaluation of this application was carried out taking into account different combinations of collector technologies and system configurations over the U.S., identifying promising near-term SIPH possibilities. This kind of detailed systems analysis appears to be necessary to obtain a valid assessment of the economics of SIPH, since regional influences and system-dependent solar costs markedly affect results. It may be possible both to treat systems in the necessary detail and to cover a wide range of industrial needs by approaching the problem from the viewpoint of generic system processes (e.g., hot water heating, 125 psi steam production). In this way, a limited number of SIPH configurations could find broad industrial applicability.

The systems engineering for SIPH applications must improve beyond the present state-of-the-art to be acceptable to industry. In addition to the obvious needs for system durability and reliability, good engineering practice must be carefully implemented. In many cases, energy conservation techniques in industry can be more cost effective than adding solar energy systems, and thus a credible solar application evaluation must first fully explore conservation improvements. Other process considerations can be equally important [2]. Often high temperature sources are used to provide low temperature process heat. As an example, package boilers are often used to supply process steam for

hot water heating. There is evidence, however, that energy conservation practices are causing a shift to direct hot water heating, which is more readily accommodated by solar technology.

A number of SIPH engineering field tests sponsored by the Department of Energy are underway in phases ranging from conceptual design to operation. These projects illustrate some of the engineering practices discussed above. Most, however, are retrofit applications and do not utilize the full potential of a solar energy system. Moreover, the limited operation to date (three hot water and four hot air systems below 200°F) has shown lower than predicted system efficiencies. In addition, component or system failures and inadequate system design have resulted in unacceptably low solar system utilization [3].

In conclusion, the implementation of solar industrial process heat systems will depend not only on the successful development of reliable and efficient solar technologies, but also on the intelligent and sound application of process engineering principles. This poses an important challenge which must be given increasing attention if SIPH systems are to be adopted by industry.

References

1. Brown, K. C., Hill, A., Hooker, D. W., Ketels, P. A., Stadjuhar, S. A., "Analysis of Industries with Potential for Solar Industrial Process Heat," SERI/TR-333-468, to be published.

2. May, E. K., "The Potential for Supplying Solar Thermal Energy to Industrial Unit Operations," submitted to the 1980 ASME/AIChE National Heat Transfer Conference, Orlando, Fla., July 1980.

3. Proceedings of the Third Solar Industrial Process Heat Conference, Oakland, California, October 31-November 2, 1980, to be published.

SYSTEMS DEVELOPMENT

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 disccussed.

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 1.

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.

*The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the U.S. Department of Energy through an agreement with NASA.

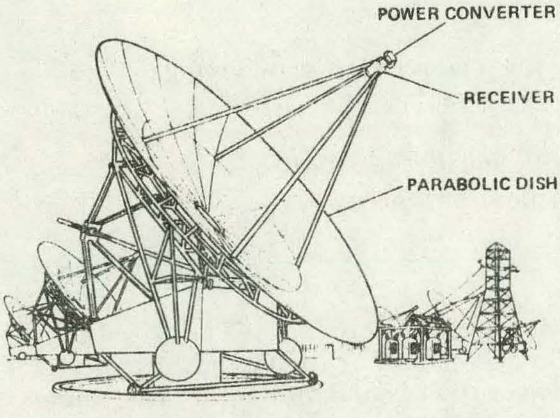

Figure 1. Dish Concentrator with Power Converter at the Focus

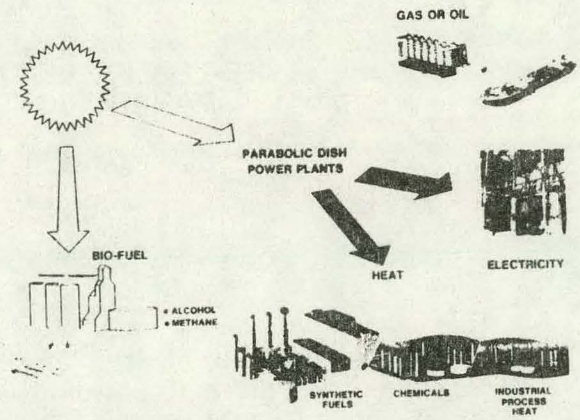

Figure 2. Versatility of Parabolic Dish Power Plants

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 (1) 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.

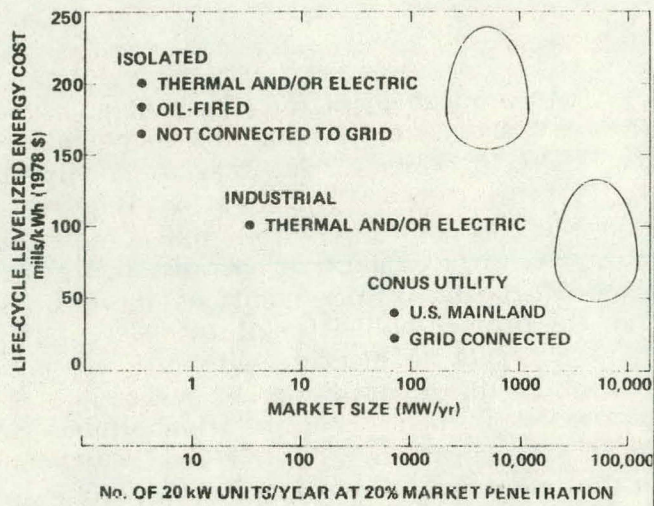

Figure 3. Energy Cost and Market Size

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.

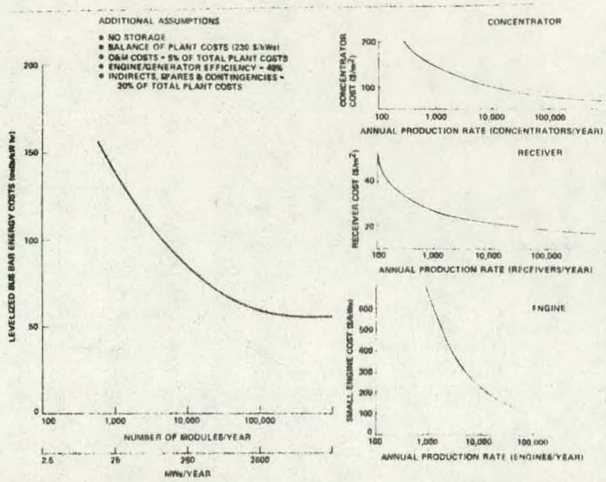

Figure 4. Effects of Mass Production on $\overline{\text{BBEC}}$

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

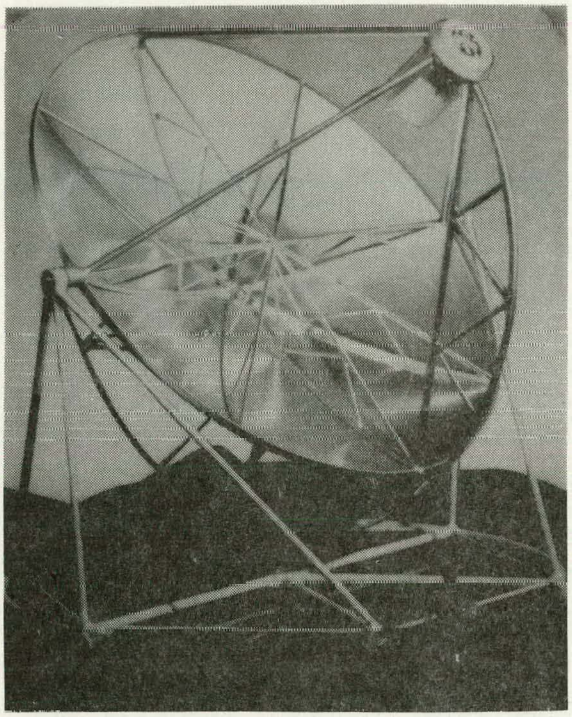

Figure 5. General Electric Low-Cost Collector Concept

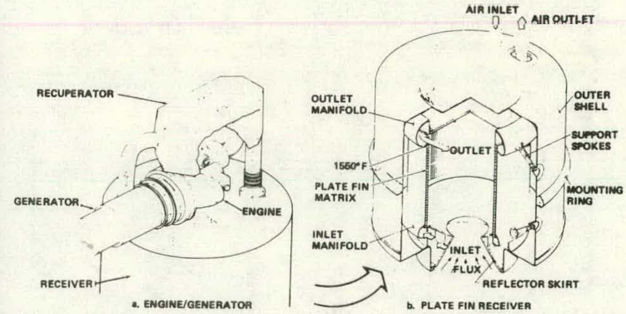

Figure 6. First-Generation Brayton Engine/ Generator and Receiver

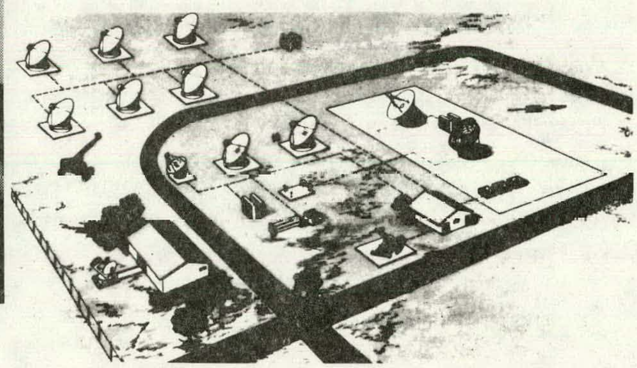

Figure 7. JPL Desert Test Site (PFSTS)

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 (~2000°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.

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.

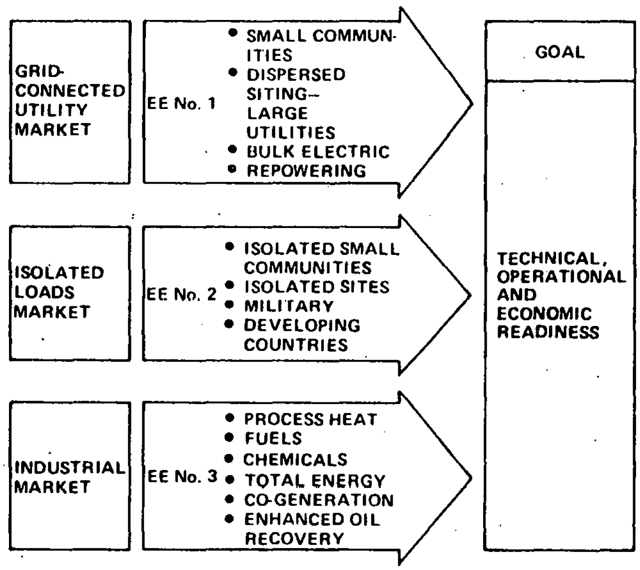

Figure 8. Engineering Experiments

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 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

In writing this paper, the authors have borrowed from the work of many solar thermal investigators at JPL and the NASA/Lewis Research Center. The contributions of Steve Bluhm and Bill Revere of JPL are particularly noted.

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DISH BRAYTON SOLAR THERMAL POWER SYSTEMS*

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ABSTRACT

Performance characteristics are determined for paraboloidal dish solar thermal power systems employing advanced Brayton (gas turbine) power conversion units. The system is comprised of a two-axis tracking dish concentrator with a cavity receiver and Brayton engine-generator assembly at the focal point. The adaptation of Advanced Gas Turbines (AGT) being developed for automotive applications is shown to offer attractive solar system performance at turbine inlet temperatures of the order of 2000°F. Addition of a Rankine bottoming cycle offers higher performance, but with an increase in system complexity and higher cost for the power conversion unit. Comparative analysis indicates that the dish-Stirling system has somewhat greater performance potential since the Stirling engine can achieve higher efficiencies than Brayton systems at lower temperatures. The Brayton engine appears to be lighter than the Stirling and can be coupled to compact advanced-technology generators.

Although the comparative assessment of dish-Brayton systems with other dish-engine systems involves many complex tradeoff considerations that are presently being addressed, the first order results in this paper indicate that the advanced dish-Brayton system should be recommended for further detailed study and development. A major driver is the potential availability of a low cost, mass-produced AGT for automobiles in the post 1985 timeframe.

INTRODUCTION

This paper presents work performed in the Advanced Studies Task of the Advanced Solar Thermal Technology Project (ASTT) at the Jet Propulsion Laboratory (JPL). Support for analyses of power conversion systems is being provided by the NASA Lewis Research Center (LeRC).

Dish-engine combinations involving Brayton, Brayton/Rankine combined cycle, and Stirling engines are being studied in a comparative evaluation context to assess performance potential in relation to requirements for technology development. The overall objective is to delineate promising systems warranting advanced technology development.

The study is on-going and the present paper will present early findings. In earlier studies at JPL [1,2] and in a more recent study [3] conducted by the Solar Energy Research Institute (SERI), the dish-Stirling system was identified as having the greatest potential. The dish-Brayton was also deemed to be very promising and appeared to offer lower developmental risks.

This paper concentrates mainly on dish-Brayton systems. Emphasis is placed on adaptation or "solarization" of Advanced Gas Turbines (AGT) which are presently under active development for automotive applications. Two parallel programs under Department of Energy (DOE) sponsorship are underway at Detroit Diesel Allison/Pontiac [4] and Garrett Airesearch/Ford [5].

APPROACH

The study approach was comprised of two basic steps: (1) development of analytical methods and (2) determination of engine system component characteristics. The analytical methods employ component characteristics to determine overall solar system performance.

Analytical Methods

A computer simulation code linking a cavity receiver with a Brayton engine was developed for the purpose of performing parametric tradeoff studies which would lead to selection of optimum designs in terms of engine component and concentrator/receiver characteristics. The solar flux distribution approaching the aperture of the cavity receiver was determined using Schrenk"s optical computer code.
Brayton engine performance is determined as a function of basic component characteristics encompassing the following key parameters: compressor efficiency, turbine efficiency, recuperator effectiveness, and duct pressure loss.

Component Characteristics

Brayton engine component characteristics were determined via a literature survey including test data on engines such as the Garrett CCPS40 coupled with performance projections for automotive AGTs [4,5]. The AGT programs were only recently initiated and further data from these programs will be used as it becomes available. Key characteristics are shown in Table 1.

TABLE 1. BRAYTON ENGINE COMPONENT EFFICIENCIES
(MAX. POWER <130 hp)

COMPONENT CHARACTERISTICS	STATE-OF-THE-ART (METAL ALLOYS)		ADV. TECHNOLOGY (CERAMIC)	
	GARRETT		AGT	
	CCPS40 (1)	SOLAR (2)	GARRETT	ALLISON
Compressor Efficiency	0.76-0.77	0.77	0.80	0.80
Turbine Efficiency	0.85-0.88	0.86	0.87	88.5/84 (3)
Recup. Effectiveness	0.89-0.92	0.94	0.93	(4)
Pressure loss Factor	0.94	0.90	0.91	(4)
Turbine Inlet Temp., °F	1500	1500	2500	2150/2350 (5)
Pressure Ratio	1.9	2.7	5.0	4.5

(1) Closed cycle test data
(2) Being developed for the Point Focusing Distributed Receiver (PFDR) project at JPL.
(3) Power turbine eff./gasifier turbine eff.
(4) Not available in [4].
(5) Power turbine Inlet Temp./Gasifier Turbine Inlet Temp.

RESULTS AND DISCUSSION

Basic results concerning selection of design operating conditions for the dish-Brayton employing the characteristics of the Garrett Airesearch AGT as given in Table 1 are presented in this paper. The free turbine Detroit Diesel Allison is also being studied with emphasis on assessing potential benefits of the free turbine system for solar applications.

Advanced Dish-Brayton Performance Characteristics

The efficiency characteristics of the dish-Brayton system are presented as a function of receiver temperature in Figure 1. Component characteristics were held fixed at values given on Table 1 for the Garret AGT. As the temperature was varied, the optimum pressure ratio and corresponding maximum efficiency were determined. The engine efficiency curve on Figure 1 is the envelope curve of maximum efficiencies.

The receiver efficiency curve is similarly an envelope curve of maximum efficiencies determined by optimizing the aperture size. The receiver curve on Figure 1 approximately matches predicted characteristics of the 1500°F Brayton receiver being fabricated by Garrett for the PFDR project. This receiver will be linked to the Garrett "solar" engine of Table 1.

The selection of the design operating condition for the dish-Brayton system depends on the combined efficiency of the receiver and engine. As seen from Figure 1, this curve reaches an optimum in the 2000°F to 2500°F range and is relatively flat so that efficiencies close to the optimum are achieved over the entire range. Thus, to minimize materials problems and improve life, systems will generally be designed to operate in the lower temperature portion of this range.

Comparison to Brayton/Rankine and Stirling Systems

The advanced dish-Brayton system is compared to the Brayton/Rankine and kinematic Stirling engines in Figures 2 and 3. Engine efficiencies are compared in Figure 2 while combined receiver engine efficiencies are presented in Figure 3. The Brayton/Rankine combined cycle efficiency curve (Figure 2) is based on using the AGT as the topping cycle with a toluene Rankine bottoming cycle. Characteristics of the Rankine bottoming cycle were selected to approximately match estimates for small toluene engines from Sundstrand (e.g., turbine efficiency was taken to be 0.65). The Stirling engine curve (Figure 2) corresponds to projections of United Stirling of Sweden for an advanced development kinematic engine in the 25-30 kW power range.

The trends shown on Figure 2 indicate that the Stirling engine achieves higher efficiencies at lower temperatures. Addition of the Rankine bottoming cycle to the AGT provides a significant improvement in efficiency. The Brayton/Rankine is seen to achieve higher performance than the advanced kinematic Stirling for high temperatures (>1800°F). This improvement is gained at the expense of added complexity and power con-

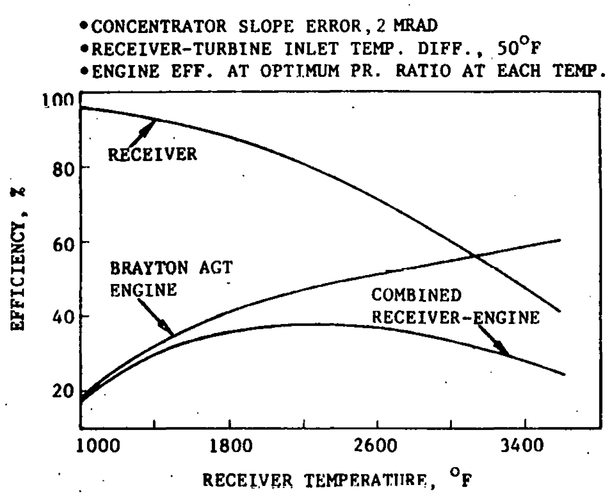

FIGURE 1. ADVANCED DISH-BRAYTON SYSTEM PERFORMANCE CHARACTERISTICS.

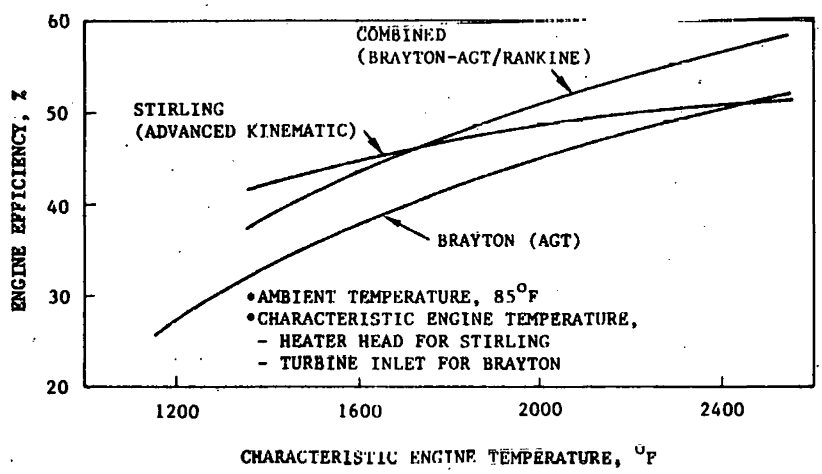

FIGURE 2. COMPARISON OF ADVANCED ENGINE EFFICIENCIES.

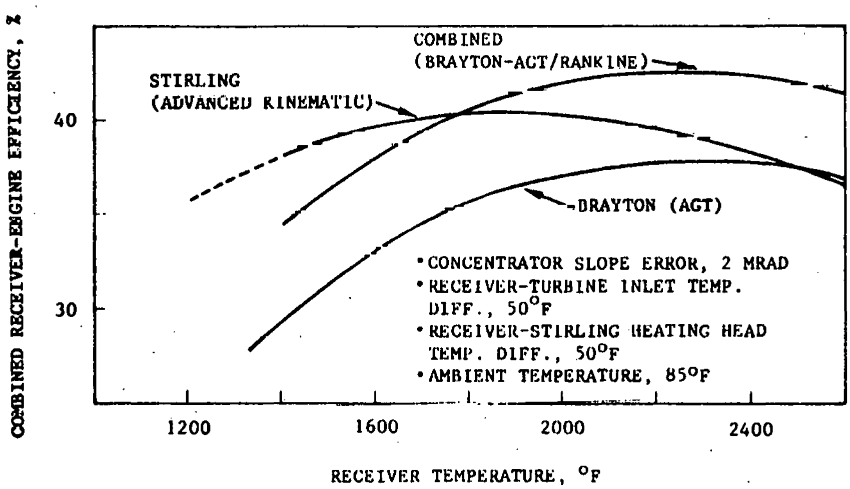

FIGURE 3. COMPARISON OF RECEIVER-ENGINE EFFICIENCIES.

version system cost. A detailed tradeoff assessment will be performed as part of the on-going study effort.

The combined receiver-engine efficiency curves on Figure 3 reflect the advantage of the Stirling engine in achieving high efficiencies at lower temperatures. The Brayton can achieve performance levels approaching that of the Stirling system at higher temperatures (>2000°F) while the Brayton/Rankine exceeds the kinematic Stirling. Additionally, the Brayton engine appears to be lighter than kinematic Stirling engines which would be advantageous for focal point mounting. Use of lightweight, high-speed generators compatible with Brayton engine rotating speeds offers potential for additional weight savings. These considerations are being addressed in tradeoff studies.

CONCLUSIONS

Based on first order considerations in this paper, further detailed study and development of the advanced dish-Brayton system appears to be warranted. The primary drivers are potential for high performance coupled with the potential availability of low cost, mass-produced AGT engines for automobiles that can be adapted for use on dish systems.

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*This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the Department of Energy through an agreement with NASA.

DISH-STIRLING SYSTEM DEVELOPMENT

J. W. Stearns

The dish-Stirling electric generation system has been identified in previous reviews as a low-noise, pollution-free system with high near-term potential for meeting solar thermal-electric applications needs. Today, with the detailed development of the dish-Stirling system underway, every indication is that original predictions will be met. At the present rate of progress, demonstration of the majority of the basic systems technologies will be done by FY 1981. By FY 1982 we should be able to demonstrate system technology that is capable of 34% solar-to-electric efficiency, has an unattended lifetime potential approaching 100,000 hours, and identifies system installed cost expectations of $500-$600/kWe in full scale production.

Limited production could commence as early as 1984. The systems are designed for hybrid operation, with options for thermal energy storage (TES). These allow a high capacity factor for the system and minimization of fossil fuel consumption.

SUBSYSTEMS TECHNOLOGY DEVELOPMENT

Technology demonstration is required to assure readiness for systems application. Strawman systems were therefore defined, and components and subsystems have been designed to meet system specifications. The focus of effort, however, is to develop and demonstrate, at the system level, a technology for a range of system applications. The technology development effort for dish-Stirling includes the Stirling engine, parabolic dish-concentrator and the point focus receiver. Power level was arbitrarily defined at 20-25 kWe, but technology should cover the range from 10 to 75 kWe.

A constant power operation of the system modules was defined for the strawman system. Such operation is easily accomplished with hybrid and TES capability. Any need to match a variable load profile at the multi-megawatt level can be met by switching individual modules on and off. Operating at constant power has significant cost advantages. It eliminates internal engine control requirements and allows engine-generator design for single-point operation at maximum efficiency. With the addition of a small amount of TES, combustor operation is also at maximum efficiency.

Advanced Concentrator Development

The low-cost structural glass gore is the key technology development for the Advanced Concentrator. A back-silvered mirror is to be cold sagged and bonded to a spherical or parabolic surface ground on a cellular glass substrate. These mirror panel elements are brought together to form sections, or gores, for the large parabolic dish. The gores will then be mounted and aligned on the concentrator backup structure.

The size of the mirror panel elements is limited by the membrane stress built up in the cold sagged glass, and is determined by the curvature in the panel. Thus, concentrator diameter and focal length are the primary determinants of element size. Thickness of the cellular glass substrate will increase with element size as well. Detailed cost tradeoffs are presently being analyzed.

Mirror panel technology is being contracted to Pittsburgh Corning Corporation. The PCC process eliminates the expensive and energy-consuming glass melting tank. Bonding of the cellular glass block will allow build-up of panels from conventional block sizes using existing facilities. The bonded panels will also minimize crack growth problems. Mirror glass selected is the 40-mil fusion glass manufactured by the Corning Glass plant in Blacksburg, VA.

Concentrator subsystem design is being accomplished by Acurex Corporation and JPL. There are two structural concepts presently being evaluated. They are shown in Figures 1a and 1b. Figure 1a is a design that is stress limited by wind loads above approximately 70 mph with the concentrator in its stowed (zenith) position. The second design, Figure 1b, shows the concentrator to be stowed in the dish down position, making it possible to minimize overturning moments. Counterweight mass is also eliminated in the second concept. Detailed analyses are still in progress. The first concept has been carried through preliminary design in order to make cost estimates. Cost of the complete concentrator subsystem is currently estimated to be well below $80/m^2$ for the 11 meter dish in large production, including foundation and tracking. Cost scaling with size is yet to be done.

The gore technologv and concentrator structural design is truly a second-generation system approach. It represents the highest possible reflective mirror performance (reflectivity above 0.95 and slope error under $\sigma = 1$ mr), at very low gore cost (under $30/m^2$). The fusion glass reflective surface also shows the minimum degradation with time of any back-silvered glass identified. Prototype Advanced Concentrators can be fabricated and installed for test within 18 months if adequately funded.

Stirling Engine Development

Although no major engine development is found necessary for the Stirling engine, modification of engines is required to optimize them for the solar application. Several items are presently receiving attention:

- addition of a dry sump for inverted operation,
- selection of seal and piston ring configurations and materials for long life,
- elimination of engine controls and provision of hermatic sealing for simplicity, low-cost and elimination of maintenance,
- evaluation of engine design for cost-reduction recommendations.

Initial work is being done with the United Stirling P-40 engine, for operation at approximatley 25 kWe alternator output. However, future requirements for the larger P-75 are not being overlooked. The cost differential between the P-40 and P-75 is very small, estimated by United Stirling as only about 30%, while the power differential is approximately a factor of three. Both of these engine designs are maturing rapidly under the impetus of automotive application programs. Limited production may be achieved as early as 1984.

At the lower power levels of 15-20 kW, there is a potential that a modified Philips 1-98 Stirling engine could be cost effective. The compact, single cylinder engine is much lighter than the P-40, and could prove to be less costly. However, significant requirements such as additional design of the thermodynamic section, seal improvement, and improved producibility and serviceability are now being studied.

Direct Coupled Receiver Development

The Dish-Stirling Solar Receiver (DSSR), being developed by Fairchild Stratos Division, is directly coupled to the Stirling engine, as shown in Figure 2. The conical receiver body utilizes copper for high thermal conductivity to the Stirling heat exchanger tubes. A fossil fuel combustor, initially using natural gas, is located behind the copper body for augmentation of solar heating.

The metallic hybrid receiver is expected to have a production cost under $15/kWt input to the Stirling engine. The application for this subsystem is towards a low capacity factor cost tradeoff. Primarily, the DSSR is designed to provide solar generation for fuel displacement. However, with hybrid operation, a reasonable contribution can also be made towards capacity displacement. A capacity factor of the order of 0.3 may be a reasonable expectation in any optimization process, although much higher capacity factors could readily be achieved by the hybrid operation.

Preliminary design of a ceramic receiver has been completed for for the DSSR. The receiver body is to be slip cast from silicon nitride, complete with tubulations and ceramic housings and heads for the Stirling engine. Its purpose is to eliminate creep problems that limit lifetime, and to increase the Stirling engine operating efficiency to approximately 48-50% at higher temperature.

Testing of the receiver requires integration with the Stirling engine. Initial testing of the metal receiver now in fabrication is scheduled at United Stirling, Sweden, in May, 1980.

Heat Pipe Receiver and Thermal Storage Development

The Heat Pipe Solar Receiver with TES (HPSR/TES), being developed by General Electric Co. in Cincinnati, places thermal storage as a buffer between the receiver and the Stirling engine, as sketched in Figure 3. Further detail is discussed in a later paper. The receiver primary heat pipes carry heat into the TES secondary heat pipe, where a nearly isothermal interchange of heat is maintained between the TES material (sodium fluoride-magnesium fluoride eutechtic) and the Stirling engine heater tubes. A fossil fuel combustor will also be designed into the TES package to augment the solar heating. The amount of TES required by the system is yet to be studied.

Present HPSR/TES studies are aimed at defining a fully low-cost design. The goal is a receiver cost of \$6/kWt, combustor cost of \$5/kWt, and TES cost under \$15/kWt + \$10/kWH(t). The addition of the TES will produce a much higher cost-optimized capacity factor for the system, possibly as high as 0.7. Again, hybrid operation can also allow an even higher capacity factor if needed, but probably at off-optimum cost.

TECHNOLOGY PLANNING

System Sizing

Initial parametric studies for dish-Stirling system sizing have recently been done by Ford Aeronutronic Division*. A key factor has been found to be the estimated production costs for the Stirling engine. At 75 kWe, the per-kWe cost of the Stirling engine is a factor of approximately 2.3 lower than for the 25 kWe engine. However, the per unit cost of the concentrator increases quite slowly with size from the approximate 11-m diameter optimum (for the 25-kWe module) to the 17-20 meter size needed for the 75 kWe module. Thus, the overall system optimum appears to be at the 75 kWe size. When concentrator cost decreases, as is expected with the Advanced Concentrator, the incentive for the 75 kWe system module increases even further.

The Ford production cost estimates for the Stirling engine have since been substantiated by independent studies. Increased emphasis is therefore being given to the 75 kWe system concept as well as to the 25 kWe module for which technology demonstration is scheduled. The smaller system modules, to be tested during FY 1981, may be used in specific remote or military applications, and their development is expected to continue.

Additional Technology Needed

All major technologies for both the 25 kWe and 75 kWe dish-Stirling system sizes, are expected to be established by FY 1981. There are secondary technology needs that must receive attention through FY 1982 and 1983. These include the following:

- Demonstration of ceramic receivers
- Development of coal-fueled combustors
- Optimization of stand-alone technology
- Final detailing of production methods
- Continued evaluation of performance and lifetime

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

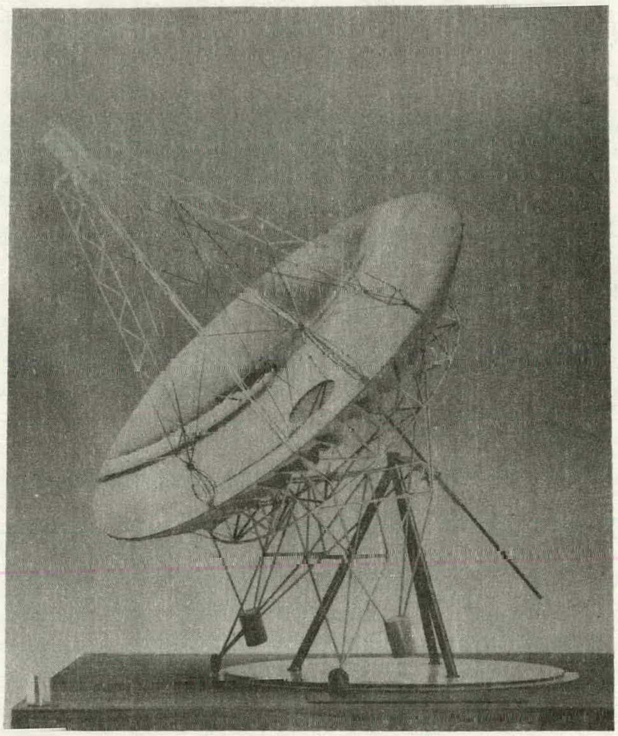

Figure 1a. Existing JPL Configuration

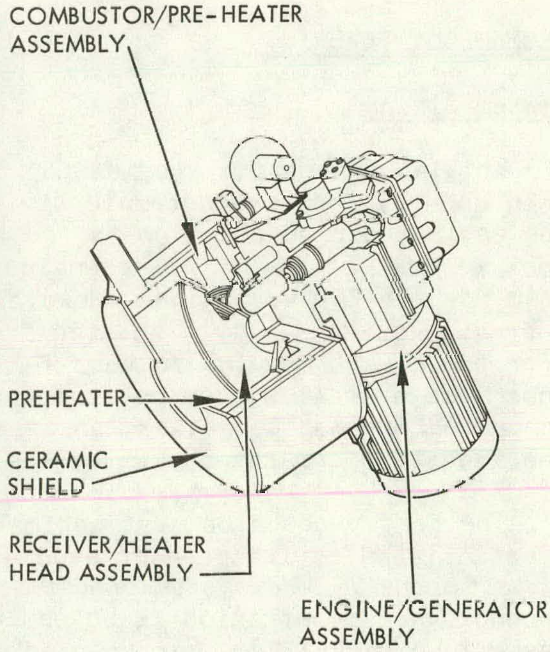

Figure 1b. Alternative Configuration- Art Required

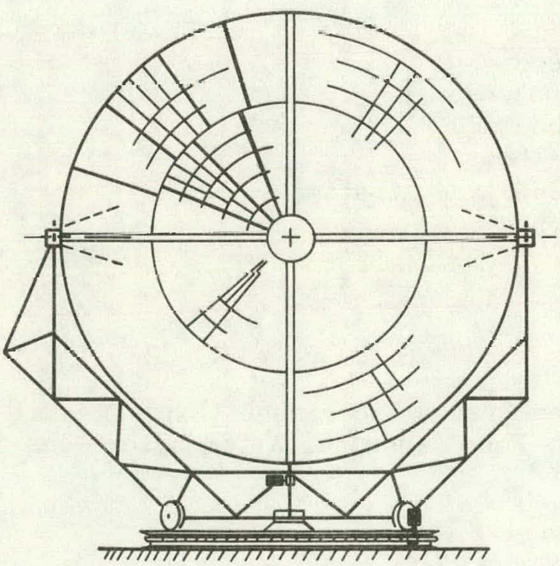

Figure 2. Dish-Stirling Solar Receiver With P-40 Stirling Engine/Alternator

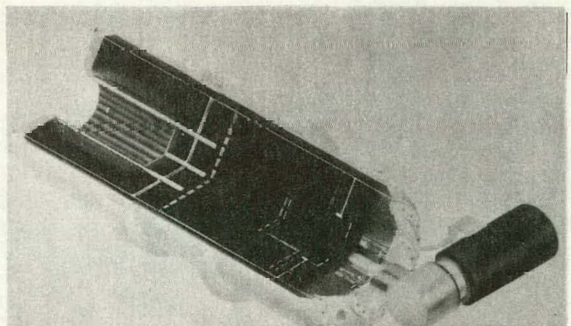

Figure 3. Heat Pipe Solar Receiver With Thermal Energy Storage

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

by

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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 tradeoffs will center on the choice of Steam versus Organic Rankine Cycle engines. 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.

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 JPL/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 ($\sim$ 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.

PROGRAM REQUIREMENTS AND PLANS

The overall schedule for the SCSTPE program is shown in Figure 1. The major constraint is the customer requirement to have a plant "on-line" by the middle of Fiscal Year 1983. The critical path is represented by

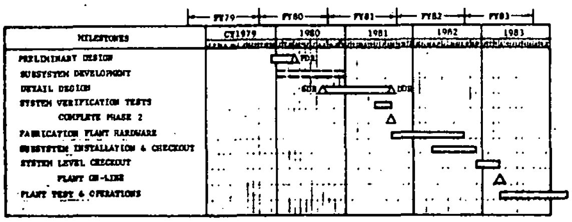

FIG. 1. OVERALL MILESTONE SCHEDULE FOR SCSTPE PROGRAM

the requirement for engine delivery in 12 months, following PDR.

The initial 4-month Preliminary Design task will provide the basis for selecting the major subsystems. In addition to program schedule and cost considerations, subsystem and component selection will be based on a commercialized, 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, CA site will be employed for preliminary design computations.

Major subsystem trades will address the following key issues:

1) Concentrator
   - Low-Cost Concentrator (LCC), or
   - Test Bed Concentrator (TBC), or
   - Other

2) Power Conversion
   - Organic Rankine Cycle (ORC), or
   - Steam Rankine Cycle
   - Piston or Turbine or Rotary Expander
   - Focal Plane or Ground Location for Components

3) Receiver
   - Direct Heated, or
   - Indirect Heated

The Energy Transport subsystem is a conventional electrical network, either AC or DC depending primarily on the type of engine and associated power control system selected. With the aid of a computer program developed by FACC during the Phase I effort, installed cable costs are minimized as part of an optimization of the geometric layout of the modules; the influence of land cost and the effect of solar blockage on annual energy output are included in the optimization process.

FACC will also provide the overall plant control subsystem. Detailed design of the hardware and software for complete control of a multi-module plant is a major undertaking, particularly in light of the requirement for unmanned operation. 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.

BASELINE SYSTEM

A baseline system has been identified, derived partly from the results of the Phase I SCSTPE study. It consists of 1) the General Electric LCC, 2) a Sundstrand regenerated ORC engine with single stage turbine expander and direct-coupled high speed alternator and 3) a Garrett AiResearch direct-heated cavity receiver. Figure 2 shows the LCC with the power conversion assembly at its focus. The LCC is a 12m diameter paraboloid with a rim angle of 53 deg. (f/D = 0.5); projected installed cost, at 100,000 units per year is about $88.80/m^2$. The dish is comprised of multiple injected-molded glass-reinforced epoxy panels, or gores, with integral structural ribs on the back side for stiffness. External front-braced steel ribs are provided for support and alignment of the gores as well as for added strength and stiffness. Solar blockage due to the front structure, the power conversion assembly and the support struts is about 5%. The LCC employs an azimuth-elevation type mount which permits stow in the inverted position to reduce wind loading, avoid hail damage and provide easy servicing of the ORC power conversion assembly. Azimuth/elevation drive is by electric motor via cable/drum arrangement. Position control is accomplished by a combination of open loop system (computer-based position prediction) for coarse control and closed loop system (fiber-optic sun sensor) for final positioning. Pointing accuracy is 1/8 deg. (1σ); overall reflector slope accuracy is also 1/8 deg. (1σ). Prototype LCC units employ aluminized polyester film as the reflecting surface, integrally fabricated with the injection molded gores. Reflectivity is about 0.8 and reflector life is about 15 years. The fabrication process is adaptable to silvered (glass) reflectors, which are currently under investigation.

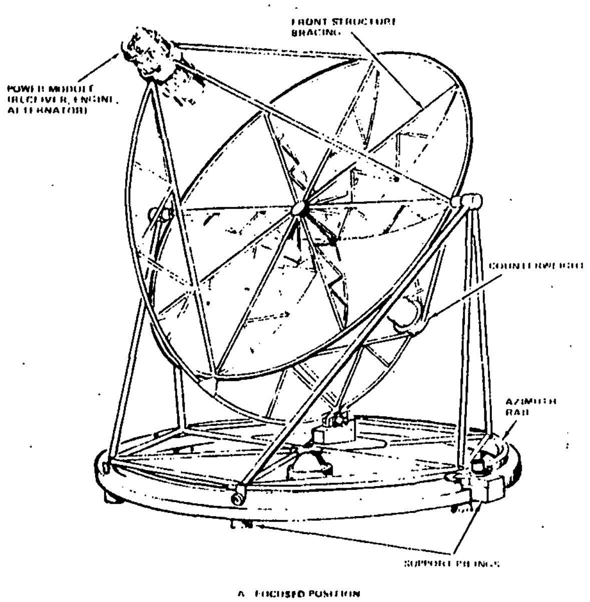

FIG. 2. LOW COST CONCENTRATOR WITH INSTALLED ORC POWER CONVERSION ASSEMBLY

Figure 3 shows the power conversion assembly, consisting of the ORC engine/alternator, the receiver and associated plumbing. Complete weight of the assembly is 547 Kg (1207 lb); it is 3.54m (8.33 ft) long and, fits within a 1m. diameter circle. The engine uses toluene as the working fluid; at 427°C (800°F) turbine inlet temperature and 4.08 MPa (600 psia), the toluene operates in the supercritical state and projected net efficiency, based on electrical output, is 27.5% at the rated ambient temperature of 28°C (82°F). Electrical output is 16.2 KW_e at rated power conditions. An air-cooled condenser is packaged concentrically with the turbine/alternator/regenerator components as shown in Fig. 3. Turbine inlet temperature is held constant by varying the

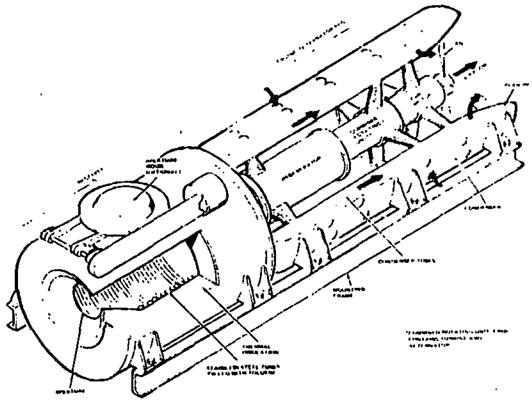

FIG. 3. ORC POWER CONVERSION ASSEMBLY

toluene mass flow rate -- in proportion to the solar input to the receiver -- with a variable rate feed pump. The variable power level is accommodated by varying turbine speed via alternator field control. By varying the speed of both the turbine and the condenser cooling fan, engine efficiency is nearly invariant with load, as shown in Figure 4. This assures high annual energy output despite significant variations in solar insolation. The high-speed alternator is connected directly to the turbine shaft and produces variable frequency AC output as the solar input (and turbine speed) varies. A rectifier and inverter are incorporated to provide constant frequency (60 Hz) input to the utility grid. Gross weight of the ORC engine, including alternator, is 296 Kg (654 lb); it is 0.86m (34 inches) in diameter and 1.55m (61 in) long.

The receiver consists of an insulated cylindrical cavity with an inner surface-to-aperture area ratio of about 17.5. The heat exchanger is a once-through design with helically-arranged welded Type 300 stainless steel tubes forming the inner (side) surface of the cavity. The helical coil is 508mm (20 in) in diameter and 635mm (25 in) in length; tube OD is 15.9mm (5/8 in) with wall thickness of 0.71mm (.028 in). The back surface consists of a ceramic disc that reflects incoming solar radiation to the side walls, which results in a more uniform flux distribution on the heat exchanger tubes. Gross weight of the receiver, including the heat exchanger coil, thermal insulation, structural housing, aperture door and mounting structure is 151 Kg (333 lb).

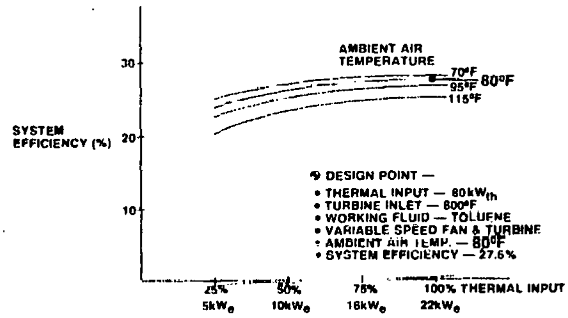

FIG. 4. PART LOAD PERFORMANCE OF ORC ENGINE

SYSTEM PERFORMANCE

Detailed performance calculations have not yet been made on either the baseline or alternate systems. However, the results of the Phase I study indicated that an optimized Dish/Rankine system, at 100,000 units per year would have a levelized busbar energy cost of 60 to 70 mills/kWh and a capital cost of ~ \$1100/KW$_e$. Typical performance parameters for the baseline ORC system are given in Table 1. The Annualized Capacity Factor (ACF) is determined by computer modeling of the total system as a function of solar insolation and ambient temperature at the site; system energy output is determined using 15 minute environmental data tapes for the Barstow, California site. Note that collection efficiency (η_{coll}) given in Table 1 is the combined efficiency of the concentrator and receiver. Overall system efficiency (η_o) is the measure of conversion from solar energy to electricity; it is approximately 19%.

TABLE 1

BASELINE ORC SYSTEM PERFORMANCE PARAMETERS

T_E(ENG), ^oC	427
T_R(RCVR), ^oC	502
η_{coll}	0.708
η_{eng}	0.275
η_o	0.185
C_{opt}	1400
ACF	0.418

CONCLUSION

The SCSTPE program will provide the first field demonstration of a modular PFDR system. It should provide valuable operating experience and establish a data base for introduction of future operational systems.

TECHNOLOGY ASSESSMENT: LINE-FOCUS CONCENTRATORS

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Introduction

Over the past five years, collector/system hardware experiences at Sandia Laboratories within the Solar Thermal Power Systems Program sponsored by the DOE Office of Energy Technology have been the following (Reference 1):

Linear Fixed Mirror, Movable Receiver Concentrator - GA
Linear Fresnel Lens Concentrator on Two Axis Tracker - MDAC
Parabolic Dish - Raytheon
Linear Fixed Receiver, Movable Mirror Concentrator - Suntec
Parabolic Trough - Hexcel
Linear Fixed Mirror, Movable Receiver Concentrator - SA
Parabolic Trough - Del
Moving Belt Fresnel Mirror Concentrator - FMC
Parabolic Trough - Acurex
Parabolic Trough - Sandia
MSSTF - 8000 Ft^2 Collectors, 32 kW_e Total Energy Plant
Willard - 14,000 Ft^2 Collectors, 25 HP Irrigation Plant

These eleven collectors and two systems were fabricated, tested, and evaluated in order to define engineering development problems requiring solution prior to commercialization initiatives. This paper describes the major engineering problems and near-term development emphasis.

Summary Status of Existing Technology

From an overall viewpoint the status of existing line-focus collector technology can be summarized by the following three points.

First, the thermal efficiencies of current collectors are not yet at the goal of between 60 and 70% at $600^{o}F$ although there appears a definite and encouraging trend with successive collector generations to meet this goal.

Second, the durability of existing collectors is low relative to requirements of 10 to 20 years dictated by economics. Both environmental degradation of materials and, as yet, inadequate treatment of system safeties contribute to this durability issue.

Third, existing technology does not yet lend itself to low-labor mass-production materials and processes which will be required to meet cost goals.

Collector Concept

The performance prototype concepts which have been evaluated at Sandia Laboratories include the tracking aperture type exemplified by the parabolic trough and the fixed aperture type exemplified by the Solar Linear Array Thermal System, the Fixed-Mirror Solar Collector, and the Faceted Fixed-Mirror Concentrator.

Utilizing measured normal-incidence thermal efficiencies, an estimate of annual average collector efficiency can be made which includes cosine losses. The results shown in Figure 1 as a function of average collector temperature indicate a substantial performance advantage to the tracking aperture type of collector mainly due to the lower average cosine losses relative to the fixed aperture type of collector.

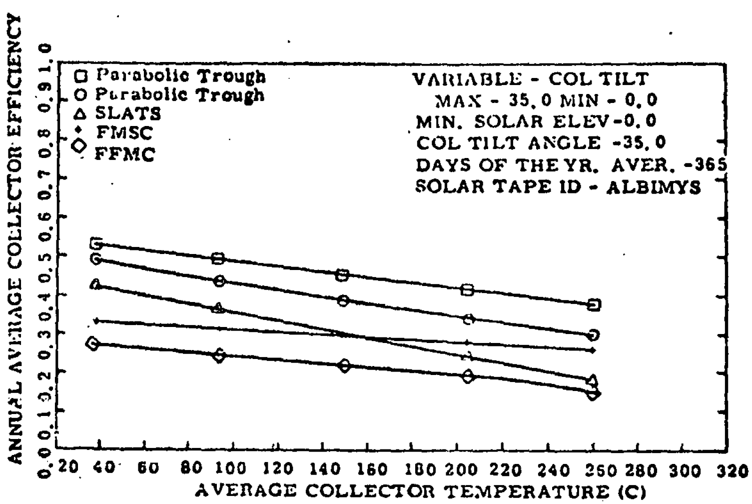

Figure 1. ESTIMATED AVERAGE COLLECTOR EFFICIENCY BASED ON MEASURED NORMAL - INCIDENCE EFFICIENCIES

This performance advantage of the tracking aperture over the fixed aperture is a primary consideration to both near-term and longer-term applications of line-focus collectors. (Reference 2).

In the near-term, process heat is the likely application market because of system simplicity. Since approximately half of the process heat usage is below 600°F, it is important, during market initiation, to identify a collector concept which is capable of giving high performance over this potential temperature-use spectrum.

In the longer-term, cogeneration which will obtain process heat from a power conversion cycle is the likely application market because of economic advantages of simultaneous production of electricity and process heat. In this case, it is important to identify a collector concept which is capable of high performance at elevated temperatures in order to provide high quality energy to the power conversion cycle to achieve reasonable thermal-to-electric conversion efficiencies.

Test and evaluation data to date indicate that the parabolic trough is the preferred line-focus collector concept for the near-term and longer-term potential markets.

Recent engineering development efforts at Sandia Laboratories have resulted in a parabolic trough collector which establishes the feasibility of meeting the thermal efficiency goal. Test data for the so-called Engineering Prototype Trough (References 3, 4) indicates 60% peak-noontime thermal efficiency at 600°F. To achieve the performance goal this collector embodies, as described in this paper, several design improvements in the areas of reflector material, structure, tracker, receiver and selective coating.

Structures

In order to achieve cost-effectiveness in mass-production, not only must the collector structure feature a high stiffness-to-weight ratio so as to keep material content to a minimum but also the collector structure must be amenable to low-labor manufacturing processes. Three structural concepts with high stiffness-to-weight ratios and potential for mass-production manufacturability are shown in Figure 2. Structural design analyses indicate for a 90 mph wind survival criterion that these concepts may weigh three to four pounds per square foot including mirrored glass which serves as the reflector.

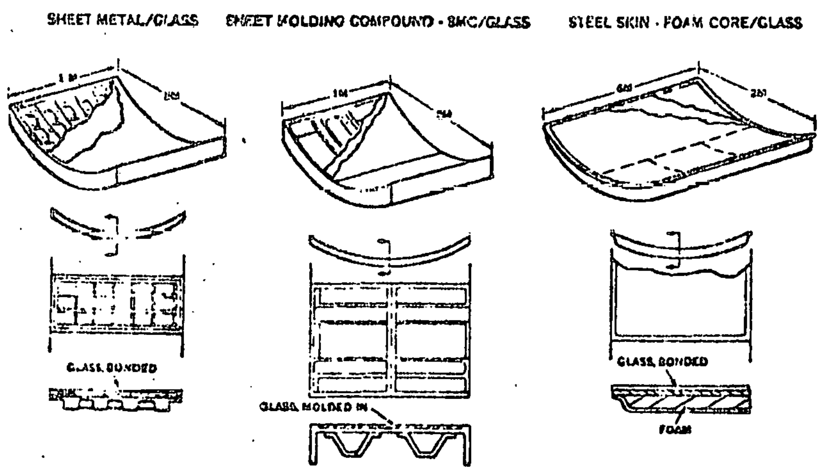

FIGURE 2. PARABOLIC TROUGH REFLECTOR/STRUCTURE DESIGN CONCEPTS.

The first concept consists of a ribbed frame panel which is stamped from sheet metal and attached to a sheet metal skin supporting the reflector.

The second concept consists of a sheet molding compound (SMC) panel into which is molded the glass reflector to eliminate a separate bonding operation; hat sections are bonded to the panel to achieve high stiffness. The 2m x 1m dimensions of the sheet metal and SMC structures are constrained by current stamping and molding press capabilities in industry.

The Budd Company has recently initiated efforts to develop prototypes of the sheet metal and SMC concepts.

The third concept consists of a sandwich structure of high density foam core and steel skins in a size potentially as large as 2m x 6m.

Reflective Materials

Over the past several years at Sandia Laboratories accelerated environmental testing of materials has been performed (Reference 5). Anodized aluminum after one year of freeze/thaw cycling in a high humidity environment estimated to simulate twelve years of real time exposure shows severe corrosion of the material which significantly degrades reflectance.

Similarly, a variety of polymer film reflective materials have been tested including aluminized acrylic. After accelerated aging the material shows severe delamination occurring between the film and the structure which significantly reduces optical performance and, more importantly, lifetime. Lifetime of typical polymer films is further limited due to poor abrasion resistance of the film.

Based on environmental test data to date, mirrored glass appears to be a preferred reflector material for at least the near-term. Its advantages over alternative materials are twofold. First, specular reflectivity of 95% has been achieved with silvered glass as contrasted to only about 75% with anodized aluminum and about 85% with polymer films. Second, as supported by environmental testing, mirrored glass gives significantly better durability.

Development of mirrored glass for line-focus collectors has been slow for the following reasons: alternative materials are currently less expensive, glass is more difficult to design into a collector due to a long-term tensile stress limitation of about 1000 psi, and, finally, production sources have been unavailable.

Three potential concepts for glass are chemically strengthened, thermally formed, and, socalled, thin glass laminates. Development problems and issues with these concepts are listed in Figure 3.

Chemical strengthening, achieved by an ion exchange process, provides a high compressive stress state at the surface of the glass sheet. Thus, chemically strengthened glass can be elastically deformed into the collector to form the reflector surface. Corning Glass Company has initiated an effort to estimate cost of chemically strengthened glass in production volumes.

Thermal forming of automotive windshields is accomplished either by gravity sagging into a frame mold or press forming between male-female surface molds. Ford Glass Division using gravity sagging and PPG using press forming have initiated efforts to develop thermally formed glass prototypes of 1m x 1m dimensions. A key problem which has not yet been addressed is the silvering of large, contoured surfaces.

Thin glass laminates consist of perhaps a 10 mil mirrored glass sheet bonded to sheet steel. The neutral axis can be placed in the steel allowing the glass to remain in compression when elastically deformed. Because of the fragility of the thin glass between forming and lamination, manufacturability has been of serious concern.

CHEMICALLY STRENGTHENED: (50 MIL x 45 IN. x 40 IN.)	o PRODUCTION COST - CORNING o LONG TERM DURABILITY IN STRESSED STATE
THERMALLY FORMED: (60 MIL x 45 IN. x 40 IN.)	o PRODUCTION COST o CONTOUR TOLERANCES AND HANDLING - FORD GLASS DIVISION AND PPG o MIRRORING OF CURVED PIECES
LAMINATED: (10 MIL x 45 IN. x 40 IN.)	o PRODUCTION COST o MANUFACTURABILITY o LONG TERM DURABILITY IN STRESSED STATE o HANDLING THROUGHOUT MANUFACTURING

FIGURE 3. DEVELOPMENT PROBLEMS/ISSUES FOR GLASS AS A REFLECTIVE MATERIAL.

Receiver

Because of an apparent near-term cost advantage, current emphasis is on receivers which are sealed to the environment but non-evacuated.

Studies have indicated a significant performance advantage of 10% increase in thermal efficiency for the evacuated receiver but requires a laboratory type vacuum (References 6, 7, 8). Furthermore, accounting for thermal expansion in an evacuated receiver is a difficult design problem within a cost budget of about seven dollars per linear foot of receiver. A definite advantage of the evacuated receiver is that the cleaning problem of the receiver interior is eliminated.

In addition, an antireflection coating on both the interior and exterior surfaces of the receiver glass envelope appears from analysis to offer a significant performance advantage of 10% increase in thermal efficiency. Corning Glass Company has recently initiated an effort to develop a prototype glass envelope with an antireflection coating for test and evaluation at Sandia Laboratories. Both cost and durability due to environmental degradation are issues of concern for antireflection coatings.

It may be of interest, before leaving the topic of reflectors and receivers, to note a phenomenon which has been observed on several collectors. Discrete focal lines are seen on the receiver tube giving an appearance of light and dark stripes. Laser ray trace data confirms that the phenomena is a characteristic of the reflector. The effect has now been seen on the Acurex trough with either anodized aluminum or thin glass laminate, the Solar Kinetics trough with aluminized acrylic, the Custom Engineering trough with sagged glass, and the Sandia trough with chemically strengthened glass. Thermal analysis indicates a one percent efficiency degradation from the effect; of more concern may be the influence of the effect on performance of a photovoltaic receiver which requires more uniform illumination.

Selective Coatings

In order to achieve reasonable efficiencies at elevated temperatures, an external receiver in a line-focus collector must feature a selective coating. Such coatings maximize absorptance in the visible spectrum and suppress radiation in the infrared spectrum. Black chrome has been the most popular selective coating for line-focus collectors as well as flat plate collectors.

A thermal instability has been previously noted from typical black chrome plating baths in which solar absorptance is significantly reduced after only a few hundred hours at temperature (Reference 9).

It appears that current emphasis will remain with black chrome as a selective coating. It should be noted that SERI has recently initiated efforts to develop black cobalt as a selective coating.

Based on work over the past two years at Sandia Laboratories in cooperation with Harshaw Chemical Company, thermal stability of black chrome has been achieved in the laboratory using a modified plating bath composition.

Two efforts over the past year are being used to formulate a plating process definition. Honeywell has produced a preliminary draft of a plating handbook which relates optical properties to bath composition and plating parameters. Sandia in conjunction with Highland Plating has recently completed a production run of black chrome plating to investigate production process problems. It appears that typical production plating instrumentation may be inadequate to achieve at this time a specification for high quality selective coatings (Reference 4).

Trackers

Sun-tracking by means of the shadow band detector has been the popular method of providing the tracking function. Using sun-tracking, the average high intensity point in the sky is tracked. Problems to date include poor tracking accuracy, false locks on clouds or buildings, biases due to selective drifting of differential amplifiers, and maintenance due to dirt accumulation.

In addition to sun-tracking, there are two other methods of tracking: computer-tracking and aperture-tracking. Using computer-tracking the sun's theoretical position is computed based on a clock input; the collector can then be pointed to the computed angle using feedback from a position sensor. Using aperture-tracking the collector is positioned to maximize the flux on the receiver by means of a flux sensing device.

Current emphasis in tracking is directed (Reference 10) toward combining computer-tracking and aperture-tracking as shown in Figure 4. A search algorithm is periodically initiated to correct computer-tracking biases by means of aperture-tracking. Furthermore, aperture-tracking serves to integrate the flux distribution down the length of the receiver to find the best average position for the collector drive string.

A fine resistance wire, helically wrapped down the receiver, is being investigated as a fast responding flux sensor. Flux sensing based on fluid temperature appears to be too slow in response due to the relatively large thermal mass involved.

The key problem at this time appears to be identification of a collector position indicator giving tenth degree accuracy at a cost of only a few hundred dollars.

If microprocessors are utilized to support the tracking function, it is suggested that a process computer should be designed to integrate the tracking function, the fluid control function and the systems safeties.

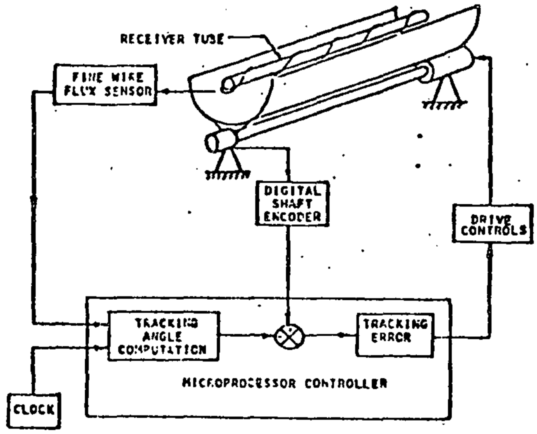

FIGURE 4. TRACKER BASED ON COMBINATION OF COMPUTER-TRACKING AND APERTURE-TRACKING.

Drive

Current emphasis in the drive system is the concept of an integral drive pylon which consists of an electrically driven pump interfacing with a hydraulic pressure accumulator and a hydraulic actuator to rotate the collector drive string. Several advantages can be listed for this concept: field layout only requires electrical wiring, high force capability at low speed, low instantaneous power requirement, and multiple speed capability with little additional cost. Perhaps the key advantage results from the emergency defocus requirement. The hydraulic accumulator in operation remains pressurized at all times; in an emergency stow condition the accumulator is dumped to drive the collectors to stow. Electromechanical drive systems must provide standby generator power or batteries both of which are subject to reliability problems. Design of a gearbox specifically for an electromechanical drive system is a key area requiring engineering development.

Wind Loads/Foundations

A consistent problem with existing solar collector installations has been high cost associated with pylons and foundations. Two recently completed test programs indicate that designs have been very conservative.

Wind loads on parabolic trough arrays have been measured by Colorado State University (Reference 11). Results indicate that fences combined with row-to-row shadowing cause reductions of peak lift and lateral forces by factors of two and four respectively. No significant reduction in pitching moment was observed by CSU indicating that reflector structure design has been adequate using previous wind loads. Finally, the test data indicates that mounting height of the collectors from the ground should be as small as possible to minimize wind loads and thereby reduce structural weight and cost.

A foundation design study and test program has been conducted by Higgins, Auld, and Associates (References 12, 13, 14). Results of the design study indicate that cylindrical reinforced concrete piers provide the most cost-effective foundation system of fifteen designs considered. Test data verified that restraining forces provided by the soil are substantial and should be accounted for in the foundation design at sites featuring good soil properties. This foundation work indicates that a goal of fifty cents per square foot of collector aperture for foundations may be feasible.

Collector Field Subsystem Layout

Two other consistent problems with existing solar collector systems have been high cost of the piping and high thermal losses in the field piping.

An ongoing field layout design study by Jacobs-Del Engineering has reached a number of preliminary conclusions. Unlike refinery type systems which run under steady state conditions, solar systems experience high thermal losses due to night cooldown; it appears that increased insulation is cost-effective in decreasing thermal losses. Furthermore, downsized piping to further reduce heat losses and thermal mass appears overall cost-effective even though cost of parasitic pumping may increase. Finally, and perhaps most importantly, the study indicates that a piping cost goal of twenty percent of installed field cost may be feasible.

State-of-The-Art Trough Design Features

Figure 5 summarizes suggested trough design features. A thermal efficiency goal of greater than 60% at 600°F requires a system error budget of seven milliradians which implies accurate structures with two milliradian slope error. Dimensions such as two meter aperture, 92° rim angle and six meter module length are suggested in order to begin some standardization to stimulate production oriented sources for structures and reflector materials during market initiation. Modular systems based on 50,000 square feet of collectors may be appropriate to attract user interest during market initiation but it is suggested that such modules be designed to be expandable to larger installations in the longer-term. Likewise, fluid control systems can be simple in concept for say 300°F process heat utilizing collectors capable of 600°F, however, cogeneration systems will require more accurate temperature controllers.

- SYSTEM ERROR BUDGET = 7 MR.
- 2 METER APERTURE, 92° RIM ANGLE, 6 METER COLLECTOR MODULE LENGTH
- 24 METER DRIVE STRING LENGTH WITH CENTER DRIVE
- 4608 SQUARE METERS FIELD MODULE EXPANDIBLE TO 46080 SQUARE METERS
- INTEGRAL DRIVE PYLONG WITH ELECTRIC PUMP/HYDRAULIC ACCUMULATOR AND ACTUATOR
- SEALED/UNEVACUATED RECEIVER WITH BLACK CHROME SELECTIVE COATING AND OIL HEAT TRANSFER FLUID
- MICROPROCESSOR BASED TRACKER WITH CLOSED LOOP INTEGRATING FLUX SENSOR
- CHEMICALLY STRENGTHENED OR THERMALLY FORMED GLASS REFLECTOR
- STRUCTURES BASED ON SHEET METAL, SMC, SANDWICH TECHNOLOGIES

FIGURE 5. SUGGESTED TROUGH DESIGN FEATURES.

Conclusion

In conclusion, our common current aim in line-focus collector technology should be toward engineering development to establish a target collector with high performance, durability, and reliability utilizing mass-production technology with potential for low cost.

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ADVANCED RECEIVER TECHNOLOGY*

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ABSTRACT

Development of advanced receiver technology for solar thermal receivers designed for electric power generation or for industrial applications is reviewed. The development of this technology is focused on receivers that operate from 1000°F to 3000°F and above. The development program is organized to promote development of innovative and efficient concepts, rather than hardware. Current advanced receiver development projects are categorized in terms of application temperature or function and their status and progress are reviewed.

INTRODUCTION

The receiver is a key component of a solar thermal power system. It is designed to capture concentrated solar energy from a concentrator and convert it into thermal energy within the working fluid of the receiver. This process must be performed with a minimum of losses to achieve attractive system efficiencies.

It is important to be able to achieve high operating temperatures in advanced receivers to permit the use of higher efficiency engines and open the door to an increased number of useful industrial processes. Thus, the impetus in receiver technology is toward higher efficiency and higher temperature designs, while satisfying the needs of particular applications.

The goal of the receiver technology program is to promote the development and demonstration of innovative and efficient receiver concepts for application to advanced electric, industrial process heat, and fuel and chemical applications. The focus of the program is on technology development for receivers that operate from 1000 to 3000°F and above for special application. The emphasis is on development of technology rather than hardware per se. Technology is developed at the most appropriate level starting with subscale and laboratory experiments when feasible, then proceeding to point focus experiments to minimize costs, and then finally to central receiver systems if appropriate.

A number of key technical challenges must be met to arrive at the required receiver technology. For instance, receivers have to be designed to: minimize energy losses, provide efficient energy transfer, be compatible with buffer storage and fossil fuel operation, provide stability and proper distribution of flow, withstand extended thermal cycling, and be economically viable.

SUMMARY OF CURRENT EFFORT

Key programmatic and technical characteristics of all receivers covered here are summerized in Table I for easy reference and to provide a quick overview of the current status of receiver technology program. The receiver technology development program also forms a basis for a whole range of industrial process heat applications although no specific areas have been selected as targets.

Table I.

SUMMARY OF RECEIVERS DISCUSSED

CATEGORY	COGNIZANT ORGANIZATION	PERFORMING ORGANIZATION	RECEIVER SIZE (kWt)	OPERATING TEMP., °F	WORKING FLUID	PROJECT STATUS
High Temp.	JPL	Sanders	75	2000/3000°F	Air, He, N_2	Conceptual Study
High Temp.	JPL	General Electric	75	2000/3000°F	Air, He, N_2	Conceptual Study
High Temp.	DOE/JPL	MIT-Lincoln Lab's	TBD	1800°F	Air, others	Component Test ('79)
High Temp.	EPRI	Black & Veatch	1000	1950°F	Air	Model Solar Test ('80)
High Temp.	Sandia/L	Sanders	250	1950°F	Air	Model Solar Test ('79)
Adv. Brayton	EPRI	Boeing	1000	1500°F	Air/others	Model Solar Test ('79)
Adv. Brayton	JPL	Garrett	75	1500°F	Air	Solar Test ('80)
Stirling	JPL	Fairchild-Stratos	75	1500°F	He	Solar Test ('80)
Stirling	JPL	General Electric	75	1500°F	He/Na*	Evaluation and Solar Test ('81)
Adv. Rankine	SERI	Georgia Inst. Tech.	300	1100°F	H_2O	Performance Test ('79 - '80)
Adv. Rankine	JPL	Garrett	75	1300°F	H_2O	Solar Test ('80)
Fuels & Chem's	DOE/JPL	NRL	TBD	1700°F	SO_3	Advanced Development
Fuels & Chem's	SERI	SERI	TBD	1200°F	NA**	Advanced Development
Fuels & Chem's	SERI	SERI	TBD	1600°F	Gas+	Advanced Development

* Heat pipe concept
** "Thermosyphon" concept
+Entrained solids in gas (biomass)

High Temperature Receivers

High temperature receivers are covered here individually because the goals can be considered generic and because a number of requirements are characteristic and unique of high temperatures.

High temperature ceramic receiver concepts for application between 2000 and 3000°F are being investigated by Sanders Associates and General Electric Company. Two concepts have been selected and are being evaluated in detail in a 75 kWt size. One of them is based on a ceramic honeycomb matrix heated through a quartz window, and the other is based on a single ceramic coiled tube heated through a ceramic thermal inertia sleeve.

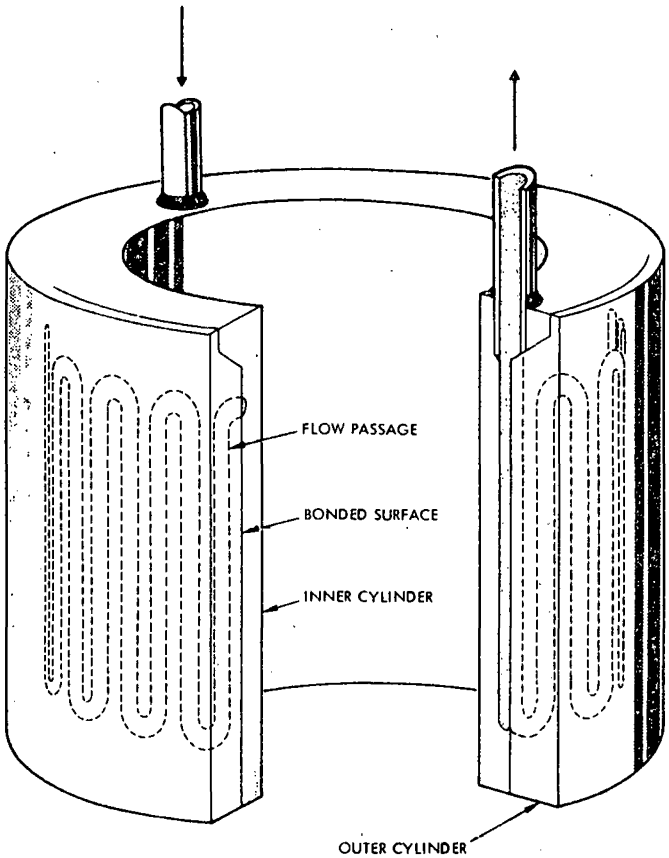

Figure 1. Ceramic Receiver Concept
(Two slip-cast cylinders)

In addition, the feasibility of fabricating a ceramic receiver using slip-casting techniques is being evaluated. A typical design that could be produced using this technique is illustrated conceptually in Figure 1. It would be manufactured by slip-casting two concentric cylinders and by incorporating the coolant passages on the outer surface of the smaller cylinder. Then the cylinders would be fired and bonded to form the seals for the cooling passages.

Ceramic receiver configurations can be adapted for Brayton, Stirling, and thermochemical applications. The most attractive concepts will be selected for solar testing.

A ceramic dome receiver concept for operation at 1800°F has been evaluated by MIT-Lincoln Laboratories. Analyses were completed for application of single and multiple dome concepts to Brayton and Stirling cycles. Ceramic metallization and brazing designs were developed and shown to be suitable for metal-to-ceramic seal transition. Acceptable seal leakage demonstrations were performed for 2 and 12 inch diameter domes under limited steady state thermal conditions.

A one MWt ceramic tube and header type bench model receiver is being fabricated for testing by Black & Veatch for the Electric Power Research Institute. The working fluid is air which is heated to 1950°F as it flows through 1.125 inch ID, 7.5 feet long SiC tubes. At this time assembly and pretest checkout of this receiver are being performed. It is scheduled for solar testing at the CRTF (Central Receiver Test Facility) in Albuquerque, in 1980. The goal of the test program is to provide creditable indications of the performance that could be anticipated in a commercial-size system.

In addition, a 250 kW ceramic honeycomb receiver using air at ambient pressure as a working fluid has been tested at 1950°F by Sanders at the Advanced Component Test Facility (ACTF) in Atlanta.

Advanced Brayton Receivers

Brayton cycle receivers require low pressure drop through the heat exchanger to minimize losses, and a relatively large heat exchanger area, and may require a thermal buffer.

A 1000 kWt bench model metal tube and header receiver designed by Boeing for the Electric Power Research Institute has been recently tested at CRTF at air exit temperatures up to 1500°F. Its heat exchanger tubes are 0.2 inch ID and 50 inches long, and are made from Inconel 617. Both steady state and transient tests were performed. Convection losses through the aperture were higher than expected. Basically these tests provided data that verifies this type of concept for a commercial solar power plant. While some of the data are still undergoing analysis, it is expected that this receiver will demonstrate an efficiency in the mid-eighties in percent.

A plate fin metal receiver has been designed and is being fabricated by Garrett Corporation for 1500°F operation with air. This receiver is illustrated in Figure 2. It features a 75 kWt plate-fin heat exchanger made from Inconel 625. This receiver is scheduled for solar tests by JPL in 1980.

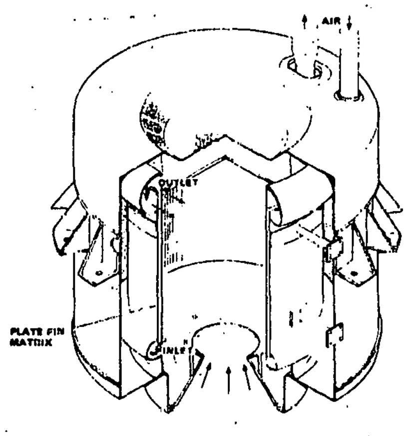

Figure 2. Plate Fin Brayton Solar Receiver

The high temperature ceramic receiver concepts discussed are expected to be readily applicable for Brayton cycle application, and it is anticipated that one or more will be selected for Brayton demonstration. Such a demonstration might utilize the advanced automotive gas turbine being developed by DOE.

Advanced Stirling Receivers

Receivers designed for Stirling engines have to meet some rather unique and strict heat transfer and structural requirements because the heat exchanger tubes are connected directly to the engine cylinder heads, contain the engine working fluid, and their volume is directly dependent on the cylinder engine displacement volume.

Two separate receiver concepts are currently being developed for the Stirling engine program. One involves design and fabrication by Fairchild-Stratos of a 1500°F metal tube receiver which can operate either on solar or fossil fuel input. It does not incorporate any integral thermal storage. The heat exchanger features 0.145 inch ID Inconel 617 tubes encased in a copper slab to optimize thermal performance. The receiver is sized at 75 kWt, and is scheduled for solar tests by JPL with a United Stirling P-40 engine in late 1980. The other receiver project involves evaluation and development of a 1500°F receiver by General Electric with thermal storage and hybrid operation capability based on a sodium heat pipe concept. It is being designed for 75 kWt to operate with a Phillips Stirling engine based on their 198 model. Also advanced concepts for temperatures greater than 1500°F are under consideration.

Advanced Rankine Receivers

Receivers for Rankine cycle application can be expected to operate at 600 to 1100°F using steam, organic, or bi-phase fluids. Since the Rankine cycle is widely used and accepted, it is important to develop the full potential of solar systems that may use this system.

Currently, a test program is underway for a Francia receiver at the Georgia Institute of Technology. This 300 kWt receiver has been operated at its design temperature (1100°F) and pressure (1700 psi) for a brief period. It features a large aperture with glass tube heat traps.

A 75 kWt metal coil receiver is being developed and fabricated by Garrett. This receiver will deliver primary steam at 2500 psi and reheat steam at 160 psi, both at 1300°F. The primary heat exchanger consists of a single Inconel 625 coiled tube (0.3 inches ID) that serves as a steam generator and a super-heater, and the reheat section features a 0.5 inch ID coiled tube. This receiver is scheduled for solar tests by JPL without an engine in mid-1980.

Fuels and Chemicals

Receivers here are intended for use in fuel or chemical manufacturing processes or for conversion of solar thermal energy to chemical energy for subsequent storage and use. The temperature range required for such processes can range anywhere from 600 to 3000°F and upward. This means that both metal and ceramic material technologies will be involved. The initial steps in this area have been to demonstrate technology feasibility.

A ceramic counterflow heat exchanger/converter is being developed by the Naval Research Laboratory to chemically dissociate SO_3 in a high temperature receiver using a platinum catalyst. Recently, thermal SO_3 dissociation has been demonstrated in this project at the New Mexico State University test facility in a configuration applicable to solar using quartz tubes and platinum coated pellets. The feasibility of using a metal heat exchanger/converter for this process is being evaluated analytically and experimentally at the Jet Propulsion Laboratory.

A so-called "thermosyphon" receiver is under development at SERI for operation at 1200°F with sodium as the primary fluid. Emphasis is on feasibility evaluations, such as study of sodium pool boiling stability. This receiver would be targeted for chemical production. A receiver (targeted for biomass applications) operating with entrained solids in a gas stream is also under development at SERI. The first phase involves building a receiver with a copper body to operate at 1600°F using water/steam as heat exchange medium to demonstrate thermal and structural feasibility.

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*This paper presents one phase of work carried out at the Jet Propulsion Laboratory, California Institute of Technology, under sponsorship by the Department of Energy, Division of Solar Technology, through an interagency agreement with the National Aeronautics and Space Administration.

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

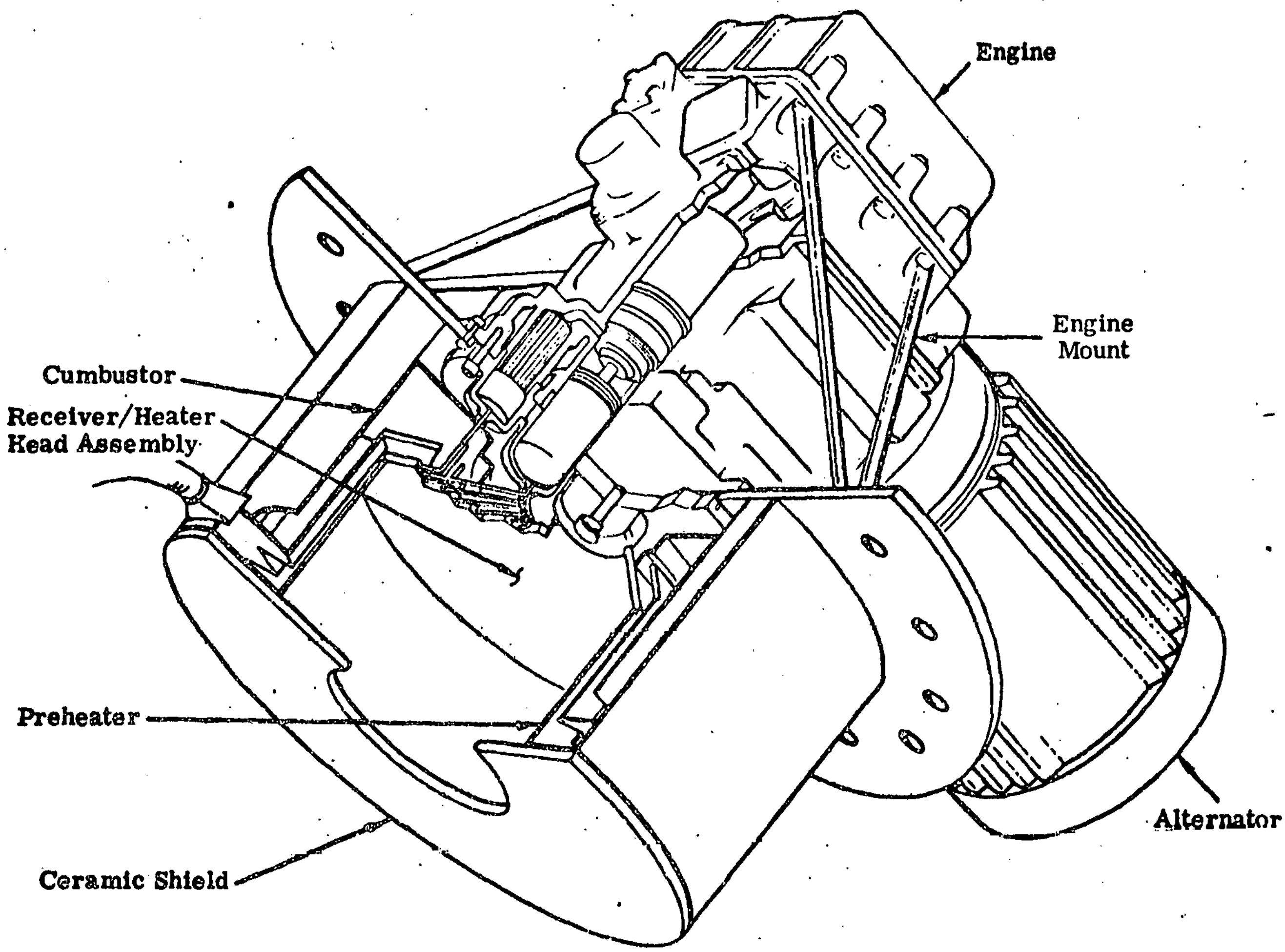

FIGURE 1. NON-HEAT PIPE/P-40 STIRLING ENGINE

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

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_t
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.

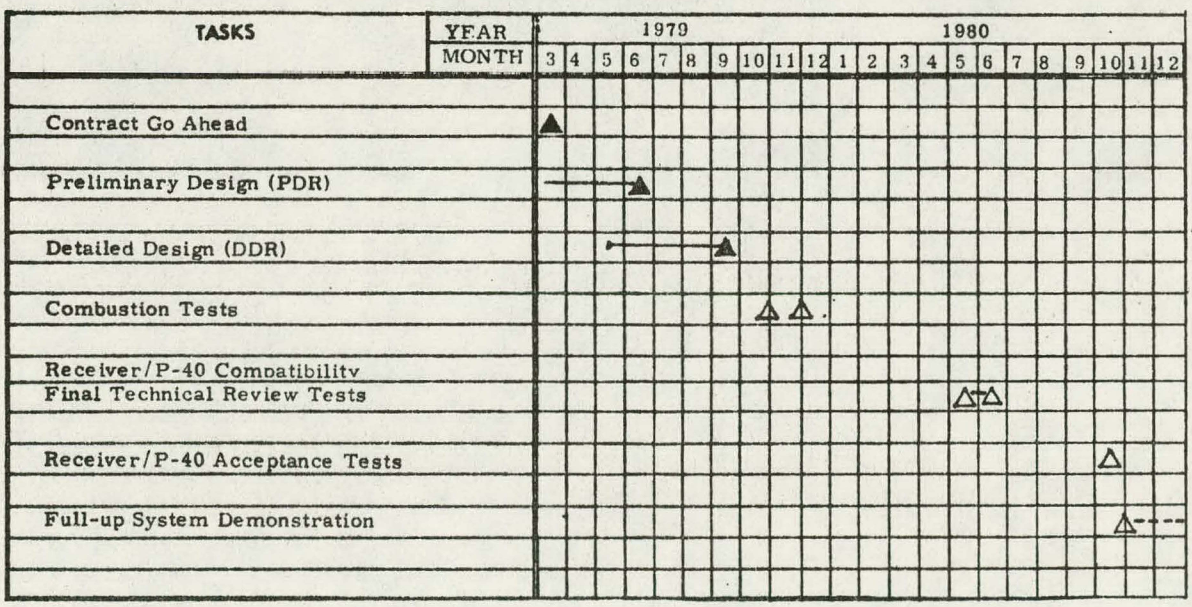

FIGURE 2. MAJOR TECHNICAL MILESTONES CONTRACT 955400
30 November 1979

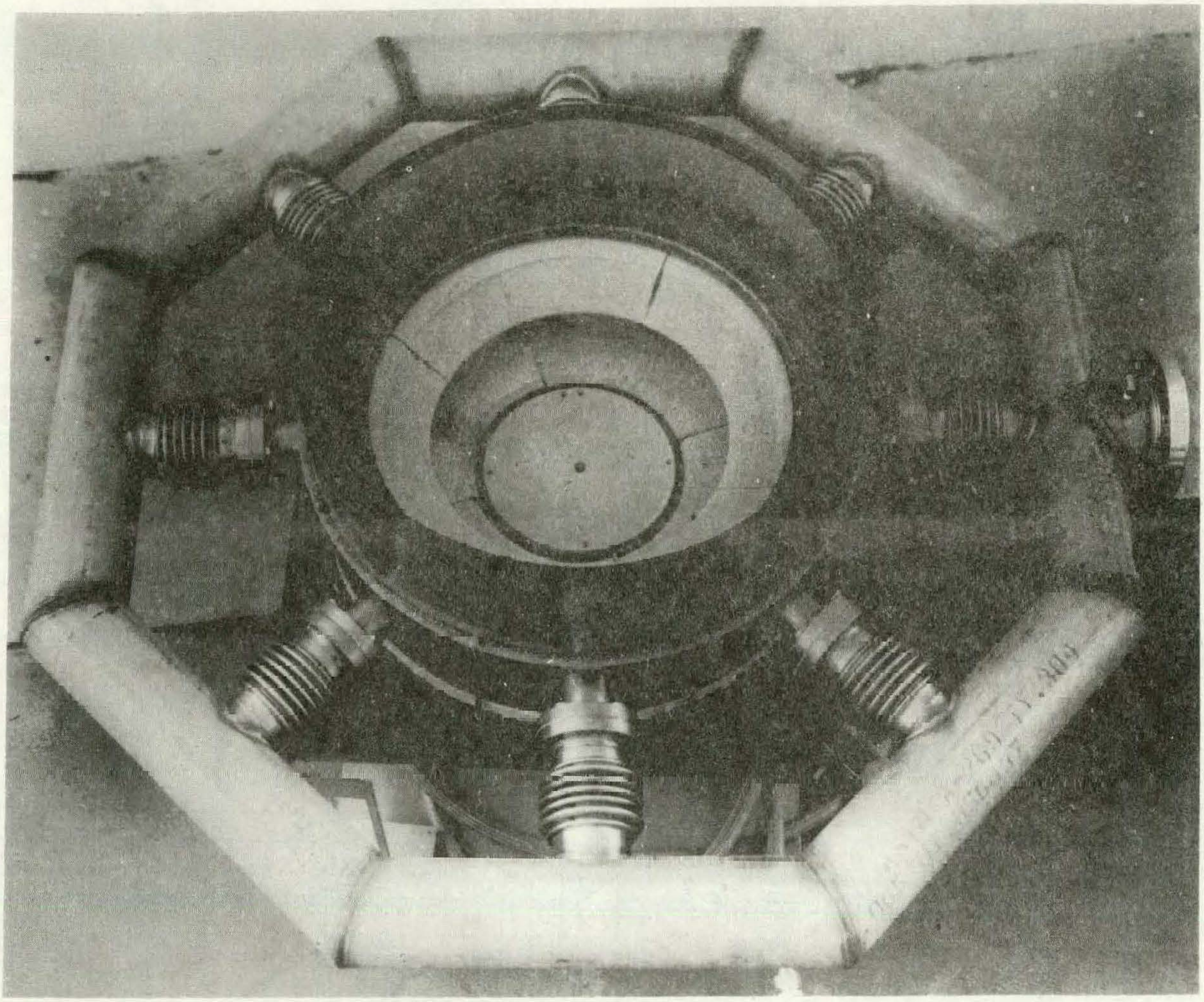

FIGURE 3. PHOTO OF TEST RIG

HEAT PIPE SOLAR RECEIVER FOR THE STIRLING ENGINE

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ABSTRACT

A heat pipe solar receiver, with integral latent heat storage provided by a sodium fluoride-magnesium fluoride salt, has been conceived and is under study. The system can readily accommodate fossil fuel hybridization. Design configuration testing on primary heat pipes and secondary heat pipe wicking has been completed successfully and a modular experiment to confirm the performance and define the operating characteristics of the thermal transport and storage systems is ready to start. Further conceptual design studies have indicated that the cost targets in mass production are achievable utilizing oxidation resistant ferritic or austenitic stainless steels, inexpensive high thermal conductivity sialon type ceramic materials and only a minimum use, if any, of superalloys.

INTRODUCTION

The initial conceptual design of an integrated, focus mounted distributed concentrator solar Stirling power conversion system with sodium heat pipe thermal transport and latent heat thermal energy storage has been described in previous reviews. It had the following features: (1) a solar receiver with the cylindrical wall cooled by thermal diode sodium heat pipes which rejected their heat into a secondary heat pipe, (2) a large secondary heat pipe which contained (a) the primary heat pipe heat sources, (b) latent heat TES by means of a NaF-MgF_2 eutectic salt mixture contained in cylindrical containers, (c) the Stirling engine heat exchanger tubes and (d) wicking necessary to deliver liquid sodium to the various heat sources, (3) a Stirling engine and induction generator and (4) thermal insulation and support structures. This concept is shown in Figure 1.

Some design configuration testing effort and additional design improvement work had been undertaken. The primary heat pipe performance was demonstrated over a wide range of operating conditions and receiver orientations; this included a demonstration of the thermal diode effect and of the capability of solidifying sodium in the receiver end of the heat pipe as a means of preventing reverse heat flow losses from the TES secondary heat pipe in the inverted, overnight stored position. The wicking performance capabilities in the secondary heat pipe were experimentally verified using easy fluids at room temperature and recalculating the anticipated performance in sodium at operating temperatures near 1520°F. Some initial design effort had also been directed toward the introduction of a recuperated, fossil fuel burner around the outside of the primary heat pipes for fuel hybridization purposes. A low velocity, luminous diffusion gas flame was intended for radiant heat transfer to these primary tubes; as an alternate, efficient convective heat transfer from a fossil fuel burner providing heat to the large surface area of the secondary heat pipe was considered but was not followed because of the significant adverse consequences of a possible "burn-through" of that large heat pipe. Other design assessments included the cost and weight effectivensss of utilizing fiberous insulation in place of multifoil vacuum radiation shield insulation at an acceptable increase in shadowing diameter and the need to reduce or eliminate the use of more expensive superalloys, particularly the cobalt base alloys for which rapid price increases were being experienced.

The advantages of the compact focus mounted solar receiver with latent heat TES are numerous. They include near isothermal operation of the Stirling engine heat exchanger without hot spots, ability to configure the system to permit engine operation with gravity oil seal drainage (no inverted seal operation), a minimum T from the receiver cavity surface to the Stirling engine, stable system operating temperature without significant thermal and performance fluctuations, self regulating heat flow to and from the TES and engine heat exchanger through heat pipe principles, simple on-off efficient fuel combustor operation without combustor turndown ratio problems, minimal sensible heat temperature drop overnight, orderly startup and shutdown procedures and simple field installation and change-out for effective maintenance and repair.

CURRENT EFFORTS

During the past several months effort has been concentrated in two areas: first, on the design and fabrication of a modular test experiment involving a full size primary heat pipe linked with a secondary heat pipe containing latent heat TES and an air cooled heat exchanger simulating heat extraction by the Stirling engine and, second, on the conception and evaluation of alternative design concepts which would be most cost effective in mass production as contrasted to development demonstration. These continuing efforts are reported below.

Modular Test Experiment

The purpose of this subscale research experiment in the operating of a selected thermal transport and latent heat storage system is to verify the design concepts and to determine operating performance characteristics which should be applicable to the full size hardware.

The test equipment is shown in Figure 2. A single primary heat pipe from the solar receiver with a maximum thermal rating of 7 KW provides heat input into the secondary heat pipe. The nominal heat transfer requirement in a solar receiver would be 2.3 kW_t for a 27 heat pipe receiver or 4.14 kW_t for a 15 heat pipe receiver. In the test experiment two 3000 watt electrical heaters will provide heat input. Three standard size TES salt containers, each 2 inch in diameter x 26 inches in length and filled to 90 volume percent with $67NaF-33MgF_2$ molten salt are located within a 5 inch diameter secondary heat pipe which also contains the air cooled heat rejection coil. This salt will provide about 2 kWh thermal storage. The heat input and heat extraction rates

rates to the secondary heat pipe can be controlled to simulate the input and output heat transfer rates per unit area of TES containment at the design levels for the full scale system. This will permit verification of the ΔT across the solidifying salt and the performance of the TES system as regards heat transfer in the salt and the sodium wicking characteristics and sodium heat transfer rates. Electrical measurements of the heat input and the flow rate and ΔT measurements for the cooling air will provide heat balance data for initial steady state evaluation of heat losses and, later, thermal performance evaluations of the system during charging, discharging and other transient conditions. Performance in the horizontal position and at various angles of inclination will provide an assessment of wicking capabilities, particularly of the wicking located along the outer OD length of the TES containers.

All components for the test have been fabricated and the molten salt containers have been filled, the salt has been melted in place under vacuum outgassing conditions and the containers have been sealed under vacuum. Final cleaning, pickling and assembly operations remain to be performed before charging the system with a prescribed amount of sodium and initiating testing in December.

In the near future, it is expected that modular heat pipe/latent heat TES experiments of this type can be refined and extended to evaluate (1) more specific wicking and liquid metal flow conditions, (2) performance characteristics of flame sprayed powder metal or other types of low cost wicks, (3) endurance life of secondary heat pipe components under steady state and cyclic conditions, (4) the use of alternate TES materials and (5) containment and structural support problems which might develop during testing.

<u>Alternate Design Concepts</u>

Alternate design concepts are currently being investigated in order to point the way toward competitive low cost design. These designs, in mass production on the order of 100,000 - 300,000 15 kW_e units per year, should meet JPL established goals of \$6/kW_t for the receiver and \$15/ kW_t plus \$10/kWh_t for TES. By applying these cost goals to a 15 kW_e base case heat pipe solar receiver with TES in which the receiver is rated at a peak power of 62.1 kW_t and the TES nominal output is rated at 52.5 kW_t with a 1.25 hour storage period, the allowable unit selling price becomes about \$1800. Assuming, from the selling price breakdowns for other mass produced products, that raw material and mill product costs are about one half of the selling price, a material cost objective of about \$900 per unit is reached. This is the target for total raw materials costs for a unit without a fossil fuel burner at which the current study is aimed.

Low Cost Design Philosophy

To reduce costs towards those long term production design requires (1) progressive design improvement based upon testing, development, design iteration, and identification of multifunctional design methods and (2) utilization of lower cost materials and processes in the design.

From the conceptual design viewpoint there are many potential concepts to reduce weight and cost, to introduce multifunctional design and to operate at progressively higher levels of design refinement as regards allowable stresses, corrosion limits, etc. In the area of new materials and processes there is a potential for the use of less strategic and lower cost materials such as ferritic and austenitic stainless steels and inexpensive, high strength, thermal shock resistant ceramic materials in appropriate places in the design. To predict the ultimate low cost production design which could evolve may be difficult, but the potential developments required, alternative design possibilities and materials and process recommendations can be identified to indicate the potential for achieving low cost targets in mass production.

The efficiency and economy of the TES salt is one key consideration which must be continuously appraised. The sodium fluoride-magnesium fluoride eutectic appears to offer the best compromise of low salt cost and thermal efficiency. Sodium carbonate is slightly less expensive but would require larger weights, volumes and structural costs in its use. Although lithium fluoride is much more efficient, its higher bulk cost would require considerable reductions in the weights and costs of containment wicking and structures than currently appear possible even considering the excellent thermal efficiency of this salt.

Design Concepts

Some elements of design which are currently being considered include improvements and cost reductions in the receiver, TES, insulation, structure and materials and processes.

In the heat receiver a reduction in the number of primary heat pipes is possible trading off higher reradiation losses vs. reduced weight and cost or in using high conductivity receiver cavity materials such as copper or one common heat pipe. Pool boiler receivers with direct incorporation of TES and an aperture plug or as thermal diodes to the conventional secondary tES heat pipe are being considered.

It is in the area of the secondary TES heat pipe, however, where the greatest potential for cost reduction exists. A reduction is possible in the amount of fiber metal and wire screen wicking and, more effectively, the replacement of that wicking with integrally prepared or flame sprayed porous metal wick surfaces. Accepting a larger ΔT across the TES salt could reduce containment, wicking and structure.

The TES system is a high temperature component which operates at relatively low stresses because of the low vapor pressure of the sodium. Thus it is possible to consider either less expensive alloys (by designing for their lower allowable stresses) or low cost thermal shock resistant ceramics while reserving, to a more limited use, the more expensive high strength alloys for key structural loads. Table 1 indicates the prices and estimated design allowable stresses for several such materials. Oxidation resistant alloys are not required for salt containers or for wicking within the sodium environment. Ferritic alloys of this type can be further strengthened by solid solution alloying or by Ti-N dispersion hardening methods without significant cost increases. A low cost sialon type ceramic material prepared from clay, coal and nitrogen, as proposed by Lee and Cutter [1] could be mass produced at the estimated cost of 40-85 cents per pound from inexpensive starting materials; such a low density material could be used as salt containers using metallizing and brazing for sealing or, more effectively, as the structural supports for the TES containers within the secondary heat pipe. The load imposed design stresses for these parts would be well below those predicted by Weibull failure stresses.

The use of more expensive, higher strength high temperature alloys can be limited to the hot load structure which transmit the TES loads to the outer low cost structure. The latter structure supports the engine-generator in relation to the receiver/TES and provides mounting surfaces for installation on the concentrator. Approximately nine inches of inexpensive fiberous insulation with sheet metal covering complete the system.

One of several possible designs which can meet the $900 materials cost target for the receiver/TES subsystem is shown in Figure 2. Its low cost features include some of those discussed above.

CONCLUSIONS

The early operation of the modular experiment will provide a source of heat pipe/TES performance prediction and design confirmation data. Its continued utilization will be most helpful in the demonstration of alternative, lower cost design concepts such as reduced wicking, flame sprayed powder metal wicking and both lower cost containment materials and containment concepts.

The reduction of the cost of heat pipe solar receivers with TES can be achieved under mass production methods. The extension of current technology which may be required is entirely feasible. It will require utilization of economic, high temperature materials at low imposed stress levels through component development, testing and design iteration. More accurate long term, low stress creep data will be required and some improvements in ferritic alloy strength can be expected. The availability is anticipated of an inexpensive entirely non-exotic structural ceramic material operating at low imposed stresses.

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[1] Lee, J.G. and Cutler, I.B., "Sinterable Sialon Powder by Reaction of Clay with Carbon and Nitrogen", Ceramic Bulletin V58, N9 (1979) pp. 869-871.

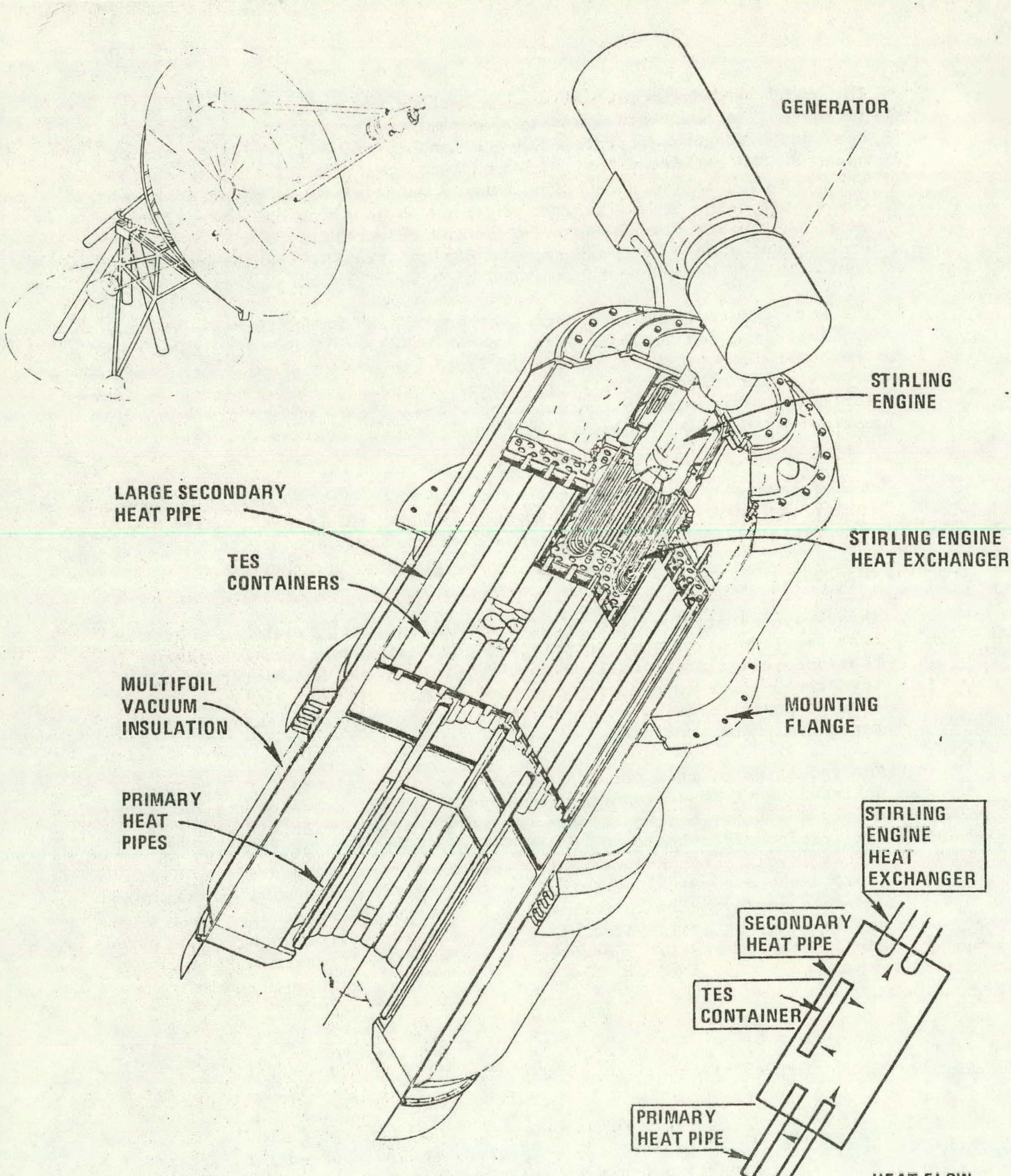

Figure 1. Heat Pipe Solar Receiver with TES for Stirling Solar Power

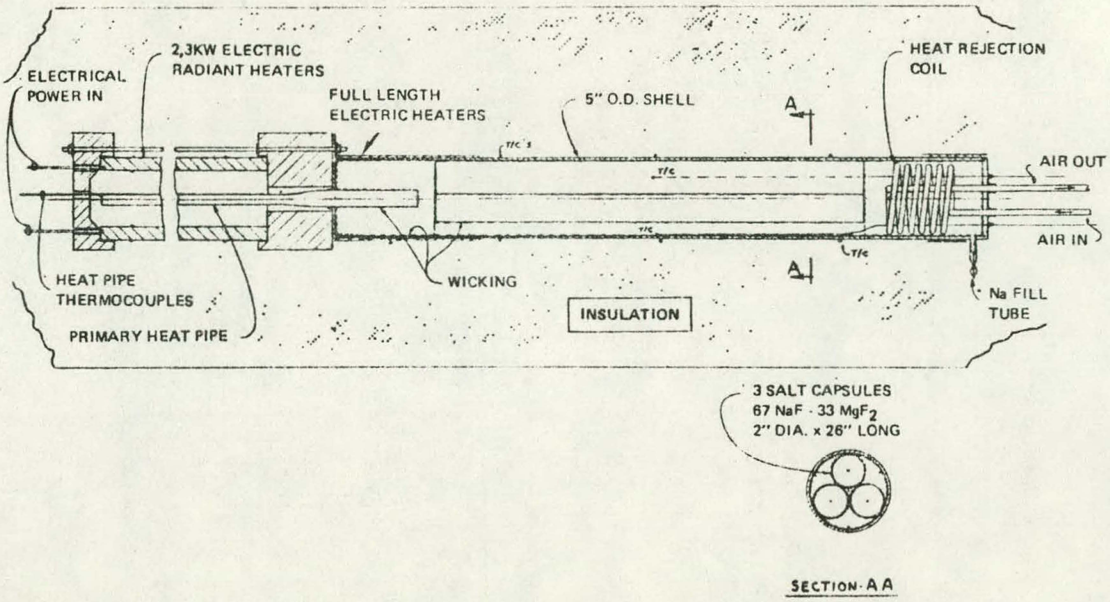

Figure 2. Modular Test Rig

TABLE 1

COST AND ALLOWABLE STRESSES FOR POTENTIAL HEAT PIPE SOLAR RECEIVER MATERIALS

Material	1978 Cost/lb-$	Estimated S_a at 1600°F-psi
Ingot Iron	0.16	150
406 Ferritic S.S.	0.67	200
304 Austenitic S.S.	0.80	350
310 Austenitic S.S.	2.35	300
321 Austenitic S.S.	0.84	500
Inconel 625	6.70	1200
Hastelloy X	6.45	2500
HA-188	12.01 (27.05)*	2500
Sialon	0.40-0.85**	12,500

* 1979
** Mass Production

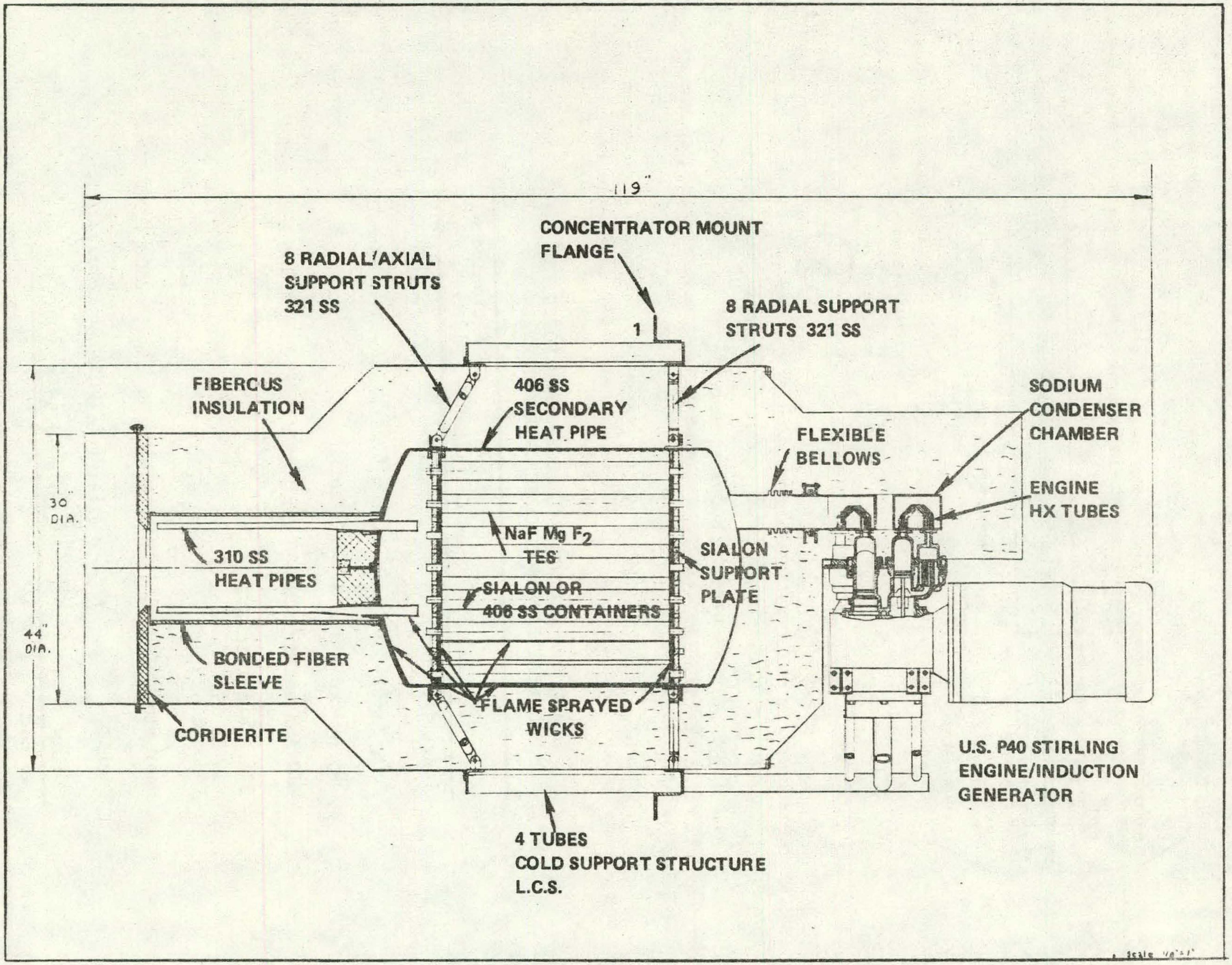

Figure 3. Focus Mounted Heat Pipe Solar Receiver with TES
(Alternate Concept No. 1)

ADVANCED COMPONENTS AND SUBSYSTEMS

HIGH TEMPERATURE SOLAR THERMAL RECEIVER

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Evendale, Ohio

ABSTRACT

A conceptual design has been made for a solar thermal receiver capable of operation in the 1095-1650°C (2000-3000°F) temperature range. This receiver is designed for use with a two-axis parabaloidal concentrator in the 25 to 150 kW_{th} power range, and is intended for industrial process heat, Brayton engines, or chemical/fuels reactions. Three concepts were analyzed parametrically. One was selected for conceptual design. Its key feature is a helical coiled tube of sintered silicon nitride which serves as the heat exchanger between the incident solar radiation and the working fluid. A mechanical design of this concept was prepared, and both thermal and stress analysis performed.

OBJECTIVES

The objective of this program is to prepare a conceptual design of a receiver for solar thermal applications in the 1095-1650°C (2000-3000°F) temperature range. The receiver is intended for use with industrial process heat, Brayton engines, or chemical/fuels reactions. The power level range to be investigated is 25 to 150 kW_{th} and the receiver is to be used in conjunction with a two-axis paraboloidal concentrator. Table 1 shows the design boundaries and goals of this program.

TABLE 1

DESIGN BOUNDARIES AND GOALS

Design Boundaries	
Working Fluids	Helium, Air, and Nitrogen
Receiver Outlet Temperature	1200-1650°C (2200-3000°F)
Inlet-Outlet Temperature Rise	110-330°C (200-600°F)
Pressure Level	2-8 Atmospheres
Pressure Drop	Less than 4% $\Delta p/p$
Power Level	25-150 kW_{th}
Flux Distribution	1-2 milliradian slope error
Design Goals	
High Performance	High Efficiency
Low Cost	Potential for Low Cost in Mass Production

This program is organized into five tasks:

Task 1 - Parametric Analysis
Task 2 - Conceptual Design
Task 3 - Receiver Operation and Performance Requirements
Task 4 - Production Cost Estimates
Task 5 - Documentation and Briefings

The objective of Task 1 is to conduct parametric analysis of several concepts and design options. Based on an evaluation of the performance and potential mass production costs, a single concept is to be selected for further conceptual design. Task 2 provides a complete conceptual design of the selected concept, along with engineering drawings and performance analysis. Task 3 will characterize the receiver operational requirements which are necessary for successful operation of the entire receiver-concentrator unit. In Task 4, the unit cost of the receiver in mass production quantities will be estimated.

This program is being conducted by the General Electric Company under contract to JPL. It began in June of 1979 and will be completed in early January 1980.

STATUS

Task 1 was completed in August 1979. Three concepts were evaluated parametrically. At the conclusion of this task, a concept using a helical coil of sintered silicon nitride tubing was selected for conceptual design. Task 2 was completed in November 1979. A design using air at 3 atmospheres pressure for a 1370°C (2500°F) Brayton cycle application was selected. Tasks 3 and 4 were completed in early December, and the final report is in preparation.

This paper presents the results of the Parametric Analysis and the Conceptual Design. Results of Tasks 3 and 4 will be presented at the meeting.

PARAMETRIC ANALYSIS

Concepts Studied

Three concepts were evaluated during this task. All utilized ceramic components in order to permit operation at above atmospheric pressure and at high temperature.

Concept No. 1 - Coiled Tube Design

The first concept employed a single helical coil of ceramic tubing as the heat exchanger. Solar radiation impinged on a cylindrical thermal inertia sleeve which reradiates to the coil, thus reducing thermal shock and providing a small amount of thermal energy storage. Only two connections to external ducts are required, there are no internal pressure bearing joints, and pressure stresses on the tube appear well within the capability of several developed ceramics.

Concept No. 2 - Honeycomb Design

The second concept employed a cylindrical honeycomb matrix as the heat exchanger. This component resembles a rotary regenerator for an automotive gas turbine engine. In order to allow above-atmospheric operation, the honeycomb matrix is located in an insulated cavity, a fused silica window allows solar radiation to impinge on the honeycomb, and the entire unit, including the insulation, is operated at the system pressure level. This permits the use of only two connections to the external ducts, but requires sealing of the fused silicon window to prevent leakage.

Concept No. 3 - Tube and Header Design

The third concept is similar to the first, except that the heat exchanger component is different. This heat exchanger consists of two toroidal headers of ceramic tubing, connected with a number of smaller hairpin tubes. It features excellent heat transfer, at the expense of many joints. It is analogous to many metallic heat exchanger designs.

Materials Selection

Materials were selected for each component for each concept. In most cases, several potential choices were available. Properties were collected from various sources and reviewed to determine their operating limits, compatibility with the three working fluids, and thermal shock capability. In addition, potential suppliers of commercial materials were identified and a start at determining mass productions costs was made. A key component is the helical coiled tube required for Concept 1. A leak-tight ceramic tube is needed, formed into a relatively complex shape. For the temperature levels required, sintered silicon nitride and silicon carbide appeared to be potential candidates. Because of its lower thermal expansion and lower modulus, silicon nitride was selected for conceptual design purposes, although silicon carbide, with its lower thermal conductivity, is also acceptable. Figure 1 shows an unfired coil of silicon nitride.

Results and Concept Evaluation

The three concepts were compared over the entire range of parameters. The overall results showed that the honeycomb matrix concept would have the best efficiency but could be limited in temperature range by the fused silica window to approximately 1370°C (2500°F) exit gas temperature, using the maximum temperature rise allowed. It was also light in weight and relatively low cost.

The helical coiled tube concept had relatively high efficiency, a wide range of applicability, and relatively low weight and cost. It could handle the entire temperature range, with good performance. At low pressures and low temperature rise, pressure drop restrictions tended to make it rather heavy and costly.

The tube and header concept showed no performance advantages with respect to the helical coiled tube concept. In addition, its development would require the use of many joints of questionable reliability.

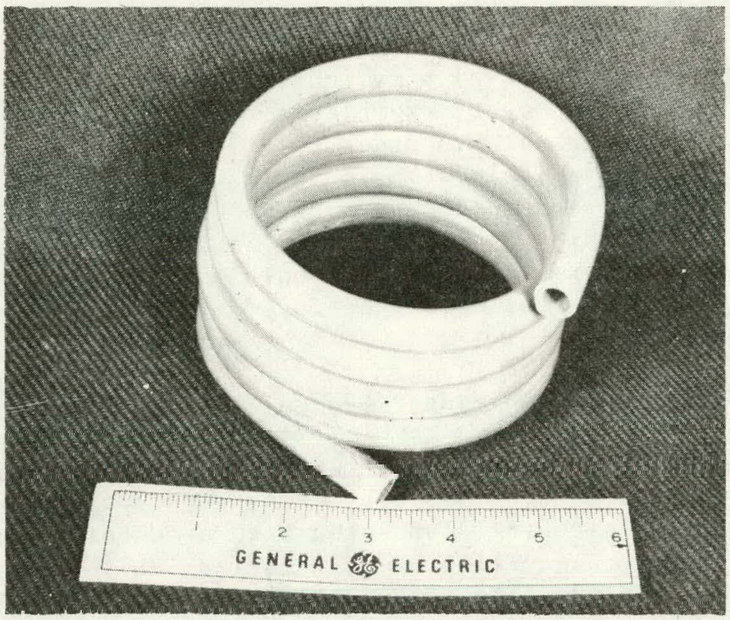

FIGURE 1 EXTRUDED AND COILED 1/2" O.D. SILICON NITRIDE TUBING BEFORE FIRING TO REMOVE THE BINDER AND TO SINTER THE CERAMIC PARTICLES.

As a result of this evaluation, the helical coiled tube concept was selected for further study.

CONCEPTUAL DESIGN

Description

Table 2 shows the design point selected by JPL for a potential high temperature Brayton cycle application.

TABLE 2

CONCEPTUAL DESIGN POINT DATA

Working Fluid	Air
Outlet Temperature	1370°C (2500°F)
Inlet-Outlet Temperature Rise	417°C (750°F)
Mass Flow	0.113 kg/sec (0.25 lbm/sec)
Inlet Pressure	0.31 MPa (45 psia)
Pressure Drop	0.04 $\Delta p/p$ Maximum
Concentrator Slope Error	2 mrad

Figure 2 shows the conceptual design. The key component is the helical coiled tube with an overall length of about 10 m (33 ft), an outside diameter of 60 mm (2.4 inches) and a wall thickness of 2.5 mm (0.1 in.). It is made of sintered silicon nitride. It is located between a thermal inertia sleeve of silicon carbide and an insulation package. Solar energy impinges on the inner surface of the thermal inertia sleeve and reradiates to the coil. Its thermal performance resembles a muffle furnace. The insulation package is made out of several pieces of rigidized, fiberous material with varying density. The higher density, more rigid sections provide resiliant support for the coil during operation. Two metallic bellows seals provide a connection to the exit and inlet.

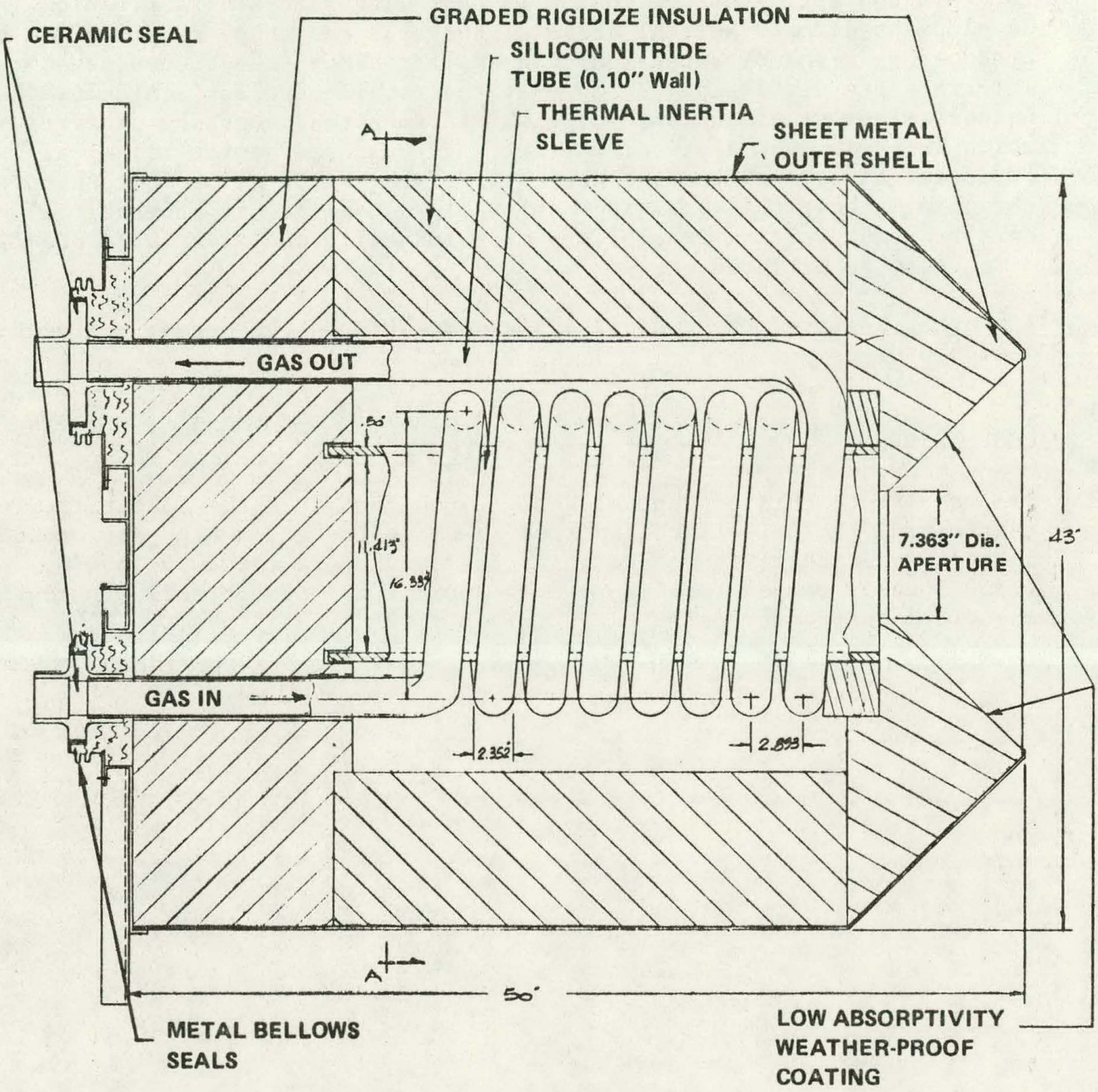

FIGURE 2. CONCEPTUAL DESIGN OF THE HIGH TEMPERATURE SOLAR RECEIVER

Performance

Analysis has shown that this design has relatively high performance. The receiver efficiency is approximately 62% and the pressure drop is a little over 3% $\Delta p/p$. Detailed thermal analysis has confirmed the conceptual analysis. The weight is about 150 kg (330 lbm), mostly insulation.

Feasibility of the Concept

Questions have been raised concerning the feasibility of producing large, helical coils of ceramic tubing of the type and size required for this concept. Our conclusion is that with suitable fabrication development effort, helical coils of the size and shape required can be produced by means of extrusion. In smaller sizes, the processes and materials are developed. It is only the requirement for achieving the necessary set of dimensions while maintaining the necessary properties which is beyond the state of the art. Experienced senior technical personnel at several leading producers of this type of product support the opinion that this goal is achievable. However, it appears that only by demonstrating feasibility experimentally can a definite proof of concept be achieved.

All other areas of the concept appear amenable to the normal engineering design process.

CONCLUSIONS

The results of this conceptual design show that once the feasibility of fabricating the helical coiled tube is demonstrated, a high-performance solar thermal receiver can be built for service in the 1095-1650°C (2000-3000°F) temperature range. It appears to have potentially low cost in mass production.

HIGH TEMPERATURE SOLAR THERMAL RECEIVER CONCEPTUAL DESIGN DEVELOPMENT

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ABSTRACT

Sanders Associates has developed a design concept for a High Temperature Solar Thermal Receiver (HTSTR) to operate at 3 atmospheres and 2500°F outlet. A parametric analysis wherein several receiver types were compared was performed during the first two months of the study. The performance and complexity of windowed matrix, tubeheader, and extended surface receivers were evaluated and the windowed matrix receiver proved to offer substantial cost and performance benefits. Subsequent effort was devoted to definitizing and pricing the receiver as a production unit.

The unit has evolved as an efficient (80%) and economical ($20/KWt) receiver for operation at temperatures of 2500°F or less.

STUDY RESULTS

JPL has identified areas of Advanced Technology requirements wherein, study level funding could lead to development of conceptual designs for solar receivers to augment or displace fossil (or other conventional) energy sources for application in the 2000 - 3000°F and 2 to 8 atmosphere range.

Sanders Associates has under the aegis of one such program performed parametric analyses of high temperature receivers in the 25 - 150 KWt range. Based on the findings of the parametric study, Sanders recommended further effort be applied to a windowed matrix receiver operating at 60 KWt output, 3 atmospheres absolute, and 2500°F outlet. Sanders has during the second performance interval of this contract developed and analytically evaluated a hardware design for a cost effective high temperature solar thermal receiver which can be readily interfaced to fuels and chemicals processes or to heat engines for power generation. Our strict adherence to Design-to-Cost-Goal principles, and our parallel effort to employ only those materials currently within present production technology, has led to a design which offers an efficient and immediately cost effective alternate to other pressurized receivers in the above 540°C (1000°F) range. The design is fully within today's materials' state of the (manufacturing) art. This receiver could be built in production for less than $20.00 per KWt. The design performance analyses support an efficiency prediction of 85% to 90% including wall losses and reradiation effects.

The Sanders HTSTR (Figure 1) is a pressurized cavity receiver which utilizes a fused quartz window at the aperture for pressure containment and employs silicon carbide honeycomb panels as the active solar conversion element. Internal receiver structure and integral thermal impedance is provided by the use of preformed semirigid insulation.

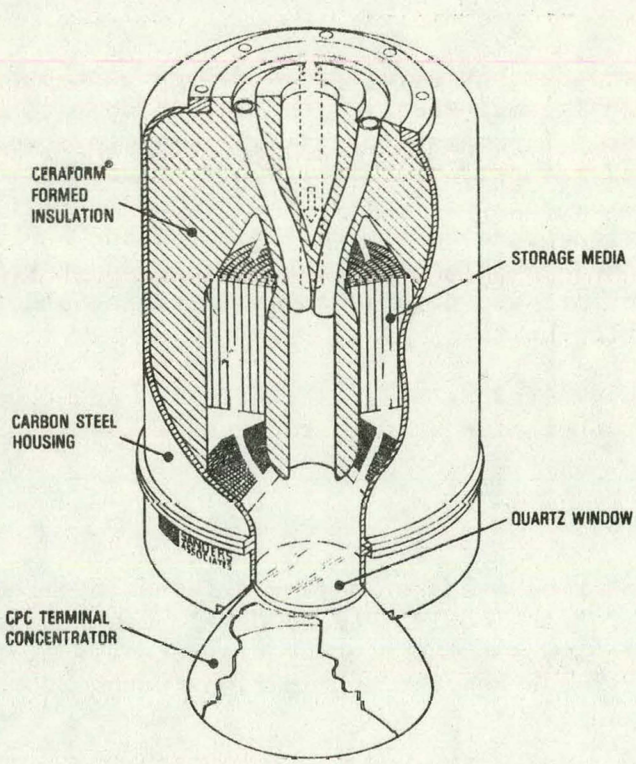

FIGURE 1. PRESSURIZED MATRIX HTSTR

The receiver housing functions both as an ecto-skeleton and pressure vessel, per the ASME boiler code using 0.25-inch thick cold-rolled steel. In view of the small internal volume of the receiver and dissimilitude of air and steam as working fluids, an obvious area of potential cost reduction is present in the housing structure. Cost savings of up to $3.50 per kilowatt could be realized by use of a functionally-designed housing in lieu of a boiler code constrained pressure vesssel. This is a problem which appropriately should be addressed before mass production is initiated.

Silicon carbide (SiC) was selected for the active receiver panels because of its demonstrated suitability to the application. The panels are well within the present firing capacity size limits. Reliable and extended service is predicted for SiC in air at temperatures in the 2700° - 3000°F range. Its high thermal conductivity, visible absorptivity, and thermal shock resistance support its selection as an unstressed matrix material.

The mullite storage material was chosen for its high temperature stability, sensible heat storage capacity, and low cost. As employed in the Sanders receiver, the mullite is not subject to sudden or severe thermal transients.

The key consideration in establishing the functional viability of the design is the development of an in-depth understanding of the flux distribution and its effects on the receiver. To this end, extensive flux modeling, window analysis, and receiver thermal simulation was conducted according to the flow chart of Figure 2.

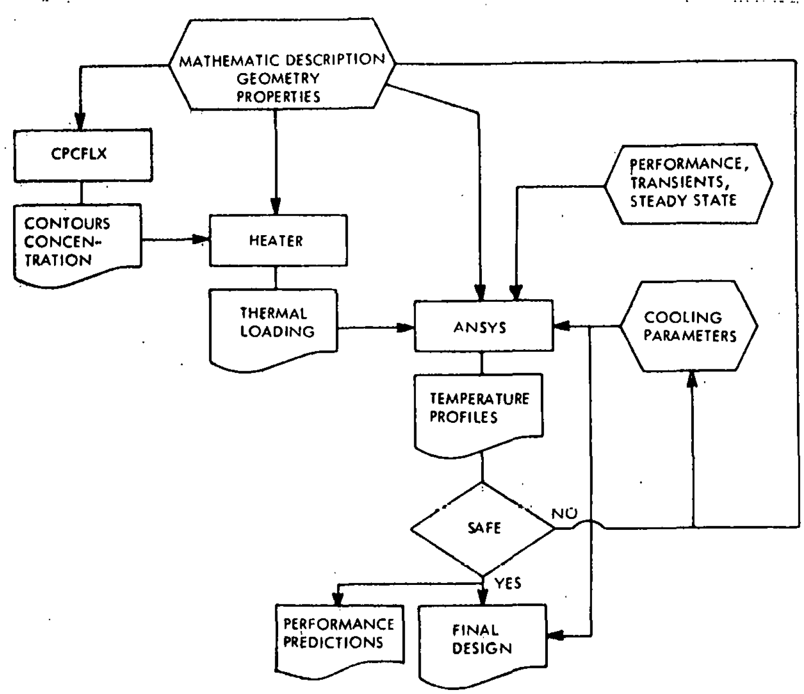

FIGURE 2. METHODOLOGY FLOW CHART

The flow chart portrays the methodology employed in the iterative design and analysis process used to evolve the receiver from concept to preliminary prototype status. CPCFLX is an in-house code developed to predict flux distribution and power capture at the receiver.

Typical flux distributions are shown in Figure 3 for a receiver operating both with and without a CPC. Based on these projected flux levels at the receiver aperture, a window thermal analysis was performed using the optical and physical material properties of the selected fused quartz window. The window heat loading results from the spatial integration of the convoluted solar, cavity IR, and window transmittance spectra. Thermal analysis shows maximum window temperatures of 950°C or less.

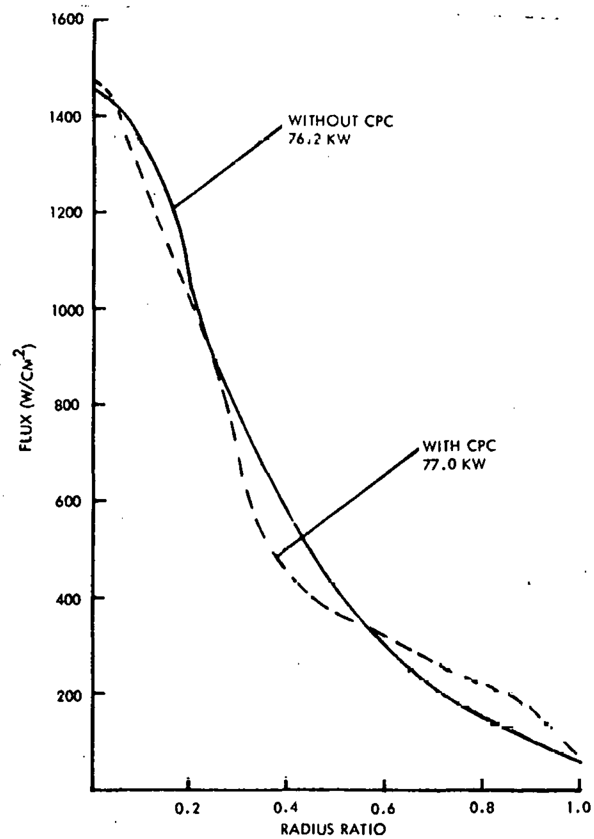

FIGURE 3. TYPICAL FLUX DISTRIBUTIONS

The window analysis predictions, combined with our own real experience at White Sands in 1977, lead us to predict long-term reliability for the windowed matrix HTSTR.

DEVELOPMENT OF A SOLAR THERMAL RECEIVER FOR HIGH TEMPERATURE APPLICATIONS

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ABSTRACT

A thermal receiver for point focus collectors has been designed and is currently under construction. The design, which was based upon experience with a commercial receiver utilizes some of the advantages of that receiver while making improvements in some of the design features. The new receiver utilizes a thermal mass as a buffer between the cavity surface and the heat transfer fluid. This buffer smooths the heat flux distribution to eliminate hot spots; it does so with a very small temperature drop penalty. Maximum operating temperature range has been extended from 620°C to 870°C and receiver efficiency has been improved significantly. The receiver has a design feature which allows a significant portion of spillage flux at the receiver to be utilized. This makes possible the usage of lower quality optics in applications not requiring very high temperatures. Design and construction features of the receiver are presented and the testing program is described.

INTRODUCTION

Several high temperature receiver concepts have been proposed recently for point focus application. Such applications include electric power generation, process heat, and fuels and chemicals production. For example, in the previous Review of Advanced Solar Thermal Power Systems, reference 1, two receiver concepts for Stirling engine application were presented.

Interest in fuels and chemicals production in the SERI Solar Thermal Conversion Branch has led to the development of a high temperature point focus receiver. The receiver is primarily intended to be a research tool for field testing of thermochemical receiver concepts, but may prove to be practical for other high temperature applications.

Some of the design features of this receiver are based on experience gained with a commercially available, point focus receiver/concentrator, reference 2. Our experience indicated three key features of that system. First, the optical matching between the concentrator and the receiver was relatively poor. Second, the receiver was limited to an operating temperature well below our range of interest. Third, the concept of using a thermal mass would be useful for many applications, especially for thermochemical receivers.

In this paper we describe the design features of this receiver, constructions details, and the proposed testing plan for the receiver

DESIGN FEATURES

This receiver is designed around the thermal mass concept, see accompanying figure. In the figure, the thermal mass is the cast copper portion of the receiver (the receiver is axisymmetric). The purpose of the thermal mass is to give both temporal and spatial smoothing to the heat flux impinging upon the cavity surface. This is a useful feature because it minimizes the chance of coolant tube burnout and it adds thermal inertia to the entire system. Tube burnout may be a significant problem for receivers which are used to heat endothermically reacting fluids.

The thermal mass concept has two disadvantages compared to exposed tube receivers. In tracking concentrators the framework, tracking controls, and tracking motors must support the additional mass. The second disadvantage is the temperature difference from the cavity surface to the heat transfer fluid - a loss of second law efficiency. However, if the thermal mass has a high thermal conductivity, this temperature difference will be small compared to the absolute operating temperature of the mass.

A second design feature is seen in the figure. The flat portion of the thermal mass is exposed to spillage flux at the receiver aperture plane. Our experience with the commercial concentrator/receiver indicated a poor match between the 6 meter concentrator and the 10 cm. receiver aperture, i.e., a significant portion of focussed energy spilled outside the receiver aperture. One solution to this problem is to increase the cavity aperture diameter - at the expense of more reradiative losses at high operating temperatures. Our approach was to retain the 10 cm. receiver aperture and absorb spillover flux on the exposed face of the receiver. For the optical quality we presently have at the ACRES facility, reference 1, this face will be exposed to a significant spillover flux, perhaps as much as half the total energy crossing the receiver aperture plane. Depending on the absorptance of this face, a significant fraction of this spillover energy can be utilized. In addition, thermal gradients in the mass can be minimized thereby allowing a higher average operating temperature. Re-radiation from the face is not significant at the expected operating temperatures.

In the event that improved optics are used at the ACRES facility in the future, the exposed face can be insulated and only the cavity portion of the receiver used. In many applications where very high temperatures are not required, high precision optics are not required and an approach such as this may be one method of utilizing a relatively large solar image.

CONSTRUCTION DETAILS

As seen in the figure the thermal mass consists of a copper shell cast around a helical stainless steel cooling coil. A castable insulation is used on the outside of the shell which is in turn surrounded by a ceramic wool layer. The insulation is protected by a stainless steel shell. The cast copper portion is held in the receiver in such a way that interchanging these parts will be simple - thus providing experimental flexibility. The spherical shape of the cavity was chosen to facilitate analysis.

Some of the more important dimensions are:

Receiver aperture diameter	10 cm.
Cavity inside diameter	12.5 cm.
Exposed face outside diameter	20 cm.
Cooling tube	1/4" o.d., .049" wall
Copper casting weight	22.7 kg
Support frame weight	13.6 kg

Most of the problems in construction of this receiver are related to the use of copper and the desire to operate at relatively high temperatures. Copper was chosen because of its high thermal conductivity, its relative low cost, and because it extends the operating temperature well above that of the commercial receiver we tested. The two major problems related to the use of copper are the actual casting process and protecting the exposed surfaces of the receiver from oxidation during high temperature operation.

Casting pure copper is difficult because voids tend to form throughout the casting. One technique used to overcome this problem is to add 3-5% zinc to the copper melt. One of our recent castings with 3% zinc was cut in half to expose any voids. We found that compared to some initial castings on small samples, reference 3, the result looked very promising. In addition, bonding between the copper and the stainless steel cooling tube was very good. It should be noted that adding 5% zinc reduces thermal conductivity of the mass to about 70% that of a pure copper thermal mass.

Exposed copper oxidizes at temperatures well below our desired operating temperatures. The oxide coating is not self-protecting, however, in that oxygen diffuses through the coating causing further oxidation at the copper/copper oxide interface. The oxide coating very quickly spalls off. Thus a protective coating for the copper casting will be necessary. This coating should prevent diffusion of oxygen to the copper, it should tolerate temperatures as high as 980°C, and on the exposed face of the receiver the coating should absorb a reasonable fraction of impinging solar flux.

Coatings currently under investigation (in cooperation with the SERI

Materials Branch) include flame sprayed coatings and nickel electroplating. The first flame sprayed coating (a three-layer commercial coating) proved unsatisfactory in that it was not an effective oxygen barrier. Other flame sprayed materials are under investigation. Nickel electroplating oxidizes to produce a highly absorptive coating which is quite durable up to 704°C but appears to fail at higher temperatures.

TESTING PROGRAM

Copper has a melting temperature of approximately 1066°C and this was one of the major reasons we chose copper in designing a receiver to replace the commercial receiver which is limited to 620°C. Because of the temperature difference from the center of the casting to the surface of the cavity, it is clear that maximum operating temperatures (measured at the center of the casting) will be limited to well below 1066°C. Our first application for this receiver will require operating temperatures of at least 870°C. Assuming that a durable coating can be found, this does not appear to be an unreasonable goal for this receiver.

The first tests will be optical efficiency measurements to determine if we have succeeded in improving optical matching between the receiver and the concentrator. These experiments are carried out at low operating temperature. Next, operation up to 600°C with high pressure water/steam will be attempted to compare this receiver to the commercial receiver previously tested at this temperature range. Finally, a gas coolant will be used to explore operation above 600°C.

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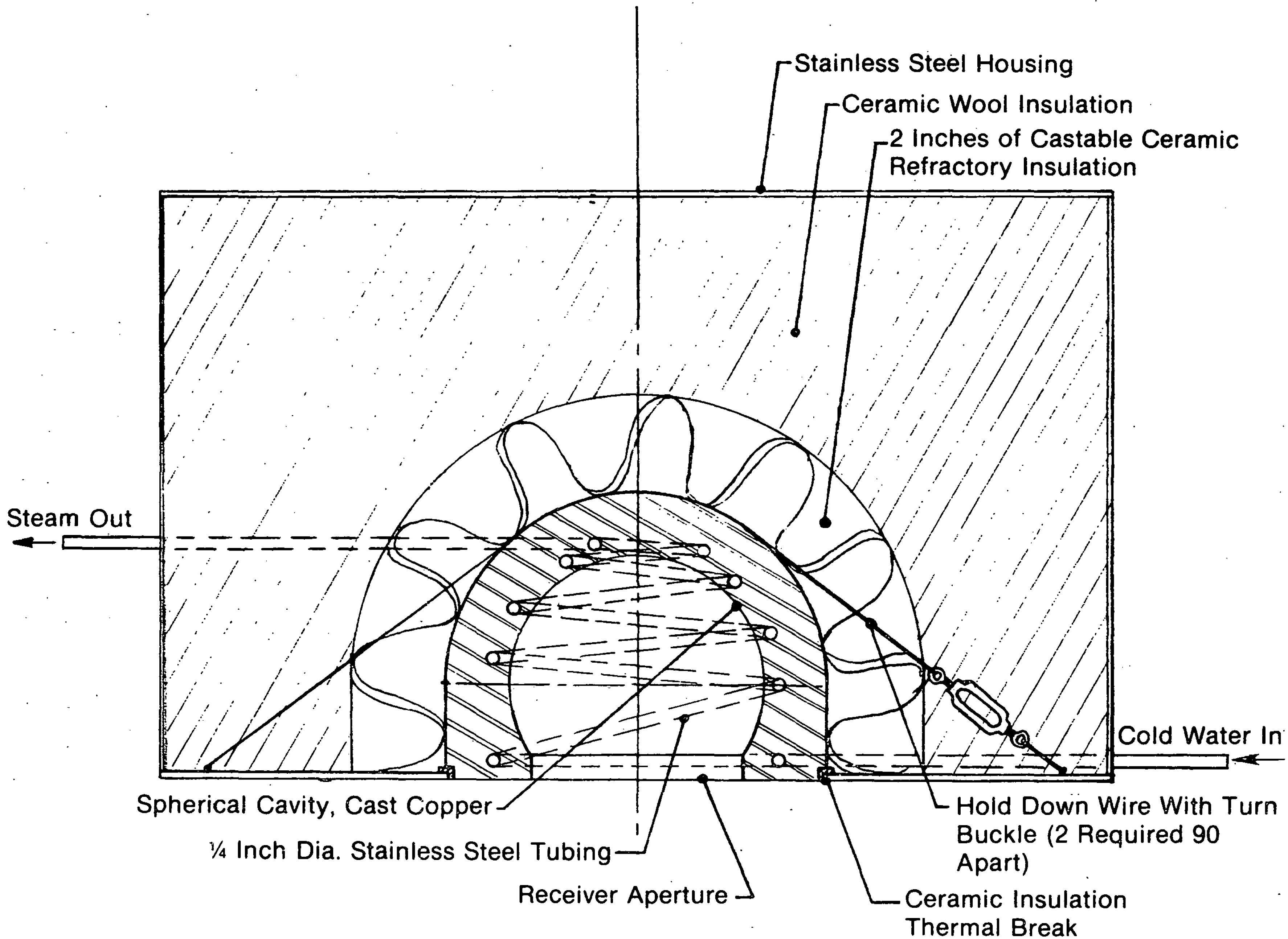

Crossection of Advanced Thermal Receiver

SMALL SOLAR ELECTRIC SYSTEM DEMONSTRATION

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ABSTRACT

Several components of a small solar power system module were analyzed to verify performance and to demonstrate that a checker stove concept represents a viable candidate for dispersed solar power system applications. The three-phase program to fulfill these objectives is in its third phase. During the first phase a design point analysis was performed on a checker stove. During the second phase, a preliminary system analysis was performed and prototype components were fabricated. Phase III encompasses fabrication of the checker stove and ancillary and test equipment, and equipment performance testing. These tests, to be completed by February 1980, will verify the design and provide the data needed for evaluation of the concept.

SUMMARY

Sanders Associates has performed a design analysis on the following components of a small solar power module system:

- Ceramic checker stove as a heat exchanger/storage device
- An open cycle Brayton turbine
- Alternator
- Valving and manifolds
- Associated controls for use in a 20-KWe Brayton cycle solar power system

The objectives of this effort were to verify the performance of the above selected components and to demonstrate that the checker stove concept represents a viable candidate for dispersed power systems applications.

A three-phase program was designed to meet the above objectives. During Phase I, a design point analysis was performed on a checker stove of approximately 50-KWt rating appropriate to the application.

During Phase II, a preliminary systems analysis was performed to define the design requirements and the following components were designed:

- A prototype checker stove of approximately 50-KWt rating
- Prototype upper and lower valve modules with manifolding
- Interconnecting ducting and support structures for the entire power module
- Instrumentation and controls

Phase I and II have been successfully completed.

During Phase III, which is in progress, a checker stove is being fabricated, as is ancillary equipment and a heat source for testing the components. In addition, test procedures are being developed. These procedures will test the equipment to: (a) verify the design and (b) provide the data needed for evaluation of the concept as a viable option in a Brayton system. Fabrication of the valves and modules will be completed by December 15. Testing will begin at that time, and will continue into February 1980.

THERMAL STORAGE MODULE

Figure 1 shows the Solar Brayton power module which consists of four thermal storage modules, interconnecting ducting and support structures. The Thermal Storage Module, shown in Figure 2, is composed of a 36-inch diameter by 31.5-inch long core of cordierite ceramic matrix suspended in a pressure vessel. In operation, air enters the diffuser through the inlet pipe, and is redistributed to evenly flow through the ceramic material. When heat is added to the thermal storage module, the air enters from the top. Air enters the bottom of the module when heat is to be withdrawn. The space between the ceramic core and the outer shell is filled with insulation to minimize thermal losses.

VALVES

The thermal storage modules are valved into either the turbine inlet loop or turbine exhaust loop using high-temperature valves. Valve cooling must be avoided in order to maximize cycle efficiency. This restriction, and the 1700°F operating temperature of the valves, eliminated all of the current valve sources, and forced the development of a high-temperature, four-way Valve.

The new high-temperature valve is a three-inch ball valve with flow passages as shown in Figure 3. Thermal expansion is accommodated by using floating seats which are spring-loaded to maintain a good seal with the ball. All components can operate at 1700°F without cooling. The castings for the major components are shown in Figure 4.

The test setup for the thermal storage module and the valve is shown in Figure 5. The module will be fully instrumented to monitor the progress of the thermocline as it travels through the ceramic core. The burner can supply air at temperatures between 300°F and 1700°F, and at pressures up to 30 PSIG.

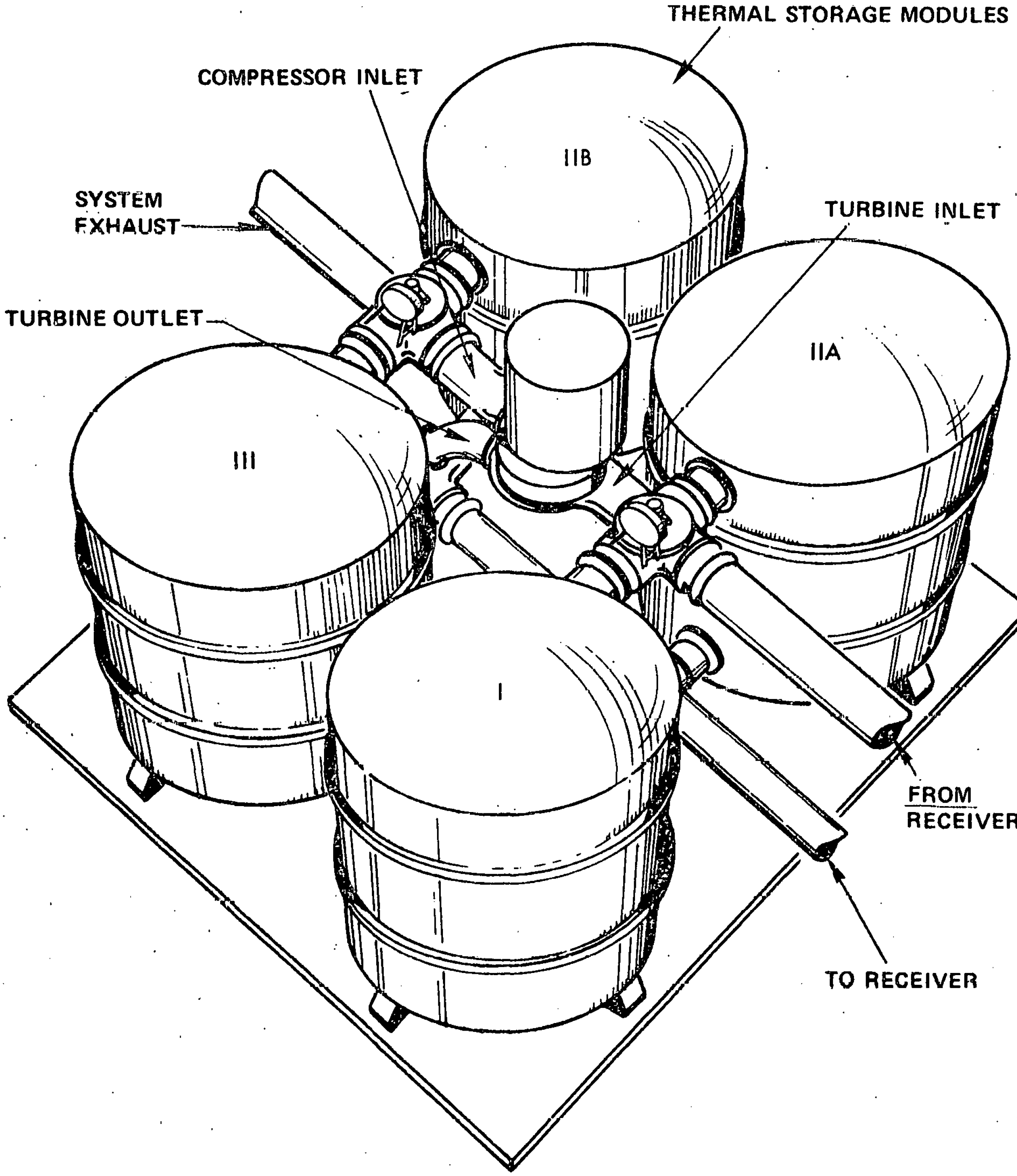

FIGURE 1. SOLAR BRAYTON POWER MODULE

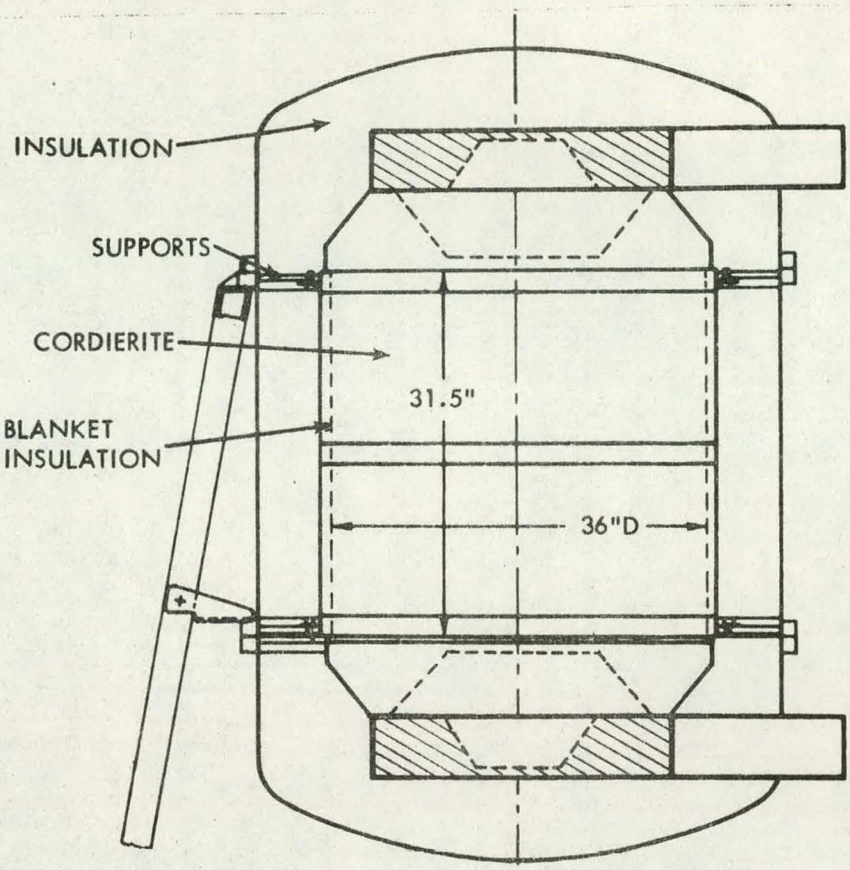

FIGURE 2. THERMAL STORAGE MODULE

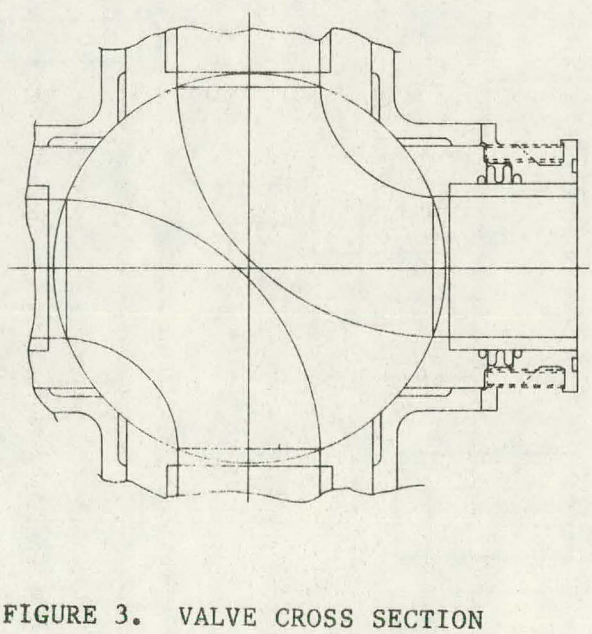

FIGURE 3. VALVE CROSS SECTION

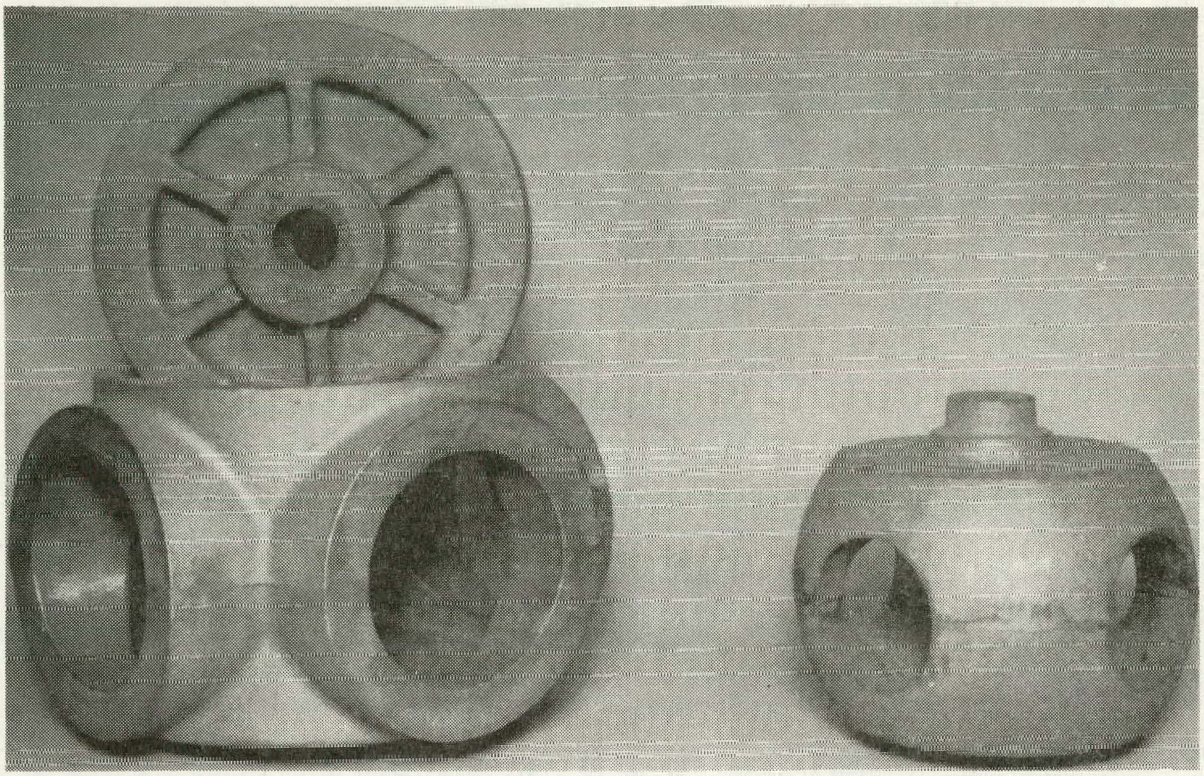

FIGURE 4. CASTINGS FOR MAJOR COMPONENTS OF HIGH TEMPERATURE VALVES

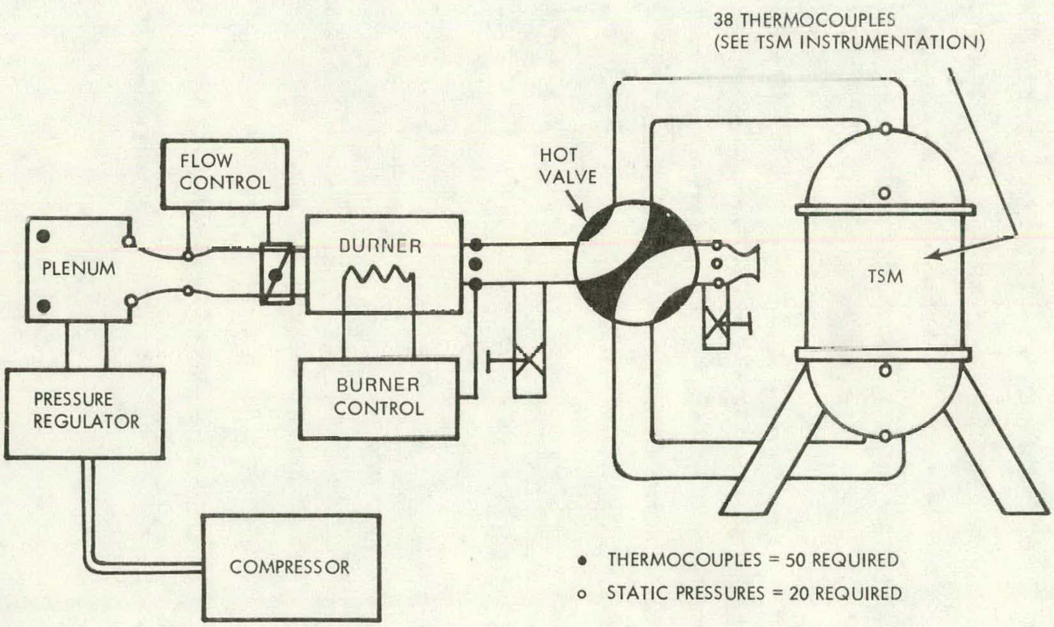

FIGURE 5. THERMAL STORAGE MODULE TEST SETUP

FREE-PISTON SOLAR STIRLING ENGINE-ALTERNATOR

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INTRODUCTION

Over the past few years, MTI has concentrated on the development of free-piston Stirling engines. MTI is committed to product commercialization of free-piston Stirling engines in the power size ranges from 1 to 25 KW. The free-piston Stirling engine (FPSE) product development program is investigating a number of potential applications. A complete description of programs and potential products is given in Reference 1. Free-piston Stirling engines are attractive because of their high system efficiency and potential for long life, inherent reliability, and maintenance free characteristics (Fig. 1). It is these characteristics which make the free-piston engine driving a linear alternator desirable for small, dispersed solar thermal electric power systems.

This paper will review the general conclusions of a recently completed study with NASA/Lewis for a conceptual design of a 15 KW free-piston solar Stirling engine, and discuss how the required technology identified in that study is presently being addressed with hardware testing.

CONCEPTUAL DESIGN STUDY

The design study performed for NASA/Lewis included the conceptual design of a 15 KW solar free-piston Stirling engine-alternator, and an implementation assessment of that design. The detailed results of that study are presented in Reference 2. In summary, it was concluded that a near term solar FPSE can be developed, it results in high overall system efficiency of 35%, and has the potential for long life and high reliability. The conceptual design layout is presented in Fig. 2. Unique features incorporated into the design to promote life and reliability include:

- gas bearings (eliminate wear)
- close clearance seals (no lubrication required)
- gas springs (no mechanical failure)
- cast heater head (no multiple brazed joints or tubes)

A brief, general description of the conceptual design is continued in Table I.

Table I - Conceptual Design

Working Fluid - helium	Charge Pressure - 58.2 Bar
Heater Head Material - Inconel 713LC	Gas Bearing Supply Press. - 64 Bar
Heater Head Temperature - 1500°F	Radial Clearance - .00075"
Displacer Cylinder Diameter - 4"	Bearing Material - chrome oxide
Piston Cylinder Diameter - 7"	Alternator - permanent magnet
Displacer Amplitude - 1.5"	Alternator Radial Airgap - .010
Piston Amplitude - .67"	Alternator Efficiency - 92%
Phase Angle - 36°	Alternator Voltage - 240 Volts
Regenerator - annular-knitted wire	System Efficiency - 38%
Cooler Temperature - 110°F	

As part of the implementation assessment, it is concluded that the design has the potential for mean times between failure of 47,940 hours. The projected prime cost (direct labor plus material) is $90 per KW, utilizing a high magnetic flux permanent material of Mn-Al-C in place of the originally identified high cost samarium cobalt magnet material.

Further evaluation of the economics of dispersed solar thermal electric system (Reference 3) indicates power conversion machinery that has the above characteristics of high efficiency, high reliability, and little or no maintenance, can significantly reduce the operating costs projected for solar thermal electric power system and, therefore, enhances the commercialization potential of such systems.

DEVELOPMENT TESTING

As discussed, the primary goal of the MTI program is to develop a commercial Stirling engine-alternator unit. Substantial technical effort has been directed at solving development problems of engines in the 1 to 3 KW output range. The present engine undergoing testing is a 1 KWe power output engine-alternator (FPSE-010-3) for the Department of Energy. The engine layout is presented in Fig. 3. The design of this engine incorporates many of the same features that are necessary for an attractive solar FPSE. The engine design includes gas bearings, close clearance seals, gas springs, and an internally finned heater head. An internally finned heater head was selected for the solar conceptual design because of the requirement on the engine to interface with a liquid sodium receiver. It was considered that a tubular head with a large number of brazed joints would not provide the life necessary for operation in a dispersed solar application.

Testing of the engine has recently begun. The projected performance of the engine is shown in Table II.

Gas bearings and close clearance seals appear to be operating satisfactorily. No wear has been observed on gas bearing surfaces. Engine running time has been approximately 50 hours with a program goal of 200 hours to be obtained.

Table II - Demonstrator Engine Growth Potential

	40 Bar 700°C Nominal Spring	40 Bar 700°C Maximum Spring	70 Bar 650°C Nominal Spring
Frequency (Hz)	45	45	60
Power (KW)	1.4	2.9	3.0
(%)	38	42	38

At the present time, the engine has developed 835 watts electrical AC output at 650°C, 30 Bar pressure, and frequency of 40 Hz. First order analytical code indicates that the engine will meet design goals when tested at design conditions.

CONCLUSIONS

MTI is actively pursuing, and is committed to the development of free-piston Stirling engines for a number of potential product applications. Small dispersed solar thermal electric power systems offer an excellent match of the free-piston's high efficiency, reliability, long life, and maintenance free characteristics with needed solar system requirements for full economic potential. The key design features required in a solar free-piston Stirling engine are presently under development, and are being demonstrated on a 1 KWe engine designed and developed for the Department of Energy. The successful development of the engine, and the application of the key design features to a solar free-piston Stirling engine-alternator, offers the most attractive potential for small thermal electric power system commercialization.

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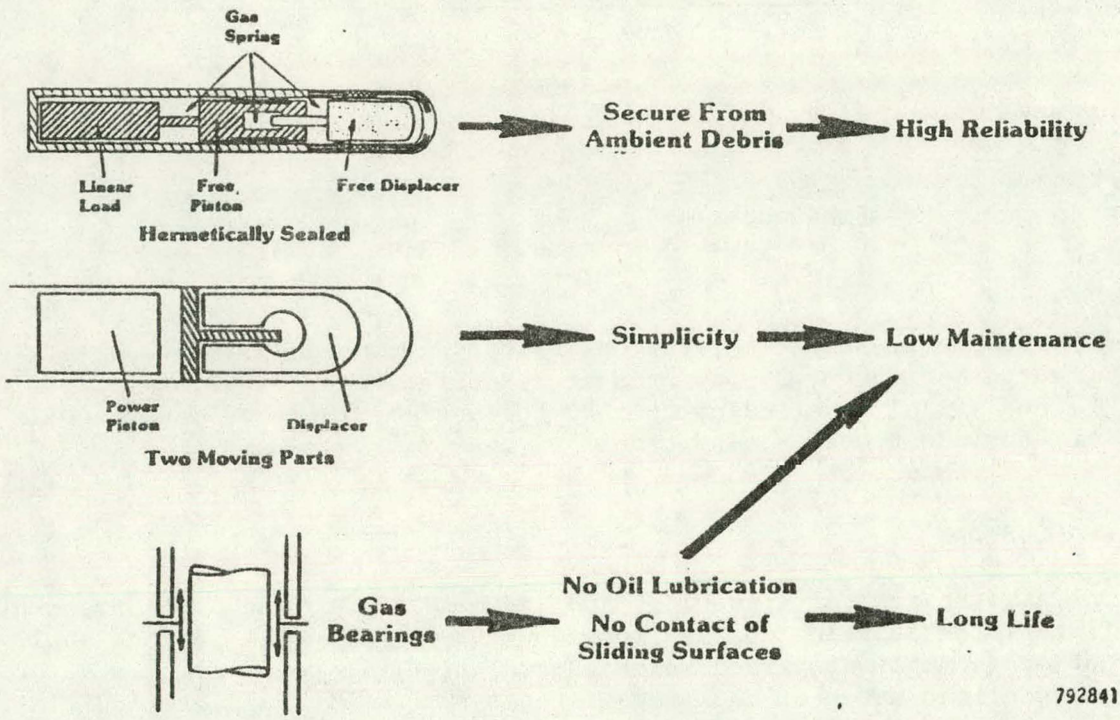

Fig. 1 - Free-Piston Stirling Engine Durability Characteristics

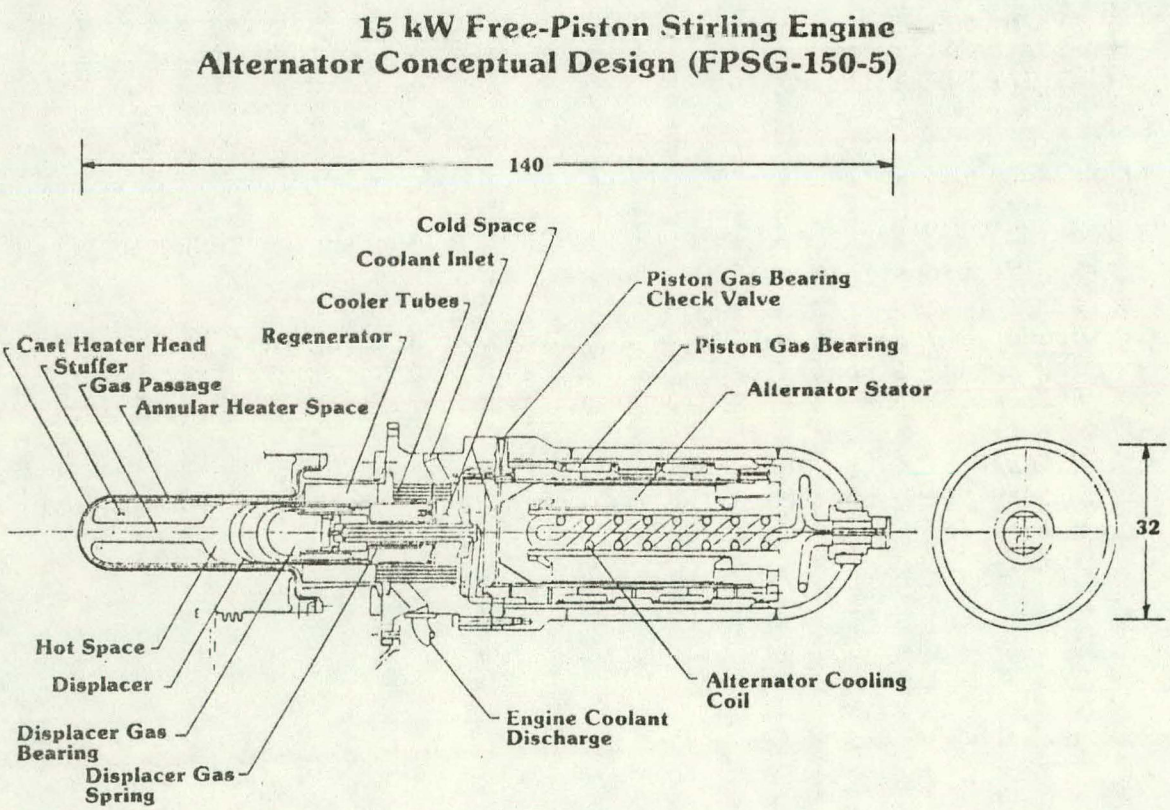

Fig. 2

Free-Piston Stirling Engine Stationary Power System (FPSG-010-3)

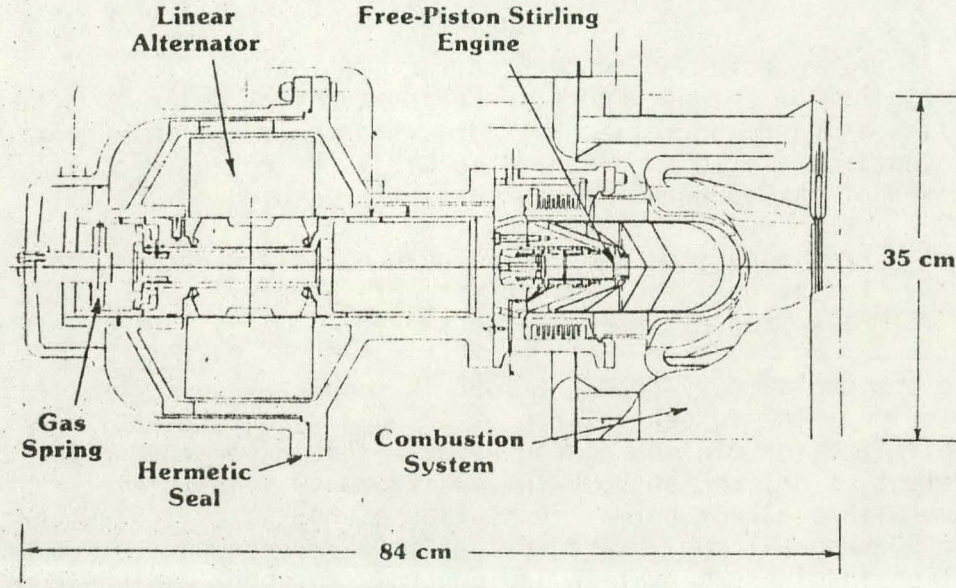

Fig. 3

ABSTRACT OF PRESENTATION

AN ADVANCED SOLAR CONCENTRATOR DESIGN

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Acurex Corporation, under contract to the Jet Propulsion Laboratory, is developing the 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. The objectives of this program are currently threefold:

1. Preliminary design of an advanced solar concentrator
2. Detail design of reflective gore panels
3. Mass production cost assessment

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 weight 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.

SUPPORT ACTIVITIES

OVERVIEW - SUPPORTING PROGRAMS

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The supporting programs are administered within the DOE Advanced Solar Thermal Technology Program. The supporting programs include those activities that are critical to the successful implementation of the various Solar Thermal Power Systems and contribute significantly to all the solar thermal technology areas. Activities included herein are Technical Information Dissemination, Resource Assessment, Reliability and Standards, Environmental Control and the Solar Thermal Test Facilities Users Association. These supporting programs are managed by the Solar Energy Research Institute (SERI) within its management responsibility of the Advanced Technology Program.

Technical Information Dissemination (TID) activities for Solar Thermal Power are being coordinated by Ms. Margaret Cotton. Effective dissemination of price and product technical information and of other significant developments within the program have become increasingly important as major concentrator concepts approach wider use and commercial production. Major activities within TID include preparation and dissemination of topical reports on areas of R&D interest, annual technical progress reports, newsletters covering overall program activities, and packets of information useful to people actively considering investments in either the use of or production of solar thermal equipment and systems. Close interaction of TID activities with the Solar Thermal Energy Association (STEA) Division of the Solar Energy Industries Association (SEIA) will augment industry information resources.

The Resource Assessment activity is conducted through the DOE Insolation Resource Assessment Program (IRAP) and is being technically directed by Mr. Roland Hulstrom. The primary objectives of the program are to provide an accurate insolation data base, characterizations, and models for prediction and forecasting. Due to inadequacies in the existing data bases, a new 38-station network has been established to record hourly values of the horizontal and direct(beam) insolation. This network is operated by the National Oceanic and Atmospheric Administration (NOAA). Through the efforts within this program, the historical and future network insolation measurements will be converted into useful information for sizing, design and more accurate prediction of energy delivery from solar thermal systems.

The Reliability and Standards program is designed to ensure the commercial acceptability of solar thermal systems through performance criteria and test methodology development, support for accreditation/certification guideline development, and liaison with national organizations active in consensus standards and codes. The objectives of the program are to promote reliable and safe solar thermal systems by stimulating the adoption of performance criteria and industry established standards for their design, use and operation. The program, recently initiated, is in the process of developing a plan for future work. Development of voluntary consensus standards are desired to reduce costs and unnecessary product lines, enhance interchangeability with other solar products and conventional systems, encourage industry growth, and provide bases for developing codes and product certification programs.

The objective of the Environmental Control Technology Program is to ensure that identified generic environmental control issues are resolved prior to significant public deployment of solar thermal systems. To accomplish the objectives, assessments are being conducted to a) define the nature and scope of potential impacts arising from specific projects and provide adequate control engineering, b) interject environmental considerations in the design of the solar thermal systems, and c) develop appropriate new control technology applicable to large and small power systems.

The Solar Thermal Test Facilities Users Association (STTFUA), organized in 1977, serves as a framework within which experimental use of solar thermal test facilities capability, beyond that originally envisioned within the solar thermal program, is encouraged and recommended. The association is operated for DOE by the University of Houston and managed by SERI. The association provides a vehicle for independent researchers to obtain funding for preparation and performance of experiments which may provide important and basic information on materials, thermal behavior, and receiver design principles for high-temperature solar components and subsystems.

Participation of university and small business community is of special importance to the Solar Thermal Program. A summer faculty program is being coordinated through the American Society of Engineering Education (ASEE) whereby members of the faculty from engineering institutions will spend a few months working closely at SERI and other national solar research and development centers. A procurement recently conducted by DOE was set aside for small and minority owned businesses to encourage development of new ideas potentially useful to the solar thermal power systems. Five contracts have been awarded as a result of the procurement. These contracts will conduct development effort in glass and polymeric materials, experimental evaluation of convective losses in thermal receivers, tracking and control, and high efficiency heat engines.

QUALITY ASSURANCE AND STANDARDS FOR ADVANCED SOLAR THERMAL SYSTEMS

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INTRODUCTION

The goal initially established for FY 80 for Quality Assurance and Standards within the total solar thermal program is the development of a plan for establishing input to codes and standards development, performance and safety criteria and test methodologies and a coordinated quality assurance program. The advanced solar thermal technology program emphasises development of subsystems, components and materials that are specific to its requirements. Therefore it follows that its contribution to standards development will most likely be of a relatively specialist nature. This can be put to an advantage because the input will be generated from a smaller and, hence, more direct and advanced base of expertise. However full cognizance of the national dialogue on standards development should be given and the final product therefore submitted with appropriate supporting documentation to the consensus process of standards making.

THE ROLE OF STANDARDS

The process of standards development will become a management aid in the overall solar thermal programs because in addition to the main purposes of Codes and Standards which include:

1. Assurance of Reliability

2. Enhancing Safety

3. Providing Interchangeability,

there will be the following natural outcomes in the cooperative efforts needed to generate the products to provide:

4. Aid in development of a strong industrial technology base.

5. Definition of the engineering aspects of systems and components to facilitate value engineering analysis.

6. Aid in accelerating the commercialization process of solar thermal systems by establishing standard acceptance criteria in the industry.

7. Assistance in demonstrating the technical rationale and economic practicality of systems.

8. Some of the bases for assurances to utilities, institutional lenders, local authorities of the engineering practicalities of proposed systems.

STANDARDS PRODUCTION

A major role of SERI will be to foster and to stimulate the development of industry consensus standards. To do so, it is essential that directives and management of the cooperative effort be implemented through matrices which define (through common acceptance) the functions of systems, subsystems, and components and also the applicable, necessary, and existing rules, codes and standards (See Fig. 1 and 2).

Where possible standards development will piggyback on the solar heating and cooling and photovoltaic standards development in progress. However compared to solar heating and cooling technologies for example, the expertise in the advanced solar thermal programs is presently relatively more compact and possibly more concise, which is a benefit to the process of standards development and is expected ultimately to be the lead in many areas of the total solar thermal programs. (Some possible problems with this role are discussed later).

Effort in the first half of FY 80 will be concentrated upon identifying all required standards as completely as possible and upon gaining acceptance of their need by industry. Standards requiring research support from laboratories and engineering institutions will be identified so that the conduct of such work may be in progress in subsequent fiscal years. Throughout the standards development process, committees will need to remain cognizant of, and to include, in all their considerations any implications of the proposed FTC regulation (1) and of the proposed OMB circular (2) pertaining to standards development, and also of the dialogue on such matters by ANSI members (3) (4).

It is expected that development of accreditation procedures and the establishment of testing and certification laboratories will extend well into the 80's and the process of updating standards will be continuous. One aspect of the program to be developed, with potential savings to the consumer, is the coordination leading to acceptance between states and various governmental jurisdictions of given existing documents applicable in the first instance to only one state or jurisdictional body's needs. It will also be beneficial to the application of codes and standards if aid, by way of interpretations to the requirements in all standards, is documented for use at the local authority level.

It is likely that some standards development will be specifically peculiar to a small segment of the industry and, though necessary, could be held back by lack of contribution to the consensus process by the acknowledged experts. The prudent role of SERI in such cases would be the funding of research and development programs to develop standards or methods of test. For expediency the draft document in the case of a standard would be given wide distribution for comment by the public and the solar thermal industry before being submitted -- with a disposition on the resolution of such comments -- to the appropriate standards body. A proposed line function for management of standards development within this project is given in Fig. 3.

CONCLUSIONS

The goal of the SERI program is the establishment of a Quality Assurance and Standards Program in support of the development of solar-thermal technology with the overall objective being to foster the development and adoption of rules, codes, standards, performance criteria, methods of test etc. leading to safe, reliable and nationally acceptable procedures for operation of solar thermal power systems.

Development of the necessary standards will be firstly through the industry wide consensus process. In the absence of appropriate input, development may be sponsored by SERI of codes, standards, rules, methods of test, etc. for subsequent submission to the appropriate national committees. Directions for standards development will be based upon matrices outlining component functions, applicable and required rules, codes, etc. which will be generated from input by the solar thermal industry, some proposed time scales for the development and operational work are given in Fig. 4.

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2. "Interaction With Voluntary Consensus Standards Developing Bodies". Office of Management and Budget Circular.

3. Letter M. R. Green ASME to L. A. Fettig O M B "Proposed OMB Circular on Federal Interaction With Voluntary Consensus Standards-Developing Bodies" February 1978.

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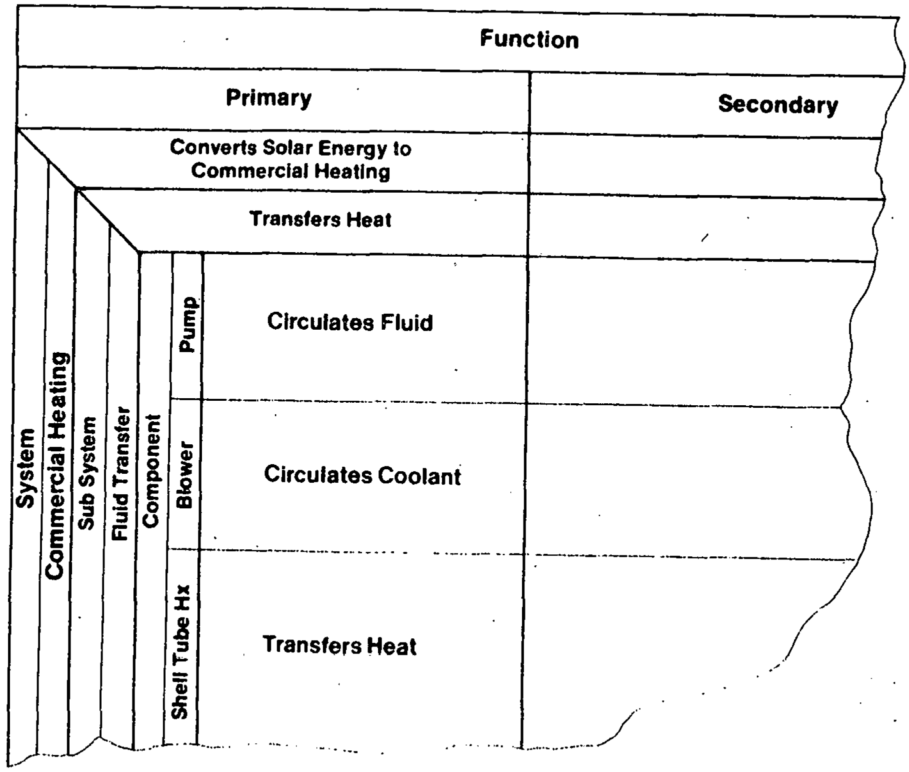


Figure 1. Equipment Functional Definition Matrix (Example)

Subject \ Item		Site Location & Plant	System: Foundation	System: Heliostat Field	System: Power Generation	System: etc.	System: etc.	Component: Mirror	Component: Boiler
Loading Event			AISCxx ASMExx		IEExx				
Load Combination			ASMExx etc.						
Seismic			R.G. 1.60 R.G. 1.61 etc.						
Design Criteria	Mechanical		ASMExx etc.		etc.				
	Thermal		etc.						
	Hydraulic		etc.						ASME xx
	Materials		ASTM ASMExx						
	etc.								
	etc.								
Quality Assurance	Materials Handling		ASTM xxx						
	Materials Certification								
	Materials Testing		ASTMx xxx						
	etc.								
	etc.								

Figure 2. Standards Matrix (Example) Solar Thermal Systems

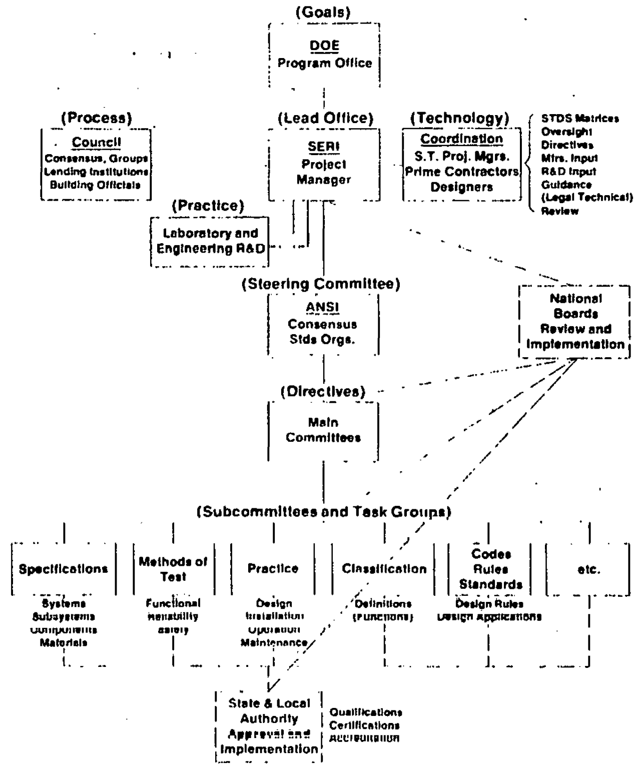


Figure 3. Proposed Line Function (Management)
Solar Thermal QA and STD

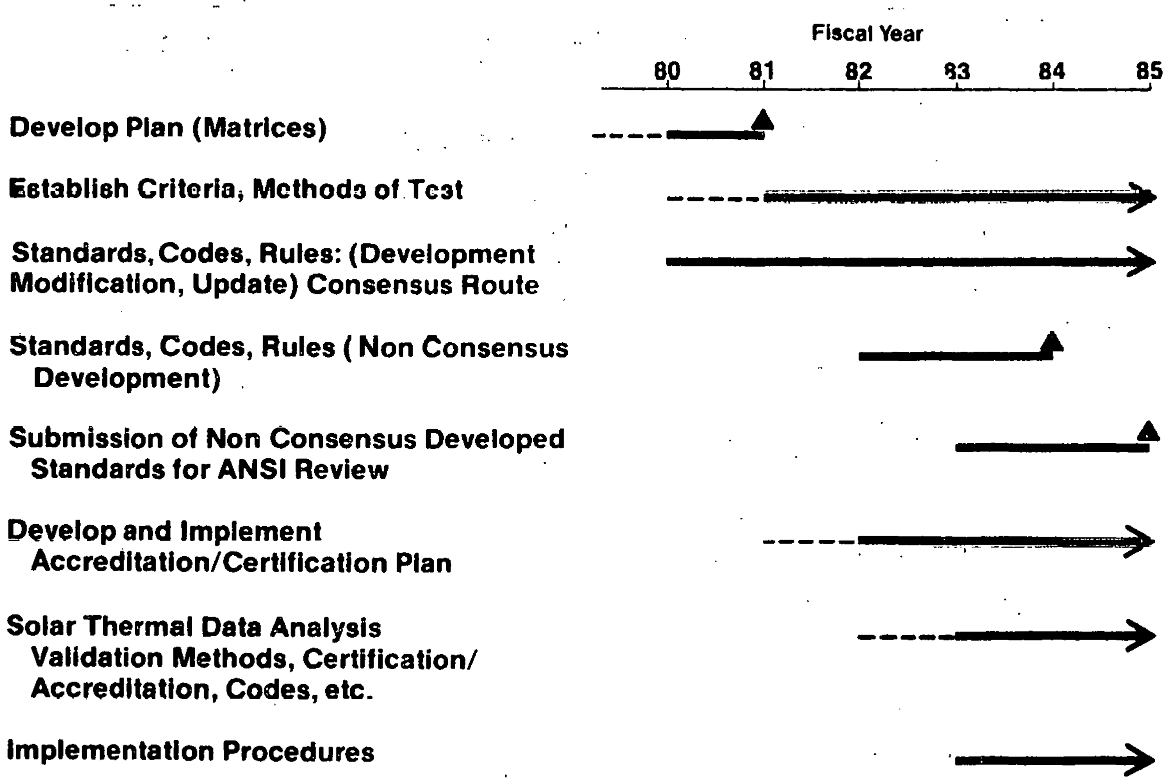


Figure 4. Solar Thermal Standards Development Proposed Schedule

REPORT OF THE TECHNICAL INFORMATION

DISSEMINATION PROJECT--FY 80

Early commercialization of solar thermal technology depends in great part upon the identification and characterization of potential users, and the skill with which DOE tech transfer programs anticipate and satisfy their information needs.

For FY 80 solar thermal TID is committed to a marketing plan which singles out the industrial sector and university faculties as target audiences most in need of characterization and cultivation during the second year of the TID/tech transfer effort. With this priority in mind, certain strategies (and activities which follow naturally from them) have been undertaken to identify the members of these two audiences, to determine the kinds of technical information needed by them, and to establish fast flowing channels which link data sources to information users.

There are two premises which significantly influence TID method: (1) the belief that we can facilitate and accelerate the process by piggybacking on existing communication channels, and (2) the acknowledgement of the information user as our primary customer, i.e. the one to please.

Market analysis tasks during the first year of TID operation indicate that we can stimulate both a demand for information products and a willingness to participate in the federal R & D effort.

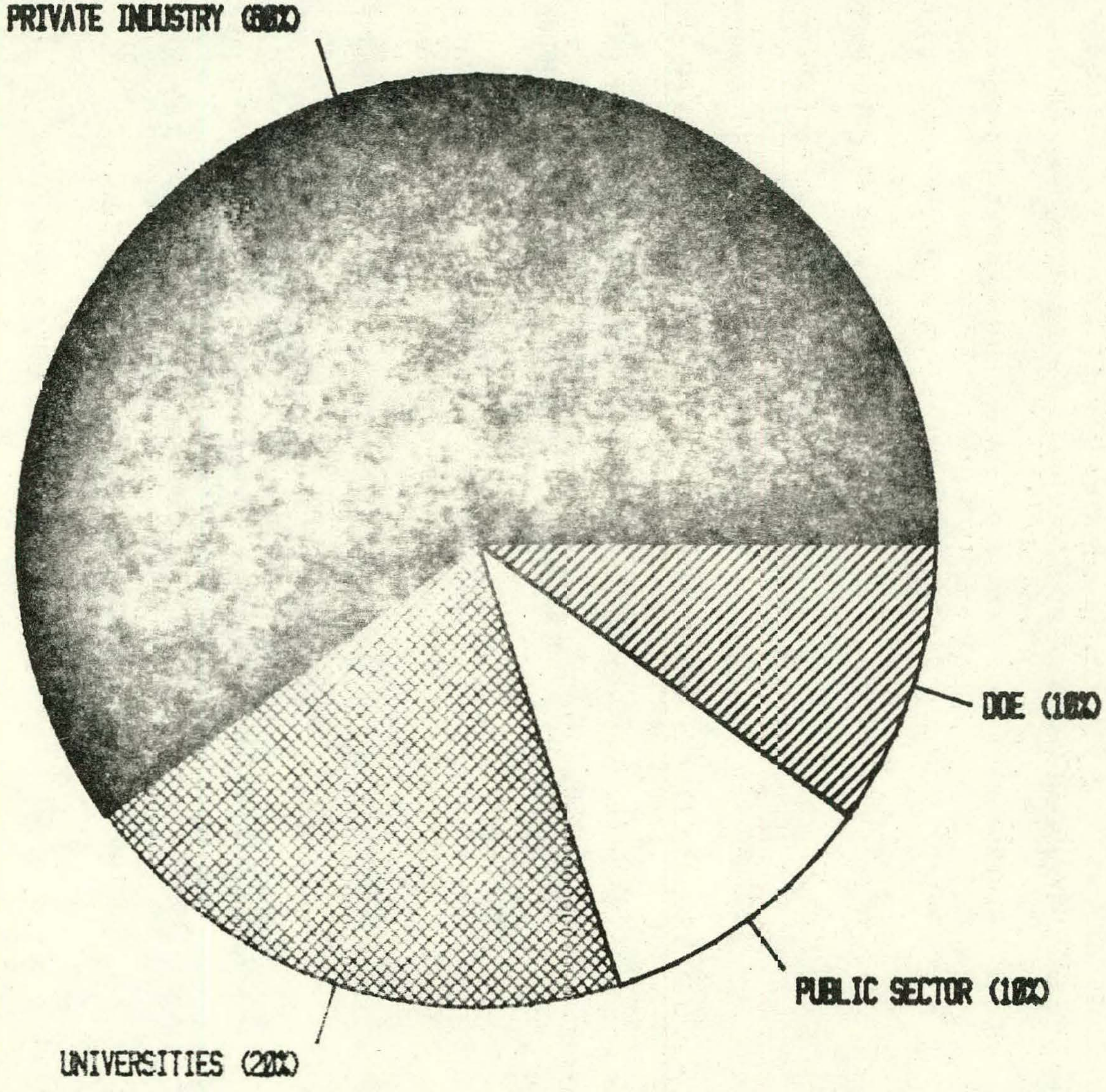
- Development of a promotion flyer listing information products including maps, slides, viewgraphs, pamphlets, and a SERI newsletter which are available free from the TID office, led to the dissemination of more than 20,000 maps alone.
- Announcement of our willingness to supply the same materials to annual meetings, energy conferences, engineering schools and state fairs, led to the distribution of the Solar Thermal Program map to 300 corporations and 100 universities.
- Proceedings of the first STP User Review Panel Meeting, held in March 1979, SERI report #TP-69-221, has been through 2 editions and is currently out of print, with backlog of orders.

Requests for information packages which solve specific problems--such as planning for a utility--indicate that a market for solar thermal power systems already exists.

To encourage the manufacture of systems and the development of new applications, during FY 80 the TID program will concentrate on moving federal R & D information into the hands of industrial managers in a position to initi ate solar programs or take advantage of government opportunities. In addition, we will establish channels to university faculties with the intent of encouraging teachers to (1) teach current findings and processes, (2) initiate research projects which lead to new applications, and (3) share with us international programs information and opportunities.

Program efforts will be apportioned among the audiences deemed critical to commercialization as described in the figure below. Sixty percent of effort is directed at private industry, twenty percent toward universities, ten percent toward improvement of information services within the DOE community, and ten percent at the public sector.

FY 8Ø STP TID EFFORT



Specific goals of the dissemination task are:

1. to establish direct channels of communication to 5,000 selected businesses
2. to multiply by 3 the circulation of technical reports
3. to double private sector responses to RFPs
4. to double STTFUA membership, and
5. to reach 300 universities regularly with communiques and reciprocal programs that make available federal assistance and research opportunities.

Objectives to help reach these goals are to:

a. Compile mailing lists useable both for dissemination and information gathering.
b. Develop a catalog of all the publications available in the program.
c. Introduce a newsletter which reflects the activities and achievements of the whole Program.
d. Initiate joint ventures which increase private sector participation and benefit, and
e. Organize research data into information packages which increase its utility to private industry and other information users.

During FY 80 the tasks and activities of the TID program are diversified to make use of special skills and resources at the national laboratories. In addition, contractors from publishing, media, and business management disciplines have been brought on board to increase the effectiveness of selected projects.

Some projects include:

1-hour cable TV production airing to 16 million viewers in January

105-slide color-and-sound multi-media program describing the technology and 4 test facilities

introduction of an academic/news publication titled Solar Thermal Report

publication of a directory listing addresses of 5,000 users of solar energy R & D information as well as titles and authors of all publications in the Program

development of a traveling display and a calendar of Program events

workshop for engineers offered at the ASME Centennial at San Francisco in August, and

preparation of integrated technical information kits, such as a utilities planning package and "What the Glass Industry Should Know about Solar Thermal Technology."

The dedication of demonstration projects at Coolidge and Crosbyton, as well as active construction of the pilot plant at Barstow, California, present new opportunities for sharing with businesses and the public some of the challenges and achievements of the rapidly expanding Program. Development of the solar thermal national library collection at SERI, and the publication of increasing numbers of articles in trade magazines broaden the interest group which will result in a market base. These activities and others, which spring from development activities with industry are our hope and our gamble for the 1980s.

STTFUA ACTIVITIES & EXPERIMENTS

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Introduction

The Solar Thermal Test Facilities Users Association was organized in 1977 to promote and enhance the use of the DOE Central Receiver Test Facility at Sandia and Advanced Components Test Facility at Georgia Tech. The UA activities include operation of an office in Albuquerque; organization of workshops to promote research in high-temperature chemistry, physics, materials, and processes at solar test facilities; dissemination of information to potential users of the facilities; technical review of proposals requesting access to the facilities; and recommendation to SERI concerning funding priorities for proposed research at the facilities.

Some research efforts proposed are more effectively conducted at a solar furnace type of facility with a horizontal beam as opposed to the two DOE central receiver facilities with upward focused beams. To this end, access agreements were negotiated with the U.S. Army Solar Furnace at White Sands, New Mexico and the French CNRS facility at Odeillo, France. Specification data on all four facilities can be obtained by contacting Mr. Frank Smith at the UA office in Albuquerque.

Operation of the UA is funded by SERI through a subcontract to the University of Houston. The UA operating budget averages about $250,000 per year. During FY79, $536,000 in research funds were awarded by SERI to nine subcontractors at the UA recommendation.

Experiment Activity - FY79

Beginning in 1977, a number of unsolicited proposals were reviewed and funded by SERI at the UA recommendation. The status of the subcontracts developed from these unsolicited proposals is summarized in Table 1. Note in particular that two of the subcontracts are still active: (1) NMSU, "Abrasion Resistance of Concrete," and (2) University of Kansas, "Properties of Oxygen Alloys of Electropositive Metals." Also, two of the research efforts have earned additional research funding: (1) Princeton, "Flash Pyrolysis of Biomass," and (2) Colorado State University, "Ammonia Dissociation Reactor Design."

The subcontracts resulting from a UA solicitation issued in January 1979 were recommended for funding to SERI the last week in July 1979. Thirty-six proposals were reviewed resulting in the recommendation to fund seven of the proposals as first-priority and three proposals on a second-priority basis (if funding were available). Nine of the ten proposals could be funded based on available dollar resources.

Eight of these proposals are now under contract. The proposals and respective funding are as follows:

1.	XP-9-8321-1, Westinghouse (Dennis Bachovin)--Fluidized Bed Receiver	$ 66,800
2.	XP-9-8322-1, Dynatherm (Walter Bienert)--Heat Pipe Receiver	54,200
3.	XP-9-8323-1, Solar Turbines, Int'l (Alan Campbell)--High Temperature Steam Loop	50,000
4.	XP-9-8324-1, Princeton (Mike Antal)--Flash Pyrolysis of Biomass	98,600
5.	XP-9-8325-1, IGT (Stephen Foh)--Cadmium Oxide Decomposition	76,800
6.	XP-9-8326-1, IGT (Dennis Duncan)--Calcium Carbide Formation	36,600
7.	XP-9-8327-1, LLL (Dave Gregg)--Solar Coal Gasification	23,000
8.	XP-9-8328-1, NMSU/NRL (Jim McCrary/Talbot Chubb)--CO_2-CH_4 Reforming	30,000
9.	XP-9-8347-1, LASL (Bob Skaggs)--Molybdenite Ore Processing (in negotiation)	100,000
	TOTAL	$536,000

Table 2 indicates the schedules for testing and respective test facility for the experiments.

An examination of the test facilities chosen and the background of successful proposers leads to a number of preliminary conclusions that will be further refined from the results of subsequent solicitations. Through UA contracts, it was desired to provide research funding and test facility access to university researchers in the solar thermal research area. The FY79 UA solicitation was limited to proposals offering actual testing at a solar test facility. Most of the proposals sumbitted by university researchers did not propose actual facility testing but instead, addressed basic analytical or laboratory research tasks eventually leading to test facility usage. The university proposers that won an award were acknowledged leaders in their field with previous solar facility test experience (Antal of Princeton) or with substantial research and development experience in their field (McCrary and Chubb of NMSU/NRL). It appears that those with prior applied research expertise are more likely to provide good test facility proposals.

Another interesting result of the solicitation is the facility selected for testing by the subcontractors. Four of the experimenters chose the ACTF, four selected White Sands, one experimenter used the CNRS at Odeillo, and none identified the CRTF as the choice for testing. A possible conclusion is that small, proof-of-concept experiments require test facilities in the thermal energy range of the 30 kW solar furnace up to the 400 kW central receiver. Once these proof-of-concept experiments are completed, some of the concepts are likely to be carried forward leading to the next stage of engineering development. These early experiments may shape the future of the solar thermal components and subsystems and verify new uses of solar thermal systems.

Planned Activity - FY80

The SERI/UA activities for FY80 are structured around workshops, technical monitoring of the existing subcontracts, and organization and issuance of another soliciation for experimentation at the test facilities.

A workshop was organized about two weeks ago by the UA with the subject being application of solar energy to fuels and chemicals research. Copies of the proceedings will be available from the UA office. The only other meeting scheduled is the annual UA meeting held in conjunction with the ISES conference.

A mechanism is being established for periodic review of progress made on the subcontracts and dissemination of valuable information obtained during the design and experimentation at the test facilities. For making the public aware of the existence and capabilities of the Solar Thermal Test Facilities, an audio-visual set has been recently completed under the Technical Information Dissemination (TID) activities at SERI in cooperation with the UA.

TABLE 1. STATUS OF UA UNSOLICITED RESEARCH SUBCONTRACTS

TITLE & SERI S/C NUMBER	SUBCONTRACTOR (P. I.)	FUNDING $K	STATUS	COMMENTS
STTFUA Absorber Coatings Experiment XL-9-8019-1	Oak Ridge (J.M. Schreyer)	7.5	Final report received Aug. 79	
Ammonia Dissociation Reactor Design XD-9-0637-1	Colorado State University (Terry Lenz)	21.0	Final report received Dec. 78	Follow on funding for $145K negotiated. XP-9-8224-1
Carbon Gasification Experiment Design XJ-9-8017-1	SRI (Dan Cubicciotti)	24.8	Final report received Nov. 79	
Flash Pyrolysis of Biomass EH-9-8025-1	Princeton (Mike Antal)	16.1	Final report received Sept. 79	Follow-on recommended by UA to SERI; $98.8K testing - summer 1980
Properties of O_2 Alloys of Electro-positive Metals EI-9-8034-1	University of Kansas (Paul Eilles)	25.0	Contract slipped; completion date Feb. 1980	
Abrasion Resistance of Concrete AM-9-8149-1	New Mexico State University (Ray Willem)	24.0	Contract slipped; completion date March, 1980	

TABLE 2. SERI/UA EXPERIMENT SCHEDULE - FY80

TEST FACILITY	EXPERIMENT	FY80 TEST SCHEDULE 1st QUARTER	2nd QUARTER	3rd QUARTER	4th QUARTER
ACTF	STI - Hi Temp Steam Loop	△ ◆	○	● ▼	
↓	Dynatherm - Heat Pipe Receiver	△ ◆		○● ▼	
↓	Westinghouse - Fluidized Bed	△	◆	○ ●	▼
↓	Princeton - Biomass Pyrolysis	△		◆	○● ▼
White Sands	IGT - C_aO Decomposition	△	◆	○●	▼
↓	LLL - Coal Gasification	▼ completed			
↓	NMSU - CO_2CH_4 Reforming	△ ◆ ○●	▼		
↓	LASL - Molybdenite Ore Processing	TBD			
Odeillo	IGT - Calcium Carbide Formation	△○● ▼			

START DATE △
TEST PLAN ◆
TEST BEGINS ○
TEST ENDS ●
FINAL REPORT ▼

UPDATE ON
U. S. DEPARTMENT OF ENERGY
ADVANCED COMPONENTS TEST FACILITY

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Abstract - The U. S. DOE Advanced Components Test Facility is a 400 kW solar thermal test facility located in Atlanta, Georgia and operated by Georgia Institute of Technology for the U. S. Department of Energy. The facility was first operated in September 1977 against a 300 kW solar steam generator of Italian design. Since that time, various facility modifications have been made and several major test programs have been undertaken. This paper includes a description of the Facility, a summary of current modifications and research activities, and a summary of test programs planned for calender year 1980.

INTRODUCTION

The U. S. DOE Advanced Components Test Facility (ACTF) is a 400 kW solar thermal test facility patterned after Professor Giovanni Francia's solar steam generating pilot plant near Genoa, Italy. The ACTF is operated by the Engineering Experiment Station of the Georgia Institute of Technology and is located on Georgia Tech's campus in Atlanta. Initial operation of the Facility took place in September 1977 and since that time a major test program for a Brayton cycle solar receiver has been completed, various facility modifications have been made, hot checkout of a beam turning light pipe has been completed, upgrading of the mirror field to provide a tighter beam geometry has been completed, construction of a control building is nearing completion, and a test program for a steam generator is currently underway.

FACILITY DESCRIPTION

The ACTF is designed to test experimental solar thermal hardware constructed by industrial organizations, universities, government laboratories, and individuals. It provides concentrated solar radiation at power levels up to 400 kW thermal and peak incident fluxes up to approximately 2.5 MW/m^2, as well as test support services such as equipment installation, data collection and processing, and measurement of input power levels while tests are in progress. The test hardware supplier is ordinarily expected to provide personnel to operate his equipment during testing periods.

Major components of the facility, see Figure 1, include a heliostat collector field, an experiment platform located above the center of the mirror field, a computerized data acquisition system, a soon to be occupied instrument and control building, and various heat rejection equipment. A heat flux calorimeter scanner is available for measurement of the heat flux distribution and power incident on the aperture of the test object.

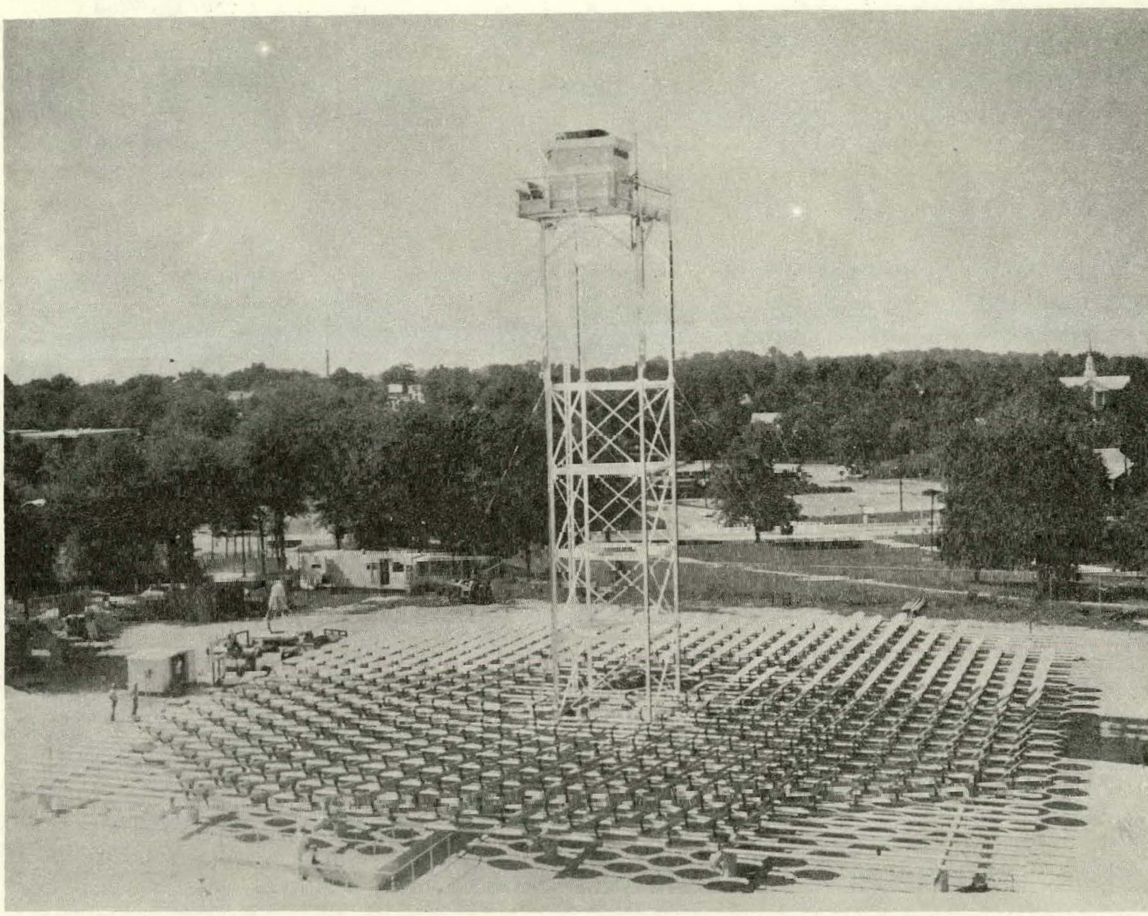

Figure 1. Aerial View of U. S. DOE Advanced Components Test Facility.

The heliostat field contains 550 second-surface glass mirrors which are each 111 cm (43.7 in.) in diameter. Solar radiation is focused into a focal zone 21.4 m (70.3 ft) above the plane of the mirrors and coincident with the plane of the tower floor. Solar tracking is accomplished by a mechanical system so that the position of the focal zone is stationary throughout the day.

Experiment packages weighing up to 9100 kg (20,000 lbs) and having dimensions up to approximately 4.0 meters square (13 ft square) with unlimited height can be positioned on the tower for testing. Equilibrium temperatures approaching 2300° C (4280° F) are possible at the center of the focal zone.

CURRENT ACTIVITIES

Since the last Semi-Annual Review of the DOE Advanced Solar Thermal Technology Program in June 1979, onsite effort has been concentrated in five major areas: (1) improvement of heliostat tracking, (2) implementation of closed loop heliostat tracking, (3) construction of a new control building and a perimeter access road around the heliostat field, (4) hot checkout of a beam turning light pipe for subsequent use at the French CNRS Solar Furnace, and (5) detailed characterization of the Francia steam receiver purchased at the time the facility was constructed.

Improved Tracking

The improved tracking task arises from the fact that the heliostats are mechanically driven by a single electric motor; the motor speed can be varied by operator control to correct the position of the focal zone as a whole but individual heliostat corrections are not possible. Therefore, alignment errors in individual heliostats can cause an overall spreading of the composite focal image formed by the 550 mirrors.

It has been determined that the three most significant sources of tracking error are misalignment of the equatorial axes of the mirror supports, inadequate stiffness in the structure supporting the fixed pivot point of the mirror supports, and inadequate alignment tooling and technique. Means for correcting these problems have been identified, tested and implemented. Identification of the major sources of tracking error was a six month analytical and experimental effort, culminating in the demonstration of a proof-of-fix on eight of the heliostats. The demonstrated proof-of-fix involved realignment of each of the eight polar axes using precision surveying equipment and techniques, stiffening of each pivot point support structure to greatly reduce elastic deformation of the support, and the design, construction and use of new improved mirror aiming fixtures.

Implementation of the fix for the 550 heliostats required approximately three months and was completed late in November 1979. The ACTF flux scanner is presently being used to experimentally determine the magnitude of the improvement in tracking. It is anticipated that the improvement will result in a higher peak flux and smaller diameter beam.

Feedback Control of Mirror Field

Controls for the ACTF mirror field are in the process of being upgraded to include a closed loop, sun tracking system. Design of the feedback portion of the system has been completed and a subcontractor has been selected to fabricate the system. Installation of the system is expected to occur in the late December 1979 time frame. Installation of the system will augment the existing clock controlled system by providing the feedback necessary for small error corrections in the concentrated beam.

Control Building/Perimeter Pad

The new control building is a 55 m^2 (600 ft^2) structure designed to provide a proper operating environment for the computerized data collection system, and to locate the data collection system, the facility control module and the experimenters control module into one work area. The building has been designed to provide flexibility for meeting the needs of many experimenters and to minimize the time spent in setting up and dismantling equipment. A paved access roadway and improved site drainage are also part of this task.

Implementation of these facility improvements are currently underway with a projected completion date of December 15, 1979.

Science Applications, Inc. Light Pipe Test

Science Applications, Inc. completed the design and fabrication of a beam turning light pipe in July 1979. The device was given a successful hot checkout and function test at the ACTF prior to being shipped to France for further testing at the CNRS 1000 kW Solar Furnace. Test objectives accomplished at the ACTF included survivability and flux throughput. The device was subsequently operated at the French Solar Furnace in support of a DoD materials evaluation program.

Francia Receiver Test

The Francia steam receiver is currently on the experiment tower and undergoing tests. The unit has been operated at design temperature and pressure, but appears to be rather sensitive to aperture beam position. Further testing is planned after completion of the current volume flux mapping activities. Efficiency determinations will be made with and without the glass honeycomb structure in place.

PLANNED ACTIVITIES

Scheduled test activities for the next ten months are shown in Figure 2. These activities include:

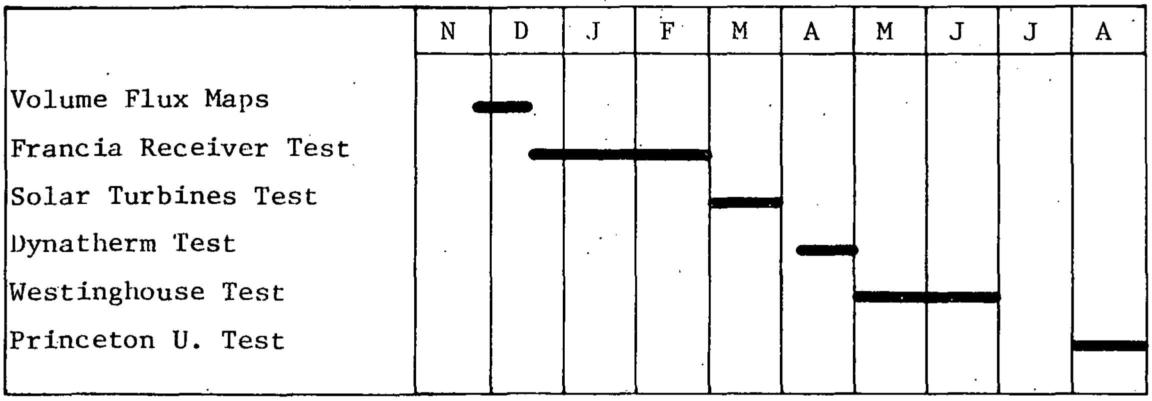

Figure 2. Near Term Testing Activities at the ACTF.

- Francia Receiver Test: determine efficiency of the 300 kW solar steam generator with and without its glass honeycomb structure. Gain operating experience with the unit.

- Solar Turbines Test: coordinate with Solar Turbines International to test and evaluate a 20 kW solar steam loop. The unit will operate at 1500° F, 1700 psi (815° C, 11.7 MPa).

- Dynatherm Receiver Test: coordinate with Dynatherm Corporation to test and evaluate a 100 kW receiver module consisting of seven liquid metal heat pipes. Objective is to gain performance information and operating experience with the liquid metal heat pipe.

- Westinghouse Receiver Test: coordinate with Westinghouse Corporation to test and evaluate a direct absorption fluidized bed receiver concept. Performance information will be acquired at various power levels to 150 kW and with various bed materials.

- Princeton University Test: coordinate with Princeton University to test and evaluate a direct absorption biomass gassifier receiver concept.

PARABOLIC DISH TEST SITE*

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ABSTRACT

A Parabolic Dish Test Site (PDTS) has been established for the Department of Energy (DOE) at the Jet Propulsion Laboratory (JPL) California Institute of Technology's Edwards Test Station (ETS) to provide a site for test and evaluation of solar thermal energy conversion systems and subsystems. ETS was selected because of the high insolation level which is considered one of the best in the United States and because of the excellent meteorological conditions. Described are PDTS capabilities and facilities including the computerized data acquisition and reduction system and circumsolar telescope equipped weather station. Initial tests of the Precursor Concentrator and Omnium-G solar powered electric generating plant are discussed. Also described are two Test Bed Concentrators (TBCs) (installation completed during October 1979) which are scheduled to enter a testing program during November 1979.

INTRODUCTION

The PDTS is a unique facility that provides a site for testing solar point-focusing concentrator systems and related hardware such as: concentrator-receiver-power conversion systems, concentrators, high flux density receivers, thermal heat transport systems, power conversion systems, and any other hybrid systems using Point-Focusing Solar Concentrators and fossil fuels. The PDTS has been established and is operated by JPL for DOE and is located at the JPL ETS, Edwards Air Force Base, California. This site is located approximately seventy airline miles north of Los Angeles.

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

*Sponsored by DOE through an agreement with NASA.

prototype solar thermal power systems will be accomplished at the PDTS before committing to full-scale 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:

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 wather.
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.

SAFETY

Safety is a first order consideration at the PDTS. Written test procedures are required prior to the start of any testing activity. Safe operating limits of critical parameters (temperature, pressure, etc.) are remotely monitored during subsystem and system testing and displayed in the Control Room. An emergency override procedure is implemented should a safe operating limit be exceeded or anticipated. Safety glasses (gas welding goggles) and hard hats are required for operating personnel in the test area during "on sun" operation of solar concentrators. Operating personnel are not permitted to work closer than two focal lengths from the concentrator while tracking the Sun.

DATA ACQUISITION AND REDUCTION

A computerized data acquisition system at ETS is available to condition, display, record, and reduce data. This system 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, 4-20 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.

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.

Operational experience to date has pointed up the value of real-time printout of data as well as real-time displays of critical parameters. Graphic displays are also considered to be very desirable. A data logger with high common mode rejection is essential because signals being measured are in the millivolt range.

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 1,000 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^{o}.

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^{o}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.

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.

EXPERIMENTS AT ETS

Experiments initiated 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 are mounted on the structure and reflect the Sun's energy to a cold water calorimeter at the focal point. This cold water calorimeter measures thermal performance of the mirrors, one at a time or combined. Twenty-five data signals were monitored. Testing was begun during October 1978 and included evaluation of degradation of mirror performance caused by dust and film accumulation on the mirror surfaces. A flux mapper was fabricated for use in characterizing concentrator flux pattern and intensity. The precursor was used for development and initial checkout of this flux mapper. (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 sensor presently used with the mapper is a water-cooled "pin" diode capable of measuring flux densities from one hundred milliwatts per square centimeter to approximately 500 watts per square centimeter. Scan resolution for the existing program is in increments of one-hundredth of an inch; scan speeds are on the order of three inches per second.)

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 ETS. Testing of the concentrator was begun in December 1978 and other subsystems were added later. Fifty signals were monitored and/or controlled. This test provided the first opportunity for acquiring operational experience with a point-focusing system and development of operations and maintenance parameters at the system level.

Test Bed Concentrator

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 TBCs 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. Full scale testing of the TBCs was begun during November 1979.

As constructed, the TBCs are nominally 11 meters in diameter with a focal length of 6.6 meters. Each TBC has a parabolic concentrator area of 94.5 m^2 consisting of 232 mirrors producing a concentrated beam 17 cm in diameter which intercepts 95 percent of the energy at the focal plane. The TBCs provide an elevation over azimuth, two axis tracking system. The total thermal energy available at the focal plane (no aperture) for each TBC is 85 kW_t, with a peak flux of 1,000 W/cm^2, and a peak equilibrium temperature of $3,600^oK$.

Figure 1 shows a photograph of the TBCs at the PDTS.

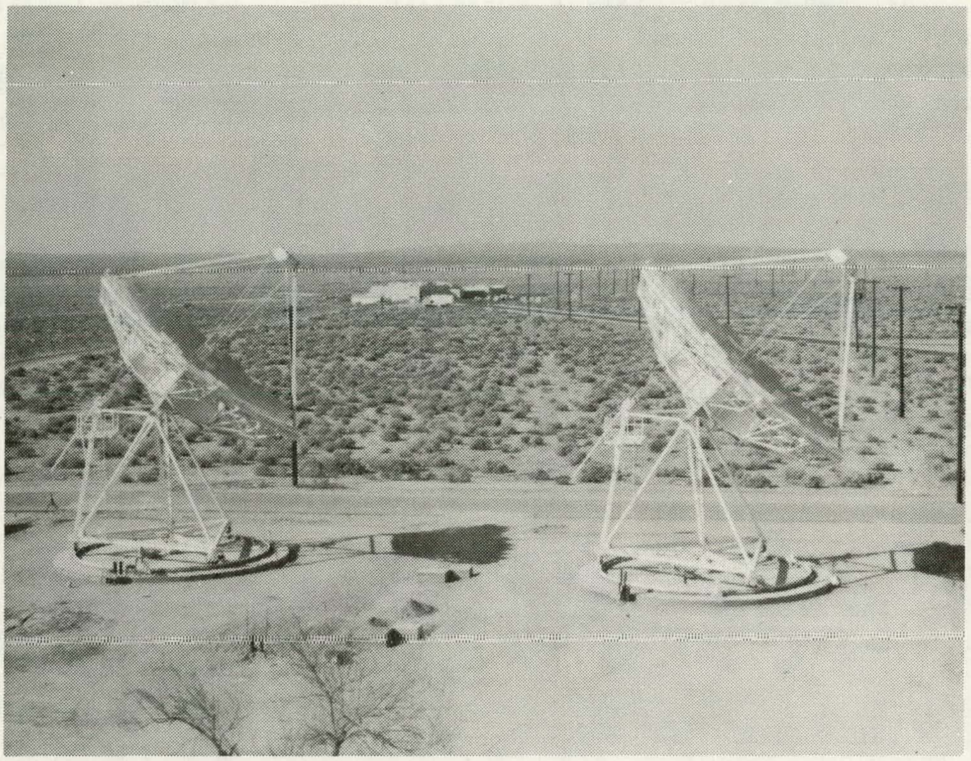

FIGURE 1. TEST BED CONCENTRATORS

SERI SOLAR THERMAL TEST FACILITIES

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ABSTRACT

Solar thermal test facilities are presently operational at SERI and expanded operations are being planned. Currently, the Interim Field Site is occupied by a point focus collector component evaluation facility (ACRES). A single concentrating collector test installation (STAM) will be added in 1979. All activities will eventually be transferred to a nearby and larger Permanent Field Site. SERAPH, a solar system test facility directed toward industrial process heat applications, will be the first solar thermal test facility at the Permanent Field Site. SERAPH installation will commence in 1980, and by 1982 all field work will be consolidated at the Permanent Site. Research results have already been generated at the existing ACRES facility.

INTRODUCTION

The Solar Energy Research Institute is currently developing plans and implementing facilities to address, in a field test environment, a number of solar technologies. Subject areas include biomass, passive, PV, insolation, solar thermal conversion, and wind energy. This paper will address the present situation and near-term plans pertaining to the solar thermal test facilities at SERI. The objective will be to briefly describe the facility equipment, its capabilities and expected uses. A portion of the solar thermal facilities are currently operational at the Interim Field Site and useful information has been generated. The Interim Site allows SERI to initiate field testing while the Permanent Site evolves. This latter, considerably more complex installation has a development schedule that is tied to the implementation of the SERI permanent office building.

INTERIM FIELD SITE

Field experiments are currently underway at the SERI seven-acre Interim Field Site in Golden, Colo., that will accommodate near-term SERI field activities until they can be transferred to the nearby and larger Permanent Field Site beginning in 1981. All Interim Site work is to be discontinued by 1982. The major Interim Site experimental areas are shown in Fig. 1. The site status as of November 1979 is that the ACRES installation consisting of two parabolic dishes is complete and construction is underway on site support items (utilities, foundations, etc.) needed for the STAM and IRL installation. The Interim Site abuts the property which the State of Colorado has offered for SERI's permanent building and field site.

The next four paragraphs will describe the Interim Site experimental areas.

ACRES

High temperature solar research is being conducted at the Interim Site ACRES facility (Advanced Component Research). ACRES provides a test bed for evaluating point-focus collector components such as receivers, optical elements, tracking devices, and thermal transport mechanisms. This research capability presently makes use of two six miter parabolic dishes (commercially available from Omnium-G) now installed at the site. Receiver-related activity will center on advanced thermal, thermochemical, and solids-handling receivers. Thermal transport studies will address energy transfer from the focus to the base and between dishes. Results to date at ACRES are: (1) receiver failure modes identified; (2) optical efficiency and thermal losses measured; (3) scatter plate flux mapper; and (4) focal area flux characterization (using JPL equipment).

STAM

Thermal performance testing of concentrating collectors and associated components will take place at the Interim Site STAM (Standard Module) facility. The facility is designed to provide fluid to the collector under carefully controlled flowrate and temperature conditions so that steady state collector energy delivery can be measured. The STAM design was prepared by Stone and Webster Engineering and fabrication took place at Measurements, Inc. The design evolved from flat plate test loop configurations and the Sandia Collector Module Test Facility fluid loops. Capabilities are:

• Fluid temperature	$\leq$ 230°C water
	$\leq$ 400°C oil
• Circulation rate	$\leq$ 5 ℓ/min
• Heat Rejection	$\leq$ 45 kW
• Warm-up heating	32 kW

Figure 2 shows the STAM physical layout. The fluid loop is broken into two major elements. The pumping skid contains the circulating pump, storage tank, and heat rejection exchangers and is enclosed in a shed. The pumping skid delivers fluid to one or two flow metering units that sit outside alongside an associated test collector. The flow metering unit also contains the calorimetric ratio heater that will be used to monitor collector performance in a manner not susceptible to fluid specific heat and fluid flow rate uncertainties that may compromise the conventional $\dot{m} C_p \Delta T$ measurement technique at high operating temperature. STAM is expected to be operational in the second quarter of FY 1980. Detailed STAM assembly drawings and equipment lists can be obtained from SERI.

IRL

The IRL (Insolation Research Laboratory) will also be located at the Interim Field Site. Objectives of this installation are to: (1) monitor and record SOLMET data; (2) develop advanced instrumentation; (3) provide insolation data for collector tests; (4) calibrate radiometers; and (5) provide spectral data for PV testing. The information made available by IRL to the other site activities will assure that each has a thorough description of the solar conditions. IRL will also provide a broad spectrum of general meteorological data such as wind speed/direction, dew point, H_2O vapor, particulates, cloud cover, etc. Installation of IRL should be complete in the second quarter of FY 1980.

Other Interim Site Activities

The solar thermal activities at the Interim Site will be complimented by material exposure racks and a series of passive technology modular units. These items will also be transferred to the Permanent Field Site.

PERMANENT FIELD SITE

SERI is presently preparing detailed plans for the creation of a Permanent Field Site as part of its permanent office installation in Golden, Colo. The site would occupy 25-40 acres and would be adjacent to the future office complex. The solar thermal test activities would be complimented by numerous other solar technologies that would be under investigation at the same site. Figure 3 indicates the tentative layout for the 25-acre field. Additional acreage is available. An environmental assessment has been prepared for the Permanent Field Site and submitted to the Department of Energy for approval.

Development of the Permanent Site is scheduled for 1980 and will proceed in phases with activity areas being added to a basic site support infrastructure (i.e. utilities, roadways, central data acquisition, visitor control, safety and fire protection service, material handling, and storage) over a several year period. The first installation at the Permanent Site will be SERAPH, an IPH solar system test facility. The desire to limit the cost of relocating Interim Site activities has resulted in the decision that SERAPH and all subsequent field experiments will be erected on the Permanent site.

SERAPH

The SERAPH (Solar Energy Research and Applications in Process Heat) solar thermal test facility will form a system test installation that will address the technical issues that must be resolved prior to widespread application of solar thermal energy in industry. SERAPH will provide a carefully controlled and monitored environment in which component and system characteristics can be evaluated. It will permit the interaction of the concentrating collector field, storage, auxiliary heater, controls, energy transfer mechanisms, and a real or simulated load. Figure 4 shows the facility layout at the permanent site. The equipment building contains the mechanical equipment that permits energy to be exchanged in multiple paths between the surrounding collector field areas, thermal storage, the auxiliary heater (300 kW, oil fired), and a real test load or simulated load (350 kW cooling tower). Collector fields under evaluation will be typically 100–300 m^2 in aperture. All mechanical equipment is modularized to facilitate equipment modifications and reduce costs. Subcontracts have been placed for the mechanical equipment and the first collector field (183 m^2 parabolic trough). Operation of SERAPH is expected to take place in late FY 80.

CONCLUSION

The Solar Energy Research Institute has begun operation of field experimental facilities pertaining to solar thermal and other solar technologies. Research is being carried out on a seven-acre Interim Field Site in Golden, Colo. The thermal facilities at the Interim Site will address single collector evaluation and point focus solar components. Beginning in 1980, field test activity will be underway at a larger nearby Permanent Field Site. All field experiments will be consolidated at the Permanent Site by the end of 1982. The completed field research capability will be extensive and cover a broad range of technologies.

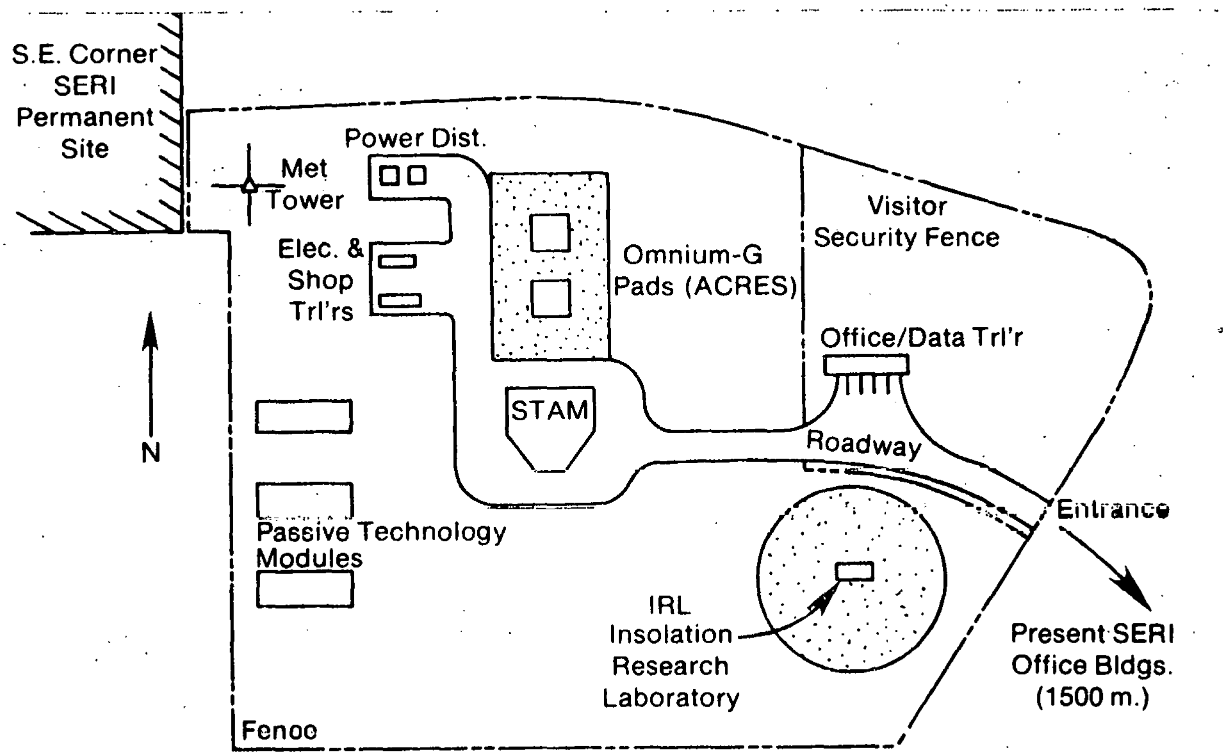

Figure 1. SERI Interim Field Site (Approx. 7 Acres)

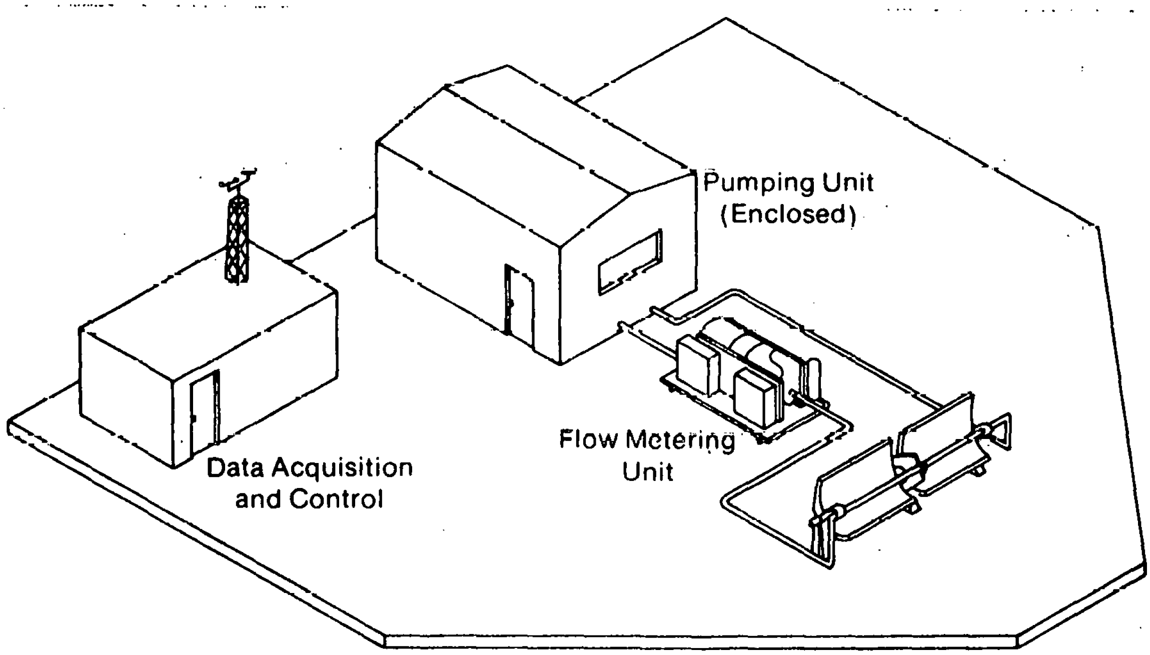

Figure 2. SERI Mid-Temperature Research Facility (STAM)

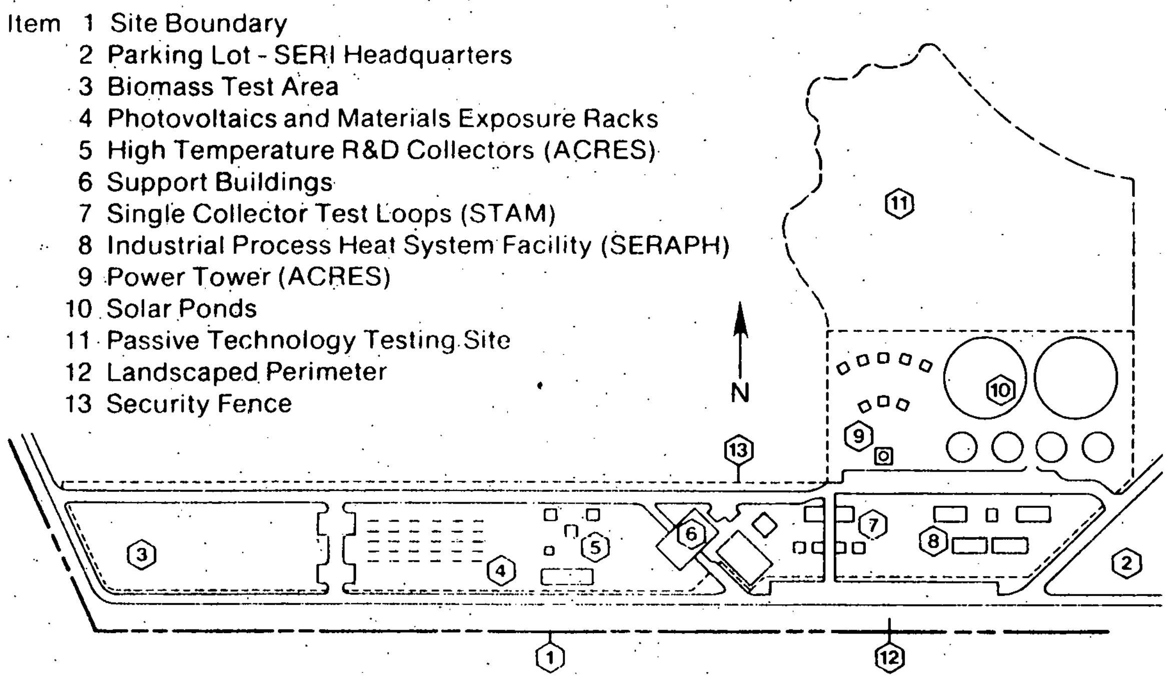

Figure 3. Permanent Field Site (Approx. 25 Acres)

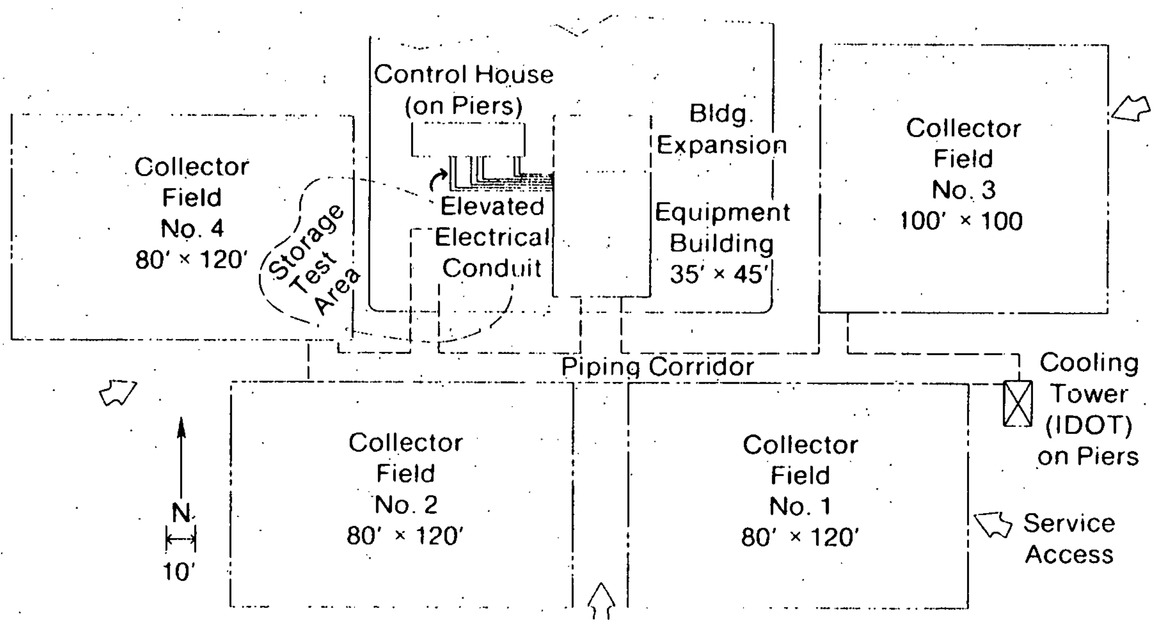

Figure 4. SERAPH Facility

SOLAR MATERIALS

OVERVIEW OF MATERIALS DEVELOPMENT FOR ADVANCED SOLAR THERMAL TECHNOLOGY PROGRAM

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Recently a Solar Thermal Program Office was established at SERI with the responsibility for managing the DOE Advanced Solar Thermal Technology Program. Solar materials research and development is an important part of this program. The Absorber Surfaces Program, as well as other SERI materials research subcontracts are managed within the materials element of the program.

The primary goal of the solar materials task is to achieve improvements in the durability, performance and potential reduction in cost of materials for solar thermal applications. Areas of immediate interest are:

1) Develop low-cost durable Ag/Glass mirror system;
2) Evaluate thin glass for reflecting and transmitting application;
3) Evaluate low-cost, stable polymers for reflectors and transmitters;
4) Establish the high-temperature stability of black cobalt and black chrome;
5) Evaluate cellular glass, plastics, wood/paper products, and composites as support materials;
6) Evaluate ceramics for high-temperature receivers;
7) Develop measurement techniques and formulate a solar materials data base; and
8) Gain an initial understanding of degradation mechanisms.

Objectives for the intermediate and longer term have also been identified. They include:

1) Develop intermediate temperature (to 500°C) selective absorber coatings;
2) Identify composite structural materials;
3) Develop compatible fluid/alloy containment combinations;
4) Develop a detailed understanding of degradation mechanisms leading to accurate materials lifetime prediction.

These objectives have been determined with the assistance of manufacturers and users. The various interlaboratory planning committees organized by SERI over a year ago, such as the glass committee, the fluids/containment committee, and the solar optical materials planning committee were the major contributors. As new information becomes available, these objectives may be revised.

Over two million dollars are planned for solar materials research and development in FY80 in the Advanced Solar Thermal Technology Program. Materials R&D has been divided into five basic categories. Table I is a compilation of the FY79 and planned FY80 expenditures by category. This work is distributed in the various national laboratories, SERI and subcontracted research. The large proportion of resources devoted to absorber material research reflects the historical emphasis this area has received. A more appropriate balance is expected in the future as additional funding flows into the reflector and transmitter materials.

The research in absorber materials is directed toward developing stable high-temperature coatings and numerous coatings are being examined as alternatives to black chrome. Degradation mechanisms of absorber coatings presently in use for lower temperatures ($< 200^{o}C$) applications are also being studied in an effort to extend their performance to higher-temperature applications. A recent development in this program has been a stable high-temperature paint developed by Exxon Research and Engineering. Dr. A. Muenker (Exxon) describes this coating elsewhere in this publication. Mr. R. Livingston (SERI) is coordinating expanded testing of this material. Other coatings currently under continued development are a chemical vapor deposited molybdenum coating which Dr. B. Seraphin (University of Arizona) described elsewhere in this publication. A Pt/Al_2O_3 cermet and an organometallic-based material are also being studied. Feasibility studies are planned to evaluate the capability of commercial production of absorber coatings using vacuum sputtering or chemical vapor deposition techniques on the variety of substrate geometries required in solar thermal systems.

Reflector materials development is an area of strong interest in the materials program. Recent developments include the promising performance of silicone-based resins as protective coatings for substrate silver mirrors. Dr. W. E. Dennis of Dow Corning elaborates further on this technique elsewhere in this publication. Sophisticated techniques are being developed at Battelle/Pacific Northwest Laboratories for mirror specularity measurements. Dr. M.A. Lind, the principal investigator, is also studying the use of dopants in the mirror silvering process to increase the resistance of wet-process silver mirrors to moisture attack. B/PNL is also providing service measurements to various DOE subcontractors.

The National Bureau of Standards (NBS) is completing certification of a set of optical standards under the direction of Dr. J. Richmond. These will be for sale through the National Bureau of Standards' Standard Reference Materials (SRM) program. Three types of standards will be sold: (1) a diffuse low-reflectance standard ($\rho \simeq .06$); (2) a diffuse high-reflectance standard ($\rho \simeq .80$); and (3) a specular, high-reflectance standard.

In the area of transmitting materials, work is continuing to evaluate the Corning thin glass and various polymers. Cleaning studies are also continuing. Cellular glass characteristics are being evaluated by Dr. M. Adams at JPL; Sandia Laboratories at Albuquerque is evaluating foam-core composite structural materials. High-temperature fluids/containment materials are being studied at SERI, JPL and SLA.

TABLE I

MATERIALS CATEGORY	PLANNED FY80 OBLIGATIONS	FY79 OBLIGATIONS
Absorbers	220	930
Reflectors/ Transmitters	980	850
Structures	300	120
Fluids/Containment	350	330
Support/Fundamental Studies	140	460

CHEMICAL VAPOR DEPOSITION OF SPECTRALLY SELECTIVE SURFACES FOR HIGH TEMPERATURE PHOTOTHERMAL SOLAR ENERGY CONVERSION

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ABSTRACT

A method is described for the chemical vapor deposition of spectrally selective multilayer coatings of good durability at 500 C. A molybdenum film of high infrared reflectance is overlaid by a solar absorber made of amorphous silicon stabilized against crystallization. Molybdenum films deposited in the presence of an oxygen bleed combine after anneal and panivation a solar absorptance of 0.92 with an infrared emittance of 0.11.

As photothermal solar technology for low temperature applications matures, emphasis shifts to conversion at intermediate (300 - 500 C) and high temperatures (> 500 C). Although systems of moderate (X <250) flux amplification critically depend on the spectral selectivity of the surfaces that intercept and convert the incident radiation, few coatings fabricated in a cost-effective manner have sustained such selectivity at temperatures greater than 300 C.

Candidate coatings for intermediate and high-temperature photothermal conversion have been developed during the last six years at the Optical Sciences Center of the University of Arizona under, successively, NSF/RANN, ERDA, and DOE support. The distinguishing feature of this work is the use of Chemical Vapor Deposition (CVD) for the fabrication of spectrally selective multilayer coatings of high-temperature durability. In this method, novel in its application to optical thin-film technology, the substrate to be coated is placed into the hot zone of a furnace, and exposed to a gas mixture that contains a compound of the material to be deposited. If all parameters are properly chosen, the compound breaks up at the substrate surface through the transfer of thermal energy, leaving behind a thin film of the desired material. If the substrate is exposed to a sequence of different reactants and conditions, successive layers of various materials and functions can be deposited, resulting in an optical multilayer stack. [1]

CVD offers a number of advantages particularly attractive for the production of spectrally selective stacks. First, deposition at temperatures typically above 500 C causes most deterioration processes to occur during fabrication. Second, deposition in an open tube at atmospheric pressure permits sequential flow-through operation difficult to perform in a vacuum. This will simplify the coating of long pipes, the preferred collector configuration at elevated temperatures. Third, unlike most physical vapor deposition methods performed in vacuum, CVD proceeds at thermal equilibrium with the substrate surface, with positive consequences for coating purity, composition and microstructure.

In this way, coatings of the dark mirror type were produced in which the thermal emittance ϵ is suppressed by a stabilized silver layer deposited by evaporation, and the solar absorptance α is generated by a polycrystalline film of CVD silicon on top, giving values for α/ϵ of 12 at values α of 0.76. They survived anneals in a vacuum of 1 torr at 500 C for several thousand hours, and were cycled several thousand times to 500 C. Note that both absorptance and emittance were evaluated at 500 C. Most reports on temperature-stable coatings cite the absorptance at room temperature *before and after* heating to operation temperature - a method clearly unsatisfactory and inconclusive, considering that most optical properties are strongly dependent upon temperature. In simple terms: what is 95% solar-black at room temperature need not be so at 500 C.

Since proving the laboratory feasibility of the fabrication process, we improved the original absorber-reflector coating configuration. We replaced the evaporated silver reflector by a thin film of CVD molybdenum, thus establishing the feasibility of an all-CVD stack. By pyrolytic decomposition of molybdenum carbonyl, films are deposited which, after anneal in a reducing atmosphere at 1,000 C, surpass the infrared reflectance of super-smooth bulk molybdenum by half a percent, as determined in the Bennett Precision Absolute Reflectometer. [2,3,4] Reflectors are thus obtained that combine the refractory nature of molybdenum with the high infrared reflectance of conventional mirror materials.

FIGURE I

ABSOLUTE REFLECTANCE FROM 3 TO 15 μm OF

1) A CVD MOLYBDENUM FILM AFTER ANNEAL
2) BULK MOLYBDENUM POLISHED TO SUPERSMOOTH FINISH
3) A MOLYBDENUM FILM SPUTTERED UNDER ULTRACLEAN CONDITIONS.

FOR DETAILS, SEE REF. 2 - 4.

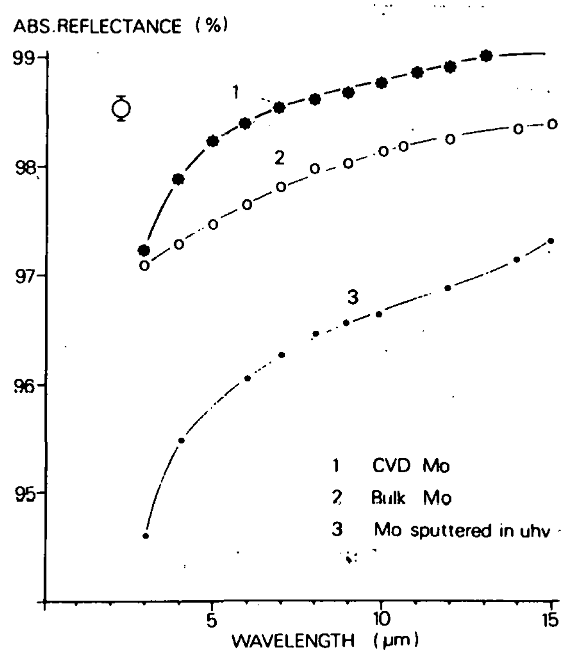


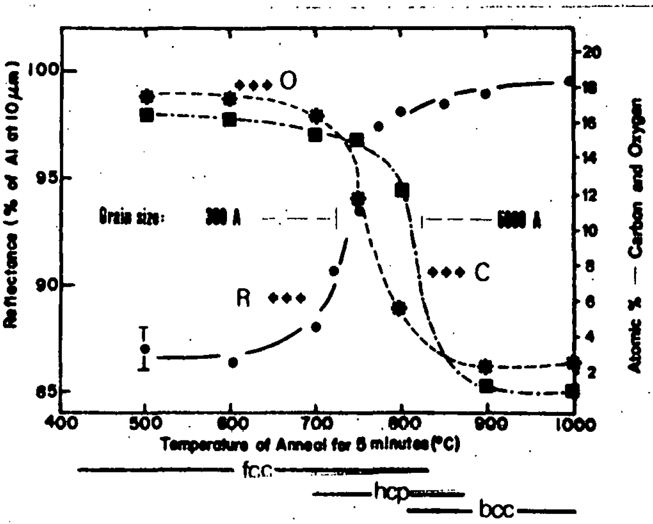
Figure 2 shows the importance of structural rearrangements and the departure of impurities during anneal in obtaining the optical performance and stability of "Super Molybdenum." This is also evident in the optical spectrum of Black Molybdenum, a single layer coating that, when annealed, combines high infrared reflectance and promising solar absorptance.

Obtained by pyrolyzing molybdenum carbonyl in the presence of oxygen, the films acquire, through subsequent anneal, a solar absorptance α of typically 0.75 at 25 C accompanied by a thermal emittance ϵ of 0.10

FIGURE 2

CHANGES OF REFLECTANCE, OXYGEN AND CARBON CONTENT, STRUCTURE, AND GRAIN SIZE DURING ANNEAL OF A CVD MOLYBDENUM FILM.

FOR DETAILS, SEE REF. 2-4.



for 500 C black body radiation. An antireflecting layer of Si_3N_4 raises the absorptance to 0.92 and the emittance to 0.11, with both values expected to be further improved through continued studies. The time profile of the optical properties indicates that annealed "Black Molybdenum" - of monoclinic structure as deposited - represents an intermediate anneal state that presents structurally a mixture of monoclinic MoO_2 and body-centered molybdenum. It can be expected that further transformation and/or outgassing will not occur at the anticipated operation temperature of 500 C.

Degradation by oxidation can, in both types of molybdenum, be retarded by overcoats of silicon nitride, Si_3N_4. We can now anneal "Super Molybdenum: protected by 750 A of CVD Si_3N_4 for 750 hours in open air, prolonging the anneal times reported in 1978 by nearly two orders of magnitude. [5] Failures can be correlated to pinholes in the passivator, giving hope for extended performance of the entire stack when the passivated reflector is buried beneath the silicon absorber and an additional Si_3N_4 anti-reflection coating.

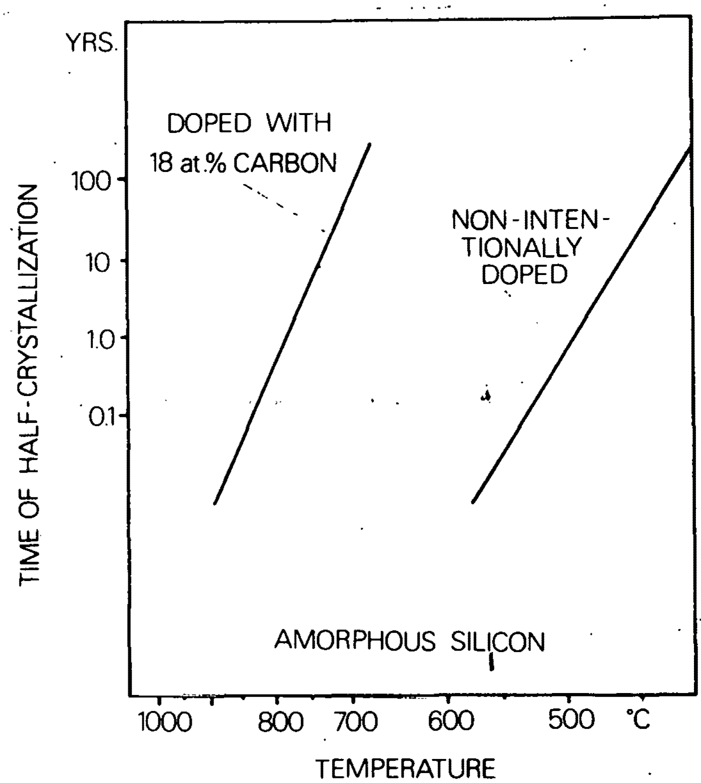
The role of impurity incorporation into a film grown by CVD is clearly demonstrated in our successful stabilization of amorphous silicon absorbers - superior in solar absorptance to the previously used polycrystalline form - beyond the 500 C crystalization temperature of sputtered or evaporated material [6,7,8]. Under support from the DOE Office of Basic Energy Sciences, we have learned to stabilize the amorphous form of silicon to temperatures approaching 1,000 C by incorporating typically 18 at.% of carbon into the growing film. Structural stability of these films can now be predicted to be hundreds of years of operation at 700C.

The availability of highly IR-reflecting Super Molybdenum and IR-reflecting, solar-absorbing Black Molybdenum recommends a positive re-evaluation of the original absorber-reflector concept for spectrally selective coatings. As shown in Figure 4, the unfaborable spectral location of the silicon transparency edge is now improved by an underlying reflector that absorbs the infrared solar photons transmitted by the absorber depicted in Figure 3.

FIGURE 3

TIME OF HALF-CRYSTALLIZATION VS. ANNEAL TEMPERATURE FOR CVD AMORPHOUS Si FILMS.

FOR DETAILS, SEE REF. 6 - 7.



We are presently modeling various arrangements of layers of amorphous silicon absorbers and Super or Black Molybdenum reflectors that our recent progress made technologically accessible. The final configurations will be fabricated accordingly, with input from on-going tests of the lifetime performance at 500 C of representative stacks. The direction of further work will depend on our understanding of Black Molybdenum, its optimal structure, and composition of this promising candidate for a refractory single-layer spectrally selective coating.

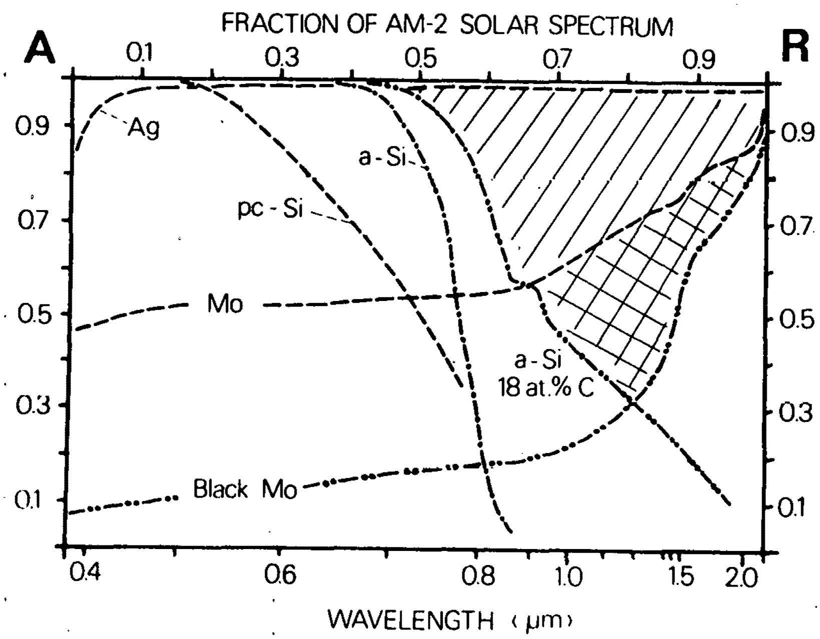


FIGURE 4

DOUBLE-PASS ABSORPTANCE THROUGH A 1μm THICK SAMPLE OF POLYCRYSTALLINE SILICON (pc-Si), NON-INTENTIONALLY DOPED AMORPHOUS SILICON (a-Si) & STABILIZED AMORPHOUS SILICON (a-Si 18 at.% C) PLOTTED ON A DISTORTED λ-PLOT. SUPERIMPOSED ARE THE REFLECTANCES OF SILVER, CVD MOLYBDENUM, & BLACK MOLYBDENUM.

See Reference 8.

The thermal-equilibrium character of CVD becomes important in the transport properties of our amorphous silicon films as well. We noticed that the optical properties, the density and porosity,and the anneal stability of our pyrolytically decomposed films differed from those films commonly deposited in an RF glow discharge for use in solar cells. The promise of a better connected lattice with potentially superior transport characteristics was recognized by the SERI-monitored Program for Innovative Concepts in Photovoltaics. We were asked to investigate the photo-electric properties of our CVD amorphous silicon films. We hope to report first results at next year's conference. Meanwhile, it can be concluded that chemical vapor deposition of multi- or single-layer coatings leads to selective surfaces that are condidates for photothermal solar conversion at intermediate and high-temperatures, by combining high-temperature stability and satisfactory optical performance with the potential for economical large-scale manufacture.

ACKNOWLEDGMENTS:

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"Chemical Vapor Deposition of Refractory Metal Reflectors for Spectrally Selective Solar Absorbers," DOE-SERI Subcontract XH-9-8217-1;

"Photo-Electric Properties of Amorphous Silicon Deposited by the Pyrolytic Decomposition of Silicon," DOE-SERI Subcontract XS-9-8041-8.

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PROTECTION OF FIRST SURFACE REFLECTORS WITH SILICONE RESIN COATINGS

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ABSTRACT

Silicone resins are being evaluated as protective coatings for first surface aluminum and silver reflectors.

The solar weighted hemispherical reflectances and specular reflectances of float glass metallized with silver and aluminum and protected with silicone coatings have been measured. The metallized squares of float glass protected on the front side with silicone resins were highly reflective. The solar weighted reflectances of the silver samples were 5-7% higher than the aluminum samples.

The reflectances of the aluminized samples were remeasured after 500 hours exposure in an Atlas Filtered Weather-Ometer. Some resin protected samples retained high reflectance and specularity however others lost their specularity.

The specularities of the initial samples metallized with silver were poorer than the aluminized samples because of the primer used to improve the adhesion to silver. The most recent silvered samples have good specularity because of better techniques of applying the primer.

Work is now in progress to determine the durability of first surface reflectors protected with silicone resins by exposing them to harsh environments including: sulfur dioxide, salt spray, high humidity and natural outdoor weathering.

This work is funded by the Department of Energy and is monitored through the Materials Branch of the Solar Energy Research Institute in Golden, CO.

H1

RESULTS AND DISCUSSION

Candidate Resins

Orginally 11 silicone resins were selected as potential candidates to be used as protective coatings for first surface reflectors. These resins were chosen because they represented a spectrum of chemical compositions, functionality and crosslink density. Silicone resins at all stages of commercialization were included in this investigation.

The functionality and degrees of substitution of these resins are listed in Table I. The "percent of functionality" is usually an indication of the reactivity of a resin and its rate of cure. In general, a resin with high functionality is lower in molecular weight and cures faster than a resin with low functionality.

The "degree of substitution" is an indirect measure of the crosslink density of a resin. The silicon atom in most silicone polymers has four valence bonds. In silicate glasses all of these bonds are used to form a highly crosslinked brittle solid. Replacing these bonding valence sites with nonfunctional organic radicals such as methyl or phenyl diminishes the number of possible cross links and decreases the brittleness. Most silicone resins have degrees of substitution between one and two which means that on an average they have slightly more than one non-functional organic group per silicone atom. The phenyl, methyl and propyl to silicon ratios of the resins are also given in Table I. The relative phenyl and methyl to silicon ratios of the resins identified as candidates for this study represent a broad spectrum of resin type.

The refractive indices of the cured resin films are also shown in Table I. All of the cured resin films have a refractive index of approximately 1.46 except Resin E which is 1.426. It would be desirable to tailor the refractive index of the cured resins so that a gradient of refractive indices could be obtained. Unfortunately, all of the silicone resins which are available have similar refractive indices except for Resin E, and there is only a 7% difference between Resin E and the other silicone resins.

Dirt Pick Up Measurements

Eight resins were coated on 4" x 4" glass squares and measured for transmittance between 350 and 2100 nanometers. Transmittances values were obtained every 75 nanometers between 350 and 650 nanometers and every 150 nanometers between 650 and 2150 nanometers. These samples were exposed outdoors at an angle of 45° South on a building roof top and remeasured for optical transmission at various time intervals. The changes in optical transmission as a function of time are a measure of the amount of dirt, abrasion, and changes in absorptance of the resin coatings.

Figure 1 shows data for Resin A plotted after two periods of exposure: 6 weeks and 15 weeks.

Replicate samples of these exposure samples were prepared and exposed in a similar manner. These samples were washed before the transmittance measurements were made. Comparing the transmittance of washed and unwashed samples shows the amount of transmittance which is easily recoverable and what portion of the optical loss is not recoverable. The samples were washed by rinsing the samples with tap water, wiping them with a soft cloth and then blowing them dry with a stream of air. The samples which were washed before reading the transmittance values were all quite close to the original value after 12 weeks outdoor exposure except for Resin I.

Measurement of Spectral and Specular Reflectance

Four inch by four inch float glass squares obtained from Libby-Owens Ford were metallized with aluminum by Coatings Research in Chicago using vapor deposition and coated with the resin candidates at Dow Corning.

Solutions of Resin A, B, C and I were sprayed on the aluminized samples using conventional techniques. These samples had a dissappointingly poor appearance after cure due to small particles. These cured resin films formed continuous protective coatings and were submitted to Battelle Pacific Northwest Laboratories (BPNL) for reflectance measurements despite their poor appearance. The reflectances of Resins C and I were high, 90% and 89.7% respectively (referenced to $BaSO_4$). The reflectance of Resin A was low, 77.2%, and that of Resin B was fair, 82.9%. The specularities of all the resins were quite good in spite of their poor visual appearance.

Resins E, F, H and J were coated on the aluminized squares by dipping the samples in dilute solutions of the resin. These samples had a much better appearance and had consistently good reflectances, 89-89.7%, and good specularity. The sample coated with Resin E had the best reflectance and specularity. See Figure 2.

Changes in Specular Reflectance Caused by Exposure to UV Radiation

The samples described above were exposed in an Atlas Filtered Weather-Ometer for 500 hours and sent to Battelle Pacific Northwest Laboratories to be remeasured for specular and spectral reflectance.

Two resins with good reflectance and specularity and which retained them after exposure to UV were Resins E and H. These are the most promising candidates for the protection of aluminum.

Resin I showed the greatest amount of degradation both in terms of solar weighted spectral reflectance and specular reflectance. The spectral reflectance dropped from an initial value of 89.7% to 83% after 500 hours of UV exposure. This loss is due to pitting of the resin which was severely spotted. The roughness of the resin surface is indicated by its poor specularity. See Figure 3.

H3

Protection of Silvered Float Glass

Float glass squares metallized with silver were coated with Resin A, B, C, E, H, and L. The resin coatings were applied using the dipping technique.

Prior to use, the solutions of resin were filtered through a Gelman Micro Pore Filter which removes all particles larger than 1.2 microns and the coatings were applied in a Class 100 Clean Room. The reflectances of the float glass squares metallized with silver were all higher than those of the aluminized float glass squares as might be expected. The specularities of the silver surfaces coated with each resin were lower when compared with the corresponding resin coated aluminum surfaces.

Good adhesion of silver to polymeric coatings is often difficult to achieve and, therefore, a silane coupling agent was used to prime the silver surface before the solutions of resin were applied. The silane coupling agent was applied as a 1% solution in aqueous isopropyl alcohol. The silver metallized glass squares coated with resin looked worse than the aluminized samples and had a haze or blush. This cloudiness is probably due to the Dow Corning® Z-6020 coupling agent used to improve the adhesion of the resin to the silver surface. The visual appearance did not correlate with the specularity measured at 10° and 45°. Reflective surfaces which looked cloudy often had higher spectral reflectance and better specularity than reflectors which appeared visually clear.

Three each of the resin coated silver surfaces were sent to Mike Lind at Battelle Pacific Northwest Laboratories. The widest variation in the solar weighted spectral reflectances of the triplicate samples was 96.2% to 93.2% for the samples coated with Resin A. The lowest spectral reflectance measured, 93%, was on a sample coated with Resin H. The average measured reflectances for silver coated with the six different resins ranged from 94.% for Resin H to 97.8% for Resin E. The specular reflectances of some resin coatings had wide variation. There was significant variation in values obtained at various places on each sample and between the three replicate samples. The variation in specular reflectance measurements was greater on samples with poor specularity than on samples with good specularity. The specularity of the silver protected with Resin E was highest at both 10° and 45° and the variation in specularity was smallest.

CONCLUSIONS

Aluminum, vapor deposited on float glass, has high specular reflectances and can be protected with silicone resins.

Silver, vapor deposited on float glass, is more highly reflective than aluminum; however, good adhesion of silver to both the glass substrate and the protective resin is difficult to achieve. The primers and adhesion promoters for the protective silicone resin coating must be chosen and used in a way that preserves the high reflectance and specularity of the silver surface. More work is needed to determine the optimum coating techniques which provide uniformly specular, durable protective coatings for silver.

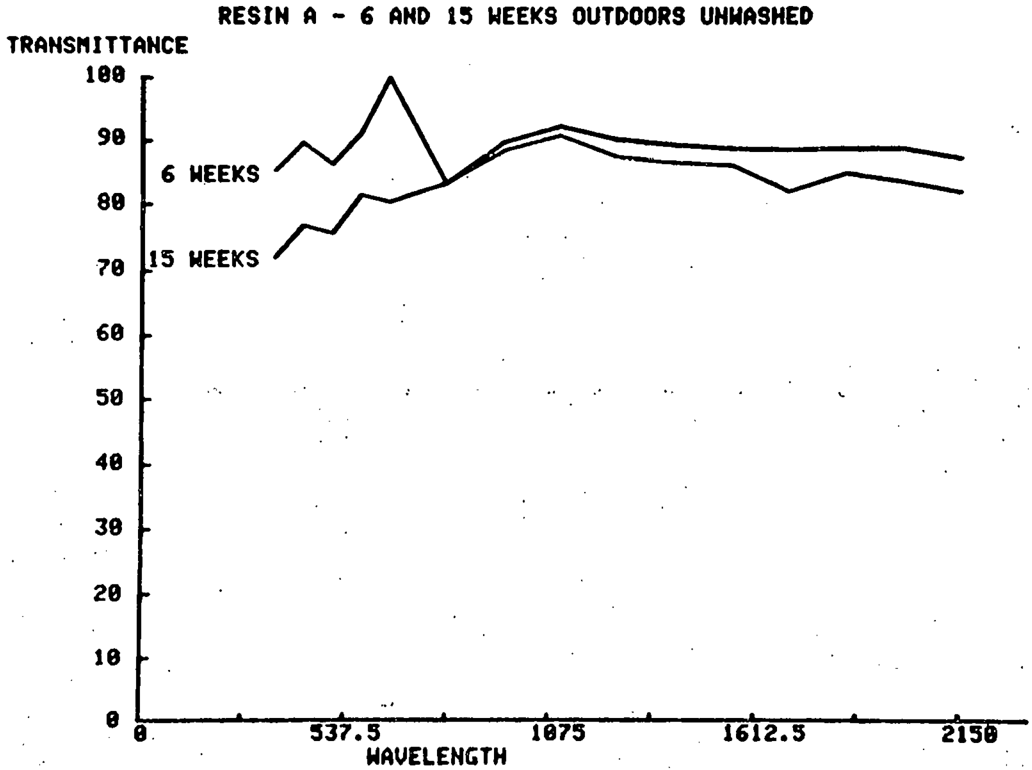

Figure 1

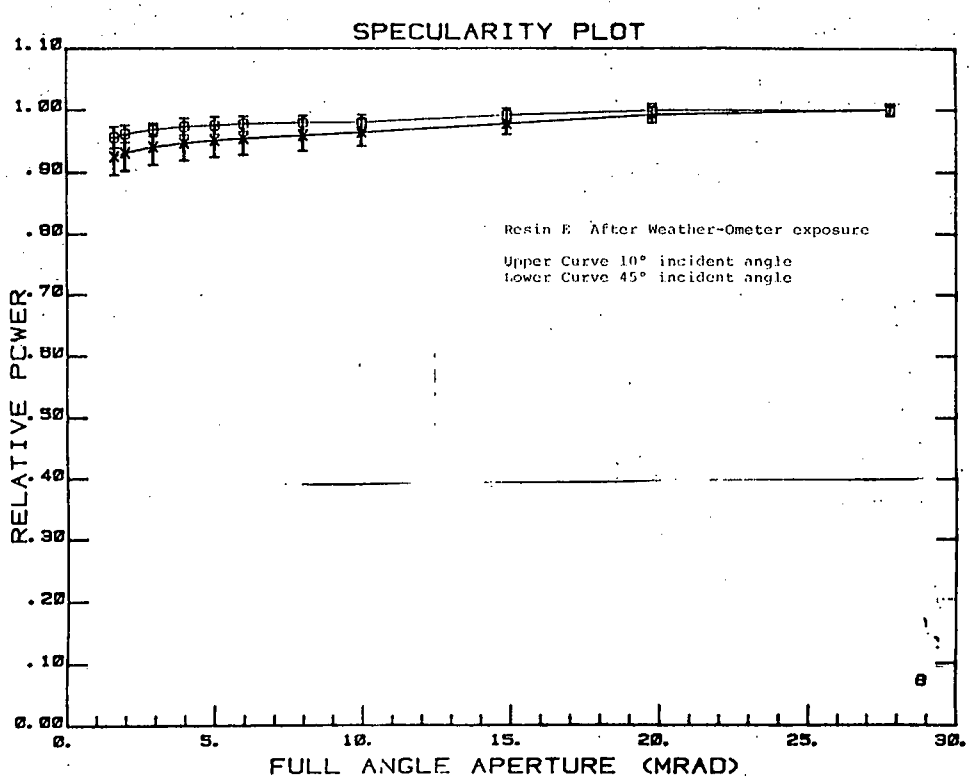

Figure 2

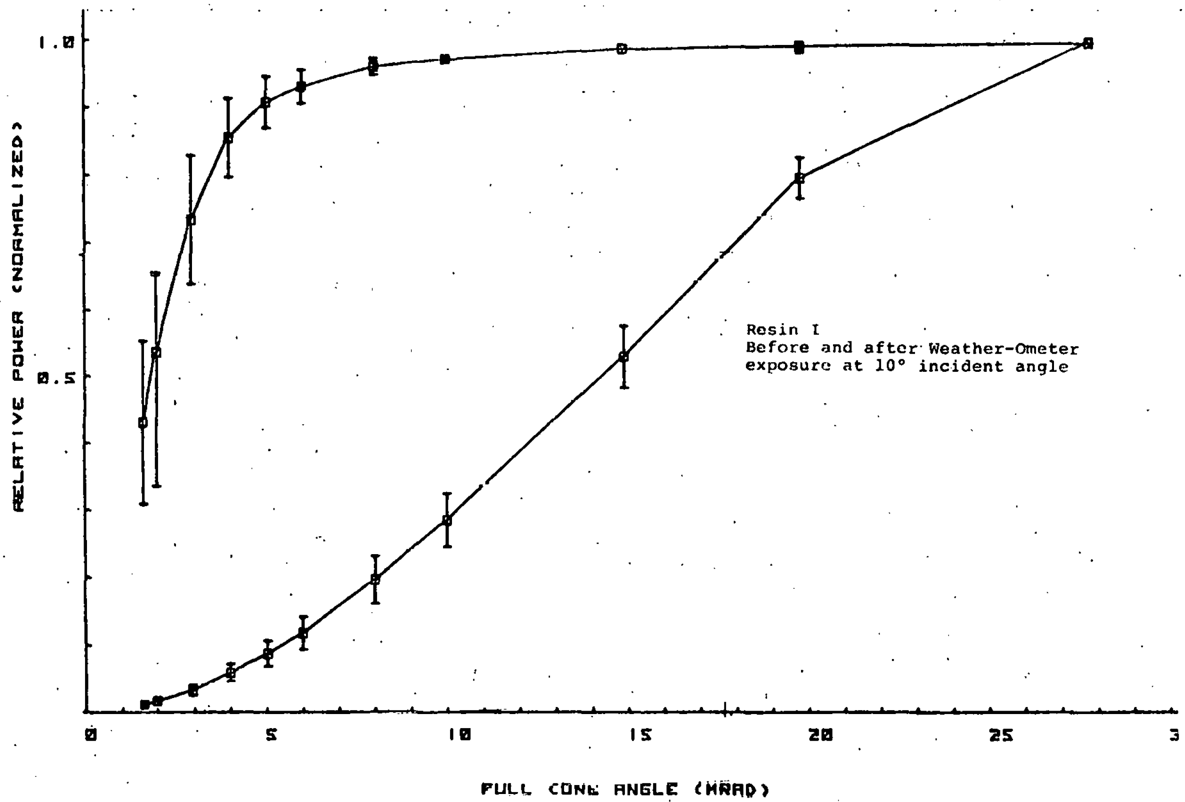
1.0
0.5
RELATIVE POWER (NORMALIZED)
0
5
10
15
20
25
3
FULL CONE ANGLE (MRAD)
Resin I
Before and after Weather-Ometer
exposure at 10° incident angle

Figure 3

THIN GLASS FOR SOLAR APPLICATION

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Corning, New York

ABSTRACT

This glass is divided into two categories in order to isolate problem areas. Thickness below 1mm require additional studies and development in order to enhance cutting, handling, shipping and silvering.

Of the several methods available to achieve a curved glass mirror substrate, the use of chemically strengthened glass appears to offer the best combination of features.

A new glass has been melted which has been specifically tailored to meet the needs for solar response, environmental hazards and volume production.

SUMMARY

The term "thin glass" as used herein, is to be construed to mean thicknesses less than 2.5mm. This category then can be sub-divided; i.e.; thicknesses down to 1mm and thicknesses below 1mm. This latter being designated as microsheet.

There are four ways in which thin glass can be produced; 1) updraw, 2) down draw, 3) float, and 4) fusion.

Grinding and polishing of rolled sheet is not a viable method. When surface quality and warp requirements are imposed, float and fusion processes remain as possibly the better production options.

Float is designed to produce one glass type, soda lime. This process produces a natural thickness of 7.1mm (.280") but by a stretching technique can currently produce down to approximately 1.8mm (.070").

Fusion can operate with a variety of glass types. Further, it can produce thicknesses down to .25mm (.010") and has, on the large production equipment, produced .64mm (.025") in widths to 130cm (50 inches). The nature of this process improves the surface quality the thinner it gets. Due to the flexibility permitted by this process, glass compositions can be melted which have characteristics needed for solar applications, i.e.; very low reduced iron, (Figure 1), excellent resistance to chemical and weathering attack, stabilized to minimize solarization and a surface quality equal to or better than 2 milli radians.

NEW GLASS

Recently SERI funded a prototype run of a glass specifically selected to meet the needs for solar applications. Corning Code 7809 was melted in a "mini" fusion facility at our Harrodsburg, Kentucky plant. Thicknesses from 1.5mm to 1mm were produced in sizes 107cm x 91cm (42" x 36"). Currently, the small inventory produced is in the hands of many potential users for evaluation and test. With the exception of some equipment problems resulting in surface quality, less than could be expected from the full size production facility at Blacksburg, Virginia, all other goals were met or exceeded. In particular, the solar transmission of both the 1mm and 1.5mm thicknesses were in excess of 91.5%, (see Figure 2). This results in a potential total hemispherical reflectance in excess of 96%. The reason this is qualified as potential is that test data has shown a range of reflective response of over 4% depending upon the source of silvering.

OBJECTIVE

Basically, the interest in this glass comes from the features that it can exhibit:

1. Higher transmission.

2. Lower total cost.

3. Flexibility.

4. As stiffness is directly proportional to the cube of thickness less force is required to deflect into shape or conversely less recovery force is exerted by the formed panel against the bonding adhesive.

Applications for which this glass would be used would be cover plates and mirror substrates for heliostats, spherical dishes and linear concentrators. These latter two would utilize all four of the above features for their applications.

Parabolic and to some extent spherical curvatures can be achieved by three techniques used in forming glass:

1. Hot form or sag by a high heat process against a shaped mold.

2. Use microsheet levels of thickness and intimately bond to a thin steel sheet backing plate which when mechanically deformed to the required curvature, puts the glass mirror body into a safe compression mode.

3. Use chemically strengthened float panels in a thickness range of 1mm to 1.27mm (.040" to .060"). This can then be force best or "cold formed" to the desired curvature either against a formed backing reference or held into shape by stops or clips.

PROCESS

The hot forming process has a number of problems to be overcome. To achieve the accuracy of curvature needed to meet most of the concentration factors required, a solid mold appears to be needed. This mold has to be machined to tight tolerances which must be maintained during the heating cycles. Generally, this means stainless steel, 410 or equivalent. The pre-forming, machining, annealing, and final dressing on the sizes involved, become quite expensive. To produce large quantities of parts, many molds are required. To compound the problem, low heat mass is needed to achieve speed of operation while a precise temperature control is required to permit the glass to come into intimate contact but not allowing the glass to stick or receive mark-off conditions. If these problems are overcome then the question of silvering a curved shape needs to be faced. Lastly, the multiple handling of curved shapes offers a high probability of breakage or loss caused by line contacts and nesting limitations which would create scratches.

The microsheet approach, while technically capable of being produced, has limitations in the current state of the art for the secondary operations. Inability to cut, handle and pack-ship become a problem. Glass thicknesses below 1mm need to have a new or different technique developed to score or cut the edges. The conventional cutting wheel, normally used, tends to leave significant checks along the cut edge. To further emphasize this problem, consider the edge strength of a glass 1mm or thicker, cut by standard cutting wheels, exhibits Modulus of Rupture values in the 352 kg/cm^2 to 492 kg/cm^2 (5000 to 7000 psi) range. Microsheet, on the other hand, using cutting wheels against a hard backing, show values as low as 18 kg/cm^2 (250 psi). The longer the edges to be cut, the more consistent this low value gets. Couple this problem with the fact that in this thickness range, production rates are in excess of 10m (400") per minute. While the body of this glass is quite strong, like a chain, the product is only as strong as its weakest link. Here, the 18 kg/cm^2 edge strength prevents achieving many of the bend radius that are being considered. This is the reason that handling and shipping become part of the problem. The silvering operation introduces a thermal shock that the weak edge could cause significant failures.

The silvering process also has the problem of handling weakness. Further, the scrubbing stage and the transport mechanics through the line are faced with the flexibility problem that prevents good contact and flatness of surface necessary to achieve uniformity of silver deposition.

The chemically strengthened panel appears to offer the best combination of known and proven features. In the thickness range 1mm to 1.27mm, cutting, handling, and shipping techniques are known and proven. Strengthening is straight forward and does not change the excellent smoothness of surface. Shipping is easily done in bulk form. Silvering of flat sheet is by conventional methods. The "cold forming" of the silvered panel has been demonstrated and no problem is experienced with the mirror backing materials. The resultant surface quality is the same as the original flat sheet. Radiuses down to 3cm (13") can be achieved. The strenghtened, cold formed panel is capable of meeting the hail impact requirement. In fact, the direction of bending increases the compression component of the exposed surface to help improve resistance to failure.

This basically covers the category of "thin glass" as now known. Many of the problems indicated herein may be solved if volume were large enough to permit the necessary studies and development that currently are only conceptual.

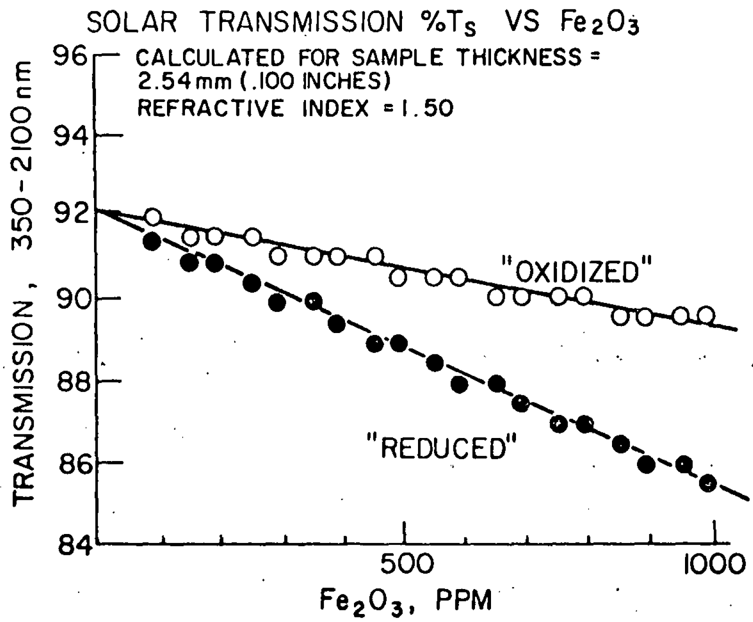

FIGURE 1

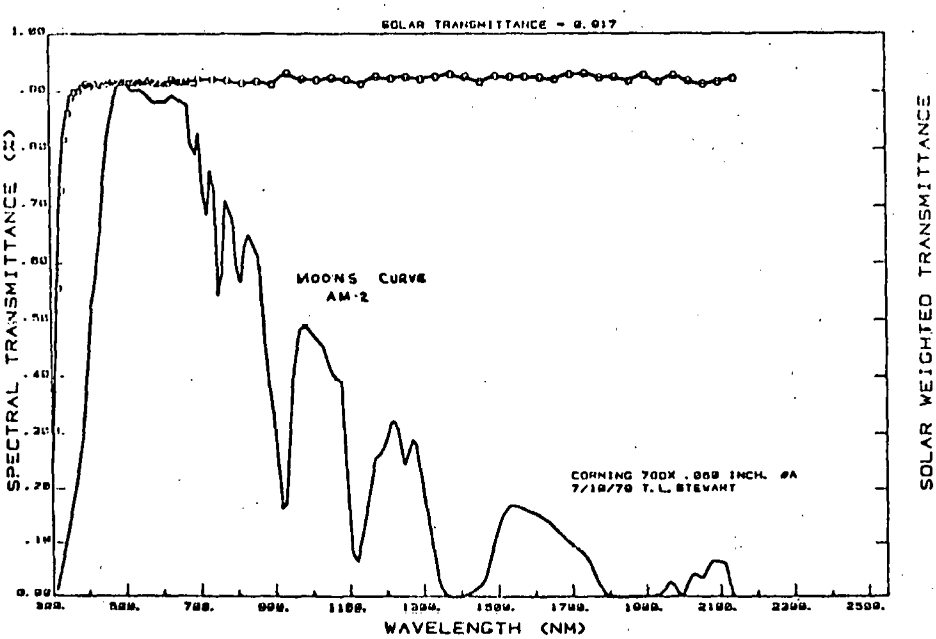

FIGURE 2

THE EFFECTS OF SOILING AND CLEANABILITY ON SOLAR REFLECTORS

W. F. Carroll

ABSTRACT

The performance of highly concentrating solar energy conversion systems can be adversely affected by accumulation of contaminants on reflector surfaces. Without artificial cleaning, glass mirrors in remote areas with frequent rain will degrade rapidly to a broad-band equilibrium with a mean value of approximately 10% loss; over extended periods, this "equilibrium" continues to degrade. Other data indicates that the degradation of polymer mirrors in remote areas, glass mirrors in urban areas, and all mirrors in remote areas during extended rainless periods could be several times greater. Artificial cleaning may be required, depending on system operation, material and location and must be optimized to minimize energy cost. This report summarizes key results of a recent soiling workshop [1].

The accumulation of air-borne particulates and aerosols on the optical surfaces of solar energy conversion systems results in undesirable absorption and scattering, adversely affecting performance.

For a given quantity of contamination, the performance degradation depends on the system optical design. At the surface of a transparent optical element, incident solar energy is: 1) transmitted directly; 2) absorbed; 3) back-scattered or 4) foreword scattered. In the case of flat plate photovoltaic and thermal collectors, only the absorbed and backscattered energy are lost; the direct and foreward scattered components reach the receiver. For second surface mirrors, the solar energy must pass through the (contaminated) surface twice. Thus, in highly concentrating systems, all of the absorbed and scattered energy from each pass is lost; only the direct transmitted (and specularly reflected from the metallization) energy reaches the receiver. Depending on relative absorption and scattering, highly concentrating systems are 2 times to possibly as high as 5 times as sensitive to contamination as flat plate collectors.

The quantity of contamination and the resulting performance degradation for any system depends on a number of interactive parameters including, at least: The nature of the contaminants, location (local contaminants, climate, etc.), season, material type and surface texture, orientation, and natural/artifical cleaning.

There is, at present, inadequate data to accurately predict the effects on performance of various systems in various locations.

Cost effective design of components and systems and cost effective operating strategy (e.g., cleaning method, allowable degradation, cleaning frequency, non-operational stowage) will require an overall understanding of parameter interactions and accurate data (or analytical models) for material/configuration/cleaning, etc. for each intended location. Net accumulation is strongly dependent on precipitation type and frequency and probably on seasonal variations in pollutants, temperature, dew cycles, etc. Therefore, if design is to be based on field experimental data, one year of site material and orientation specific data would be minimum and one year may be inadequate. There is the further probability that weathering of the surfaces can modify (most likely adversely) the rate and magnitude of the accumulation.

Mirror tests at Albuquerque [2] indicate that short term decreases in specular reflectance of silver/glass mirrors of 0.5 to 1.0% per day can be expected in that area. With natural cleaning, the Albuquerque mirrors appeared to reach a broad band equilibrium condition with a mean value of approximately 10% loss during the first few months of exposure. Extreme measured values varied from more than 16% to less than 5%. Recently, after approximately 1.8 years, the equilibrium mean degradation appears to be ~19% with extremes ranging from 23% to 16% [3]. Vertical and face down stow position reduces the accumulation significantly.

The most extensive information on soil accumulation for various materials and various locations has resulted from evaluation of flat plate photovoltaic (PV) modules and materials [4]. Although accurate quantitative translation of these results to effects on highly concentrating systems is not possible, a rough approximation of the impact can be made, recognizing that highly concentrating systems are 2-5 times as sensitive as flat plate systems.

Net power output degradation due to soiling of glass encapsulated PV modules over ~ 1 year ranged from 0-2% in Florida to 10-13% in New York City. Silicone (relatively soft polymer) encapsulated modules ranged from 2-4% in Florida, 5-7% in Mead, Nebraska to as much as 34% in New York City. These results are discussed in detail in Reference 4.

Glass and silicone modules in Pasadena all showed power loss of 6-7% per month during an extended rainless period in Pasadena during the summer of 1978. This indicates that initial soil accumulation is not strongly surface material dependent and that observed major long-term differences were due to the material-dependent effectiveness of natural cleaning. It also indicates that artificial cleaning might be mandatory in areas where extended rainless periods are possible (e.g., 2-5 months in Southern California).

The PV data shows that, in general, surfaces in urban sites are more seriously affected than those in remote areas. Industrialized urban areas tend to be the most severely affected. (This could be a significant consideration for Repowering and Industrial Process Heat.)

Two independent cleaning studies, [5], [6] using totally different approaches, have indicated that large scale, regular artificial cleaning can be accomplished for 1-2¢/m^2 per cleaning. At this rate, daily cleaning would cost approximately 1-2¢/kwhe and is obviously impractical. Cleaning on a less frequent basis may be required or economically desirable, particularly for urban areas or areas with infrequent rain, but will require optimization of cleaning method and frequency for for mirror material, system operation and location.

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5102-156

LATE PAPERS

ADVANCED FREE-PISTON STIRLING ENGINE DRIVEN 15kWe LINEAR ALTERNATOR PROGRAM

Contract Number: JPL 955468

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Oakland, CA 94608

OBJECTIVE

The objectives of this phase of the program are: 1) design and analyze critical components and subassemblies, 2) assess and optimize the thermodynamic and dynamic performance through computer simulation, and 3) perform a preliminary design of a resonant free-piston Stirling engine (RFPSE) driven 15kWe linear alternator. Particular emphasis is on: 1) heat exchanger matrices, gas bearings, narrow-clearance seals, control and stability, manufacturability, reliability and production cost of a solar-energized electric power plant employing non-strategic materials.

BACKGROUND

ERG pioneered the concept of a gas-bearing, hermetically sealed, resonant free-piston Stirling engine (RFPSE) with electric or hydraulic power output. In 1967 ERG's first RFPSE was demonstrated which employed a posted, differential drive-area displacer. In 1969 ERG began the development of a gas-fired heat pump/air conditioner with supplemental electric power generation under an American Gas Association contract. Since then ERG has been engaged in the further development of RFPSE machines for electric and hydraulic power production and heat pumping. The present JPL contract is directed toward incorporating ERG's technologies into a solar-energized electric power plant.

PROGRAM

The goals of this two-task, first-phase program are delineated in Table I.

The results obtained in the first task effort are presented in the following discussion.

RESULTS

Figure 1 presents the indicated efficiency and power for FPSE designs having four different heat exchangers and using hydrogen or helium as the working fluid. Component combination I represents engine performance obtained with Thermizer* heater and cooler and Foilfin regenerator. Combination II represents performance with Foilfin heater and regenerator and Thermizer cooler. Combination III represents performance with Foilfin heater, regenerator and cooler. Combination IV represents performance with conventional tubular heater and cooler and stacked-screen regenerator. Each of the above results represents optimized performance obtained from a large number of separate computer runs.

The effect of isothermal vs. adiabatic working volumes of the engine are shown in Fig. 2, whereas the effect of mean working pressure is shown in Fig. 3.

The effectiveness of Thermizer heat exchangers is illustrated in Fig. 4 (obtained from experimental data) where I is isothermalization factor (ratio of heat transferred in heat exchanger to heat transferred in isothermal compression/expansion process) and $\alpha/f\ s^2$ is the modified Fourier number (α is thermal diffusivity, f is frequency of reciprocation and s is half-width gas spacing between adjacent rings).

Figure 5 illustrates the correlation obtained by ERG's thermodynamic computer code with data supplied by NASA-LeRC for their GPU-3 Stirling engine. The close correlation obtained in engine efficiency and power using friction factor (f) and Stanton number (St) as sensitivity variables is evident.

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*Nesting concentric rings in expansion and compression working volumes of engine.

Heat exchange with the RFPSE is accomplished by phase-change fluids: sodium for heat addition, ammonia or fluorocarbon for heat rejection. Results obtained using solid Thermizers are shown in Fig. 6 in terms of heat flux and temperature drop as a function of displacer bore diameter for heater and cooler.

The linear alternator must produce constant terminal voltage at a constant frequency from zero-load to 50% overload (NEMA Standard). This is accomplished by the engine's capability of varying stroke of displacer and power piston. The results are shown in Fig. 7.

The alternator is designed to employ ceramic permanent magnets, silicon-steel laminations and copper windings potted in polyimide insulation. Design analysis indicate that 97% efficient alternators weighing less than 2 kg/kW are obtainable at material costs of approximately three dollars per kW.

SUMMARY

The results obtained to date on the present program indicate that the goals specified in Table I are potentially achievable and that the features of the proposed design, as listed in Table II, are necessary to meet these goals.

TABLE I

ERG - RFPSE PROGRAM GOALS

- 60% POWER CONVERSION EFFICIENCY (20-100% LOAD RANGE)
- \$60/kWe ENGINE ALTERNATOR COST
- ABSENCE OF STRATEGIC MATERIALS
- HIGH RELIABILITY & LIFETIME
- TERMINAL VOLTAGE & FREQUENCY LOAD INDEPENDENT
- 1 ϕ or 3 ϕ CAPABILITY
- DYNAMICALLY BALANCED UNIT
- 1500 °F LOW ALLOY ENGINE
- 2000-2300 °F CERAMIC ENGINE
- MATEABLE TO SOLAR RECEIVER/MULTI-FUEL COMBUSTOR
- MATEABLE TO AIR-COOLED RADIATOR/HEAT REJECTION LOOP

TABLE II

FEATURES OF PROPOSED DESIGN

- HIGH EFFICIENCY ENGINE & ALTERNATOR OVER LOAD RANGE
- LIGHTWEIGHT, INEXPENSIVE ENGINE & ALTERNATOR
- OPPOSED PISTONS PROVIDE DYNAMIC BALANCE
- ISOTHERMALIZED ENGINE & GAS SPRING CHAMBERS MINIMIZE LOSSES
- FOIL-FIN REGENERATOR MINIMIZES LOSSES & COST
- SELF-PRESSURIZED GAS BEARINGS PROVIDE LOW FRICTION, LONG-LIFE, HERMETIC SEALED UNIT
- TERMINAL VOLTAGE & FREQUENCY LOAD INDEPENDENT

FIG. 1

FPSE Component Comparison

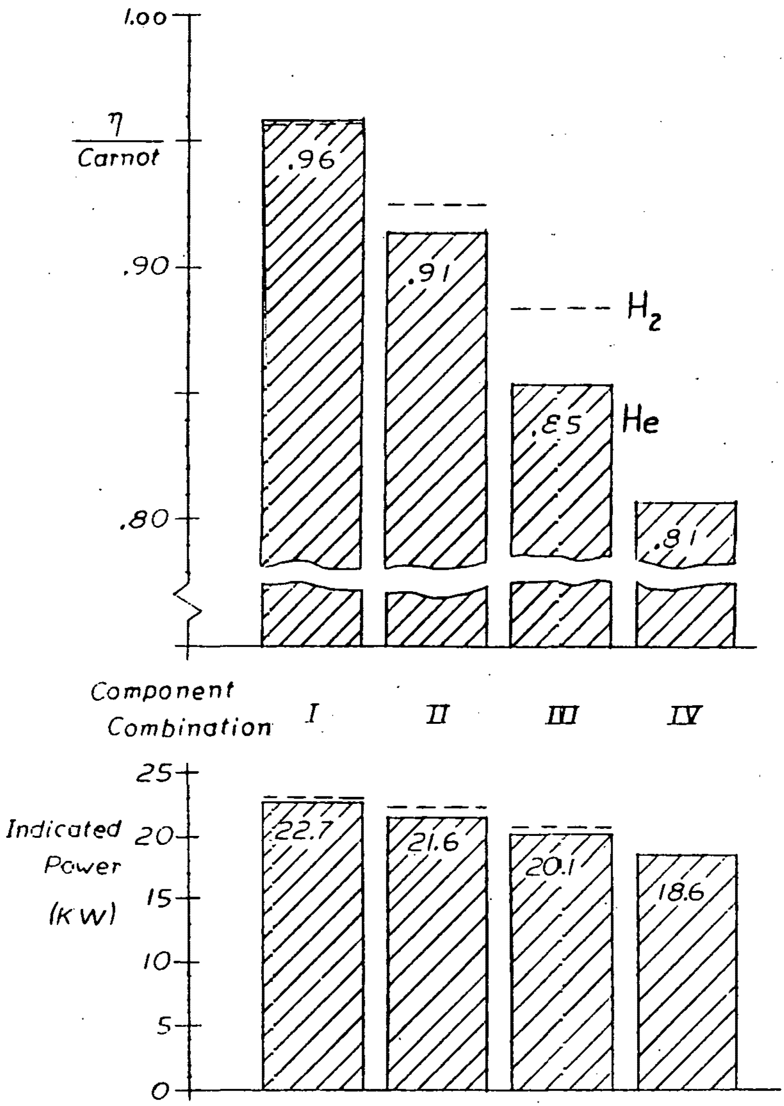


FIG. 2

Isothermal vs. Adiabatic Stirling Engines

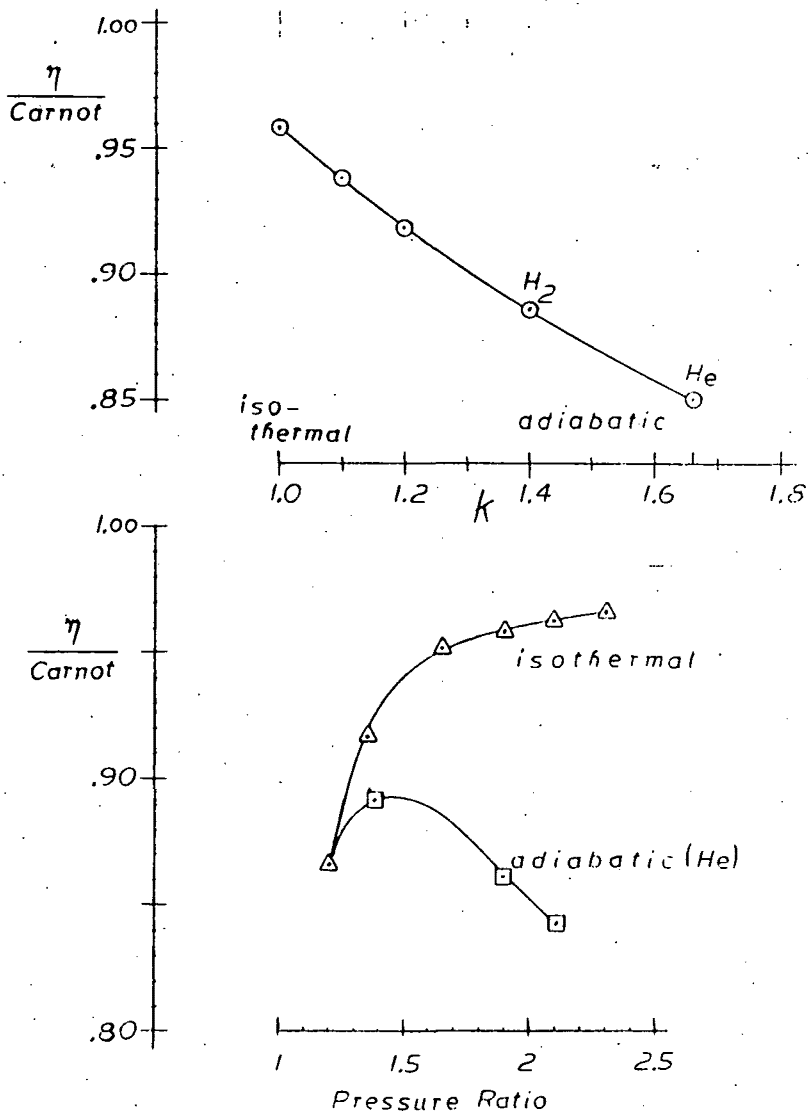
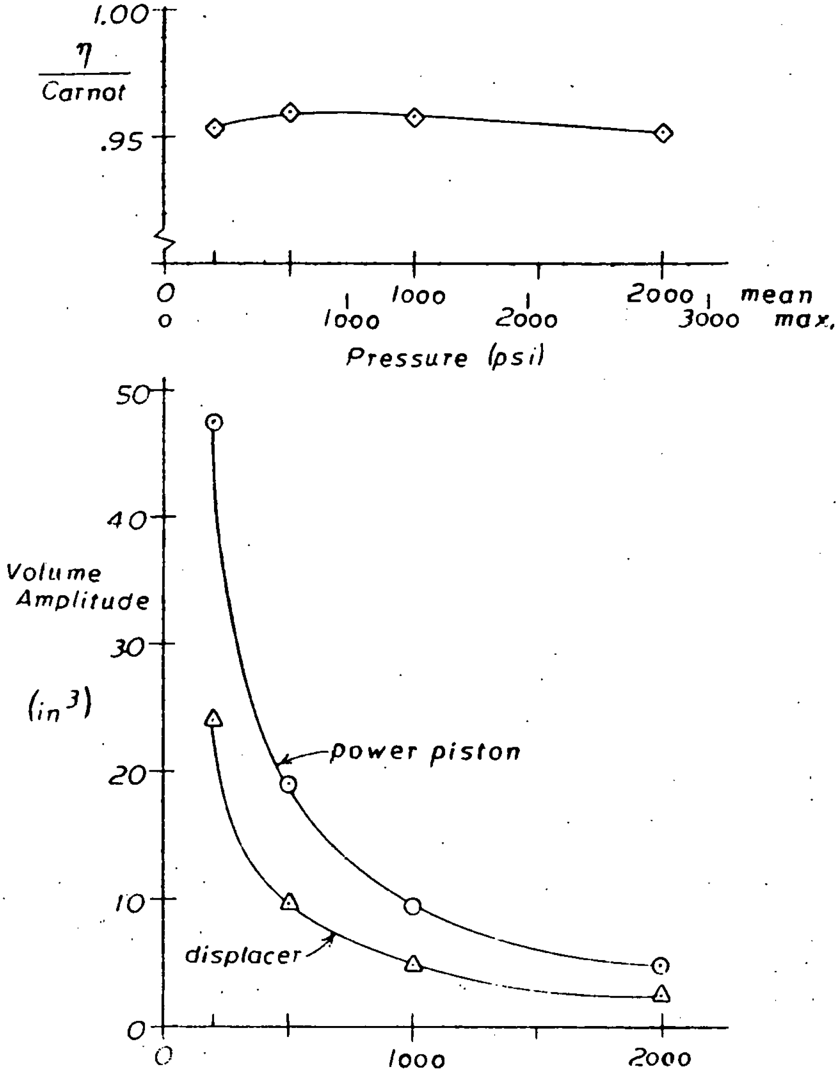


FIG. 3

Working Gas Pressure Effects



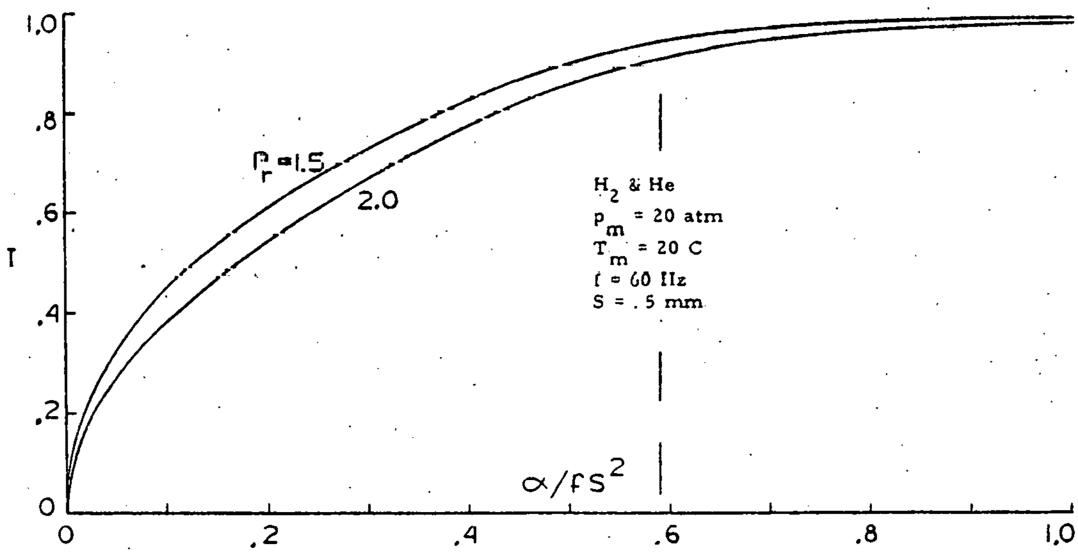


FIG. 4 NON-FLOW THERMIZER PERFORMANCE

FIG. 5
ERG Thermodynamic Computer Code Correlation
Sensitivity Study on NASA-LeRC GPU-3 engine

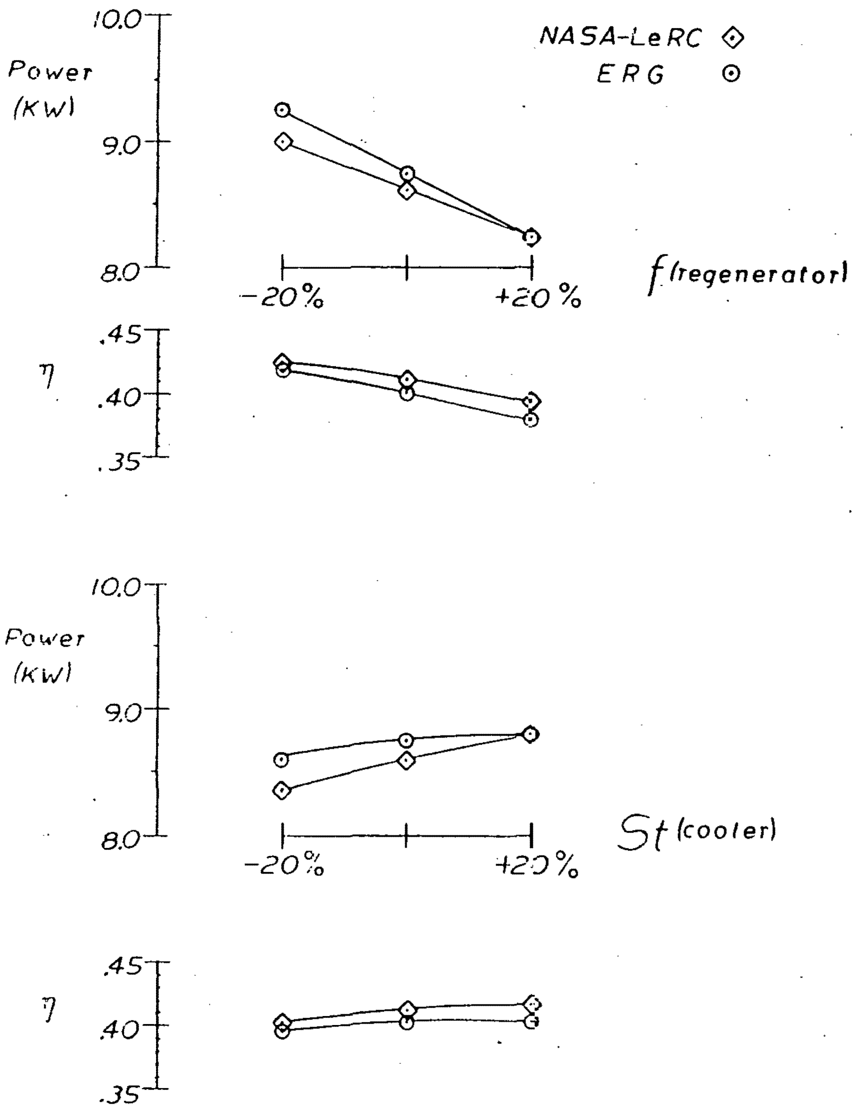


FIG. 6

Thermizer Heat Exchangers

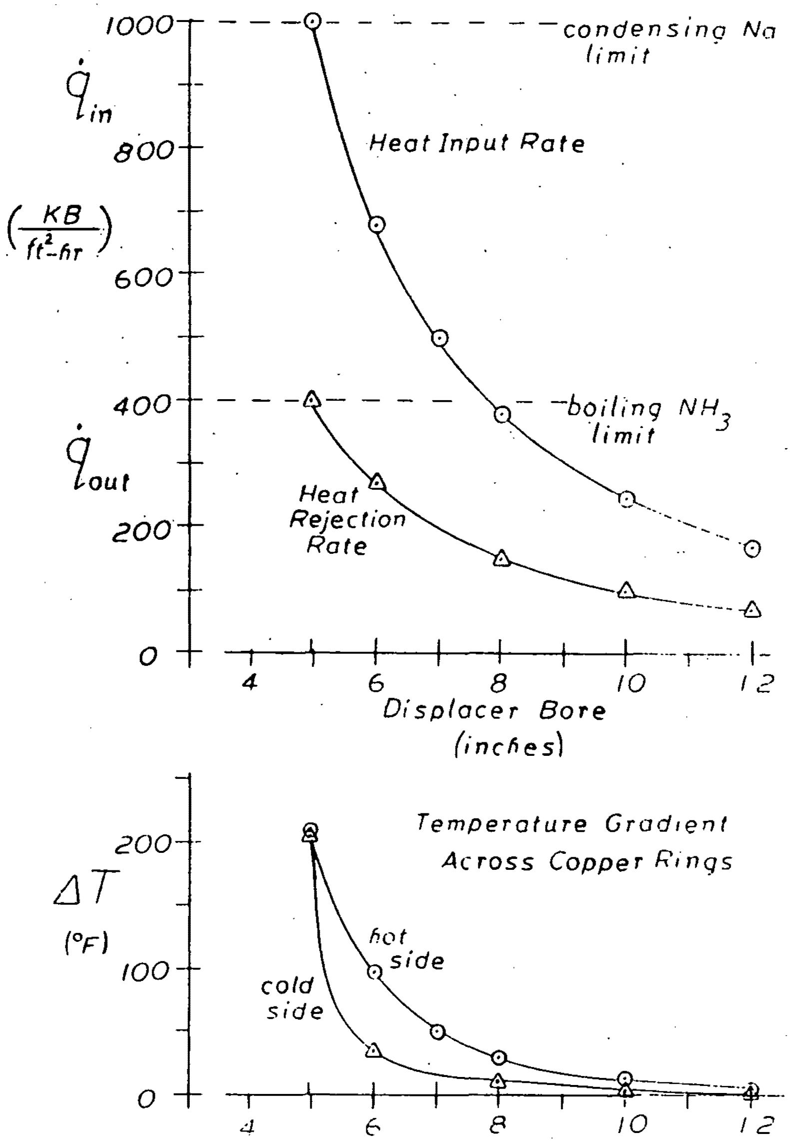
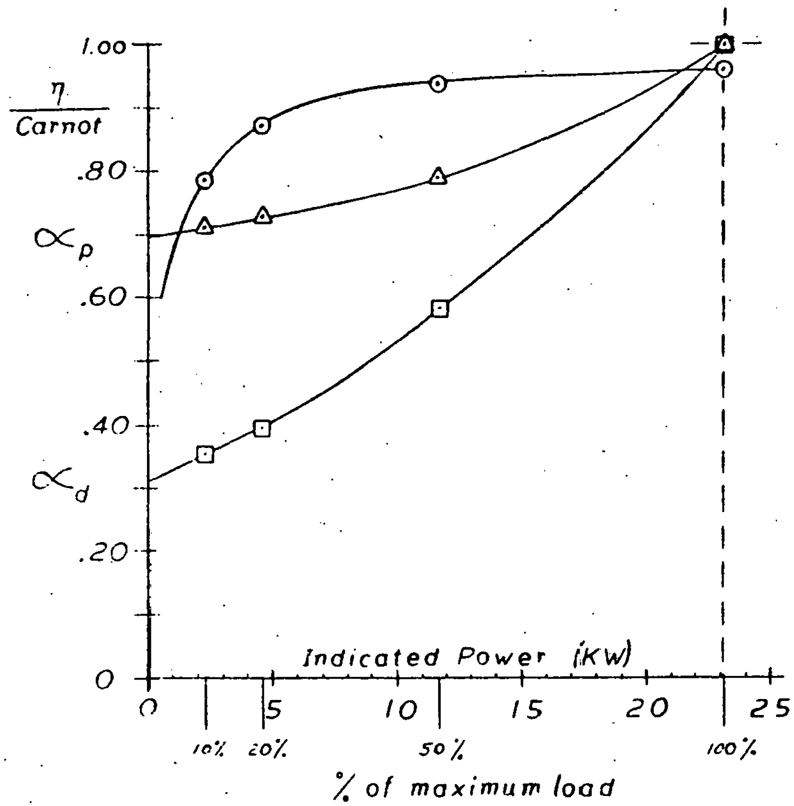


FIG. 7

FPSE Part-Load Characteristics



α_p = fraction of full power piston stroke

α_d = fraction of full displacer stroke

HIGH-TEMPERATURE SEAL DEVELOPMENT FOR THE SHARE RECEIVER+*

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ABSTRACT

The development and experimental demonstration of a high-temperature seal for the SHARE ceramic dome cavity receiver is reported. The mechanical contact seal which was tested on one-foot diameter silicon carbide ceramic dome hardware at pressure differentials to four atmospheres and dome temperatures to 2200°F (1200°C) showed negligible leakage at expected receiver operating conditions.

INTRODUCTION

This paper discusses the development and experimental demonstration using one-foot diameter ceramic dome hardware of a high-temperature mechanical seal for the SHARE receiver. Previous work under DOE Contract No. ET-78-S-02-4878 has been reported in References 1 through 6 and has included discussions of receiver and seal concepts, analytical methods for solar radiation flux distributions in cavity receivers, cavity reradiation exchange, ceramic dome and ceramic insulating ring structural analyses, metalization of silicon carbide ceramics, selection of a preferred sealing approach and experimental tests in two-inch diameter ceramic hardware of a mechanical seal.

The high-temperature mechanical seal concept which was developed in the present program is depicted in Figure 1. The primary seal is achieved at the interface between the silicon carbide dome and the insulating ring. Leakage through the high-temperature seal is controlled by the selection of the surface finishes on the two ceramic pieces which touch along an angular contact area. The insulating ring provides a thermal barrier with accompanying temperature drop between the-high temperature contact seal and the secondary seal at the foot of the insulating ring. The silicon carbide dome is mounted freely on the insulating ring with its general placement maintained with positioning snubs. Pressure forces acting on the dome provide the primary seal contact forces. The insulating ring can be clamped down in place or allowed to sit freely on the secondary metal gasket or O-ring seal. Leakage measurements are reported below for both cases; a hemispherical dome freely supported on a clamped insulating ring and a hemispherical dome freely supported on an insulating ring which in turn sits freely on a secondary seal.

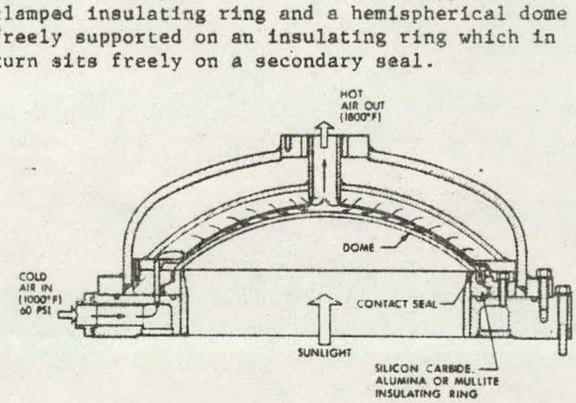

Fig. 1. High-temperature mechanical contact seal concept.

The twelve-inch-diameter contact seal leakage measurement tests reported here were undertaken after promising results were obtained in experimental tests using two-inch-diameter ceramic hardware [1-6]. The goal of the 12-inch-diameter seal tests was to demonstrate a seal with a leakage rate which is one percent (or less) of the total flow impinging on the dome for heat-transfer purposes with the seal operating in the desired temperature range from 1000°C - 1200°C (1800°F - 2200°F) and with a pressure differential of four atmospheres (60 PSI). Experimental testing of the impingement heat-transfer design in combination with the high-temperature seal was not part of contract ET-78-5-02-4878. Verification of the impingement-jet design approach was considered by DOE to be of secondary importance to the development of a seal and impingement cooling design development was deferred by DOE.

Experimental Apparatus

The twelve-inch-diameter ceramic-to-ceramic contact seal tests were performed by constructing a dome seal test unit and mounting it on the top of an existing cylindrically shaped, electrically heated radiant furnace as shown in the cross-

+ This work was sponsored by the U. S. Department of Energy.

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++ Staff member and Principal Investigator.

sectional view, Figure 2, and in Figure 3. The dome test fixture houses the dome, dome-insulating support ring and metal support structure. The space above the dome could be pressurized and the dome was radiantly heated to the desired temperature from below by the radiant furnace. Seal tests were conducted at the correct seal pressure differential and temperature, but without impingement cooling and heat transfer through the dome.

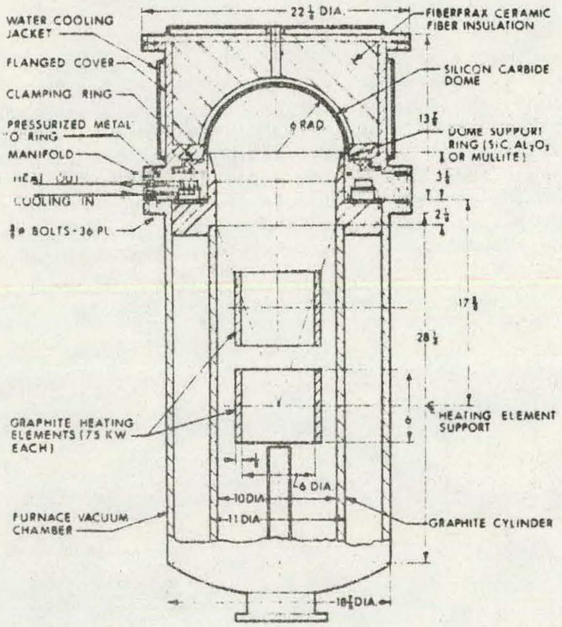

Fig. 2. Dome seal/radiant furnace test unit cross section.

The furnace contained two graphite resistance heating elements which could consume up to 75 kW of electrical power each. The upper furnace electrode is shown in Figure 4 and the furnace control console in Figure 5. Instrumentation for the experiment consisted of pressure transducers, temperature measurement equipment, and flowmeter measurement units for the leakage tests. Thermocouples were mounted at various locations on the ceramic dome, ceramic insulating ring, and metal support structure. The radiation flux profile from the radiant furnace to the dome surface was measured prior to the experiments using a water-cooled flux gage that translated along a hemispherical surface coincident to that which was later occupied by the installed dome.

Subcontracts were let with industrial ceramic manufacturers for the manufacture of the ceramic hardware required for the seal tests. One-foot diameter silicon carbide (SiC) insulating rings were delivered by Materials Technology Corporation (MTC) Dallas, Texas (Figure 6) and by Norton Company, Worcester, MA (Figure 7). The MTC insulating rings were constructed by CVD deposition of a layer of silicon carbide on a graphite mandrel while those from Norton were solid SiC; prepared by a process

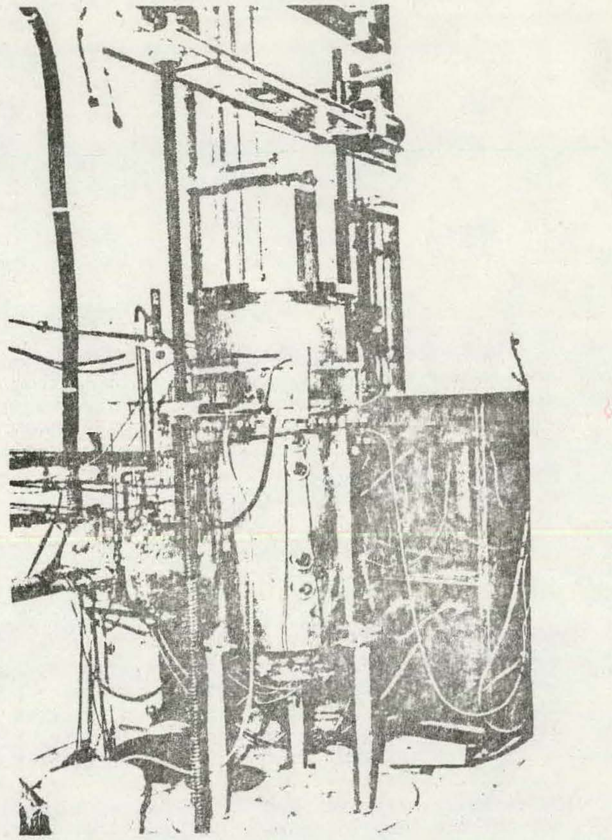

Fig. 3. Dome seal/radiant furnace test equipment.

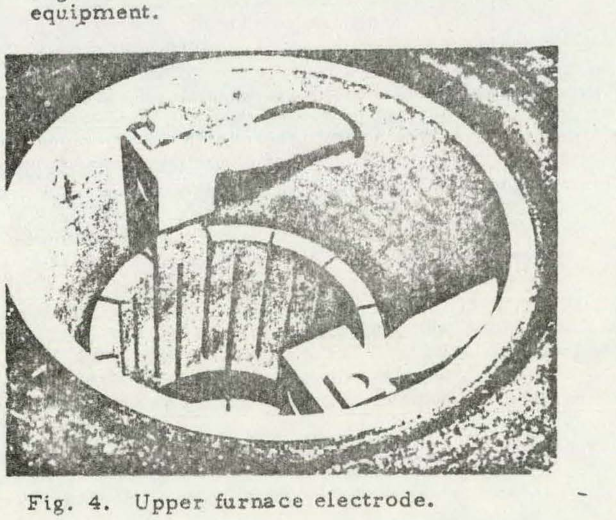

Fig. 4. Upper furnace electrode.

which employs slip casting, firing and siliconization of the piece. The finished material is designated as NC-430 SiC by the Norton Company. One-foot-diameter NC-430 SiC shallow domes and one-foot-span NC-430 SiC hemispherical domes were delivered by Norton Company (Figure 8). Aluminum oxide (Al_2O_3) ceramic hardware in the form of disks and insulating rings (Figure 9) were procured from Western Gold and Platinum (WESGO) Company. An assembled hemi-

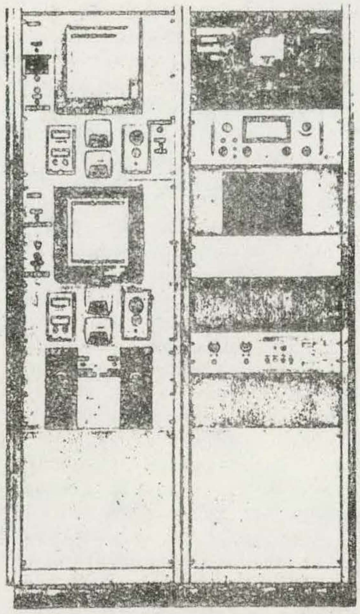

Fig. 5. Radiant furnace control console.

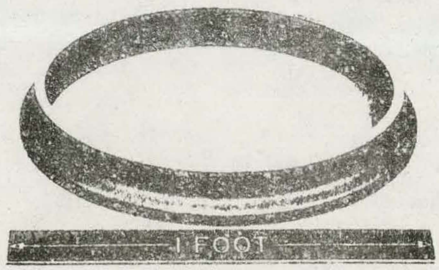

Fig. 6. 1-ft-dia. MTC CVD silicon carbide insulating ring.

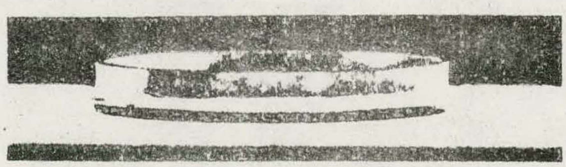

Fig. 7. 1-ft-dia. Norton NC-430 silicon carbide insulating ring.

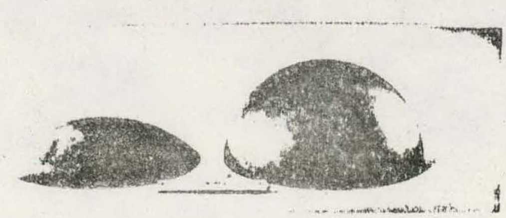

Fig. 8. Shallow and hemispherical silicon carbide NC-430 ceramic dome hardware.

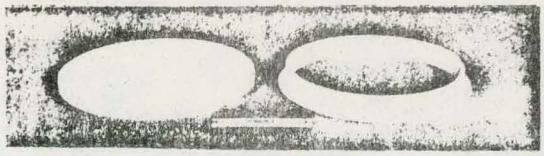

Fig. 9. 1-ft-dia. alumina ceramic disk and insulating ring parts.

spherical dome seal test unit is shown in Figure 10 and a shallow dome seal test unit in Figure 11.

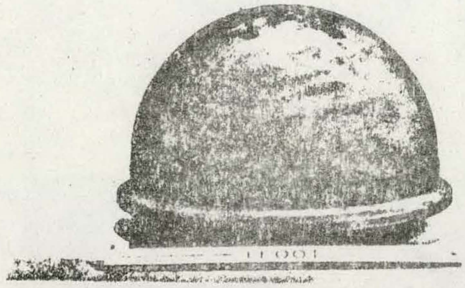

Fig. 10. NC-430 silicon carbide hemispherical dome and insulating ring seal unit.

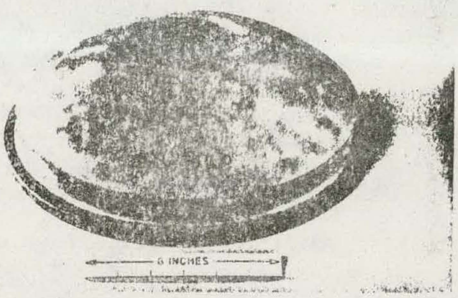

Fig. 11. NC-430 silicon carbide shallow dome and insulating ring seal unit.

Radiation Flux Measurements

Hemispherical dome radiant flux measurements were made using the radiation flux distribution test unit shown in Figures 12 and 13. In this apparatus, a water-cooled radiation flux gage can be moved along the hemispherical dome profile and/or rotated in the azimuthal direction. Experimental measurements of the radiation flux profile are offered in Figure 14 and show that the flux was constant from the center of the dome to a location half-way towards the edge (i.e., between $\phi = 0$ and $\phi = 45°$). As the edge of the dome is approached (i.e., between $45° \leq \phi \leq 90$), the radiation flux decreases slightly. At $\phi = 70°$, a 20% reduction in flux is observed. Measurements of the flux pattern were also made as a function of azimuthal angle and two measurements made 90° apart are compared in Figure 14. The agreement between the two patterns indicates that the flux pattern is symmetrical in azimuth angle as expected.

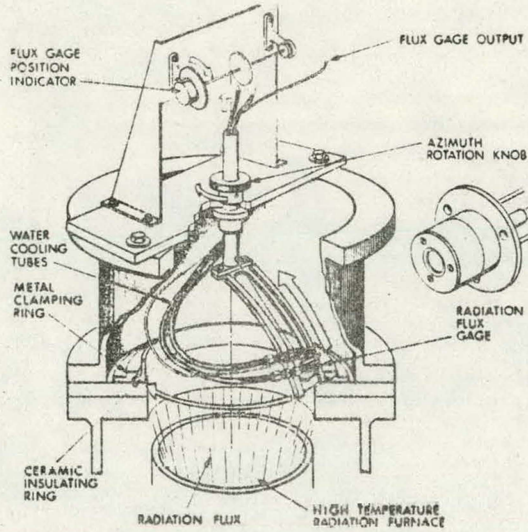

Fig. 12. Radiation flux distribution test unit.

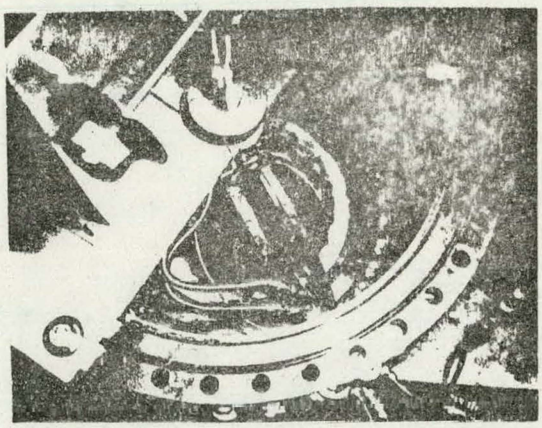

Fig. 13. Radiation flux gauge installed in radiant furnace.

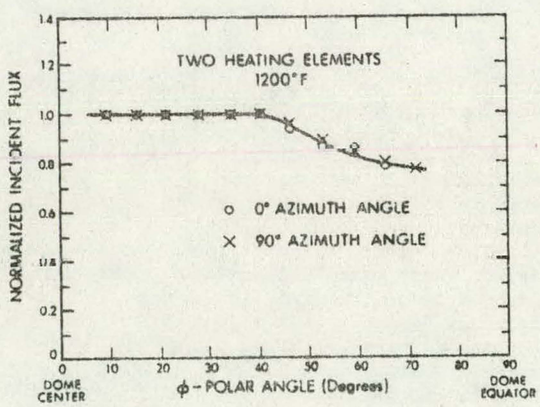

Fig. 14. Incident radiant flux distribution in furnace on a hemispherical surface.

The measured flux pattern was deemed acceptable for the planned seal tests because the absolute dome operating temperature level, rather than details of the flux distributions, was the driving experimental variable. The flux distribution on the dome could be made more uniform, if desired, by inverting the top furnace element toward the dome. This would improve the view factor between the radiating furnace element and the dome area near the dome equator, thus smoothing the flux distribution. However, for the present test program this was not necessary.

Seal Leakage Measurements

Leakage tests were performed on a number of candidate seal configurations with the baseline seal configuration consisting of a hemispherical dome sitting freely on a clamped insulating ring with a clean copper gasket for the secondary seal. A schematic view of the high-temperature seal test set-up is shown in Figure 15 and a view of a hemispherical dome seal unit mounted in the furnace, before insulating materials are placed in the space above the dome, is offered in Figure 16. The clamping system for the insulating ring was designed to have translational freedom in the vertical direction in order to avoid any buildup of temperature stresses related to differential thermal expansion between the ceramic and metal support units. Vertical freedom was achieved by placing conical-shaped washers under each clamping bolt. Forces generated by the clamping bolt and ring system seated the insulating ring down against the copper gasket or metal O-ring secondary seal. The conical washers maintained constant seating force during the heating cycle. The pressure forces acting on the dome during the leakage tests then provided additional seating forces on the secondary seal.

The same test gas was used in both the upper dome seal test unit and in the radiant furnace enclosure and gas leakage through the dome seal

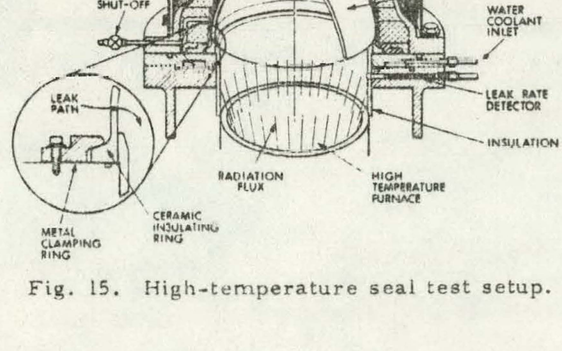

Fig. 15. High-temperature seal test setup.

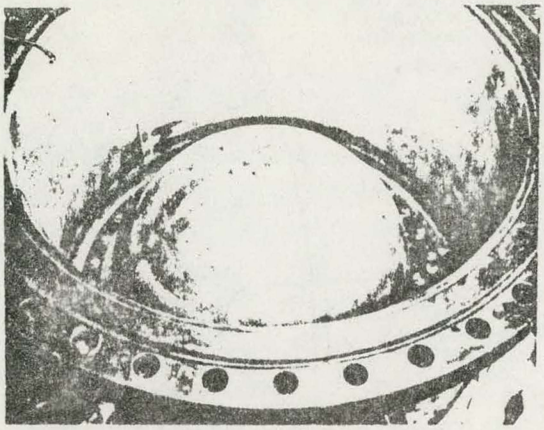

Fig. 16. Hemispherical dome-seal unit installed in test fixture.

system into the furnace space was measured by flow meters connected to the furnace space. Leakage gas exiting from the furnace was water-cooled to room temperature before passing through the flow meter measurement unit. The flow meter equipment consisted of three standard float type gas flow meters, covering the measurement ranges of 0 to .18 SCFH, 0 to 2.0 SCFH and 4 to 190 SCFH, and a highly accurate Matheson mass flow meter for the leak range from .004 to .2 SCFM.

Baseline Seal

Experimental seal leakage rates for a one-foot diameter baseline ceramic dome seal (Figure 17) are illustrated in Figure 18. The seal leak rate was found to decrease rapidly with temperature (also observed in the earlier test series using two-inch-diameter ceramic hardware) and essentially zero leak rate (< .004 SCFH) was measured for seal temperatures above 1000°F. The rapid decrease in leakage rate with increasing temperature is due to the increase in viscosity of gases with increasing temperature. The surface finishes on the dome and ring were 10 μ inches and 6 μ inches, respectively, and were prepared by a local ceramic grinding house using standard diamond-grinding techniques. Diamond-ground surfaces were more than adequate for the tests and smoother lapped surfaces were not needed. Constant leak rate levels as a fraction of the 1% leakage goal are super-imposed on Figure 18 and a comparison of the experimental leak rate data with these values shows that the baseline seal leak rate at temperature is substantially below the 1% goal. For temperatures above 1000°F, the leak rate was less than 1/1000 of the 1% goal.

Baseline Seal With Sealant On The Copper Gasket

As part of the test program, a method was explored to further reduce the component of leakage through the secondary seal, even though the leak rate goal had been bettered by a sizable amount in the tests reported above on the overall baseline seal configuration. These efforts were fostered by a desire to determine the real potential of the contact seal approach and by the desire to isolate

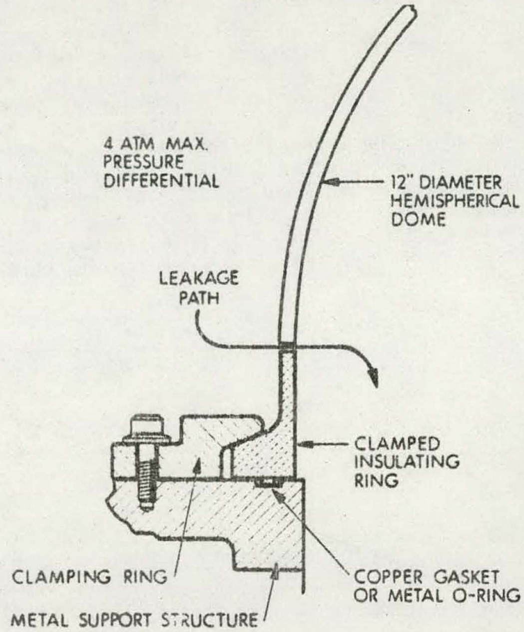

Fig. 17. Clamped ring leak test configuration for 12-in.-dia. domes.

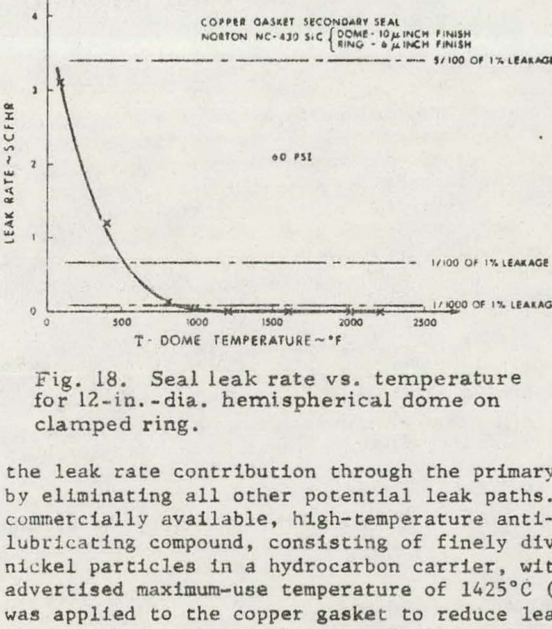

Fig. 18. Seal leak rate vs. temperature for 12-in.-dia. hemispherical dome on clamped ring.

the leak rate contribution through the primary seal by eliminating all other potential leak paths. A commercially available, high-temperature anti-seize lubricating compound, consisting of finely divided nickel particles in a hydrocarbon carrier, with an advertised maximum-use temperature of 1425°C (2600°F), was applied to the copper gasket to reduce leakage through that path. Leak tests of this seal configuration showed substantially reduced leakage rates. For example, room temperature leak rate data for this configuration (see Figure 19) shows that addition of the sealant to the copper gasket reduced the overall leak rate to .016 SCFH at 60 PSI pressure differential in comparison to the 3.1 SCFH leak rate experienced by the clean gasket test unit. The leak rate of .016 SCFH measured at room temperature corresponds to a 2/10000 fraction of the 1% leakage goal. A separate test series in which the ceramic dome was replaced by a flat metal plate supported on a gasket was carried out and showed zero leakage at room temperature and at temperatures to 500°F, the maximum operating temperature of the gasket material. It can be concluded from the supplementary tests that the addition of sealant eliminated all leaks through the secondary seal and that the leakage values shown in Figure 19 may be attributed solely to the contact seal between the ceramic parts. A reduction of the leakage with temperature was also measured as expected for this seal configuration. At temperatures above about 500°F, the leakage had decreased below the minimum mass flow meter measurement capability of .004 SCFH, corresponding to 1/60000 of the 1% goal, and measurements were suspended.

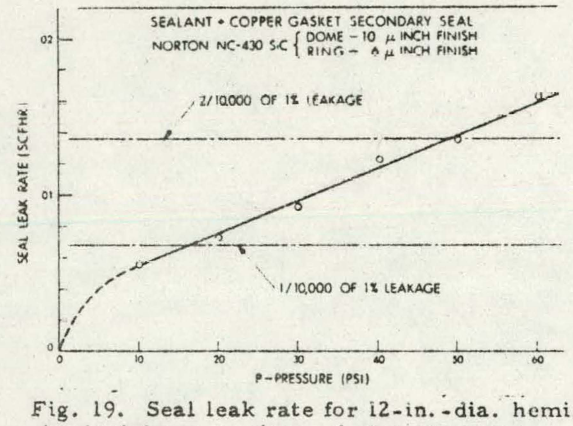

Fig. 19. Seal leak rate for 12-in.-dia. hemispherical dome on clamped ring at room temperature with sealant.

Baseline Seal With Unclamped Insulating Ring

The exceptional performance of the baseline mechanical contact seal, as exemplified by its low leakage rate in comparison to the 1% leakage goal, raised the possibility that the seal design approach could be simplified while maintaining the leakage at or below the design goal. One approach that was investigated in the test series was the possible elimination of the metal clamping ring and bolt system.

Tests were run on the baseline seal configuration with an unclamped insulating ring (Figure 20) to determine the leakage rate as a function of temperature and pressure. Leakage data at 2000°F and 2200°F are shown in Figure 21 for pressures to 60 PSI (4 atmospheres). At 2000°F, the seal leak rate is 1/10th of the goal while at 2200°F it is 1/100th of that goal. The variation of the leakage with temperature, for temperatures between room temperature and 2200°F, was also measured and is shown in Figure 22. This data illustrates that even at room temperature when the leak is the greatest the magnitude of the leakage is still less than that 1% leakage goal.

It should be noted that the ceramic dome and insulating ring finishes for the example data shown

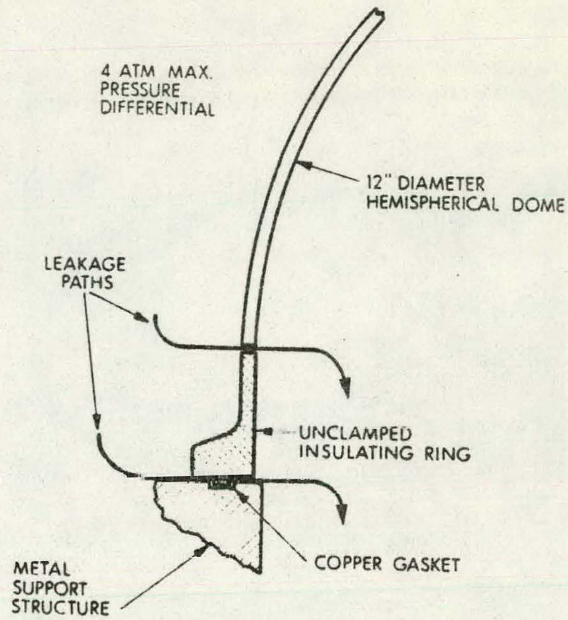

Fig. 20. Unclamped ring leak test configuration for 12-in.-dia. domes.

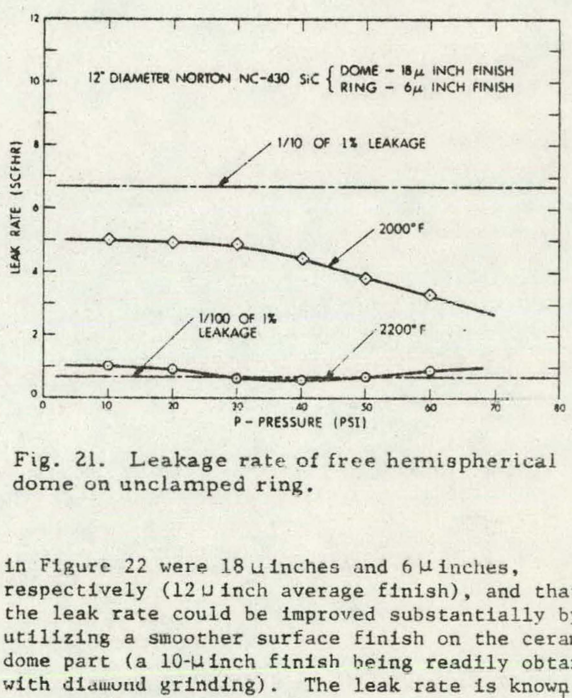

Fig. 21. Leakage rate of free hemispherical dome on unclamped ring.

in Figure 22 were 18 μ inches and 6 μ inches, respectively (12 μ inch average finish), and that the leak rate could be improved substantially by utilizing a smoother surface finish on the ceramic dome part (a 10-μ inch finish being readily obtainable with diamond grinding). The leak rate is known to vary as the average roughness to the Nth power[1], where N = 1.6. Thus a change in the average surface roughness, from the 12 μ inch average for the data in Figure 22 to an 8 μ inch average finish consistent with the data of Figures 18 and 19, would decrease the unclamped ring leak data shown in Figure 22 by a factor of 1.9.

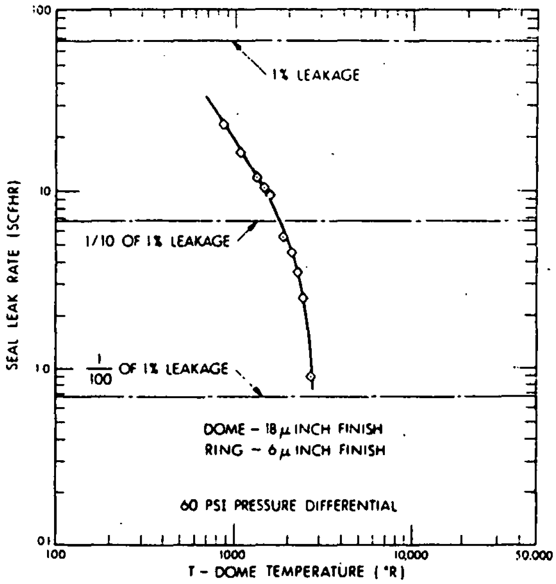

Fig. 22. Effect of dome temperature on leak rate free 12-in.-dia. hemispherical silicon carbide dome on unclamped silicon carbide ring.

Comparison of Seal Leak Data

The leak data measured on the baseline mechanical contact seal, baseline seal with gasket sealant, and baseline seal with unclamped insulating ring are compared with each other and to fractions of the leakage goal in Figure 23. The baseline seal with sealant has the lowest leak rate, the baseline seal the next highest leakage and, finally, the baseline seal with unclamped ring has the highest rate. However, all three seal configurations tested have leak rates at all temperatures which are below the 1% leakage goal. The data in Figure 23 shows that the mechanical contact seal approach is quite flexible in that leakage rates may be varied over at least four orders of magnitude by making controlled changes in the overall design approach used for the seal.

CONCLUSIONS

A mechanical contact seal has been successfully demonstrated on one-foot-diameter silicon carbide ceramic dome hardware at pressure differentials to four (4) atmospheres and at temperatures to 2200°F. Experimental measurements of the leakage of such seals have been carried out and the results compared with the goal of developing a seal with a leakage which is 1% (or less) of the heat-transfer airflow impinging on the dome. For all seal configurations tested and for all test temperatures between room temperature and 2200°F, the experiment leak data demonstrated that the contact seal approach easily bettered the 1% leakage goal. In fact the baseline seal arrangement demonstrated leakage which was but a fraction of the goal: a leak rate

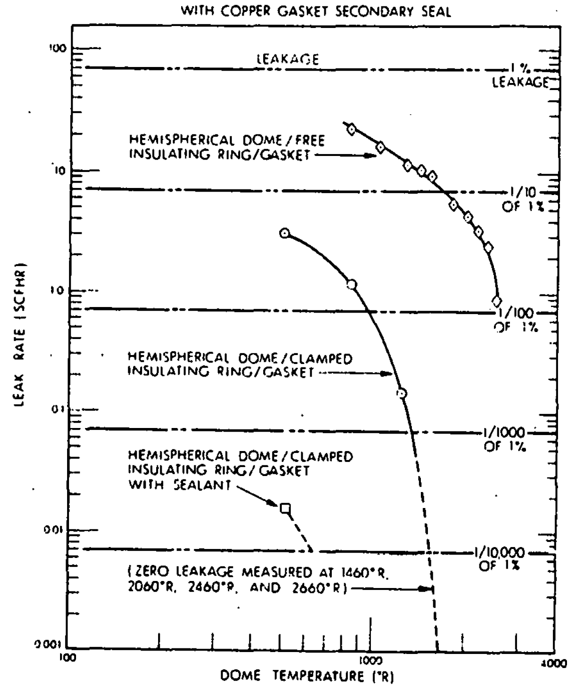

Fig. 23. Comparison of leakage rates of various configurations.

less than 1/10000th of the goal at typical seal operating temperatures. Measured leakage rates on the baseline seal were so low that the metal clamping ring and bolt system could be eliminated from the baseline design with the measured leakage still remaining below the desired level.

Tests of a number of seal configurations showed that the contact seal approach has an inherent design flexibility which allows the leak rate to be varied over four orders of magnitude by making controlled changes in the design approach used for the seal while maintaining the leakage below the 1% leakage goal. The mechanical contact seal which has been tested and proven provides a solution to the high-temperature seal question which was felt to be the technologically pacing element in the development of the Solar Heated-Air Ceramic Dome Cavity Receiver (SHARE) concept.

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