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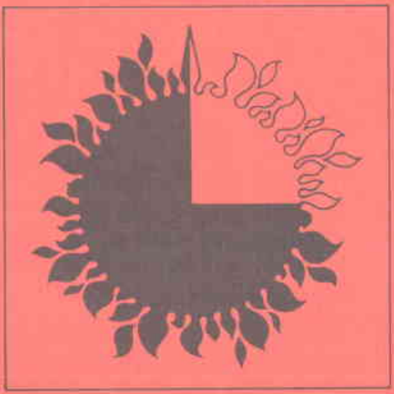
5102-129
Department of Energy

3rd Semi-Annual Advanced Technology Meeting A Review of Advanced Solar Thermal Power Systems

Meeting Abstracts

Long Beach, California
June 19-21, 1979



Prepared for
U.S. Department of Energy
Through an agreement with
National Aeronautics and Space Administration
by
Jet Propulsion Laboratory
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ADVANCED TECHNOLOGY MEETING
A REVIEW OF
ADVANCED SOLAR THERMAL POWER SYSTEMS
AGENDA
Tuesday, June 19, 1979

8:30-8:40	Meeting Announcements	JPL	J. Becker
8:40-8:55	Advanced Technology Meeting Intro.	SERI	B. Gupta
8:55-9:40	Keynote Speaker	House of Rep.	J. Spensley
9:40-10:30	Break		
10:30-11:00	Advanced Technology Program	DOE	M. Gutstein
11:00-11:30	Planning and Assessment Overview	SERI	J. Thornton
11:30-1:15	Lunch		

ADVANCED SYSTEMS

Session Chairman: F. Livingston

1:15-1:35	Intro. to Advanced System Development	JPL	F. Livingston

SYSTEM IDENTIFICATION

1:35-1:55	Advanced System Studies for Central Power	Sandia-L	J. Fish
1:55-2:15	Advanced System Studies for Dispersed Power	JPL	T. Fujita
2:15-2:35	Break		

ADVANCED SYSTEM DEVELOPMENT

2:35-2:55	Dish-Stirling System	JPL	J. Stearns
3:00 2:55-3:15 [illegible]	Advanced Concentrator	Acurex	R. Bedard
3:15-3:35	Heat-Pipe Receiver	GE	W. Zimmerman Dick
3:35-3:55	Non-Heat-Pipe Receiver	Fairchild/Stratos	R. Haglund
3:55-4:15 4:25	Advanced Engine Overview	LeRC	R. Hyland
4:15-4:35	Stirling Engine Overview	MTI	G. Dochat
4:35-4:55	Stirling Engine	United/Stirling	L. Sjostedt
4:55-5:10	Stirling Engine	GE	W. Auxer
6:00-7:30	Mixer - No Host Bar	Queen Mary Museum	

Wednesday, June 20, 1979

8:30-8:40	Meeting Announcements	JPL	J. Becker

ADVANCED SUBSYSTEMS

Session Chairman: B. Gupta

8:40-9:00	Overview	SERI	B. Gupta
9:00-9:20	Receivers	JPL	L. Leibowitz
9:30-10:00	Thermal Storage	Sandia-L	J. Gilson
10:00-10:20	Salt Loop Tests	GA	J. Schuster
10:20-10:40	Break		
10:40-11:00	Heat Engines – Rankine	LeRC	~~M. Bailey~~ Bob Hyland
11:00-11:20	Heat Engines – Brayton	AiResearch	~~L. Six~~ Frank Dobler
11:20-11:40	Advanced Components Test Facility	GIT	T. Brown
11:40-12:10	Advanced Components Research Facility	SERI	M. Bohn
12:10-1:30	Lunch		

MATERIALS

1:30-1:50	Materials Program Overview	SERI	B. Butler
1:50-2:10	Absorber	SERI	P. Call
2:10-2:30	Transmitters	JPL	Bill ~~W.~~ Carroll
2:30-2:50	Reflectors	SERI ~~Sandia~~	TBD ← Barry Butler
2:50-3:10	Cellular Glass	JPL	Marc ~~M.~~ Adams
3:10-3:30	Break		

Dual 5#/ft² w/ cellular

FEASIBILITY DEMONSTRATION

3:30-3:50	Overview	JPL	L. Leibowitz
3:50-4:10	Checker Stove Module	Sanders	A. Poirier
~~4:10-4:30~~	~~EPRI Program~~	~~EPRI~~	~~J. Bigger~~
4:30-4:50	Low Cost Concentrator Overview	JPL	L. Jaffe
4:50-5:10	High Temperature Receiver	MIT	P. Jarvinen
5:10-5:30	Solar Ponds	Dynatech	E. Guyer

ADVANCED TECHNOLOGY MEETING
A REVIEW OF ADVANCED SOLAR THERMAL POWER SYSTEMS

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ADVANCED SUBSYSTEMS

SOLAR FUELS AND CHEMICALS SESSIONS

INTRODUCTION TO ADVANCED SYSTEM DEVELOPMENT

Floyd R. Livingston
Jet Propulsion Laboratory
Pasadena, California

Advanced solar thermal power systems are being developed for the concentration of solar power at high temperatures for electricity generation and other industrial processes. These developmental solar thermal power systems have been divided by size into large power systems and small power systems. Large power systems are able to generate more than 10 megawatts of electrical power. Small power systems generate less than 10 megawatts of electrical power. Central receiver and distributed collectors are classes of large or small power systems.

The ongoing activities include the design, fabrication and testing of central receiver and distributed collector power systems. Within the two classes of power systems are several types. Storage-coupled, utility repowering/industrial retrofit, and solar/non-solar hybrid systems are the types that are now being pursued in the central receiver power systems applications program. Design, fabrication and testing of storage-coupled, and solar/non-solar hybrid distributed collector power systems are underway at the present time.

All of the above activity is a combined government/industry effort. The DOE Headquarters has delegated responsibility for managing the development and assessment of solar thermal power systems for various applications to the DOE Operations Offices. Technical managers are at Sandia Laboratories, the Aerospace Corporation, Solar Energy Research Institute, Jet Propulsion Laboratory, Lewis Research Laboratory, and others. The conceptual design, detail design, fabrication, installation and testing functions are implemented through industry. For example, the dish-Stirling, point focusing distributed power system advanced technology development is being managed by DOE Solar Thermal Power Systems; Jet Propulsion Laboratory and Lewis Research Center provide technical management; General Electric Co., Fairchild Stratos Division, Mechanical Technology, Inc., Acurex Corporation, and United Stirling (Sweden) implement the power system development.

Because of world energy shortages, the pursuit of the development of solar thermal power systems is in the national interest. Since large investments in development are required, combined with high risk of invested capital and low return on investment (because of the long development time), the development of solar thermal power systems cannot proceed without taxpayers support in the development phases. Industry will, by its very nature, commercialize and market a solar power system which promises low risk of invested funds, coupled with a high rate of return on investment (short payback time).

At the Jet Propulsion Laboratory, the Thermal Power Systems Project Managers have laid out an orderly approach to developing distributed collector power systems. First, advanced system studies identify cost effective systems worthy of pursuit. Through industry proposals, components promising high performance potential are also identified and pursued. A distributed collector power system conceptual design is defined by laboratory personnel and major systems requirements are described. Industry is utilized in the performance of technical work to the maximum extent feasible. Industry will design, fabricate, install, and checkout test all components and subsystems. The laboratory will direct the overall systems tests and operations.

Solar Power Systems are developed to provide heat for electrical generation or other industrial processes at a reasonable cost. If cost and performance targets are met, central receiver power systems can be economically competitive with oil, gas and coal produced electricity in the southwestern U.S. Also, distributed collector power systems can, if cost and performance targets are met, be economically competitive with oil and gas electrical generation in the southwestern U.S. Latest advanced system studies have shown the solar power systems could penetrate the electrical energy market in all regions of the continental U.S. if the cost and performance targets are achieved, and the conventional energy costs escalate more than expected.

ADVANCED SYSTEMS STUDIES

FOR SMALL POWER

T. Fujita
Jet Propulsion Laboratory
Pasadena, California

This paper summarizes results of activities performed under the Advanced Solar Thermal Technology (ASTT) Project, Advanced Studies Task, at the Jet Propulsion Laboratory (JPL). A general description of present task activities is first given. Then selected results from two studies are presented. A brief description of future plans concludes the paper.

PRESENT ACTIVITIES

The primary function of this task is to support integration and coordination of subsystem and component development activities. This involves: (1) Systems Engineering, Analysis and Design, and (2) Development of Comparative Evaluation Methods and Computer Programs.

Task implementation involves the undertaking of a series of specific studies which address a broad range of issues. Specific studies being conducted in the FY 79-80 timeframe include:

(1) Regional Insolation Effects: comparison of four generic power plants when operating under differing insolation conditions encountered in different regions of the continental United States.

(2) High Temperature Thermal Applications: investigation of advanced, high-temperature (≥800°F) transport and storage systems that will enable paraboloidal dish systems to supply high-grade thermal energy for industrial applications.

800 – 3000°F

(3) Comparison of Thermal and Electric Storage: determination of differences in techno-economic potential of paraboloidal dish systems when using selected advanced thermal or electric storage concepts, together with an assessment of the technological problems/risk associated with each concept.

(4) Comparison of Advanced Engines for Paraboloidal Dishes: delineation of operating characteristics and techno-economic potential of advanced Brayton, Brayton/Rankine, and Stirling engines and the technology development effort associated with each type of engine.

(5) High Temperature Dish-Brayton Tradeoff: investigation of advanced technology Brayton engine components and optional arrangements to delineate developmental activities offering the greatest potential.

SELECTED STUDY RESULTS

Selected results from the first two studies above are presented in this paper. The regional insolation effects study has been completed and released for publication whereas the high temperature thermal applications study is an ongoing effort that is about 50% completed.

Regional Insolation Effects

The wide spectrum of advanced solar thermal power plant collector concepts was represented by four generic systems comprising (1) fixed orientation (non-tracking) Compound Parabolic Concentrator (CPC), (2) one-axis tracking parabolic trough, (3) two-axis tracking heliostat/central receiver and (4) two-axis tracking paraboloidal dish. For each system, it is assumed that goals for development of advanced technologies in the 1990-2000 timeframe are achieved and that solar penetration levels result in large mass production (of the order of 10^6 units/year) for modular components.

To assess the effect of regional differences in insolation, eight sites (within the continental United States) encompassing a wide range of insolation characteristics were selected. The four generic power plants were evaluated under these differing insolation conditions. Over the entire range of insolation patterns, it was found that two-axis tracking systems, viz., the central receiver and paraboloidal dish, have the highest potential for electric power production .

As expected, all the solar power plant concepts achieved their highest performance in the solar-intensive Southwest sunbelt. Further, in view of large uncertainties in conventional power plant electrical energy costs due to fossil fuel escalation and safety/environment problems facing nuclear, two-axis tracking solar plants are potentially viable, even in the Northeast. The higher projected cost of conventional power in the Northeast tends to improve the competitive posture of solar plants and overcome a large portion of the techno-economic penalty associated with reduced levels of insolation.

High Temperature Thermal Application

Paraboloidal dish concentrators employ two-axis tracking to achieve the high concentration ratios necessary to generate thermal energy in the temperature range of 800°F to 3000°F. These temperatures meet the needs of high-temperature industrial processes encompassing a diverse spectrum of applications from meat packing to metallurgical processes. For a field of dish concentrators to supply high temperature thermal energy to an industrial process, a cost-effective means of transporting this energy is required. Further, since most industrial processes tend to operate on an essentially continuous basis, use of energy storage to compensate for the diurnal nature of solar availability is highly desirable.

Since transport of energy at high temperatures in insulated pipes (ceramic lined for the high end of the temperature range) is costly, the advanced technology possibility of using reversible chemical reactions is being investigated. Basically, high temperature solar thermal energy generated in the collector field is used to drive an endothermic reaction.

The storable chemical products of the endothermic reaction are transported from the field at low temperature to an exothermic reactor where the reaction is reversed and high temperature heat is released. The output of the exothermic reaction is then transported at low temperature to the collector field where it serves as the feedstock for the endothermic reactor.

A total of ninety-two candidate reversible reactions were considered. A systematic screening process involving considerations such as degree of reversibility, exothermic temperature level, transportability, toxicity, etc., resulted in the selection of ten candidates. Technological development problems associated with each of the candidate reactions were delineated.

FUTURE PLANS

The plans for the remainder of FY 79 and FY 80 involve the completion of the ongoing studies described previously. Reports for all of these studies will be published during this period.

DISH-STIRLING EXPERIMENT

J. W. Stearns
Jet Propulsion Laboratory
Pasadena, California

It is the objective of the dish-Stirling experiment to utilize a team of industrial contractors to develop and demonstrate dish-Stirling technology at the system level that indicates potential for electric generation competitive to fossil fuel generation. Depicted in Figure 1, key features and production cost goals are as follows:

Feature	Production Cost Goal
o A 10-meter diameter, point-focusing advanced solar concentrator	$70-100/m^2$
o A 20-kWe Stirling cycle engine driven alternator	$50-100/kWe
o An 800°-900°C (1500°-1650°F) advanced receiver	$6/kWt
o A fossil fuel combustor for hybrid operation	$4/kWt
o A thermal energy storage option	$15/kWe + $10/kWh(e)

Optimum temp range for solar collection

500-600$/kWe

Minimum risk for power conversion development consistent with system cost goals in the 1980-1990 time frame lies with the Stirling engine-alternator. Principal Stirling advantages that lead to this conclusion are:

- Exceptional efficiency inherent with the Stirling cycle indicates that 60% to 70% of Carnot efficiency is available at 816°C.
- Reasonable materials cost is associated with Stirling high efficiency because of the modest temperature.
- Quiet operation is associated with the Stirling engine.
- Optimum solar collection efficiency is obtained at 816°C with a geometric concentration ratio of 2,000.

Development schedule for the dish-Stirling experiment is shown in Figure 2. Monolithic structural cellular glass gores are being developed and evaluated for low cost producibility with thin backsilvered mirror reflector. Two solar receiver concepts are to be demonstrated: the non-heat pipe receiver without thermal energy storage (TES), and the heat pipe receiver with TES. Both receivers will operate in a hybrid mode with fossil fuel combustion. An early (Mod 0) Stirling engine is to demonstrate operation at 35-40% efficiency. With limited modification, a later (Mod 1) engine is planned, to operate at an efficiency greater than 45%.

Hybrid augmentation and TES are exceptionally important. First, such features allow a high capacity rating (0.5 - 0.7 capacity factor has been suggested). Second, these features allow operation of the 20-25 kWe units at a constant power level, yielding minimum cost, highest efficiency, and constant-frequency output. Finally, and particularly with TES, units at 20-25 kWe may be programmed to match a variable power load demand. Further study of the optimum mix of TES and hybrid combustion, with modular redundant reliability, is to be accomplished.

System development to meet all the requirements of a competitive marketplace will involve an extensive effort beyond initial development. Within constraints of realizable programs, priorities presently have been set in the order discussed below. None of these elements are being overlooked, but some will not receive major effort until later.

1. Stirling Engine-Alternator Demonstration.

   Operation of a Stirling engine-alternator with its solar receiver at a temperature of 816°C (1500°F) and efficiency of 35-40% is an early requirement. A baseline design is thereby established against which other power conversion subsystems may be compared.

2. Hybrid Receiver Demonstration.

   Assignment of a capacity rating to the dish-Stirling system in a cost-effective manner requires fossil fuel combustion augmentation. Cloud cover periods may vary from a few minutes to several days, extending beyond any potentiality of thermal or battery storage to compensate.

3. Thermal Energy Storage (TES) Demonstration.

   Optimum utilization of solar energy requires a shift of timescale by an average of 1-2 hours. TES has the potential of lower cost than battery storage in this function. In addition, TES will be needed to minimize control problems of hybrid operation, and particularly to eliminate turndown ratio constraints.

4. Unit Operation at Constant Power, Constant Frequency.

   This mode of operation, made available by TES and hybrid augmentation, promotes exceptional simplification in system control, minimizes power conversion equipment size, allows peak efficiency of operation, and eliminates power processing losses.

5. System Variable Load Application.

   The operational advantages of constant power operation will not mitigate against the overall system following a variable load demand profile. Microprocessor programming at the system level provides load following in unit steps of 20-25 kWe.

6. Low Cost Potential.

Exceptional effort is made to project reduced costs through the use of product engineering principals. Minimum cost materials are used, mass is minimized, and processes amenable to automation are defined. Control and electronics requirements are reduced where possible.

7. High Efficiency.

Technology modification to enhance efficiency has a high payoff in overall system cost reduction. Continuing tradeoff studies are expected.

8. Extended Life/Reliability.

Technology effort will be increased as possible to increase system life and reliability. Known and suspected failure modes are to be investigated to determine corrective action. Engine bearings and seals are under study, as are elements that are subject to thermal cycle fatigue. Best utilization of redundant modularity is also to be obtained. Design simplification is to be instituted where practical.

9. Safe Operation.

Operating safety is a first-order requirement. In-depth studies will be required prior to systems applications. During development, safety practices and procedures are to be generated.

10. Environmental Cleanliness.

Air pollutants, effluents, noise, and the like, are to be carefully considered in system design. All requirements will be met or surpassed.

11. Automated Operation.

Except for prototype and pilot plant systems, design is to be such that all operation is automated. Where possible, early effort will attempt to assure compatibility with this requirement.

12. Low Maintenance.

The system design is to be such that virtually no maintenance is necessary except where component failures occur. Modular redundancy shall be such that component failures will not cause systems outage.

13. Minimum Site Preparation.

Site preparation will not require extensive grading or ground preparation. Removal of obstacles (trees, boulders, etc.) and rough filling is allowable. Automatic cable laying and foundation augering is planned.

14. Low Cost Transportation.

Factory prefabrication will also take into account the need to minimize transportation costs. Reasonable packing density, load sizing, etc., need tradeoff against field assembly costs.

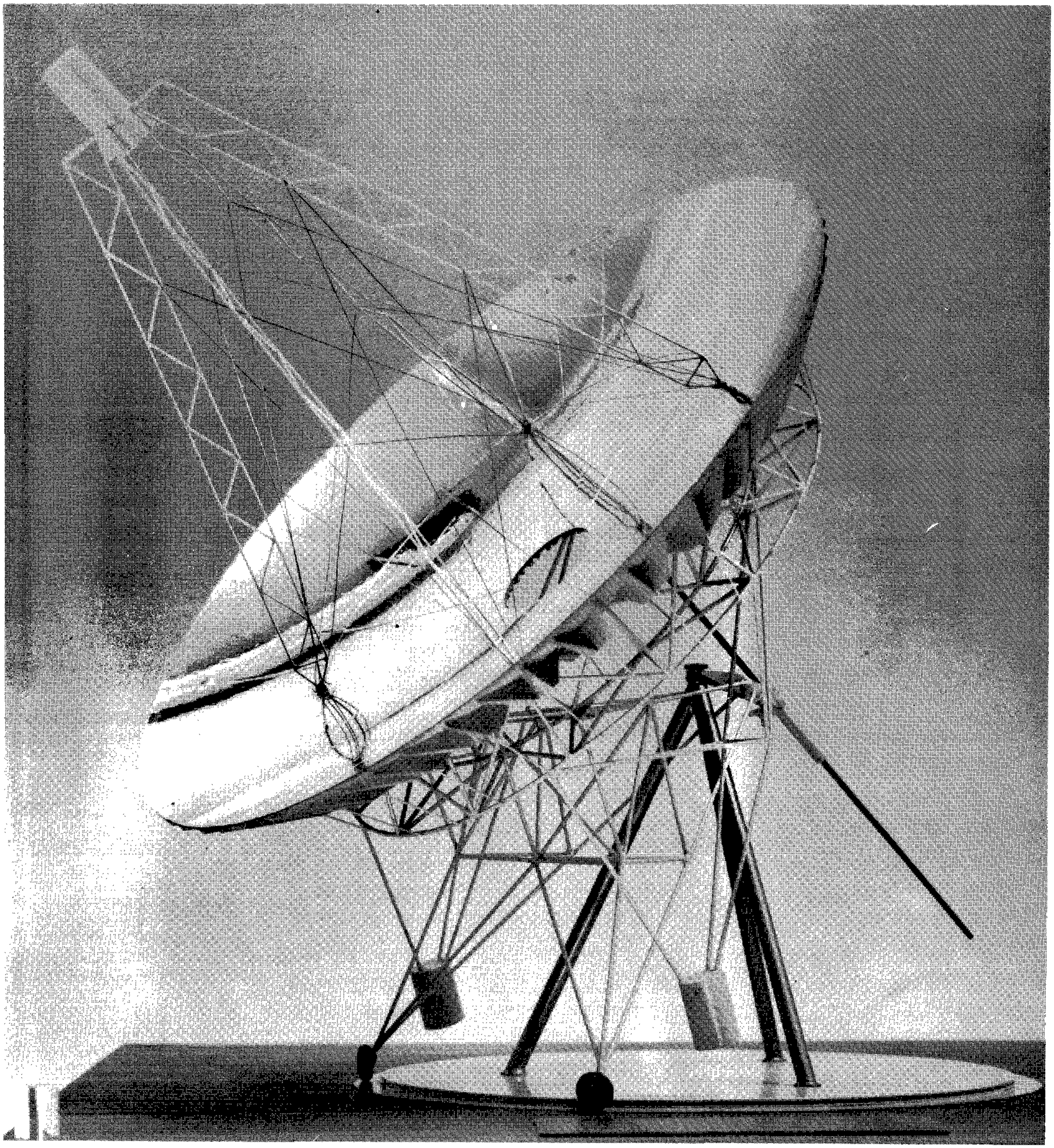

Figure 1. JPL Conceptual Design,
Advanced Solar Concentrator

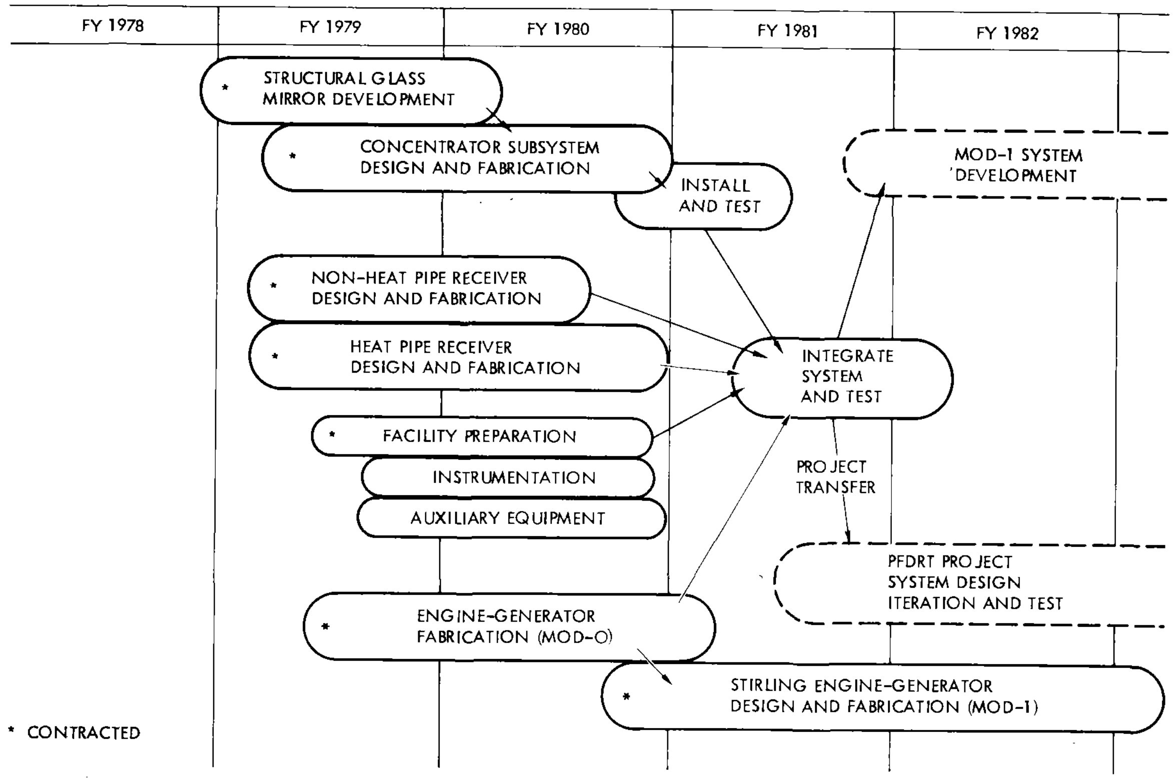

Figure 2. Dish-Stirling System Development Schedule

SUMMARY OF PRESENTATION

ADVANCED CONCENTRATOR

R. Bedard
Acurex Corporation
Mountain View, CA 94042

Acurex Corporation has been selected by JPL as the contractor for development of the Advanced Concentrator. The contract is currently in the negotiation phase with contract start anticipated for 1 July 1979. The objectives of the program are as follows:

- To design and fabricate a prototype advanced solar concentrator
- To install at the JPL Solar Thermal Test Facility
- To analyze the life cycle cost in mass production

The prototype concentrator will be representative of the current state-of-the-art for low cost fabrication and will be adaptable for fabrication on a mass production basis.

This presentation reviews the key elements of the Advanced Concentrator concept and describes the development project approach with emphasis on the initial task of preliminary design.

The Advanced Concentrator concept is a deep dish parabolodial configuration with an aperture diameter of 10 meters and a focal length to aperture diameter (F/D) ratio of 0.6. The key element of the concept is the reflective gores fabricated of thin glass mirror bonded continuously over a contoured substrate of cellular glass. The reflective surface consists of two groups of gores installed on a truss type support ring to form a complete but physically discontinuous reflector. An all-truss type structure serves as an intermediate structure between the concentrator surface and the pedestal which provides the azimuth and elevation movements. The cost target for the Advanced Concentrator is 70-100 ft/m^2 in mass production.

The reflective gores are the critical technology to be developed and demonstrated in this project. Thin, backsilvered glass was chosen as the reflective material because of its excellent reflectivity, specularity and abrasion resistant characteristics. Previous trade-off studies have shown that the performance attributes outweigh the cost disadvantage as compared to other reflective material candidates. Cellular glass was chosen as the substrate material because of its potential low cost, light weight, excellent flexural and torsional stiffness and its coefficient of expansion compatability with the mirror. Full scale gore fabrication, machining, bonding and edge sealing technologies must be developed and demonstrated.

The major design requirements of the Advanced Concentrator are in the following areas:

- Life expectancy of 30 years
- Performance of 56 kW minimum intercepted solar power
- Hybrid 2 axis tracking
- Environmental conditions including wind, temperature and precipitation

The Advanced Concentrator objectives will be achieved in a 5 task, 20 month duration project. Tasks 1 through 4 are sequentially phased tasks of which will carry the concentrator through design, fabrication and will result in an installed and checked out prototype at the JPL Solar Test Facility in March 1981. The fifth task will produce an assessment of the life cycle cost of net energy collected over a 30 year operational life.

The Task 1 Preliminary Design effort will produce a design package sufficient for ensuring the attainment of performance and design requirements and sufficient to allow a mass production cost analysis to proceed. The preliminary design effort can be divided into the following five areas, namely:

- Reflective gore
- Structural
- Mechanical
- Electrical
- Control

For each of the five areas, the preliminary design approach in terms of objectives, requirements and procedures, is summarized in this presentation.

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HEAT PIPE HEAT RECEIVERS WITH TES

W. F. ZIMMERMAN
GENERAL ELECTRIC COMPANY
Advanced Energy Programs

Two JPL sponsored programs are currently underway in which heat pipe receivers with thermal energy storage are involved. The first is a study program under the technical direction of Dr. Y. S. Won of JPL on the use of liquid metals for thermal transport and storage in dished Stirling systems. The intent of this program was to investigate the potential for liquid metal thermal transport, to conceptualize designs of merit and to assess selected designs and identify development needs. The study initially covered a range of options including single and multiple collector systems, sensible and latent heat storage, heat pipe and pumped loop thermal transport and both compact, focus mounted and separated, focus-collector mounted systems.

During this study program the focus mounted heat pipe heat receiver with thermal energy storage was conceptually defined as shown in Figure 1. The heat receiver is comprized of 27 primary sodium heat pipes which absorb solar energy and transfer it into the secondary heat pipe which contains containerized latent heat fused salts, such as LiF, and the Stirling engine heat exchange tubes. The primary heat pipes are wicked only in the evaporator section which prevents reverse flow of heat from the secondary heat pipe back into the heat receiver. The secondary heat pipe is wicked with porous media to deliver sodium to heat sources at the condenser end of the primary heat pipes and on the surface of the latent heat fused salt containers. Improvements in the above design and confirmation of the key design principles have been accomplished in the last few months.

In a second contract under the technical directions of J. W. Stearns of JPL the design, manufacture and solar test of the focus mounted heat pipe heat receiver with TES has been initiated with hardware deliverable

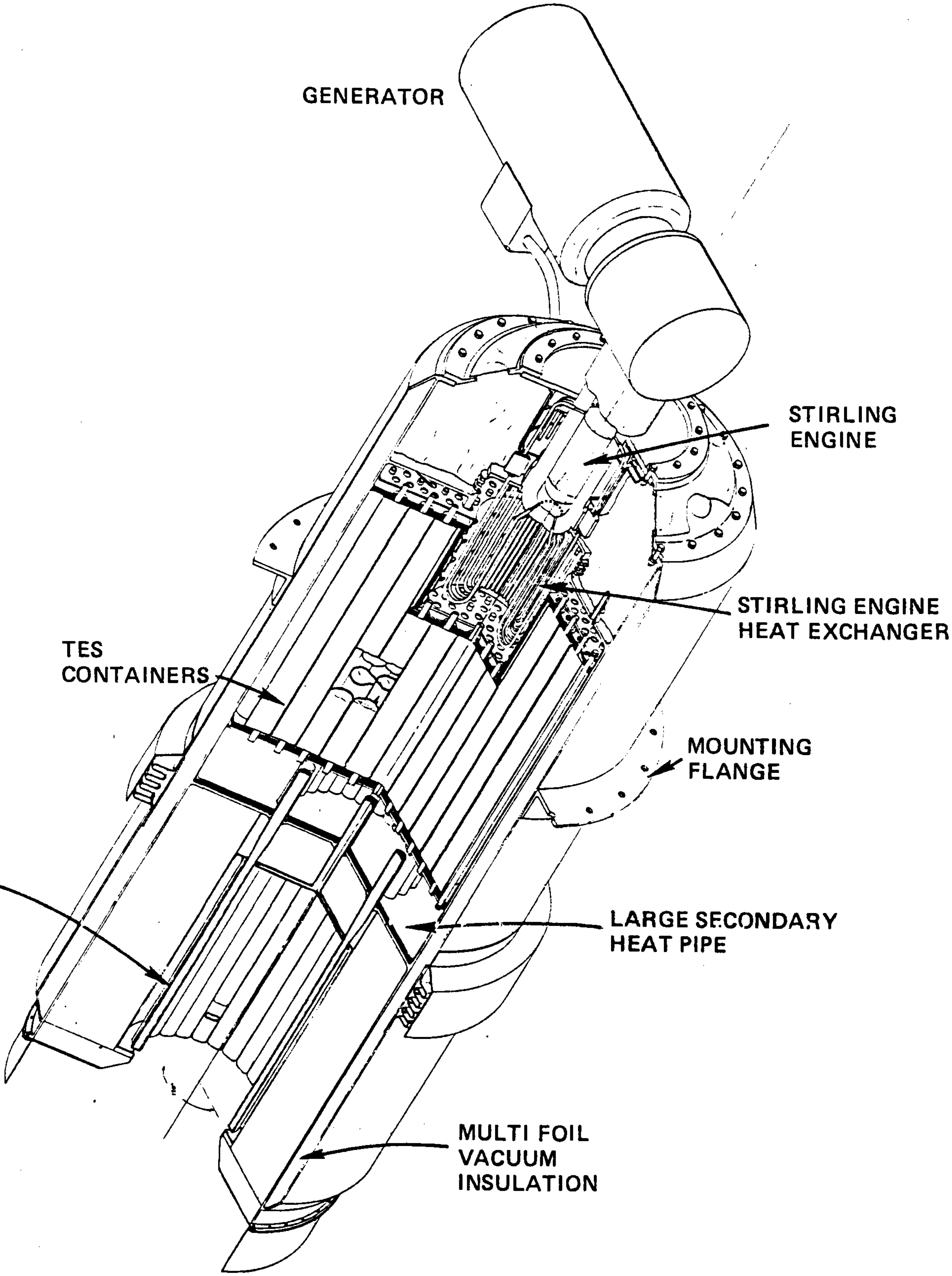


Figure 1. Heat Pipe Heat Receiver with TES for Stirling Solar Power

in late 1980. The design assessments of the previous program provides some additional guidance in the new design. For example, (1) the use of fiberous insulation rather than vacuum multifoil insulation will effect significant weight and assembly cost savings without exceeding the power package diameter and collector shadowing limits now prescirbed, (2) a truss-type external load structure is being considered in lieu of the outer vacuum shell, (3) a sodium fluoride-magnesium fluoride fused salt will be used in place of LiF at a slightly reduced (and more conservative) nominal operating temperature (1520°F vs. 1575°F) and at lower anticipated cost, (4) the full performance characteristics of the flattened and partially wicked primary heat pipes have been verified under actual tests under various angles of inclination, (5) calculations and heat pipe experiments tend to confirm the expectation that reverse heat flow will not occur from the primary heat pipes either in operating positions or in the stowed position, (6) wicking and flow tests using easy fluids at room temperature have confirmed both the pumping and flow capability of the wicks selected for use in the secondary heat pipe and the flow across joints between selected wicks, and (7) other assessments, including preliminary operation, control and reliability evaluations have identified other significant improvements to be made in the current design of test hardware.

In addition, the program for the design, construction and test of the heat receiver with TES features a modular TES experiment and a design modification to accommodate the addition of a fossil fuel combustor to be incorporated around the heat receiver as a hybrid heat source.

The modular experiment has been designed. It incorporates a single primary heat pipe, a secondary heat pipe with all necessary wicking, TES capsules and a heat extraction device. This modular experiment will be well instrumented with thermocouples and will be operated under start up, steady state and various transient modes to evaluate heat pipe and TES performance under various angles of inclination. Experience gained in this experiment will be used to guide the final design and to provide the basis for later operational testing of the solar heat receiver with TES.

The hybrid heat source fossil fuel combustor is currently being designed as an unique recuperated gas fired combustor surrounding the primary heat pipes of the solar receiver. A luminous, laminar flow, diffusion flame provides radiant heat to a ceramic sleeve which contains the hot combustion gasses and which re-radiates heat to the primary heat pipe. A ring of gas-fired nozzles will provide the combustion gasses for this annular combustion using preheated air at a temperature of about 1000°F. To verify the burner design a single such burner will be tested in a simple combustion test module experiment; the flame length, temperature profile and gravitational effects on the flame at various operating inclinations will be determined. Computerized programs are being used for calculation of flame characteristics and for the analysis of heat transfer from the flame to both the heat pipes and the recuperator.

In addition to other numerous advantages, the heat pipe heat receiver has many advantages which are inherent to an appreciable amount of thermal energy storage. With thermal storage, the system operates at near-constant temperature and engine power irrespective of the intensity of solar insolation. The heat flow is self regulating within the secondary TES heat pipe since heat automatically flows from the hotter to the colder surface under a very minimal temperature difference. The secondary TES heat pipe is completely self contained and relies upon liquid sodium wicking and slight differences in sodium vapor pressure for sodium mass flow, and thermal transport. It transfers heat using high heats of vaporization of sodium under extremely effective vaporization and condensing heat transfer film coefficients. It does so with negligible thermal transport pumping power. The low temperature drop within the heat transfer system is only of the order of 32°F and represents, principally, the Δt across the evaporator and condenser metal wall thicknesses of the primary heat pipes.

Since the overnight sensible heat losses result in only a 52°F drop when the TES system is fully discharged, the system can be started with a stable, near normal operating, temperature. This can occur once the solar insolation is sufficient to sustain continued operation; or, the TES system can be partially charged at low solar insolation and an orderly and planned start up of the system can be made at full power before nominal solar insolation is reached. Furthermore, nominal rated power can be achieved without the necessity for the use of hybrid heat sources by calling upon the TES even before the daily solar insolation reaches its average value.

The fully charged TES system can readily provide over an hour's operation without solar insolation and even longer periods if some contributing solar insolation is available. Finally, the addition of a hybrid heat source such as a fossil fuel combustor , permits on-off, rather than proportional, additions of heat to the TES chamber at full combustion efficiency. This permits planned heat additions to partially or fully recharge the TES system without the necessity of following specific fluctuations in the solar insolation.

Since the system is a single, compact, focus mounted unit, it can be readily factory produced by mass production methods and installed with minimum field site labor.

The system has the benefits of stable power generation under variable solar insolation and the added freedom to effectively supplement solar heat with a fossil fuel source using an efficient combustion process and an effective operating plan.

DISH STIRLING SOLAR RECEIVER (DSSR)

Richard Haglund, Senior Project Engineer
Robert Tatge, Director, Advanced Projects
Fairchild Stratos Division
Manhattan Beach, California

PROGRAM OBJECTIVES

The Fairchild DSSR program, as directed by the JPL Thermal Power Systems Advanced Solar Thermal Technology Group, will demonstrate the technology of a non-heat-pipe Dish Stirling Solar Receiver (DSSR) with fossil fuel combustion augmentation. Such a system will enable the Stirling engine to operate continuously at constant power and speed regardless of insolation level, thus providing the capability to operate on cloudy days and at night. (Another but similar program is aimed at demonstration of a heat pipe receiver.)

The design objective for the non-heat-pipe receiver/combustor is to achieve low cost in high volume production without sacrifice of receiver and engine efficiency for a given concentrator and engine, in this case the JPL Advanced Concentrator and the United Stirling P-40 engine respectively.

DESIGN APPROACH

The basic DSSR design is a cavity-type receiver as illustrated in Figure 1. The primary receiver surface is a conical configuration with integral passages for the helium working fluid. The cone is heated by solar insolation on the exposed surface and by combustion gas on the back surface. The receiver is attached directly to the Stirling engine heater head. Simplicity in design has been emphasized, along with extensive use of parts and assemblies based on commercial practices, processes and materials that have been proven in other applications but under similar operating conditions, normally found in industrial boilers and gas turbines. Where expensive cobalt alloys are required, their use has been minimized.

TEAM MEMBERS

To accomplish this program within the schedule and funding constraints, a team was organized from companies and organizations with capabilities calculated to produce immediate results in respective areas of technology, including optics, heat transfer, combustion and manufacturing process techniques:

Georgia Institute of Technology	Heat transfer, solar optics and high temperature ceramics.
Institute of Gas Technology	Combustion technology and design.
Solar Turbines International, Division of International Harvester	High temperature heat exchanger fabrication technology.
Met Glass Division, Allied Chemical Corporation	High temperature brazing technology.
United Stirling	Stirling engine technology

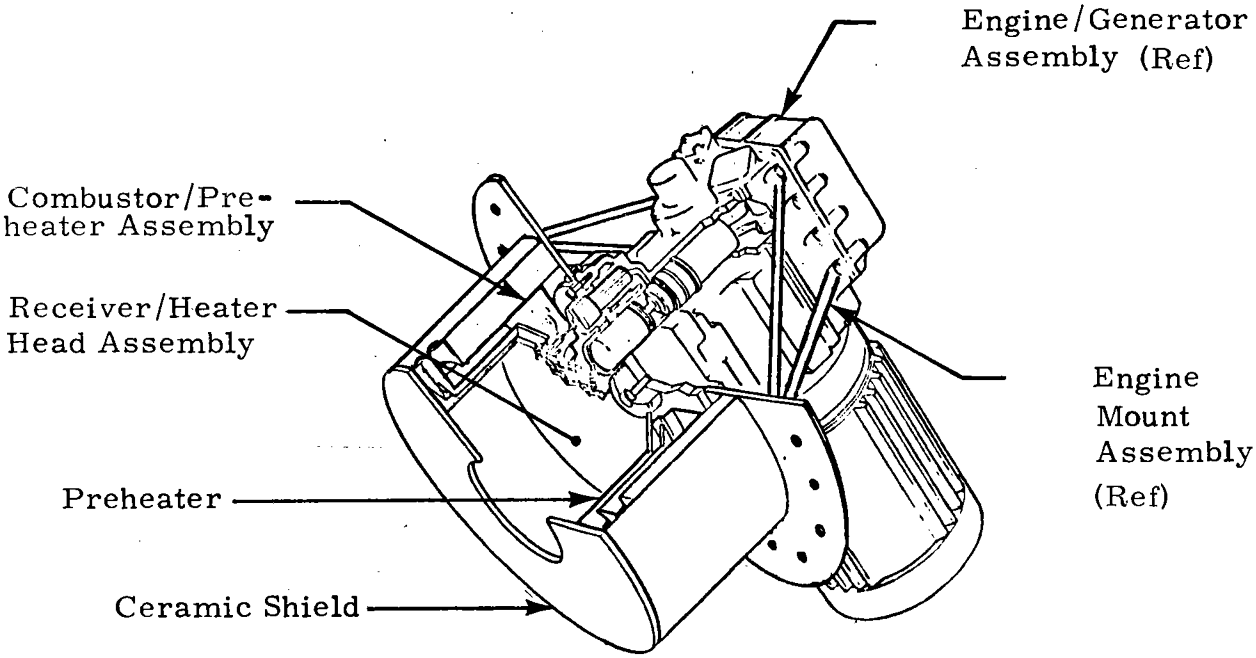


Figure 1. Fairchild Dish Stirling Solar Receiver (DSSR)

PERFORMANCE GOALS

The following performance goals have been identified by JPL for the DSSR 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	67.1 kw$_t$
Combustor turndown ratio	10:1
Allowable focal point mass (design)	1350 kg
(TBC)	500 kg
Peak engine pressure (helium)	2500-3000 psi

PRELIMINARY DESIGN ANALYSIS

The design of a solar receiver is predictably dependent upon certain variables, most of which are, at this point, analytically derived. Fairchild has developed a computer program which iterates these many variables: solar flux at focal point, combined concentrator errors, distance of receiver cone from focal point, receiver cone angle, aperture size and receiver heat transfer characteristics. Iteration of these variables yields receiver sensitivities in terms of material temperature distribution and three-dimensional receiver working stress under thermal and pressure loads.

Results of the preliminary design analysis at this point show that the physical arrangement of the DSSR will result in a compact unit having a total weight of less than 200 lb, a cylindrical shape with an outside diameter of 27 inches and a length of 18 inches from the engine/receiver interface to the front surface of the aperture plate.

The dimensional relationship of the position of the cone-shaped receiver body in which the solar heat is absorbed to that of the focal plane and the engine interface have been thoroughly investigated, and the recommended design point has been defined. Sensitivity analyses have been completed to assess solar flux distribution and performance trends for conditions around the recommended design point.

Typical sensitivity plots for key design parameters are shown in Figures 2, 3 and 5. Estimated overall efficiency accounting for radiation and convection losses for varying aperture size are summarized in Figure 4.

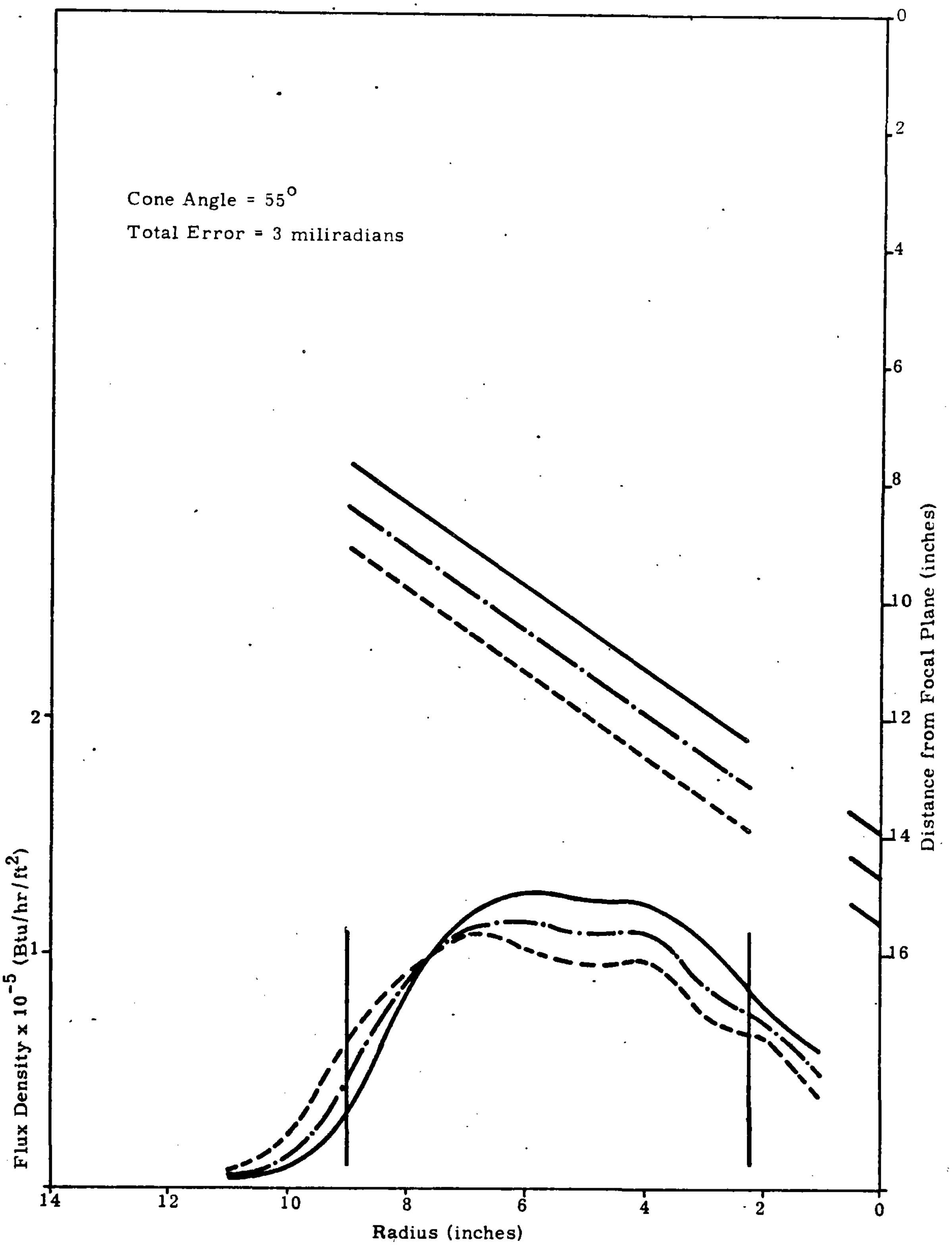


Figure 2. Receiver Cone Position Effect

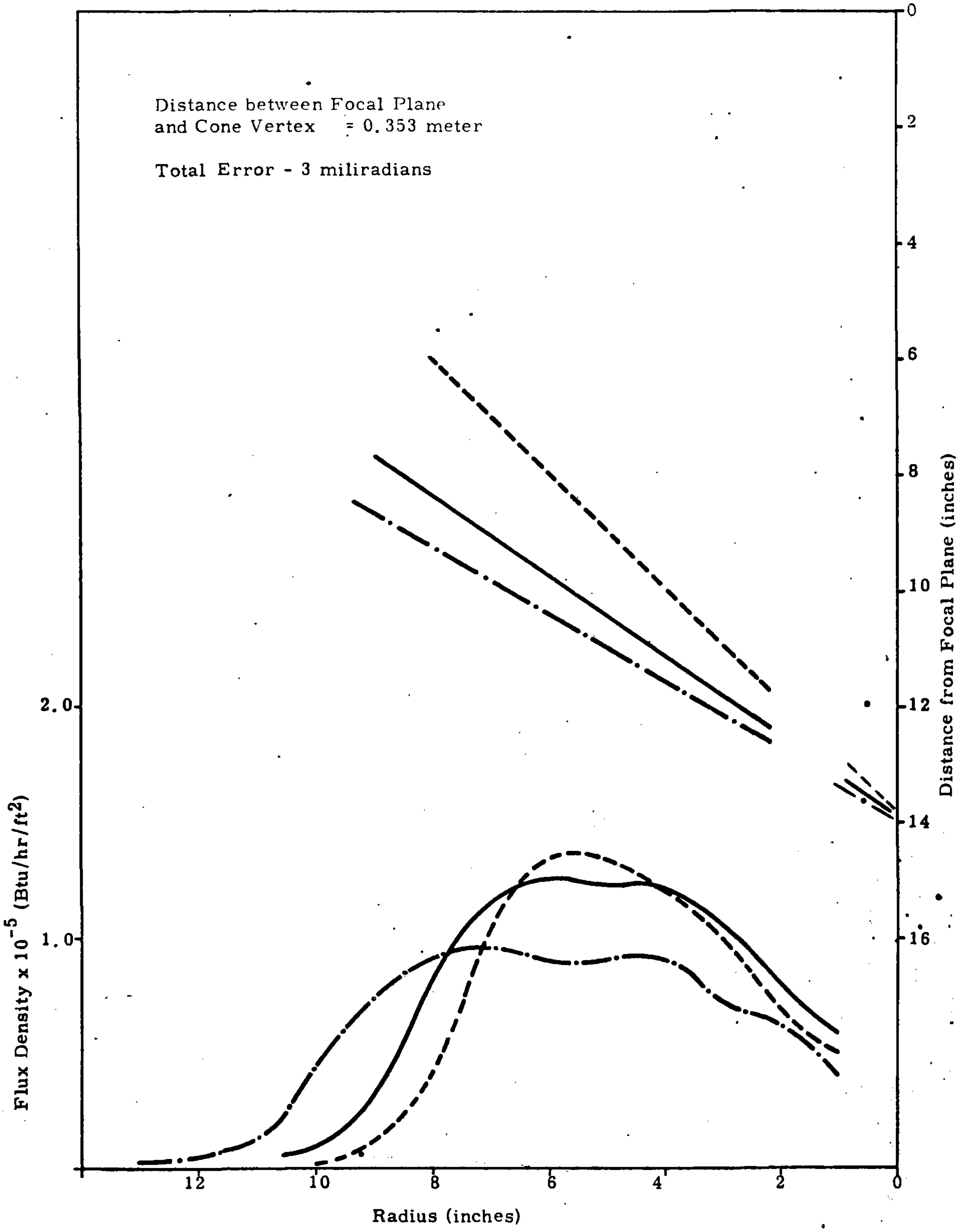


Figure 3. Receiver Cone Angle Effect

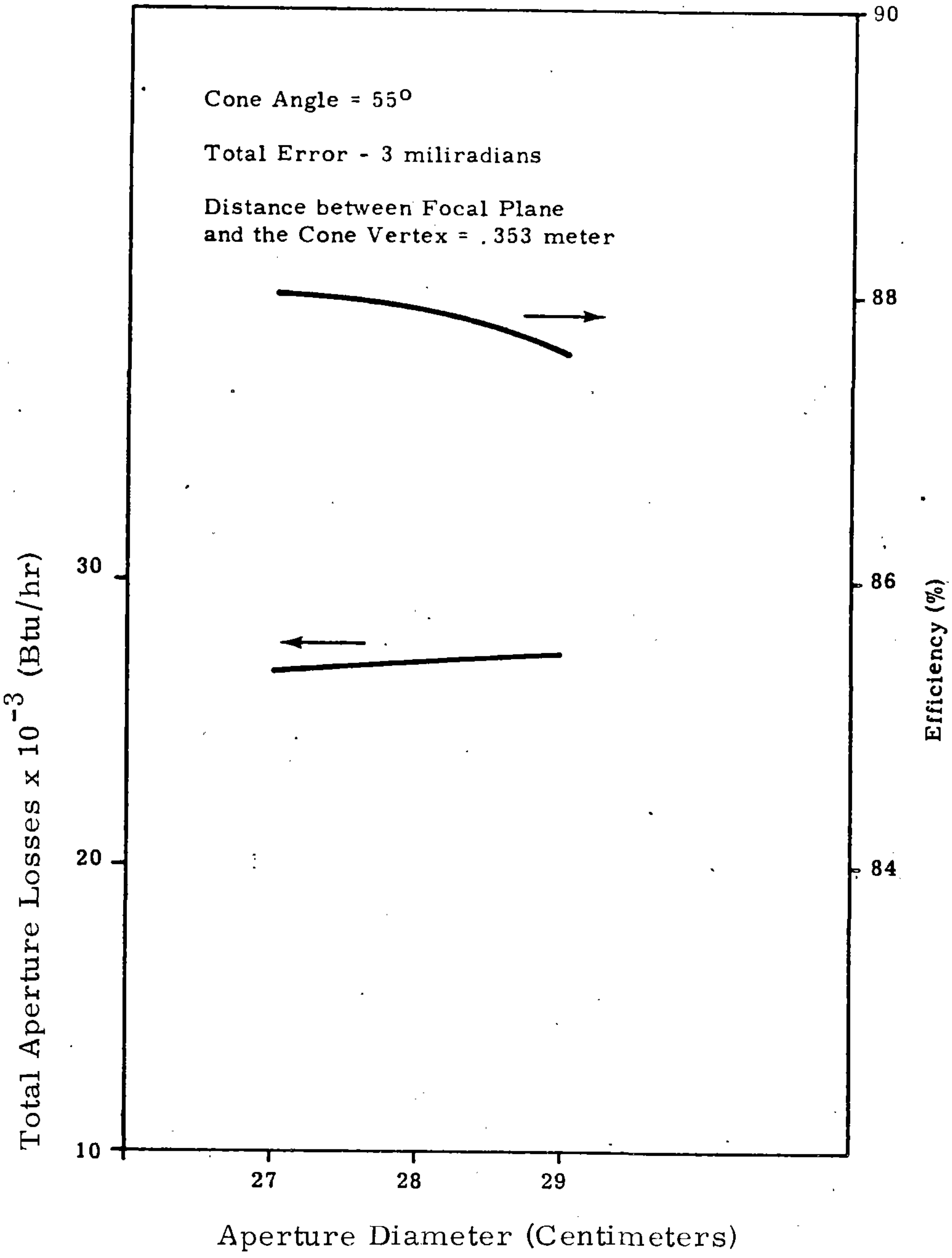


Figure 4. Aperture Size Effect

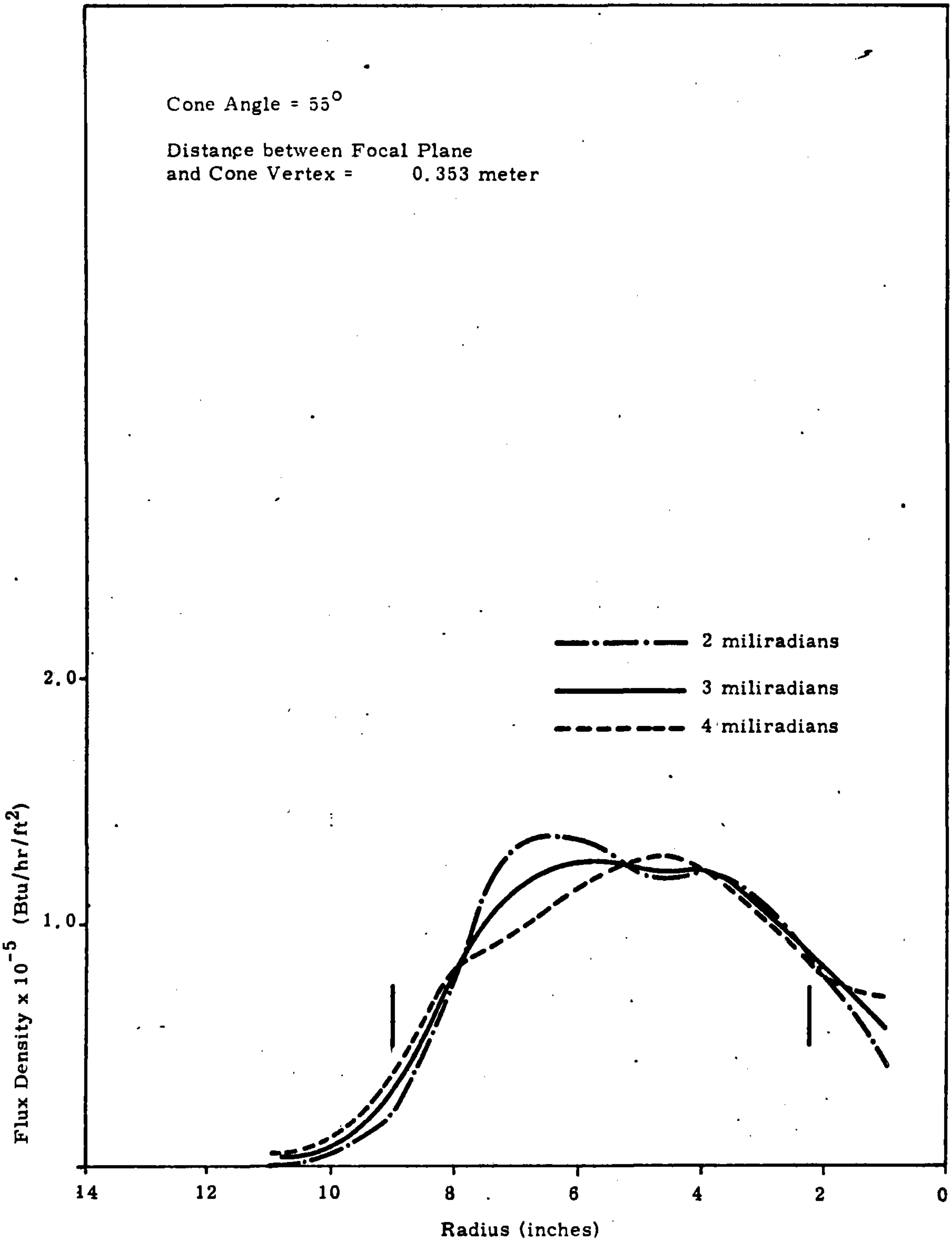


Figure 5. Concentrator Error Sensitivity

Overall temperature distribution in the DSSR cavity under full solar flux and 10% combustion heat and a working fluid temperature of 1500°F has been calculated for two receiver body designs: (1) brazed Inconel 617 plate, and (2) Inconel 617 tubes imbedded in copper. Typical temperature distribution patterns (°F) are shown in Figure 6 for these two designs.

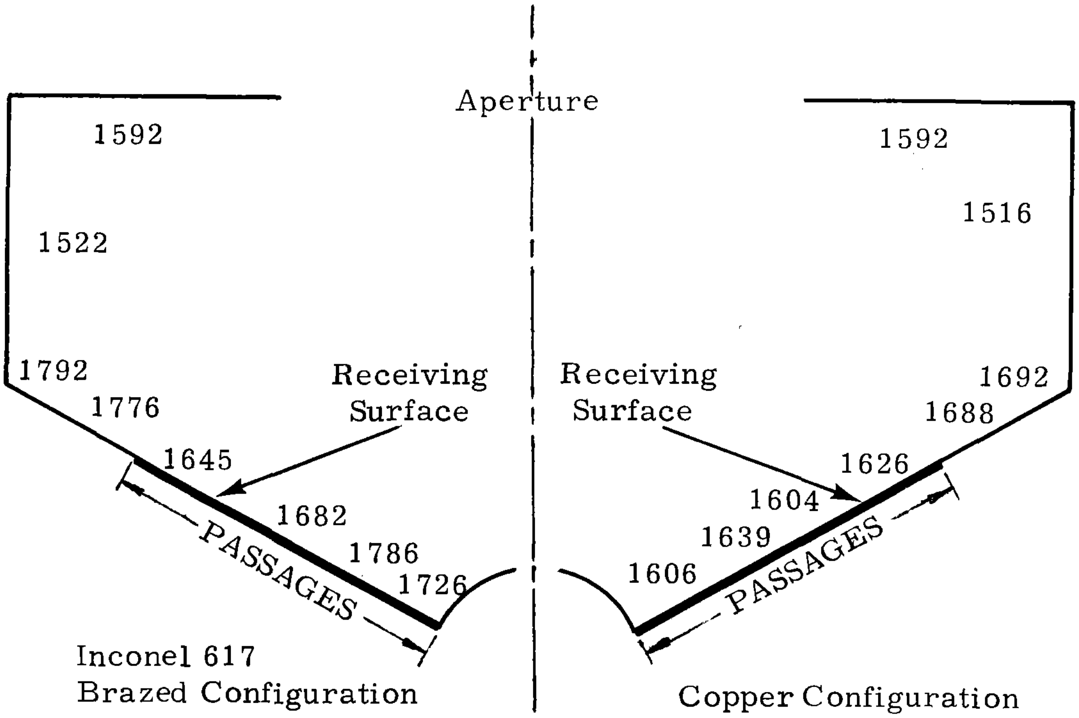


Figure 6. Typical Temperature Distribution on Cavity Surfaces

COMBUSTION SYSTEM

The combustion system for the fossil fuel combustion augmented Stirling engine solar receiver will have the following general configuration:

> The total heat transfer requirement will be provided with a combination of 1) convection directly to the receiver cone which contains the helium passages, and 2) radiation from a "cup" shaped refractory insert positioned directly below the cone.

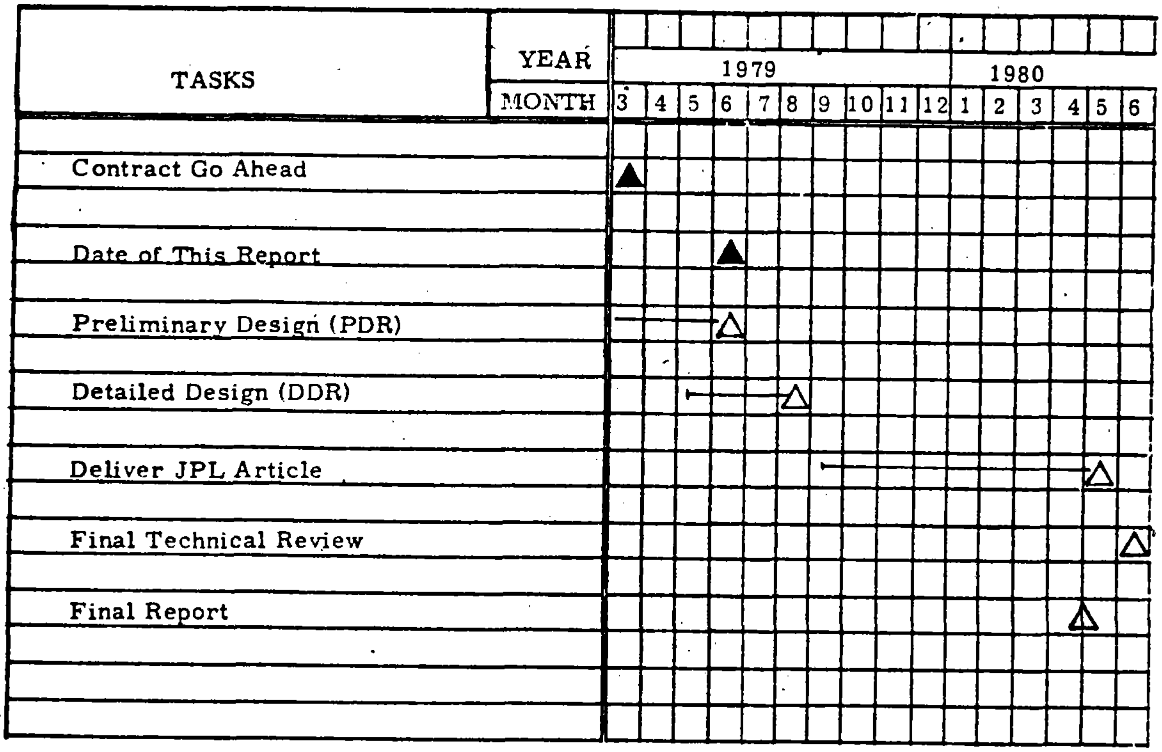
The fuel will be injected into the combustion space through 8 to 12 individual nozzles which are sized to provide flow velocities of 500 to 600 ft/sec, through a fuel injector ring positioned at the upper-outer edge of the cup-shaped insert. The nozzles will inject the fuel downward against the leading edge surface of the cup in an impinging-circumferential flow mode.

Combustion air (preheated to approximately 1300°F) will be provided by a circumferential channel positioned around the fuel injector tube. The air channel will be provided with vanes to direct the air around and parallel to the fuel jet flow. The air channel dimensions are sized to provide an air to fuel momentum ratio high enough to complete combustion prior to fuel impingement on the cup surface.

The hot combustion gases will have sufficient momentum to impinge upon and scrub the cup surface while flowing between the regenerator connecting tubes. The gases will then return along the cone surface and exit adjacent to the burner ring before entering the preheater.

PROGRAM SCHEDULE

MAJOR TECHNICAL MILESTONES
DSSR-FOSSIL AUGMENTED JPL CONTRACT 955400
19 JUNE 1979



15 KW FREE-PISTON SOLAR STIRLING ENGINE/ALTERNATOR

CONTRACT NUMBER: NASA DEN3-56
STARTING DATE: September 5, 1978

G. R. Dochat
Mechanical Technology Incorporated
Latham, New York 12110

H. M. Cameron
NASA/Lewis Research Center
Cleveland, Ohio

Description of Task

The primary purpose of the study was to develop a conceptual design of a nominal 15 KW electric solar Stirling engine/alternator. The study performed configuration definition studies, including parametric evaluation of selected concepts with a final ranking of all attractive configurations. Upon selection of the best configuration from overall system compatability, the conceptual design of a near term solar engine capable of providing nominal 15 KW electric output was developed. Paralleling the conceptual design, an implementation assessment of the selected design was performed, defining the producibility (cost), durability, and growth potential.

Summary

The results of this study conclude that a free-piston solar Stirling engine/alternator can be designed and developed to meet the requirements of a near term engine. The conceptual design developed during this study represents an adaptation of previous engine designs that have been fabricated, assembled, and tested by MTI. The engine is designed to have an overall system efficiency of 38% and provide 15 KW output. This high efficiency will enable overall system costs to be reduced. The free-piston Stirling engine driving a linear alternator offers the potential for long life, inherent reliability, and has maintenance free characteristics of a hermetically sealed power unit. The above advantages

can be realized in a near term solar Stirling engine without major development effort.

Key Results/Accomplishments

The conceptual design of the 15 KW free-piston solar Stirling engine/alternator is presented in Figure 1. The engine design incorporates the following features to provide long life and reliability:

- Gas Bearings — eliminate wear
- Close Clearance Seals — no lubricant, no contamination, no potential failure mechanism
- Gas Spring — no mechanical failure mode
- Posted Displacer — eliminate need for close tolerance between piston and displacer
- Internally Supplied Bearings — eliminate external compressor

General description of the conceptual design is as follows:

Working Fluid — helium
Heater Head Material — Inconel 713 LC
Heater Head Temperature — 1500°F
Displacer Cylinder Diameter — 4"
Piston Cylinder Diameter — 7"
Displacer Amplitude — 1.5"
Piston Amplitude — .67"
Phase Angle — 36°
Regenerator — annular-knitted wire
Cooler Temperature — 110°F
Charge Pressure — 58.2 Bar
Gas Bearing Supply Pressure — 64 Bar
Radial Clearance — .00075"
Bearing Material — chrome oxide
Alternator — permanent magnet utilizing samarium-cobalt ($Sm\ Co_5$)
Alternator Radial Airgap — .010
Alternator Efficiency — 92%
Alternator Voltage — 240 volts
System Efficiency — 38%

The overall heat balance of the conceptual design is presented in Figure 2.

The head would be an investment cast from Inconel 713 LC, a well developed cobalt free casting alloy with creep properties which are two to three time better than most wrought materials available. The head would be cast with a series of pins projecting from the inside surface. When finishing the casting, it will be necessary to grind only the tips of the pins, thereby reducing machining time and also wheel wear. The reduced wheel wear will make it easier to maintain size and straightness.

The hot end of the head is partially filled with a stuffer body. There is an axial passage for the working gas, 1.3 inches in diameter, from above the displacer which runs to the crown of the head and connects to an annular heater space, .120 inches wide, between the stuffer and the head casting itself. The stuffer is located by pins from the head surface allowing the working gas to flow through the space and back to the regenerator.

The annular regenerator is intended to be packed with a knitted wire material using a wire diameter of .003 inches. The regenerator surrounds a portion of the displacer and is followed by a fabricated tubular cooler. There are 200 tubes of .138 inches inside diameter with a wall thickness of .025 inches, 4.00 inches long, arranged in radial rows of four. The tubes are straight and parallel to the engine axis, exiting into a gallery which connects to both the cold space below the displacer and the compression space above the power piston.

The displacer is 4.00 inches in diameter, and has a stroke of 3.0 inches. It is of the "posted" type, carried on gas bearings for high reliability and low wear. The gas bearings are fed from the engine pressure wave which charges a plenum through one or more check valves. The bearing drains discharge into a plenum in the pressure vessel surrounding the cylinder. This plenum is also center ported to the working space, the piston gas spring, and the displacer gas spring, allowing all spaces to operate at the same average pressure.

The cylinder for the power piston is 7.00 inches inside diameter, with an overall length of approximately 19.5 inches, and is made from low carbon steel. The inside surface forms a two-plane gas bearing which supports the power piston. The bearing is supplied by the engine pressure wave charging a plenum through one or more check valves which can be replaced without dismantling the engine/alternator.

The bearing surfaces are coated with chrome oxide and ground to a highly accurate finish diameter. The relatively large diameter in relation to length will permit both bearing surfaces to be finished at the same time, eliminating all alignment problems. The low carbon steel piston is also coated with chrome oxide and ground in one setup, guaranteeing concentricity and alignment. Because the alternator stator is inside the piston, the finish grind of the exterior may be done either before or after the magnets are assembled to the piston.

The stator for the alternator is made of tapered cold rolled steel laminations clamped to a center tie bolt. Because the coil slots open to the outside, it should be possible to wind the coils and achieve a very good fill factor. Although the alternator is very efficient, the energy to be dissipated exceeds 1 KW due to the high power level. Consequently, a cooling coil was brazed to the interior of the tie bolt, providing a means of stabilizing the temperature. A diverter fitting routes part of the engine cooler discharge water through the alternator. The cooling lines enter and exit through a plug in the end of the pressure vessel. The same plug would contain feed throughs for the alternator electrical output.

The stator assembly is cantilevered from the end of the cylinder and would probably be subassembled using shims or a centering ring for alignment. The piston would then form an excellent guide during the insertion of the piston, preventing the permanent magnet rings on the piston from contacting the stator. The alternator and cylinder would then be installed in the pressure vessel, and then installed on the engine as a unit. The pressure vessel would be manufactured from carbon steel, designed to satisfy ASME codes as an unfired pressure vessel.

The conceptual design was required to interface with the General Electric heat receiver. The heat receiver utilizes liquid sodium as the heat transport medium to the engine heater head. For this reason, a single piece cast heater head was selected for the conceptual design (shown in Figure 1), as it was considered that a tubular head would not provide the reliability necessary for a solar engine. The free-piston Stirling engine has no preferred operating orientation and, hence, no special interface requirements with the heat receiver are necessary. The interface of the conceptual design with the given heat receiver concept is shown in Figure 3.

In addition to the heat pipe heat receiver, MTI also investigated a direct heat receiver concept. The heater head design for such a concept is shown in Figure 4. The heater tubes are half buried into a copper block and tubes are involute in shape to match solar insolation. The direct heat concept, while having the disadvantages of small heat storage, uneven heat flux, complex heater tube arrangement, and extra controls, does offer lower system cost and simplicity.

The electrical interface is a utility grid. The stability of the engine/alternator when coupled with the grid was evaluated in detail during this study. It is concluded that the conceptual design will be stable during operation between operating mode, standby, and perturbations of the system. The method of control selected was mean pressure control. Figures 5 and 6 present the transient response of the system during operation, and Figure 7 shows the basic engine control system.

In parallel with the above conceptual design, an implementation assessment was made to determine state-of-the-art, producibility, and durability. The results of the state-of-the-art assessment (shown in Table 1) indicates that the conceptual design is within the current or is an adaption of the state-of-the-art.

The producibility assessment was performed based on a production level of 25,000 units per year. This level of production was determined based on the method of reference 1. The resulting prime cost for various engine components is shown in Figures 8 and 9.

To assess the durability/reliability of the solar Stirling engine/alternator, all engine components were examined to determine function, failure mode, possible failure cause, and failure effect on the system. Failure probabilities were assigned to each failure mode. Based on this preliminary failure mode and effects analysis, an overall failure rate of 20.86 failures per million hours was estimated. This corresponds to a reliability in terms of mean time between failure of 47,940 hours. Failures that would result in shutdown of the system only have 4.05 failures per million hours, or about 1/5 of the total possible engine/alternator failures.

Conclusion

In conclusion, the study developed a design of a free-piston solar Stirling engine/ linear alternator that could provide required power, operate at high system efficiency, have potential for long life, high reliability, and can be produced at reasonable cost. This can be accomplished as a near term engine with modest development effort. It is considered that the free-piston solar Stirling engine with the above advantages will accelerate the commercialization of small dispersed solar thermal power systems.

Reference 1) Blackman, A. W.; "The Market Dynamics of Technological Substitutions," Technology Forecasting and Social Change, Volume 6, 1974, pp. 41 - 63.

TABLE I

Critical Component	Key Technology	Technology Status
1) Heater Head	• Condensing Liquid Metal Heat Transfer	• Significant Improvement
	• Cast Heater Head	• Significant Improvement For High Heat Transfer
2) Regenerator	• High-Volume Processing With Effective Material Utilization	• Adaptation of State-of-the-Art
3) Bearing System	• Internally Supplied Bearing Gas	• Adaptation of Current Technology
	• Surface Coatings Techniques	• State-of-the-Art
4) Seals	• Close Tolerance Seal	• Extension of State-of the-Art for Life
5) Displacer Drive	• Posted Displacer and Gas Spring	• State-of-the-Art
6) Alternator		
- Plunger	• Rare Earth Permanent Magnet Manufacturability	• Adaptation of Current Technology
- Stator	• Manufacturing Technique (Microlamination, etc.)	• Adaptation of Current Technology
7) Control	• Engine/Alternator Stability Matching	• Adaptation of Current Technology
	• Displacer Gas Spring Volume Control	• Adaptation of Current Technology
	• Engine/Receiver Interface Control	• Significant Improvement

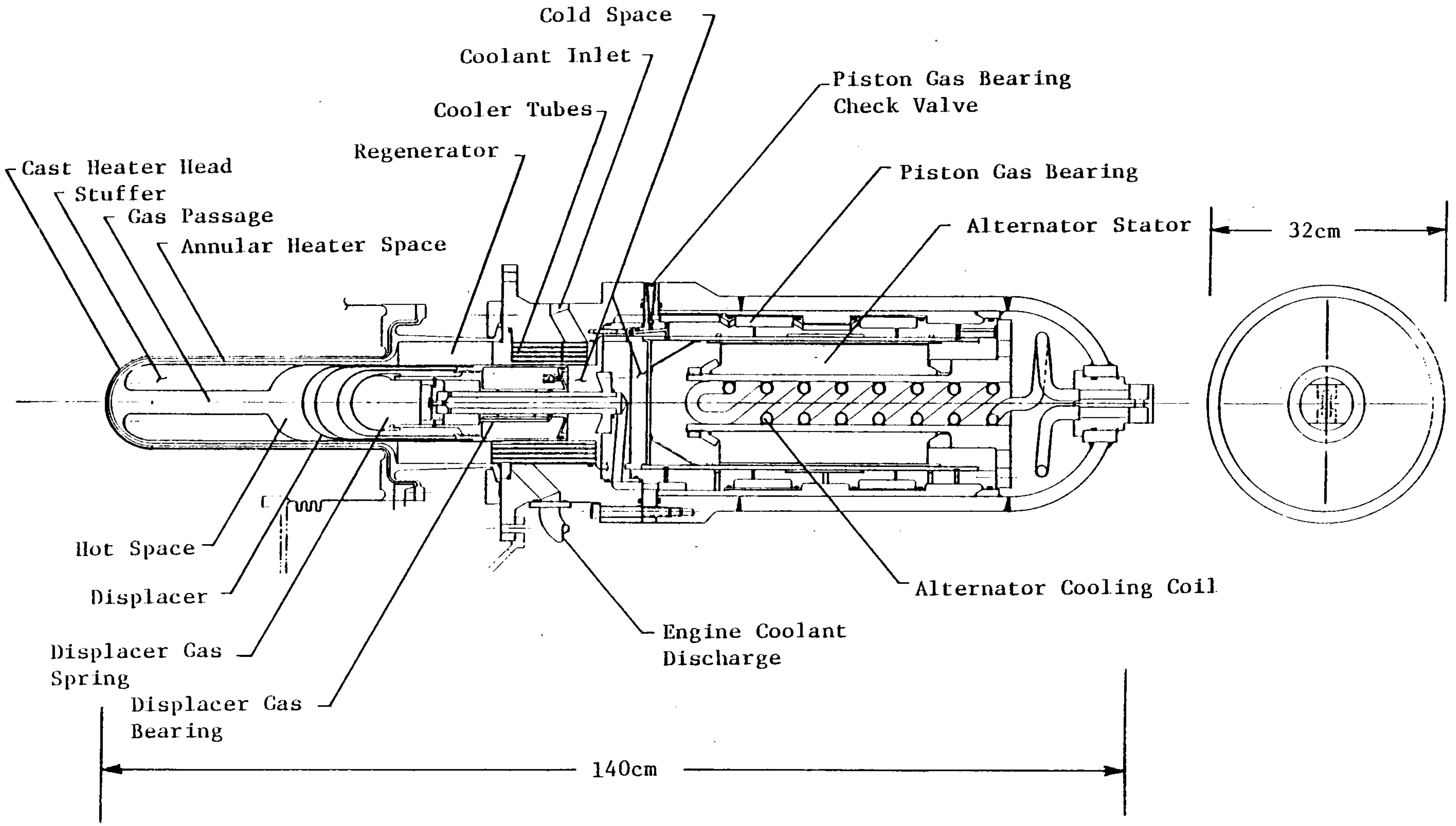


Figure 1 15 kW Free-Piston Solar Stirling Engine Conceptual Design

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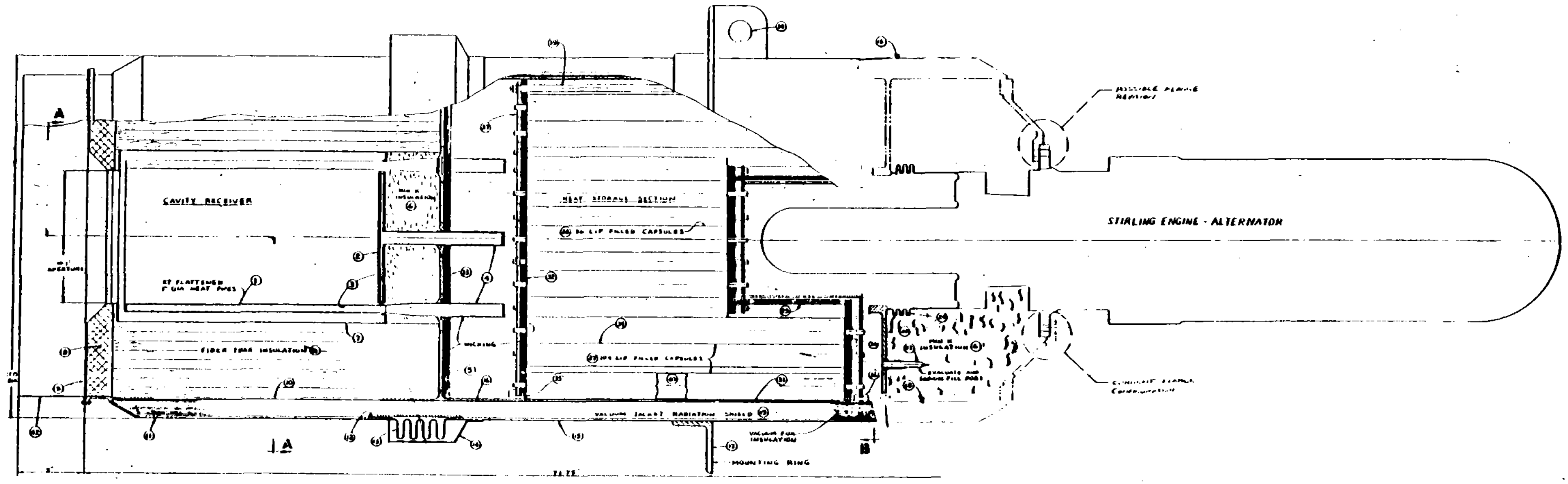

Figure 3 Stirling Engine/Heat Receiver Interface

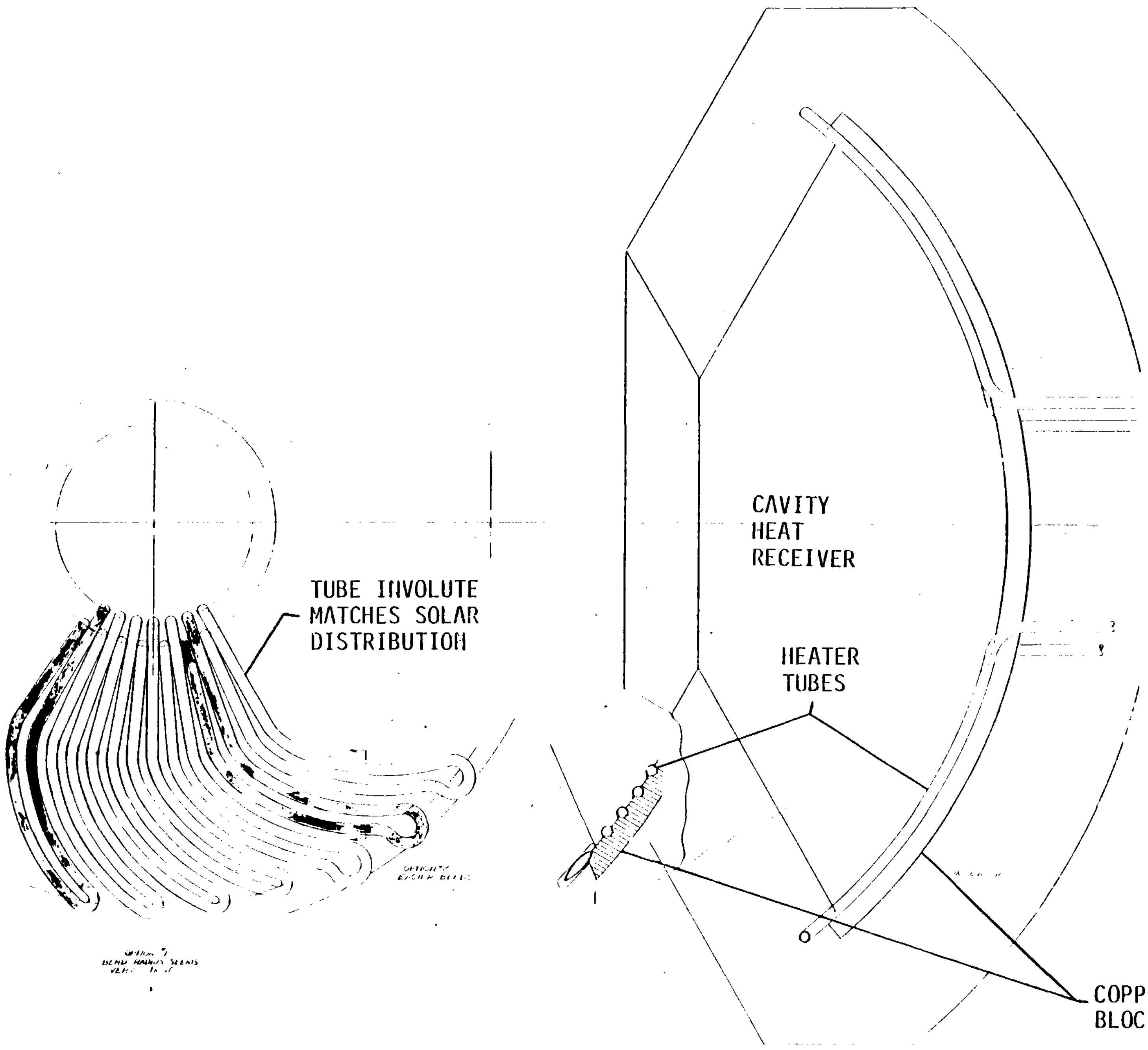

Figure 4 Direct Insolation Heater Concept

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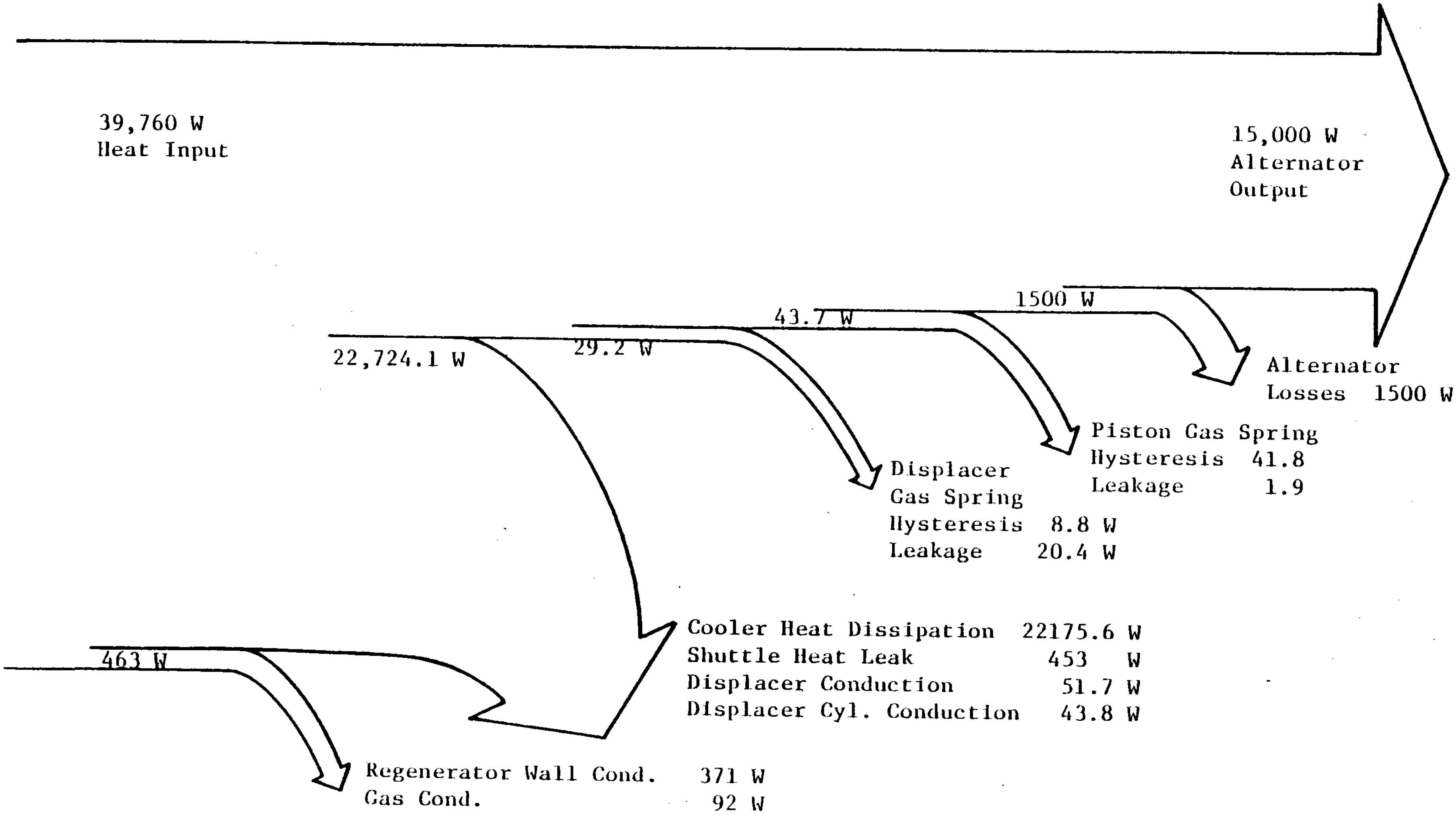


Figure 2 Engine Heat Balance

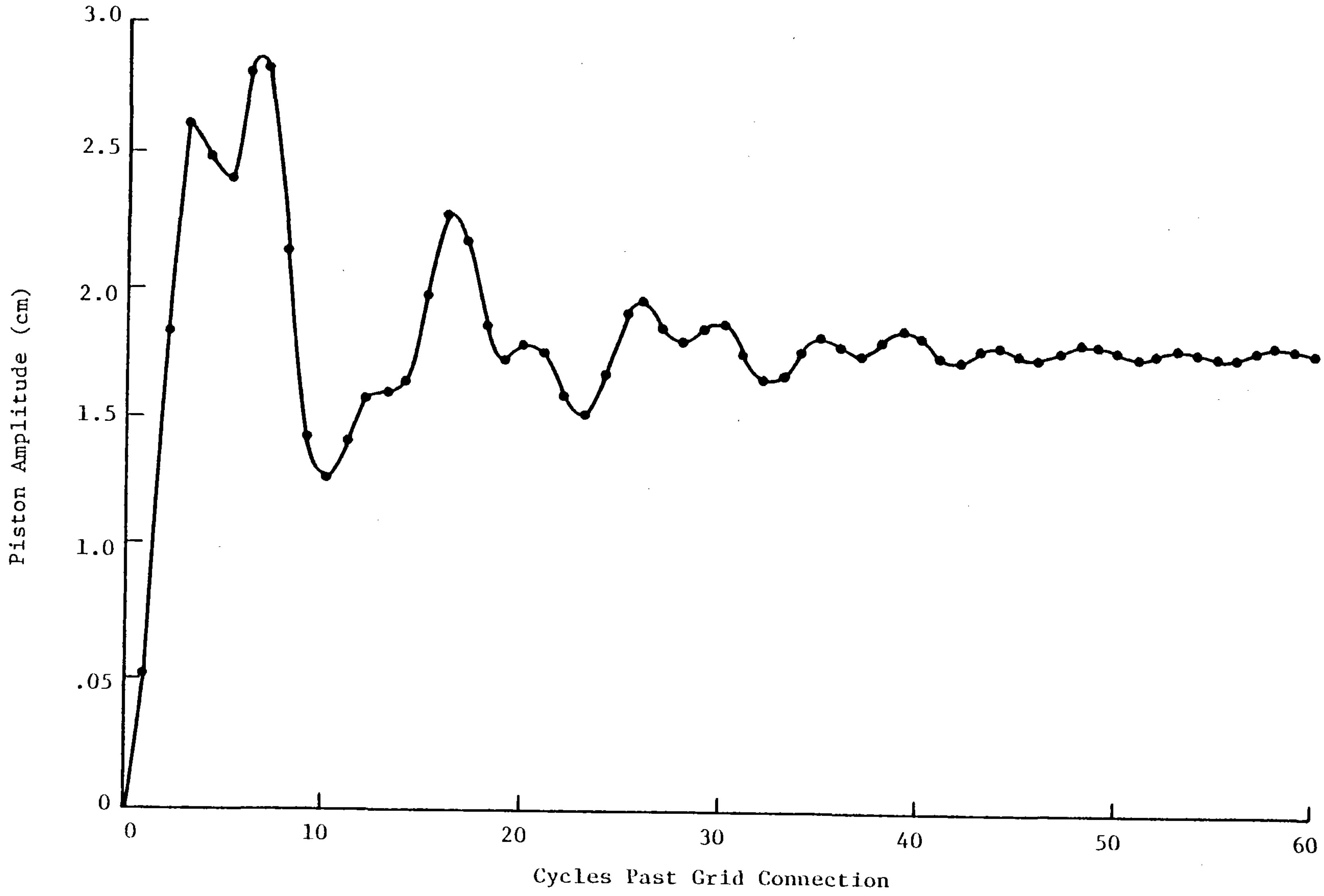


Figure 5 Transient Engine Response Standby Mode to Operate

79745

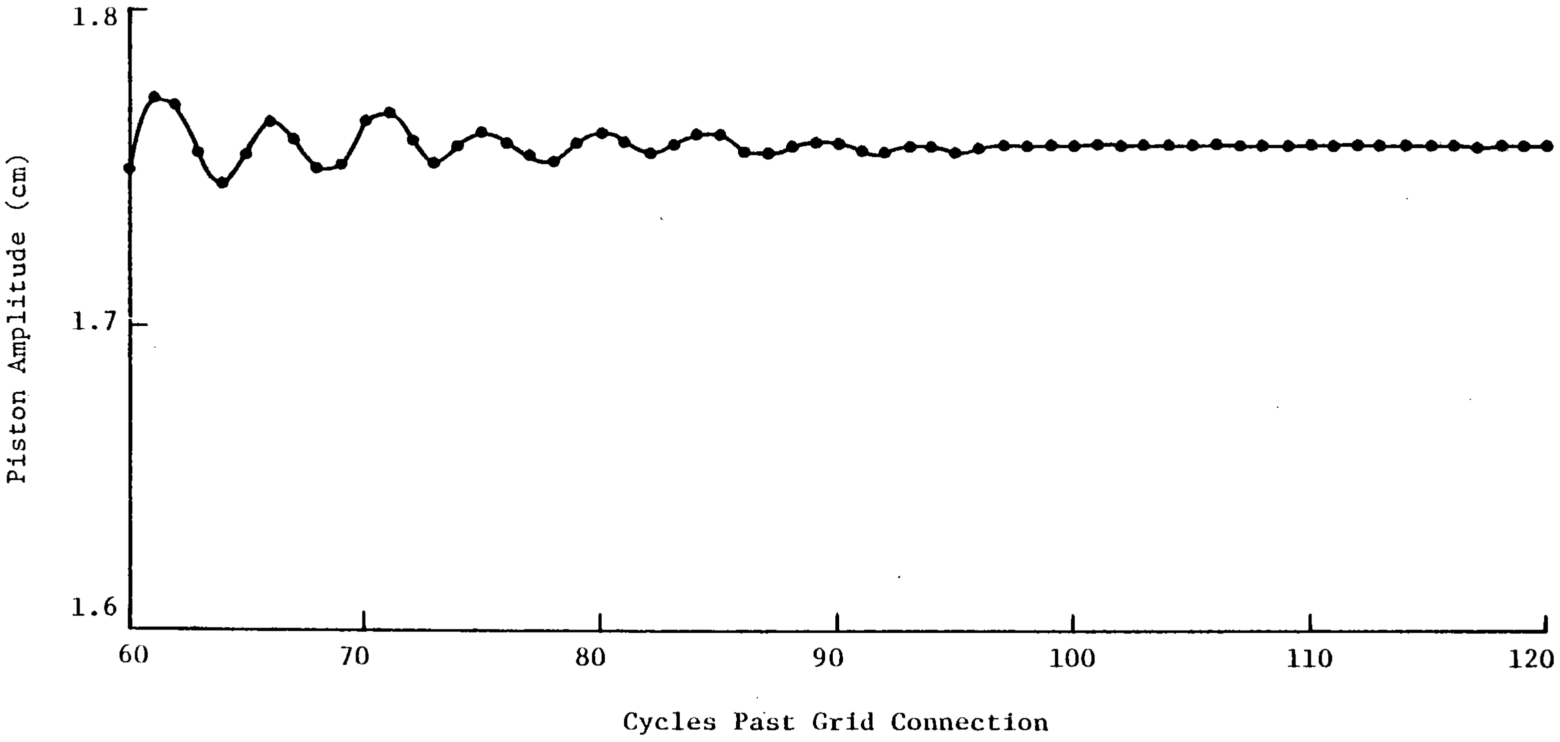


Figure 5 (Cont'd)

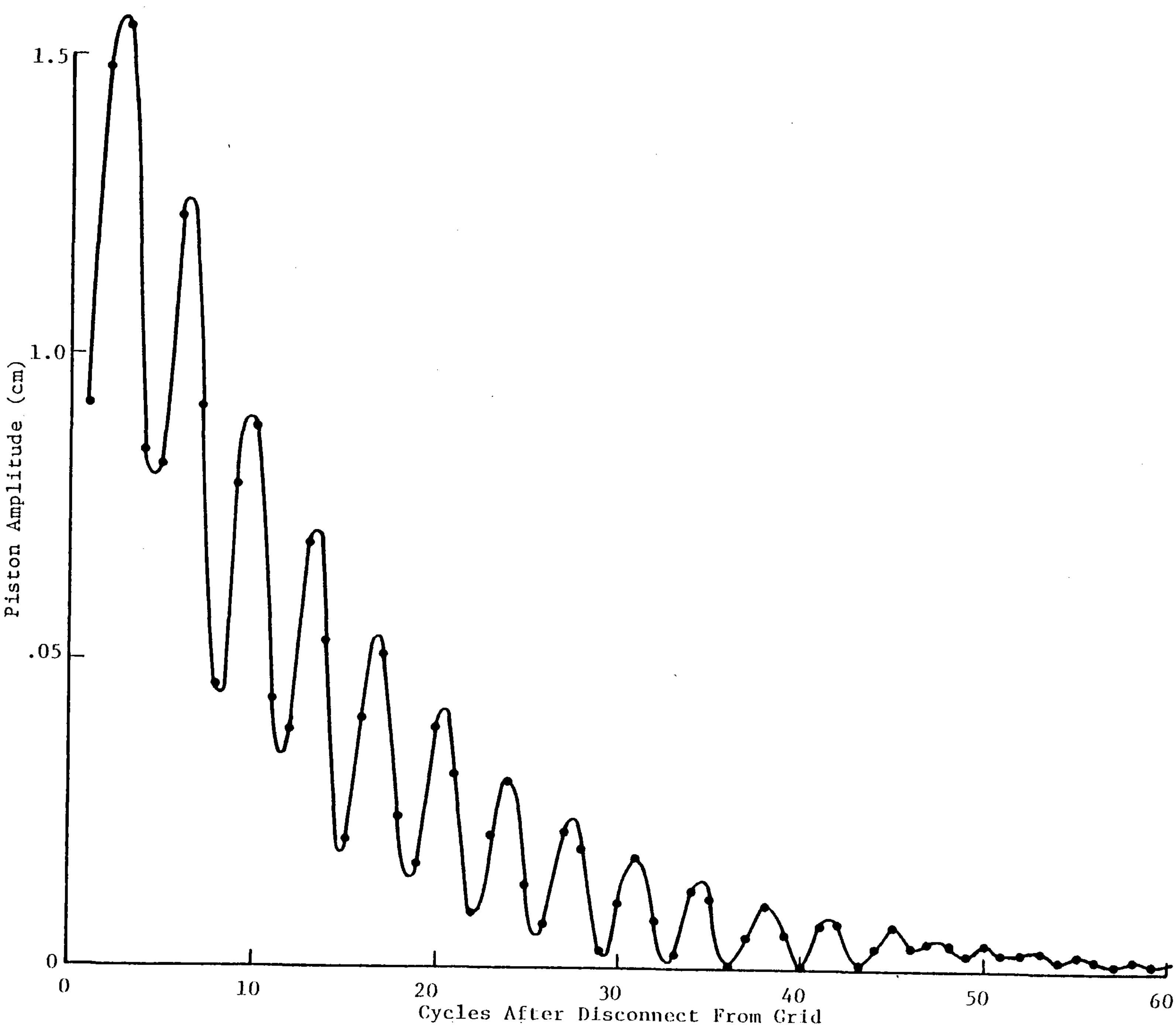


Figure 6 Transient Engine Response Operate to Standby Mode

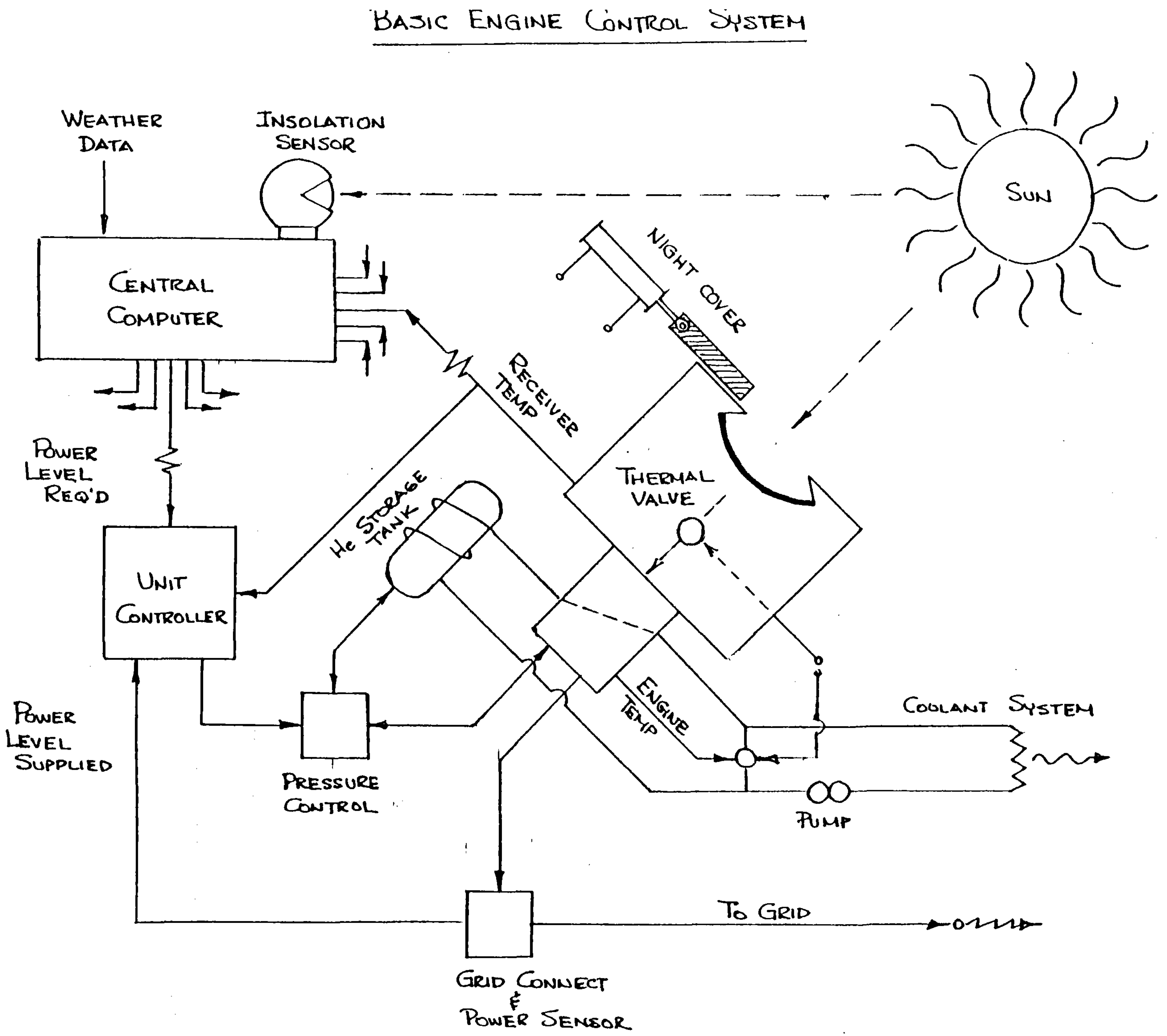
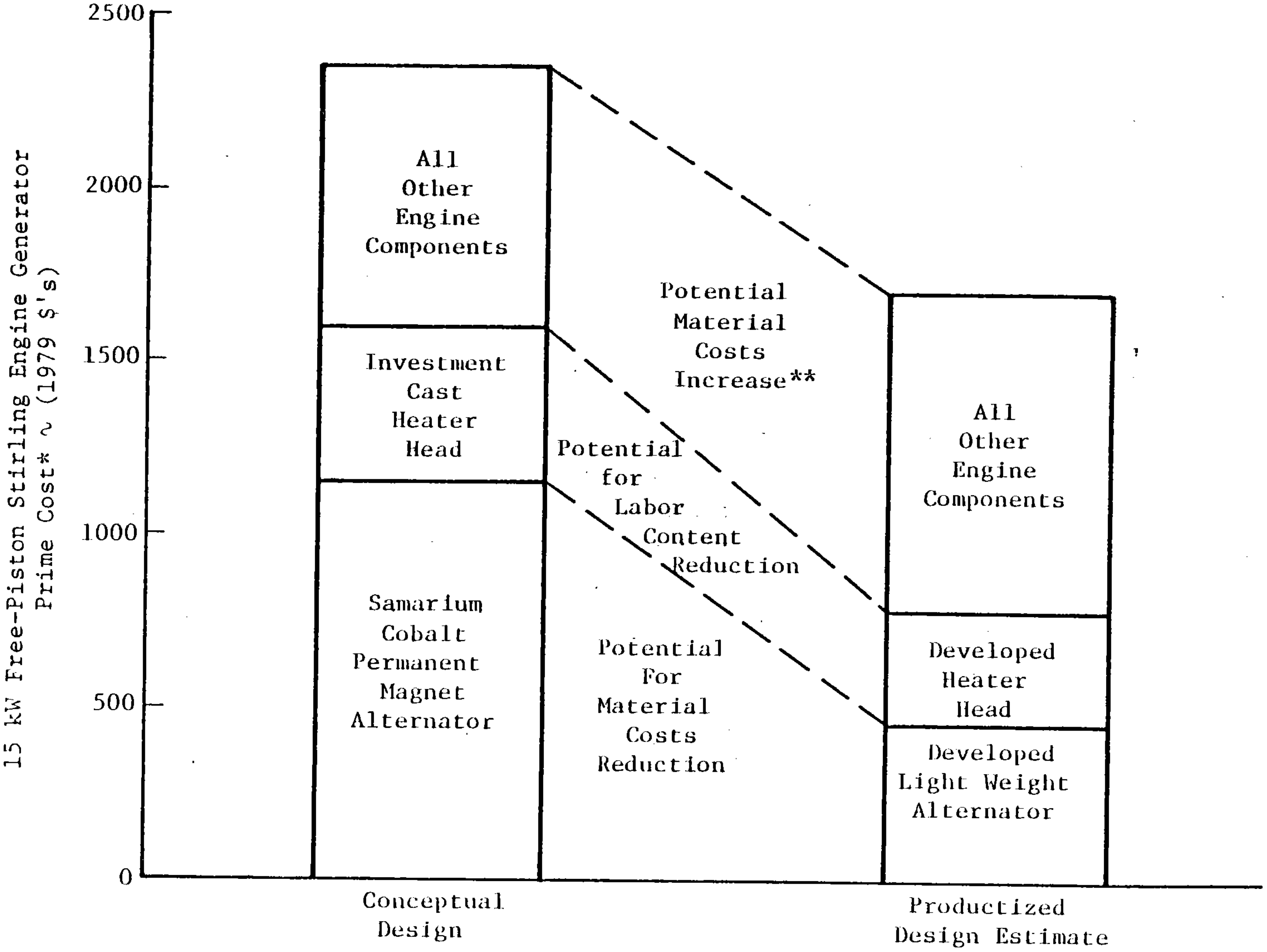

BASIC ENGINE CONTROL SYSTEM
WEATHER DATA
INSOLATION SENSOR
SUN
CENTRAL COMPUTER
NIGHT COVER
RECEIVER TEMP
POWER LEVEL REQ'D
He STORAGE TANK
THERMAL VALVE
UNIT CONTROLLER
ENGINE TEMP
COOLANT SYSTEM
POWER LEVEL SUPPLIED
PRESSURE CONTROL
PUMP
TO GRID
GRID CONNECT & POWER SENSOR

Figure 7



*Prime Cost Includes Direct Labor and Materials Only

**Possible Compromise to Accommodate Potentially Heavier Alternator Plunger Design

Figure 8 Prime Cost Estimate for Conceptual Design

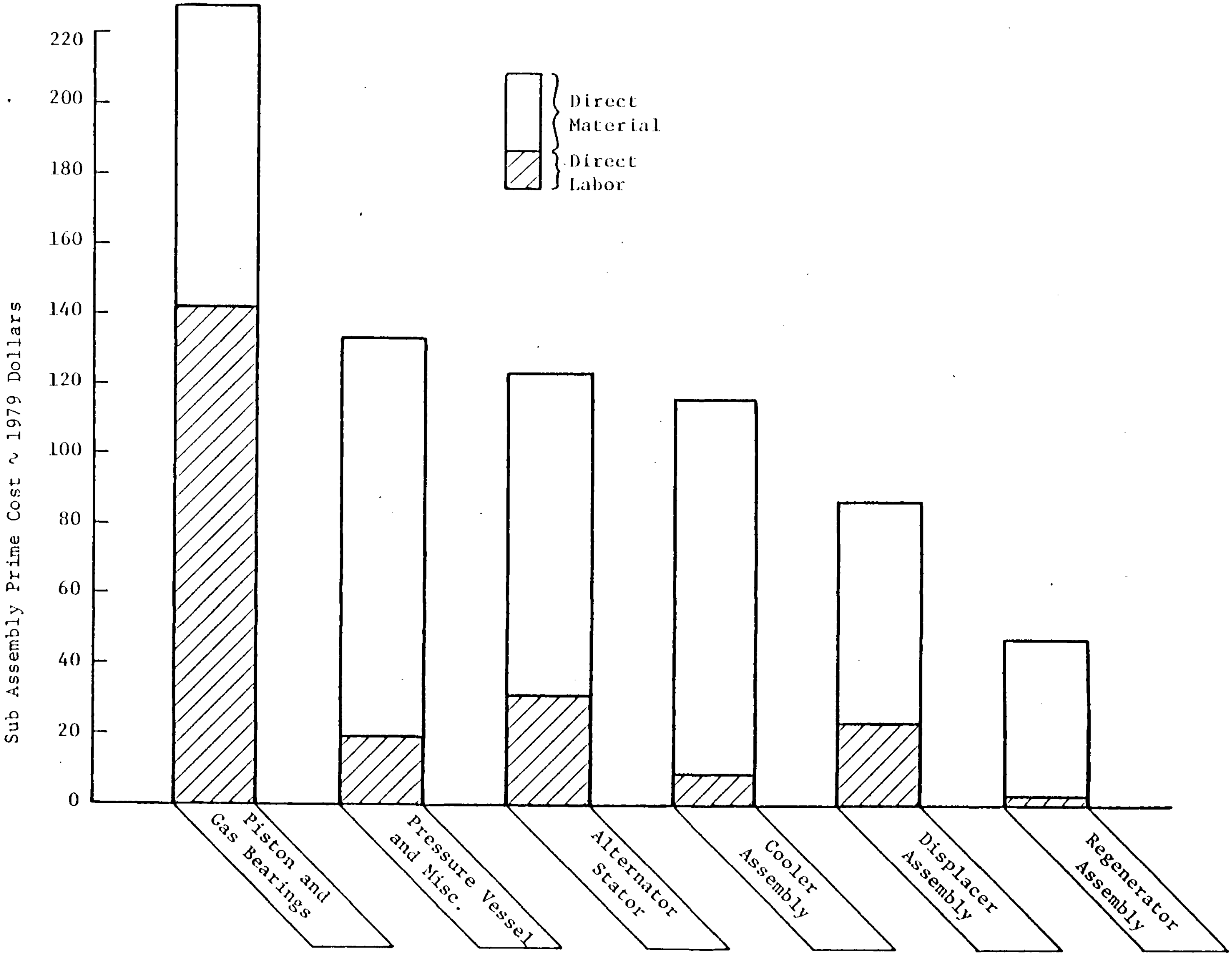


Figure 9 Prime Cost Estimate for Engine Component Conceptual Design

KOMMANDITBOLAGET
UNITED STIRLING
(SWEDEN) AB & Co

15 kW KINEMATIC STIRLING ENGINE -
- CONCEPTUAL STUDY

Contract Number: NASA DEN 3-56

Main Contractor: Mechanical Technology Incorporated
Latham, New York 12110

Starting Date: September 21, 1978

Hans-Göran Nelving, Lars E Sjöstedt

United Stirling (Sweden) AB & Co
Fack, S-201 10 Malmö 1, Sweden

SUMMARY

A number of kinematic Stirling engine concepts covering both single acting and double acting types have been studied and evaluated. A conceptual design of the engines has been performed and optimized within the constraints given by the assumptions and other characteristics of the complete system.

The results indicate that:

- No siginificant difference in performance exists for the selected single acting and double acting engines at the 15 kW power level.
- Non performance related factors, such as the possibilities to scale the engine to future higher power levels, present development status for different engine concepts and the technological risk involved in the remaining development work, favours the double acting 4-cylinder engine. Thus United Stirling has recommended a 4-cylinder U-configuration for further study which has later been approved by NASA. This engine configuration has parallel cylinders and a drive with two crankshafts geared to a common output shaft.

A short explanation of the working principle of a 4-cylinder double acting engine is given in appendix 1.

- The Stirling cycle analysis shows that an engine efficiency of 46% can be anticipated with only a moderate technological risk involved. Allowing a 95% efficiency for the alternator this gives a combined engine alternator efficiency of 44%.

SCOPE OF WORK AND OBJECTIVES

A dispersed solar electric power generating system may be looked upon as composed of three subsystems: concentrator, receiver and engine/alternator. The purpose of this study is to identify an advanced Stirling engine concept with the potential of being developed and demonstrated in a 5 - 6 year time frame.

The following assumptions were used when evaluating different engine concepts.

- 15 kW electric power from the generator
- 3 phase power
- power delivered to electric grid
- energy storage included in the receiver
- insolation profile from Lancaster, California.

The objective is to identify an engine/alternator concept which conforms with the assumptions above and which converts no less than 35% of the energy input to the engine heater into electric power.

The heat absorbed by the receiver may be transported to the engine by means of an intermediate device - a heat pipe, which is here treated as a part of the receiver. This solution is referred to as indirect heating below. The alternative is to design the heater head of the Stirling engine to absorb the insolation. This solution is referred to as direct heating and demands a complete integration of the engine with the receiver.

APPROACH

The synthesis of a Stirling engine concept can be made in several different ways and many design parameters are involved, which makes the analysis and optimization of engines a very complex process. The reason is that there are several important components and that for each of these there are a number of critical factors. This is illustrated below.

Components	Critical factors
Heater	Temperature distribution Flow losses Durability
Cylinder/regenerator	Conduction losses Flow losses Durability Dead volumes
Seals	Gas leakage Oil leakage Wear Space requirements
Drive mechanism	Mechanical efficiency Torque variations
Controlability	Control principle Gas volume
Auxiliaries	Power demand Efficiency Design adaptation

Each of the major components exist in several variations and a number of different engine working principles may be employed. Each of the following factors give rise to several alternatives:

- Single acting or double acting working principle
- Direct or indirect heating
- Annular regenerators or one or more separate regenerators
- One or more cylinders
- Sliding seal with or without a separating diaphragm, roll sock type of seal or other type of seal
- Rhombic drive, one or more ordinary crankshafts, swash plate or other type of drive
- Dead volume, temperature, mean pressure, phase or stroke control
- Auxiliaries and cooling system specifications may also influence the engine design

KEY RESULTS

By combining previous United Stirling experience with computer calculations and optimizations of engine performance a number of configurations have been identified for further analysis. Some features of these concepts are illustrated in figures 1 - 3.

Single acting		Double acting	
Indirect heating	Indirect heating	Indirect heating	Indirect heating
1-cylinder	2-cylinders	4-cylinders	4-cylinders
Multiple reg.	Multiple reg.	Annular regenerator	2 regenerators/cyl
Rhombic drive	Single ordinary crankshaft	USS U-drive	USS U-drive
Roll sock seal	Sliding seal	Sliding seal	Sliding seal
Mean pressure control	Mean pressure control	Mean pressure control	Mean pressure control

The analysis indicates that an engine efficiency of 38 - 40% is feasible for single acting engines. Engine efficiency is based on the ratio of shaft power to absorbed heat and excludes power losses from auxiliaries, such as water pump and generator. Ambient conditions are 1 500 °F on the outer tube wall of the heater and 110 °F in the cooling water to the engine and assumes that helium is used as the working gas. A reduction of the cooling water temperature to 60 °F increases the efficiency with 2 - 3%.

Under the same assumptions double acting engines give an efficiency of 40 - 41% and approximately 43% for 110 °F and 60 °F cooling water temperature respectively. The calculations were made with the existing United Stirling computer codes. These codes are well validated by comparison between calculated data and test data from laboratory engines of several types and sizes.

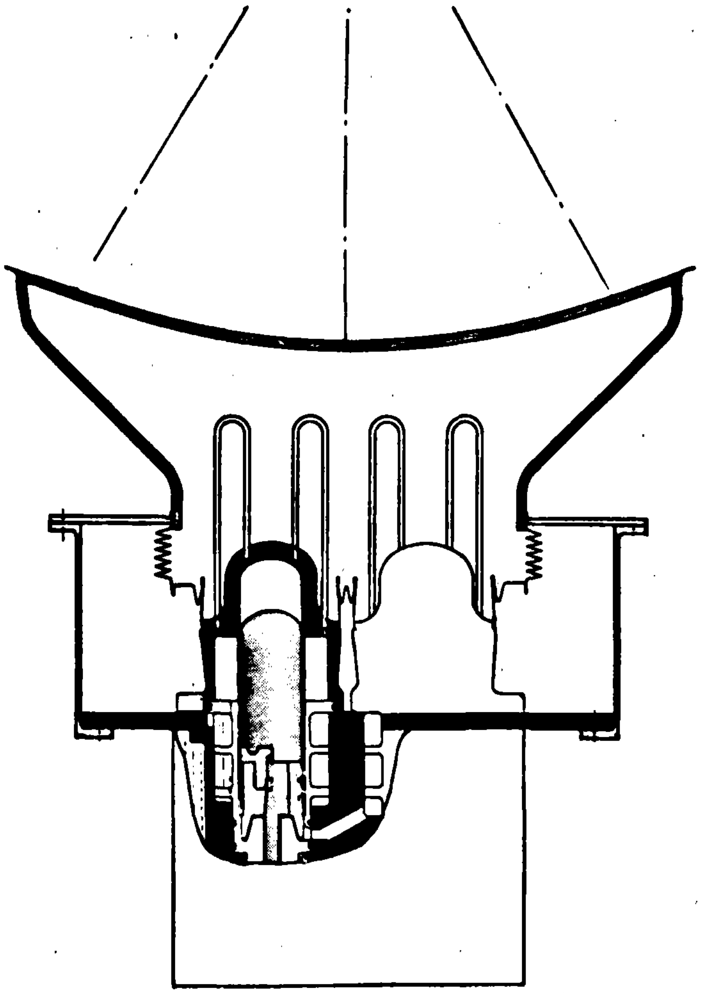
These computer codes reflect present Stirling engine technology. Within the 5 - 6 year development effort for the advanced solar engine a number of improvements will be made as specified below.

Component	Improvement
Drive	Smaller dimensions, improved mechanical efficiency
Seal system	Smaller losses from friction and pumping
Heater	Smaller flow losses, minimum dead volumes, improved temperature distribution
Regenerator	Improved design and flow distribution
Cooler	Improved water flow distribution
Cylinder and regenerator housings	Improved design, minimum conduction losses
Engine layout	Improved overall design, minimum losses

Because of the numerous empirical correction terms in the present computer codes it is not possible to incorporate the effect of these improvements implicitly. This effect has instead separately been estimated to increase the calculated efficiency at least 3%.

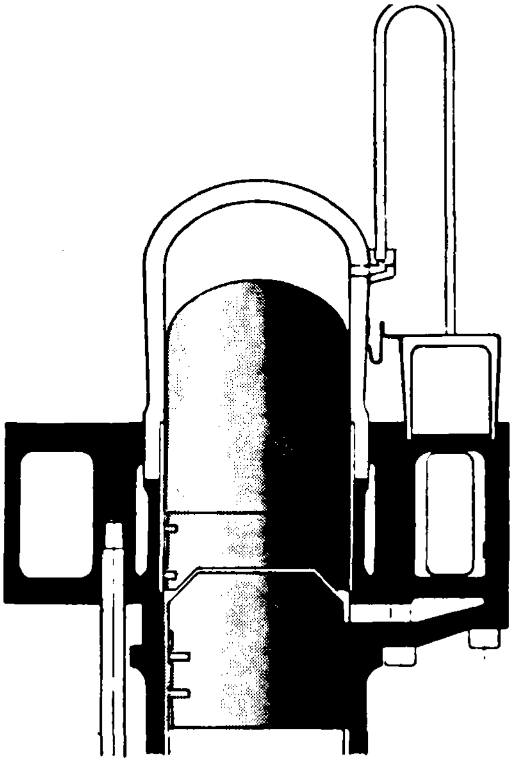
It is the opinion of United Stirling that this 3% increase in a 5-year development perspective involves a modest technological risk. If allowing for a longer development period or a high technological risk significantly higher efficiency increase is expected. The efficiency of the advanced engine is thus exptected to be 46% for a metallic engine and exceed 50%, if ceramic materials are introduced, allowing the heater head temperature to be raised. With 95% alternator efficiency this gives an engine/alternator efficiency of 44% and above 47% respectively.

The figures apply if helium is used as working gas. The same figures are applicable when direct heating is used provided hydrogen is used as working gas. It should be noted that hydrogen cannot be used in combination with indirect heating because of the risk of contaminating the heat pipe with hydrogen diffusing through the heater wall.

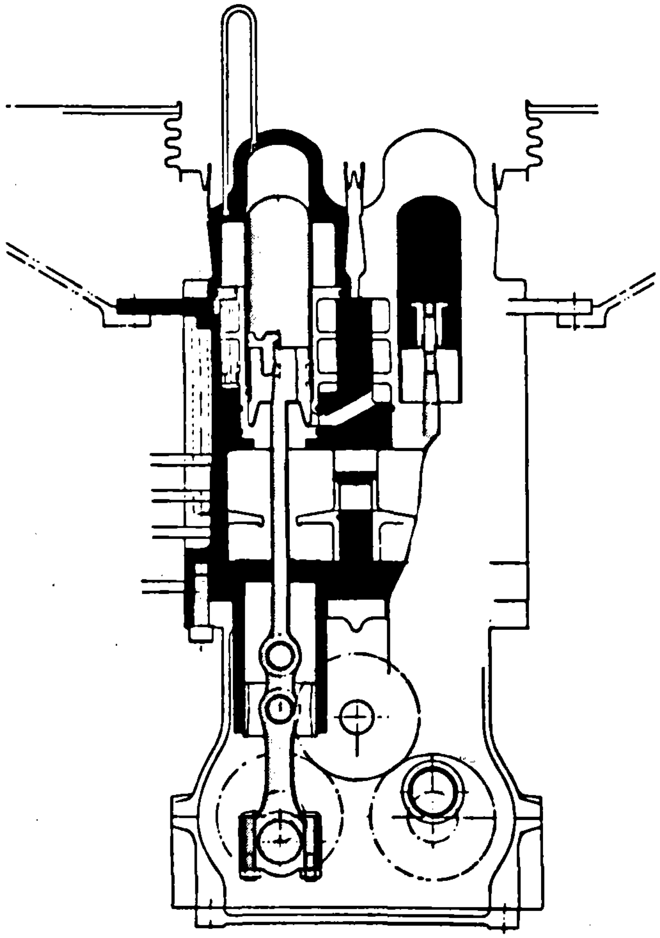


Four cylinder double acting stirling engine concept for indirect heating with a heat pipe device

Figures 1 - 3



One cylinder single acting stirling engine concept for indirect heating



Four cylinder double acting stirling engine concept for indirect heating

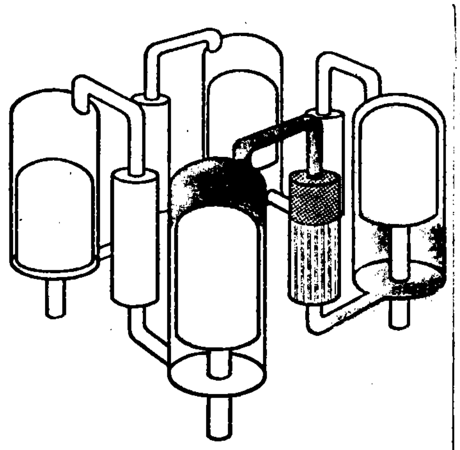
UNITED STIRLING 4-CYLINDER DOUBLE ACTING ENGINE/CONCEPT

The Stirling engine works in a similar manner in terms of compression and expansion, but it differs from a conventional engine in two fundamental respects; heat is supplied continuously and externally, and the working gas - which is usually hydrogen or helium - operates in a completely closed system. Each piston is enclosed between a hot and a cold space. The Stirling process takes place in the hot space of one cylinder and the cold space of the adjacent cylinder. The working gas, which is enclosed between the pistons, moves continuously back and forth between the hot and the cold spaces, and is continuously heated or cooled. The gas passes through a regenerator which stores heat when the gas moves from the hot to the cold side, and gives off heat when the gas moves in the opposite direction.

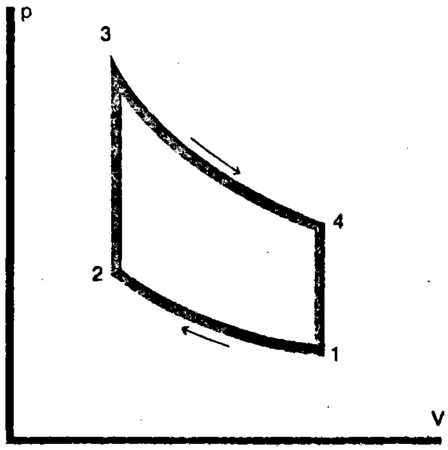
The phase shift between the two pistons is 90° which gives the following cycle:

1-2 Compression
Work is supplied by compressing the working gas on the cold side; the gas is cooled at low pressure.
2-3 Displacement
The gas is moved from the cold to the hot side at constant volume. The regenerator gives off stored heat. Pressure increases.
3-4 Expansion
Work is performed when the working gas expands on the hot side while it is heated at high pressure.
4-1 Displacement
The gas moves from the hot to the cold side at constant volume. Heat is stored in the regenerator. Pressure declines.

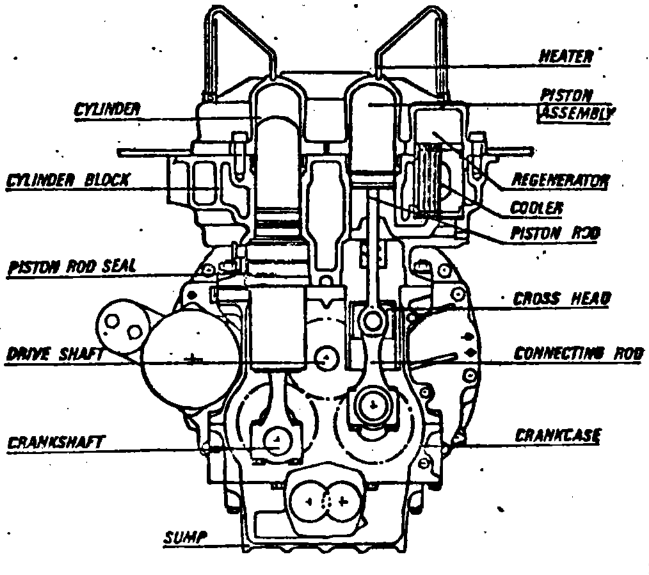
The total volume of the space between the cylinders is thus reduced (compression) when most of the gas is on the cold side and the pressure is low. And the volume increases (expansion) when most of the gas is on the hot side and the pressure is high. This produces a positive net force over the cycle which drives the engine. Theoretically, the Stirling process can be illustrated by a pressure/volume diagram.



Working gas in one of the cycles of a 4-cylinder Stirling engine module



Theoretical pressure/volume curve



Cross-section of United Stirling 4-cylinder double acting concept

Single Cylinder, Single Acting Stirling Engines
For
Small Solar Power Systems

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Many mechanical configurations and cylinder arrangements can be implemented to approximate the theoretical Stirling thermodynamic cycle. In addition to the multi-cylinder, double acting configuration as represented by the P-40 and other Stirling automotive engines, the single cyclinder, single acting engine (piston-displacer machines) is an attractive candidate for the Small Solar Power System (SSPS) application. As well as the generic Stirling engine attributes of high thermal performance, low noise and being a closed cycle machine, this class of engine is compact, has low vibration levels and inherently has a high specific power. These characteristics are beneficial for focal plane mounting of the engine to the dish concentrator for SSPS applications. A large design and test data base has been developed for the single cylinder, piston-displacer engines by Philips and their licensees. The designs encompass a range of power levels from 5 watts for an artificial heart prototype engine to 90 hp for a laboratory engine. The most well known of these is the 1-98 engine which was designed to develop a nominal 10 hp at the following conditions:

• Engine Speed:	3000 rpm
• Heater Tube Temp:	700°C
• Mean Pressure:	105 atm
• Working Fluid:	helium

A maximum power of 25 hp was achieved with this same machine, however, when operated at 3500 rpm and employing hydrogen as the working fluid at a mean pressure of 210 atmospheres; a maximum efficiency of 33% was obtained at an operating speed of 1200 rpm.

The 1-98 engine employs a rhombic drive to translate the linear motion developed by the Stirling engine to rotary motion. Since the drive is inherently balanced, both axial and lateral loads are eliminated thereby reducing seal wear and enhancing long life and reliability. The resulting low vibration levels also simplifies integrating the engine with the heat receiver and with dish concentrators. The 1-98 drive assembly also employs a rollsock seal.

More than 30 of these 1-98 engines were built and tested during the 1959 to 1966 time period.

Other single cylinder, piston-displacer machines which can provide a pertinent technical data base for the SSPS Stirling engine design are summarized in Table 1.

Table 1

Single Cylinder, Single Acting Stirling Engine Experience

ENGINE	NOMINAL POWER LEVEL	UNITS BUILT	OTHER CHARACTERISTICS
Generator Sets	1/5 & 1 hp	> 400	• Eccentric Crank Drive • Air Engine
1-365	40 hp	1	• Rhombic Drive • Wiper Type Rod Seal • > 35% Shaft Efficiency
SIPS	1.7 hp	1	• Rhombic Drive • Dry Sump Design • Wiper/Scraper Rod Seal • 37% Shaft Efficiency

In summary, single cylinder, single acting Stirling technology has been demonstrated for the SSPS power range of interest. Shaft efficiencies greater than 35% have been measured and efficiencies greater than 40% have been predicted for more recent engine designs. The engine should be redesigned, however, in order to optimize overlll engine, heat receiver, and generator performance for the SSPS application. A description and characteristics of a single cylinder engine designed specifically for the Small Solar Power System application is summarized in Table 2.

Table 2

SSPS Single Cylinder, Single Acting Stirling Engine Design

DESCRIPTION		OPERATING CHARACTERISTICS	
Displacement:	330 cc	Power:	30 hp
Bore:	82 cm	Efficiency:	> 42%
Stroke:	6.2 cm	Speed:	1800 rpm
Regenerators:		Mean Pressure:	140 atm
- Stacked Screen Matrix - 12 Canisters		Hot Wall Temp:	800°C
		Working Fluid:	Helium
Cooler:	Tube & Shell		
Drive	Rhombic		
Rod Seal:	Rollsock or Wiper/Scraper		

For an early system demonstration program, General Electric and North American Philips investigated the feasibility of another alternative; this engine design would utilize the existing 1-98 rhombic drive, thereby requiring only a redesign of the thermodynamic section to satisfy the 30 hp shaft power requirement with helium as the working fluid. The 1-98 drive was designed to deliver 30 hp and has demonstrated the capability to deliver 25 hp. A dynamic analysis of the 1-98 drive which was performed at the SPSS Stirling engine operating conditions also showed that the design provides a sufficient margin of safety. A sketch of the modified 1-98 engine is presented in Figure 1, and a description and characteristics of this design are presented in Table 3.

Table 3

Modified 1-98 Engine for an Early SPSS Demonstration

DESCRIPTION		OPERATING CHARACTERISTICS	
Displacement:	228 cc	Power:	30 hp
Bore:	10 cm	Efficiency:	40%
Stroke:	2.9 cm	Speed:	1800 rpm
Regenerators:		Mean Pressure:	203 atm
- Stacked Screen Matrix		Hot Wall Temp:	800°C
- 6 Canisters		Working Fluid:	Helium
Cooler:	Tube & Shell		
Drive:	1-98 Rhombic		
Rod Seal:	Rollsock		
Heat Source:	Direct Insolation or Heat Pipe/TES Heat Receiver		

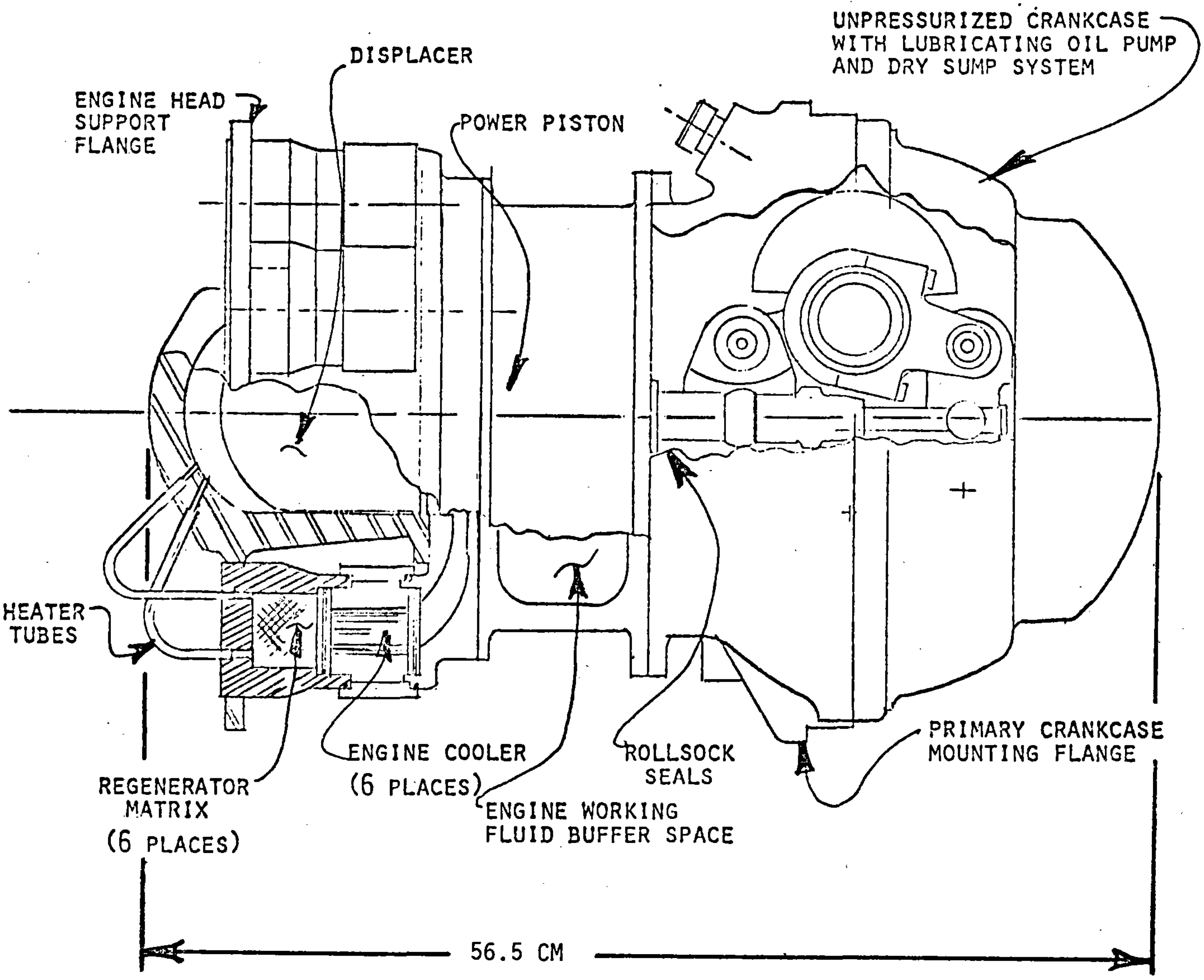

Figure 1. Modified 1-98 Stirling Engine

ADVANCED SUBSYSTEMS

ADVANCED RECEIVER TECHNOLOGY

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INTRODUCTION

The advanced receiver program is organized to promote the development and demonstration of innovative and efficient receiver concepts for application to advanced electric, IPH (industrial process heat), and FC (fuels and chemicals) needs. The focus of the program is on technology development for receivers that operate from 1000°F to 3000°F and above. The high operating temperatures would permit use of high efficiency engines, and allow application to a wide number of industrial and Fuels and Chemical processes. The specific needs of these applications and the requirements for future thermal power systems have been studied, including their potential, their limitations, and requirements for success. A plan has been prepared for the development of the required receiver technology including specific receiver requirements, schedules, and management responsibilities.

The program system efficiency target is 30 percent or greater in order to reach the 50 mil per kilowatt hour target for electric generation. Initial receiver targets are for efficiencies approaching 90 percent and receiver costs between $5 to $20 per square meter of concentrator. However, the overall system cost is most sensitive to receiver efficiency.

Significant progress has already been made in receiver technology for point focusing applications under the Small Power Systems program. A first generation prototype designed for 600°F outlet temperature has been tested and achieved an overall collection efficiency of 60 percent. A second generation receiver for Brayton cycle operation at temperatures up to 1500°F is being designed and fabricated for the Point Focusing Distributed Receiver Technology program. Under the Advanced Technology program a 250 kW ceramic honeycomb receiver using air at ambient pressure as a working fluid has been tested at 1950°F by the Sanders Corporation.

APPROACH

The strategy for receiver development is mapped in terms of application requirements, and the related system and technical requirements. Development is tailored to meet these technical requirements and thus provide a technology to permit receiver development.

For all applications of high temperature receivers minimization of reradiation losses from the receiver is a key factor in achieving high efficiencies for high temperature receivers. Heat transfer in a controlled manner to the working fluid and fluid mechanics of this fluid are also key objectives of receiver development. Both steady state and transient factors have to be taken into account. Key technical issues specific to each receiver application have been identified.

PROGRAM SUMMARY

Chemical and High Temperature Receivers

Receiver development is a prerequisite to the thermo-chemical transport and the fuels and chemicals program. The initial steps in this program, begun in FY'78 by the Naval Research Laboratory, have been to demonstrate technology feasibility. The development of a gapped ceramic coil and catalyst configurations for the reactor are underway. Plans to test the developed configurations are being made.

High temperature ceramic receiver concepts for application between 2000^{o} and 3000^{o}F are being investigated. The most attractive concept identified will be fabricated and tested in a follow-on effort. Future efforts include study of innovative cavity and component configurations and the study of receivers for temperatures greater than 3000^{o}F.

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 ceramic dome receiver concept has been under evaluation by the MIT-Lincoln Laboratories with emphasis on high temperature dome sealing techniques. The high temperature receiver concepts of GE and Sanders will be evaluated for Brayton applications and an attractive concept selected for fabrication and testing.

Advanced Stirling Receivers

The dish-Stirling advanced system is being developed in two steps. The first step includes the design and fabrication by General Electric Company of a 1500°F sodium heat pipe receiver with thermal storage and a receiver being developed by Fairchild-Stratos which can operate on either solar or fossil energy. The second step of the program is to develop a high efficiency engine (45-50%) and related receiver. Metal and ceramic receivers for operation above 1500°F will be studied.

Advanced Rankine Receivers

Advanced technology components have been conceptually designed and some have been fabricated and tested. A direct absorption salt film receiver is in conceptual development at Sandia-Livermore. The receiver provides molten salt at 1000°F to a steam generator. A Francia steam receiver has been undergoing test and evaluation at the Advanced Component Test Facility.

MOLTEN SALT TEST LOOP

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INTRODUCTION

The objective of the Molten Salt Test Loop Project is to design, construct, and demonstrate operation of an outdoor high temperature molten salt test facility. This facility can be used to evaluate materials and components, and the design features and operating procedures required for molten salt heat transport systems. The immediate application of the loop is to demonstrate the feasibility of using molten salt as the heat transport medium for a high temperature distributed collector system.

A commercially available eutectic salt blend has been selected as the heat transfer fluid. This salt has a composition of 40% $NaNO_2$, 7% $NaNO_3$ and 53% KNO_3 and is marketed under the trade name "Hitec." It has a freezing (solidifying) point of 142°C (288°F) and has been satisfactorily used at temperatures as high as 594°C (1100°F). Its attractive features include good heat transfer properties, expected adequate stability at 540°C (1000°F), low system pressure, compatibility with common construction materials, and commercial availability at acceptably low cost.

General Atomic (GA) has installed a row of Fixed Mirror Solar Concentrators (FMSC's) in the loop. The FMSC employs a fixed mirror circular trough that produces a sharp line focus regardless of sun position. The heat receiver, which employs a secondary concentrator, is moved in a circular arc to track the focal line.

The system has been installed and started up. Startup has gone smoothly, with the exception of some burned-out trace heaters. Salt temperatures as high as 571°C (1060°F) have been achieved.

SYSTEM DESCRIPTION

The molten salt test loop facility has been designed to operate at salt temperatures up to 594°C (1100°F). A schematic diagram of the facility is shown in Figure 1. Table 1 presents some of the technical parameters for the system. Corrosion resistant stainless steels have been used throughout. The salt is stored in an insulated tank from which it is pumped through the heat receiver of the FMSC array. After exiting the heat receiver, the salt is returned to the storage tank by way of two insulated pipes, one of which has removable insulation so that it can be used for heat rejection. Flexible downcomers are used to connect the movable heat receiver to the fixed piping.

Table 1

Molten Salt Solar Test Rig
Design Parameters

Maximum Design Temperature	1100°F
Salt Charge	1600 lb.
Design Flow Rate	16 gpm
Tank Heaters	48 kW(e)
Trace Heaters	17 kW(e)
Pump	304 S.S. submerged, vertical shaft, Varidrive
Piping	304 S.S.
Valves and Fittings	316 S.S.
Tank	316 S.S.
Bellows	Inconel 625

Flow rate is controlled by a variable speed drive on a vertical shaft, submerged pump. The valves on the return lines can also be adjusted, although this has not been found to be necessary. A nitrogen blanket in the system retards salt decomposition and also provides system purge capability. An electric heater in the storage tank maintains salt storage temperature, liquefies frozen salt, and regulates salt inlet temperature to the heat receiver. All salt lines, including the heat absorber pipes, are electrically trace heated.

Resistance thermometers (RTD's) are used to monitor salt temperature in the tank and at the inlet and outlet of the heat receiver. Thermocouples are used to measure skin temperature on the absorber pipe of the heat receiver. Flow rate is measured by a calibrated orifice in the discharge line from the tank. The digital readouts for the instrumentation and the tracking control panel for the FMSC array are located inside a trailer. The salt temperature control panel is located near the salt tank and the heat receiver drive motor control panel is located near one end of the FMSC array.

The FMSC array (Figure 2) utilizes six concrete and glass concentrator modules left over from the 600°F FMSC subsystem GA built for the Solar Total Energy Demonstration Facility at Sandia Laboratories in Albuquerque, New Mexico. The modules are each 12.5 ft. long with a 7.2 ft. aperture, and contain 43 2-inch wide glass mirror strips. The movable heat receiver is insulated and consists of three 25 ft. long segments. Each segment contains a 2.5 in. wide by 1.0 in. deep rectangular cross section absorber pipe through which the salt flows. The absorber pipes are connected in series by welded, in-line, expansion bellows. A CPC secondary concentrator, with an aperture of 5.5 in., is incorporated into the heat receiver. There are provisions for incorporating a flat glass cover plate to reduce thermal losses from the absorber pipe. The absorber pipe does not presently have a solar-selective absorber coating.

SYSTEM STARTUP

System installation was completed around May 1, 1979. Individual components, including the tank heaters, the trace heaters, the receiver drive system, and the tracking system, were first tested for proper operation. When all the components were confirmed to be functioning correctly, the receiver was put into the focal line and allowed to track without fluid flowing. Corning 0317 glass cover plates were used at one end of the receiver, the remainder having no cover. As it heated up, the glass broke. Without the cover the absorber pipe reached a stagnation temperature of 448°C (840°F).

After flushing the system with distilled water and pumping it to check signals from the flowmeter and the temperature sensors, the system was drained and the salt added. Using the tank heaters, the salt was melted and dehydrated for one day before attempting to pump it through the system. Using the trace heaters, the system was preheated throughout, with the minimum temperature of 177°C (350°F) being in the return line. Upon the first pumping attempt, the return line blocked, but with the trace heaters left on, it soon thawed out, and when the pump was turned on again, the salt flowed through the system and it was operated for several hours.

When the loop was operated for the second time, the flowmeter would not operate because frozen salt had blocked the small lines between the pressure taps and the transducer. After heaters were installed on the tubes, the flowmeter has functioned properly.

Tests conducted over several days gradually raised the system temperature to 571°C (1060°F), which was achieved May 24, 1979. All components were functioning satisfactorily. At this point the trace heaters on the return lines burned out, and repairs have not yet been made.

OBSERVATIONS AND CONCLUSIONS

Several observations have been made during the testing performed to date:

1. Trace heaters should be installed inside rather than outside pipes. No problem has been experienced with the internal heaters in the receiver and downcomers, but heating is inadequate and slow on the pipes heated externally.

2. Trace heaters installed outside the pipe should be long enough to spiral around the pipe so as to maintain good thermal contact as thermal expansion takes place.

3. After a run above 540°C (1004°F), the pump shaft froze up. This was probably caused by salt vapor rising to the first shaft bearing, condensing, and then freezing when cooling. The shaft frees when the tank is heated to about 315°C (600°F). Liquid metal pumps have the same problem, and this is circumvented by a special baffle.

4. Corning 0317 glass survived up to more than 370°C (698°F) pipe temperature as a connective window. Eight out of eighteen pieces survived the highest pipe temperature achieved. Use of borosilicate glass and/or fire polishing the edges very likely will solve the cracking problem.

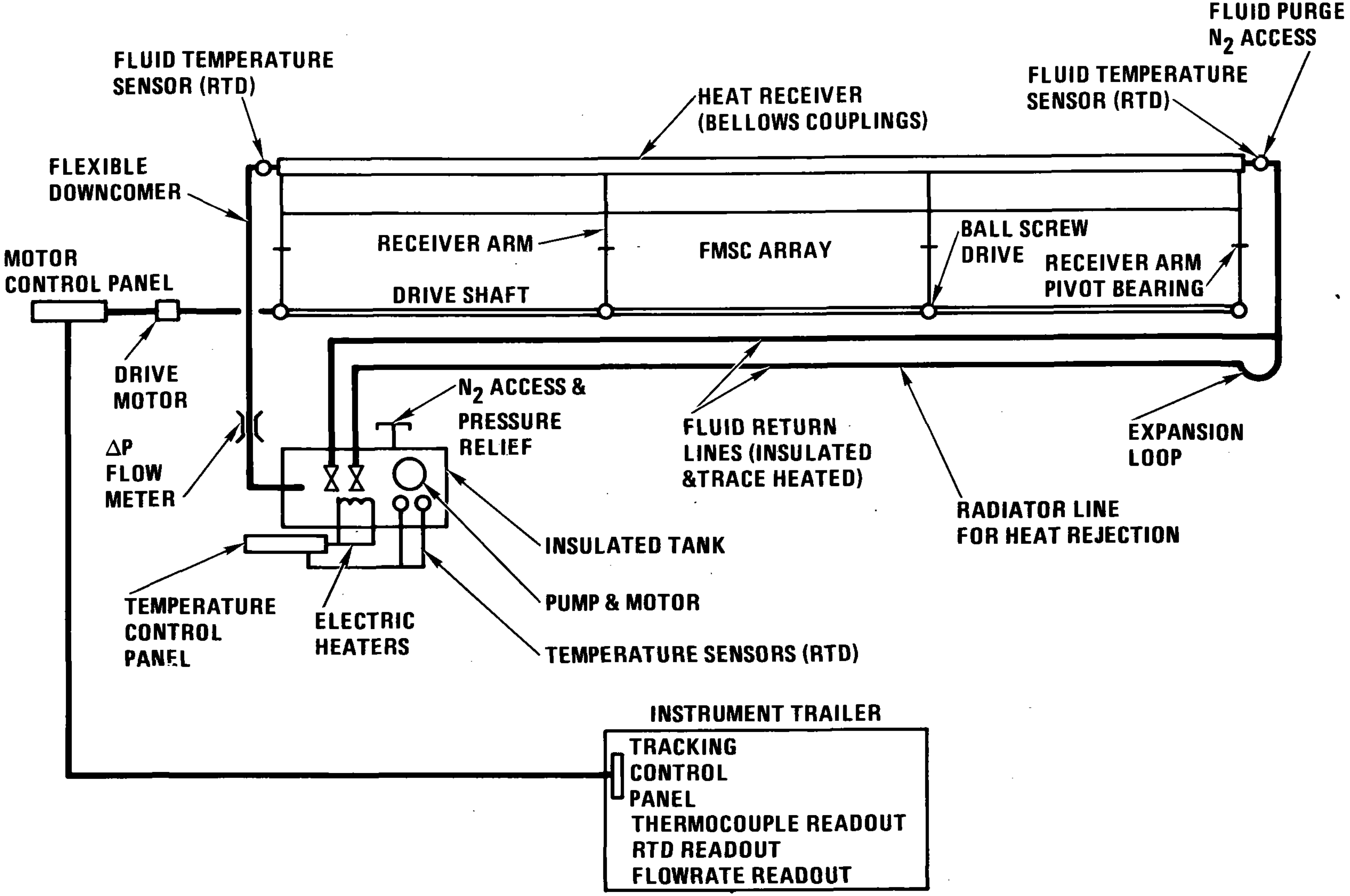
In conclusion, the molten salt system has functioned well, with the exception of the burned-out trace heaters, and has demonstrated the feasibility of using molten salt as the heat transport medium for a high temperature distributed collector system. It has been repeatedly started and shutdown, and rather straight-forward operating procedures have been developed. The system can be run with other fluids. Future use of the facility could include testing of high temperature heat receivers and other components, thermal storage evaluations, materials tests, and component freeze/thaw experiments.

ACKNOWLEDGEMENT

This work was sponsored in part under DOE Contract EY-76-C-03-0167, Project Agreement No. 66, with the San Francisco Operations Office.

Figure 1

MOLTEN SALT SOLAR TEST RIG



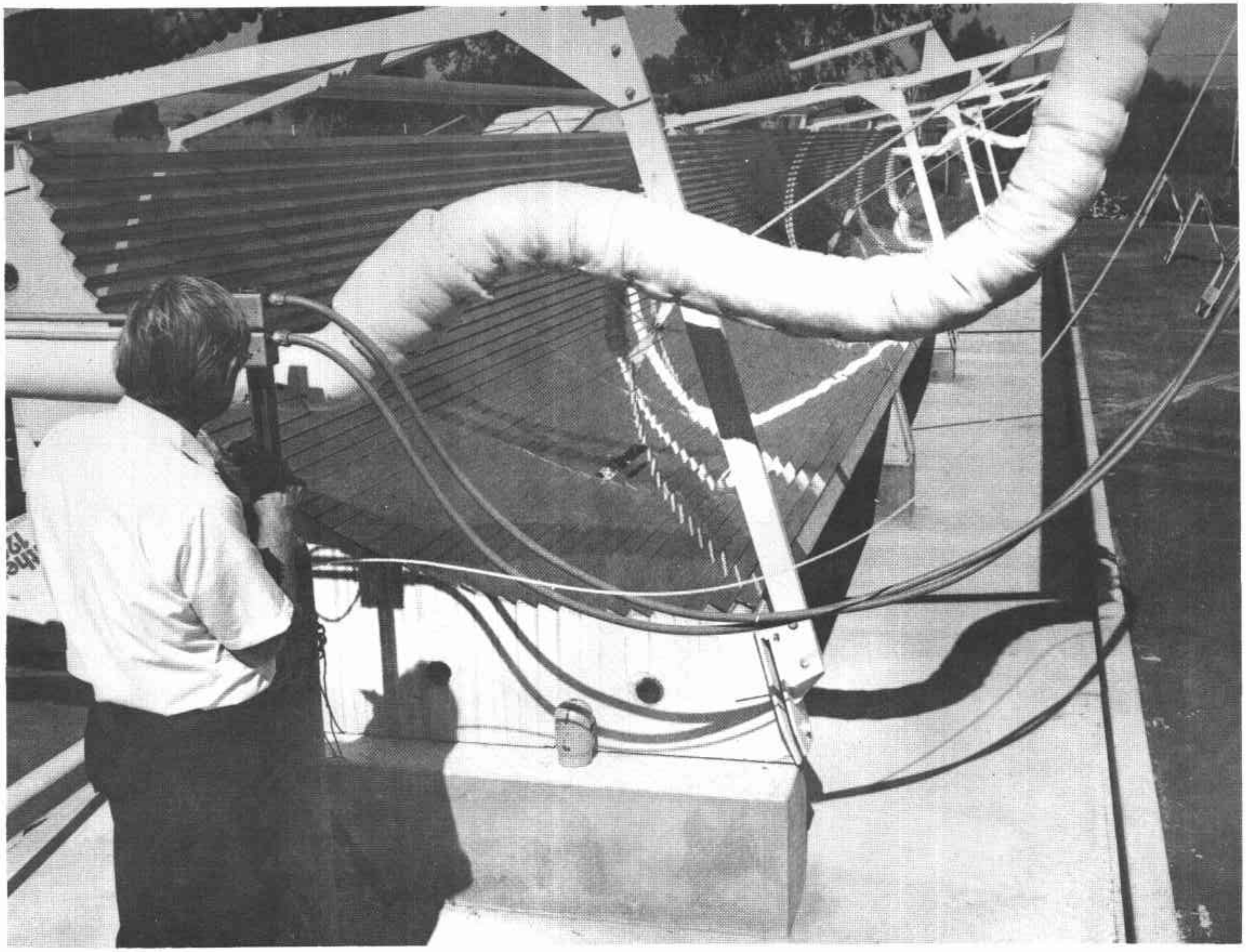


Fig. 2. FMSC Array Under Test at Molten Salt Loop

SUMMARY
BRAYTON HEAT ENGINES
DOE ADVANCED SOLAR TECHNOLOGY MEETING
JUNE 19-21, 1979

1.0 INTRODUCTION

Garrett-AiResearch is currently conducting a concept definition study for small (15-20 kW_e) Braytoon cycle engines for dispersed solar electric power systemks under a NASA contract. Individual modules would be tied together via an electrical bus to generate the required quantity of electricity.

The objectives of this study program were to characterize several Brayton engine types over a wide range of design parameters and to conceptualize three specific engine configurations:

Configuration A - An existing design open cycle engine/generator (E/G) set, modified as required, to operate over the required performance range. This engine would be capable of operating with a collector/receiver plant in 16 months.

Configuration B - An existing design closed cycle engine/generator (E/G), modified as required, to operate over the required performance range. This engine would also be capable of operation with a collector/receiver plant 16 months.

Configuration C - An advanced open cycle Brayton E/G using optimized turbomachinery and recuperator and more nearly representing a high volume (10,000 per year and up) production configuration in the 1990s.

In addition to the conceptual designs of the three engines, it was also desired to assess the technology status, production status, production costs, durability and growth potential for the selected engine types.

ENGINE SELECTIONS

Parametric analyses were made of various Brayton engine/generators to provide data for use in selecting engine designs for cost effective solar electric power modules. Major emphasis was placed on achieving minimum specific cost (dollars per kilowatt) for the complete module which consists of a concentrator, receiver, Brayton engine/generator BE/G, and the balance of plant (BOP). (Minimizing specific cost of the BE/G alone will generally not result in a module having minimum specific cost.) Low weight and compact packaging were also considered design goals to reduce the support structure and mirror shadowing.

The method of selecting an engine design point for a minimum specific module cost included an allocation for the cost of the concentrator, receiver, and balance of plant. (Use of specific cost of equipment for optimization rather than the complete expression for COE is justified for pure solar plants because the fuel costs are zero, leaving the equipment costs as the major factor in the determination of COE.)

The conclusion reached from the parametric analyses was that atmospheric open cycle engines are superior when judged on the basis of specific cost of the solar power module for the power class investigated. The closed cycle engine runs a close second and is of continued interest because it will have good part-load efficiency. The amount of cycle recuperation (E_r) and the value of total system pressure loss ratio ($\Delta P/P$) appropriate for each design were also identified by the analysis.

The performance of existing turbomachinery was characterized, and suitable matches were achieved with the desired optimum performance for the A and B engines. (The E engine, of course, is an optimally designed engine.)

Based on the results of this study, Brayton heat engines will be viable competitors for operation with concentrated point focus solar collector systems.

SERI - Advanced Component Research Facility

The Advanced Component Research Facility (ACRES) is currently under development at SERI. The ACRES is to facilitate experimental research on point-focus collector components such as receivers, optics, tracking components and thermal transport.

At this time, the facility consists of two Omnium-G 6 meter parabolic-dish concentrators. By mid-FY80, other concentrators may be added to the facility. Also, a high temperature indoor solar furnace is currently under consideration for the SERI permanent laboratory (early 1980's).

One of the 6 meter dishes is now being set up as a thermal test loop to allow testing of advanced thermal receivers over a wide range of operating conditions. The Omnium-G receiver will be tested first in this facility to de-bug the test loop and to provide a baseline for comparison with advanced thermal receiver designs.

The second dish will be used as a test bed for further development of a flux mapping instrument and the dishes will be coupled during FY79 to allow a study of thermal transport methods.

After FY79, we expect to be testing an advanced thermal receiver currently under development at SERI, and later expand the testing effort to include receivers with solids and gas-solid mixtures flowing through them. In addition, testing of other components such as reflector materials and tracking components will be carried out in ACRES. Innovative methods of transporting thermal energy both from the concentrator focus and between dishes will also be investigated.

Tests conducted to date include the measurement of Omnium-G optical efficiency and receiver thermal loss. Thermal energy delivered by the concentrator/receiver was also determined. During the course of testing, two Omnium-G receiver failure modes were identified, which led to modifications in the receiver design and in the recommended operating procedure. In addition, we have identified a technique of mapping the flux contours at the focus of the dish which appears to have several advantages over other techniques used in the past. The method involves a Lambertian scatter plate at the concentrator focus and a vidicon focused on the plate. The major advantage is the elimination of complex hardware at the concentrator focus. Also, the ability to take near-instantaneous (within 2 seconds) flux maps is useful since dish motions occur frequently enough such that contours recorded by slower methods will be smeared. This instrument will support both receiver development and optics testing, and will add to the flexibility of the ACRES facility.

MB:SF:3431.30

TRANSMITTING MATERIALS PROGRAM
SUMMARY

W. F. Carroll
6-20-79

INTRODUCTION

This report summarizes the status of the Transmitting Materials Program Plan (which is part of the Solar Optical Materials Program), and describes the content of the Plan with emphasis on the principal subsection on Polymer Materials R&D.

OBJECTIVES

The overall objective of this program is to identify and carry out materials research and development which will enable or enhance the development and economic viability of solar energy utilization. The specific objectives are to assure that: 1) technology needs are identified and prioritized; 2) research and development are initiated and carried out in a timely and cost-effective way; and 3) the resulting information is readily available to users.

STATUS

The Transmitting Materials Plan, in the outline form developed in December 1978, has recently been published as part of SERI PR 31-137. A first draft detail plan, analogous to the Reflector Plan published in PR 31-137, has been completed and is currently being reviewed and revised.

PLAN SUMMARY

The Transmitting Materials Plan follows the structure of the companion Reflector Materials Plan, including the following major sections:

1.0 Management and Coordination

2.0 Materials R&D
(Includes subsections on Ceramics and Glass, Coatings, Fluorescent Materials, and Support Materials, in addition to the major subsection on Polymers)

3.0 Large Scale Manufacturing
(The effort in this Section is to develop the technology and information so that industry can make sound business decisions regarding large scale manufacturing)

4.0 Measurements
(The measurements effort builds on and complements that described in the Reflector Materials Program)

5.0 Long Term Performance

(Major emphasis of Materials R&D, Section 2, is toward improved performance. As a result, resources in this section are relatively small.)

The first cut detailed funding level estimates indicate a \$7M-\$10M/year R&D program with a 5 year total of ∿ \$45M. Based on the simplified cost-benefit analysis reported in TR31-137, such a level appears out of proportion to the Absorber and Reflector Plans.

POLYMER R&D

Polymers, used effectively in solar energy conversion designs, can have lower cost, be easier to process and offer a wider range of properties (and thus design flexibility) than metals or ceramics. However, compared to inorganics, polymers are permeable, viscoelastic, sensitive to radiation and aging and their properties are highly process-dependent. Thus, cost effective design, fabrication and operation of systems utilizing polymers must be based on a sound understanding of their properties and predicted performance in use.

The Polymer subsection is structured to address four critical issues, each at three different levels as illustrated in the table below.

	Basic Studies	Applied R&D	Alt. Matl & Process
Mechanical Behavior	Basic Mechanical Behavior	Design Data Process Control	Tailored Matls. New Processes
Permeability	Transport Models	Diffusion & Interface Transport	Diffusion Barriers
Photodegradation	Basic Photoproprocesses	Test Methods Combined Effects	Improved Ultra-Violet Resistance
Surfaces & Interfaces	Surface Physics Soil Adhesion	Surface & Interface Analysis Cleaning Methods	Soil Resistant Polymers

SCHEMATIC SUMMARY - POLYMER R&D PLAN.

CELLULAR GLASS PRESENTATION

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Cellular glass is a low density, foamed, inorganic glass material. Due to its high stiffness to weight ration, thermal expansion coefficient which can be made to match mirror glass, its chemical and dimmensional stability and its projected low cost, it has been chosen by JPL as a prime candidate development material for the structural substrate for second surface silvered mirrors in solar dish concentrators. An ongoing activity to determine the state of the art of cellular glass technology and to characterize the mechanical and environmental properties of several cellular glass materials is under way.

There are currently two domestic suppliers of cellular glass materials; Pittsburgh Corning Corporation (PCC). Pittsburgh, Pa. and Solaramics, Inc., El Segundo, Ca. PCC has supplied cellular glasses in large volume (currently 10^8 bd. ft./yr) primarily to the self supported insulation market but also for a variety of other applications in smaller volumes. Their principal product has been Foamglas^R, an 8.5 lb/ft^3 soda lime, silicate glass material which is produced in a few locations by large scale manufacturing processes. More recently PCC has been augmenting their product line with a series of new glass compositions and densities including Foamsil^R 12, 28,35 and, under contract to JPL, an aluminoborosilicate structural cellular glass which can be made with a thermal expansion that can range from 60 to $90 \times 10^{-7}/C^o$ and which can be produced in various densities. Solaramics has been developing soda lime silicate cellular glasses over approximately the past five years. Their production capability at present is small (essentially that of a pilot plant). They are not, at present, supplying cellular glass commercially in volume. Solaramics' cellular glass development program is targeted specfically at developing a low cost, high performance structural cellular glass material which can be fabricated at low cost into the required shapes.

The assumption of use of cellular glass plates as the structural backing for silvered glass mirrors requires that the material function in a variety of environments. Careful consideration must be given to all mechanical and environmental stresses to which the material will be subjected. These stresses include gravity forces, wind loads, particle impact, and temperature and humidity cycling, which can involve coincident humidity and temperature extremes and temperature excursions through the freezing point of water, with or without puddled water present. To withstand these stresses and maintain an acceptably low failure rate the cellular glass must exhibit minimal values of several critical properties. These properties are identified and an appropriate experimental program to evaluate the properties for the selected group of cellular glalsses is described. Most of the properties have not as yet been adequately characterized; this is to be done during the course of the program as resources become available. To date much of the effort has been spent identifying the current state of the art and its limitations, developing testing techniques for evaluating the materials, and in developing a design philosophy for using the material in a structural application. It should be noted that the utilization of cellular glasses for structural applications is not a "state of the art" technology. As such a major development effort will be required to demonstrate this new technology.

ADVANCED COMPONENT DEMONSTRATION
(Technology Feasibility)

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The purpose of the Advanced Component Demonstration subprogram is to identify new, innovative concepts for solar thermal components, subsystems, and processes and to provide the first experimental demonstration of their technical feasibility in a solar thermal environment. The Advanced Component Demonstration subprogram provides the focus for taking risks where the payoff in terms of cost and performance improvements is commensurate. Based on the results of Subsystem Cost/Sensitivity Studies and Subsystem Development plans completed in FY'79, efforts have been directed to those areas with significant impact on advanced electric and industrial process heat systems. Activities are currently underway in the areas of high temperature receivers, low cost concentrators, advanced heat engines, and thermo-chemical transport and storage.

Advanced receivers are being developed for applications with Brayton cycle and Stirling cycle heat engines and for chemical and high temperature applications. Advanced receivers and components are under development to supply high temperature heat for use in high performance Brayton engines with a minimum of losses. A ceramic dome receiver concept has been under evaluation and test by the MIT/Lincoln Laboratories which would allow the heating of pressurized working fluid to temperatures of 1000°C. The development has focused on the identification of high temperature sealing techniques between the pressurized air and high temperature ceramic dome material.

The identification of promising high temperature (2000-3000°F) receiver concepts for high temperature Brayton engines, fuels and chemicals, and thermochemical heat transport was initialed with contracts to General Electric

Corporation and Sanders Associates. Parametric analysis identifying key design features and thermal losses and identification of interface and operations will be performed. The most attractive concept identified will be fabricated and tested in a follow-on effort.

The successful development of chemical and high temperature ceramic receivers opens the door to the utilization of solar thermal chemical transport and storage systems, fuel and chemical processes, and industrial high temperature process heat. A ceramic counterflow heat exchanger/converter is being developed by the Naval Research Laboratory to chemically dissociate SO_3 in a high temperature solar receiver. This effort will provide an early demonstration of the feasibility of chemical energy transport using reversible, catalyst controlled, gas-based chemical reactions.

Advanced concentrator concepts are under development which offer high potential for very low cost production. Novel concepts for point focusing concentrators which utilize advanced materials or innovative design features which will allow them to be mass-produced at substantially lower cost than current design concepts are being pursued.

An advanced Brayton cycle power module will be brought to the stage of feasibility test. Parametric studies indicating cycle efficiencies of 40 percent and conceptual design has been completed. New approaches in chemical heat pipe transport subsystems are under investigation. Areas to be considered include new thermal chemical processes, converter configurations, and catalyst systems. Advanced concepts in free-piston Stirling engines are currently under consideration. The inherent simplicity and reliability of this class of machine has led to its consideration for a new component feasibility demonstration.

In conclusion, Advanced Component Demonstration is expected to be at the forefront of technology, providing the Solar Thermal Program with significantly improved components, subsystems, and with new capabilities for using solar thermal power. The progress of the Advanced Technology effort towards successful developments can be assessed and guided using costs and performance targets. Successful commercial utilization of solar thermal power can be expected if these cost targets can be achieved.

LOW COST CONCENTRATOR OVERVIEW

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The concentrator is generally the largest contributor to the overall cost of a point focus solar thermal power system; thus, there is considerable incentive to reduce concentrator cost. This cost includes the costs of the optical elements, their support, the structure, the enclosure, if any, the drive, controls, foundation, site preparation, transportation, installation, operation, and maintenance.

Cost must be considered in connection with performance. The performance of a concentrator depends on its geometric concentration ratio and its optical efficiency. The concentrator performance needed depends upon the receiver temperature selected: the higher the operating temperature of the receiver, the better the concentrator performance must be.

Concentrator cost-performance relationships or goals may be expressed as, for example, \$70/m^2 at a geometric concentration of 2500 and an optical efficiency of 90%. Alternatively, they may be stated in such terms as \$0.012/kW$_{th}$-h for net thermal energy into the receiver.

DOE and JPL are seeking new, innovative concepts for point focusing concentrators tracking about two axes, both as possible avenues to development of concentrators with better cost performance ratio and to aid in identifying technical problems on which advance development is needed: specific materials problems, structures problems, etc. Some instances of innovations being worked on, considered, or sought follow.

In a "classical" paraboloidal reflecting dish, for example, the mirror support and support structure may be made of foamed glass or of plastic, instead of the conventional steel or aluminum. The reflecting material may be a thin aluminized plastic film instead of silvered glass. The paraboloid may be divided into separate Fresnel sections. A Fresnel lens can be used rather than a mirror. Many variations on the Fresnel idea are possible, such as crossing two line-focus Fresnels to provide a point focus, or using a singly curved parabolic mirror with Fresnel facets perpendicular to the axis of curvature.

Membrane reflectors of thin plastic or metal film may lower the costs of the reflector, support, and structure. Some concepts use inflated membranes, shaped elastically or plastically by air pressure or made from preshaped gores. Some of these are rigidized after inflation. Others use a structural framework to shape the membrane. Related is the concept of a membrane enclosure to protect the concentrator from the weather.

Other innovations may center around compound concentrators. A Cassegrainian optical system, by placing the receiver and power conversion units close to the reflector plane, may reduce structural loads and costs. Secondary concentrators around the receiver, such as a CPC or hyperboloidal, may increase concentration ratios and therefore performance. They may also permit use of a primary reflector or lens which itself has relatively low optical performance and associated low cost.

JPL expects to issue RFP's for several kinds of new concentrator concepts. Unsolicited proposals incorporating other innovative ideas for point focus two-axis-tracking concentrators are welcome. These innovations may pertain to any area of concentrator design, fabrication, operation, or maintenance.

COMBINED THERMAL STORAGE POND AND DRY COOLING TOWER WASTE HEAT REJECTION SYSTEM FOR SOLAR-THERMAL STEAM-ELECTRIC PLANTS

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Contract No. ET-78-C-92-4680

An engineering and economic evaluation of the combined thermal storage pond and dry cooling tower heat rejection system concept as applied to a solar-thermal steam-electric power plant has been completed. The combined pond-tower concept has been evaluated as a possible alternative to conventional dry cooling at such plants because it offers the potential for significant cost reduction without the consumptive use of water. The combined pond-tower dry cooling system concept involves the incorporation of a sealed water impoundment into the water flow circuit of a conventional dry cooling heat exchange loop using a surface steam condenser and finned-tube type of water-to-air heat exchanger. Use of the thermal storage pond in the dry cooling circuit allows the heat rejection load on the dry cooling tower to be spread over the entire 24 hour day and allows the utilization of the typically much cooler night air for cooling. The scope of the engineering and economic evaluation has included the preliminary evaluation of thermal performance of alternative system design and operation concepts, the assessment of the design requirements for the thermal storage pond, and the evaluation of the economics of the combined pond-tower concept in comparison to conventional alternatives.

The initial assessment of the thermal behavior of the pond-tower system revealed that a thermal storage pond coupled to a low capacity dry cooling tower will significantly increase the cooling performance of the heat rejection system. Also, it has been shown that a thermal storage pond coupled to a high performance dry cooling system either significantly reduced the amount of required dry cooling heat exchange capacity or will result in levels of performance unachievable using simple dry cooling. Additionally, the initial assessment has shown that two approaches to the operation of the combined pond-tower system are possible. One approach is to utilize the pond to maximize the electrical capacity of the plant during periods of peak electrical demand while the other approach is to utilize the pond to maximize the total daily electrical power production of the plant. Also, it has been found that an important benefit of the thermal storage pond concept is the feasibility of turning the dry tower fans off during peak electrical demand periods with no increase in condensing temperature.

The assessment of alternative thermal storage pond design concepts has considered both thermal performance and economic factors. The general result is that a stratified, vertical-flow storage reservoir appears to offer the best potential for lowest cost and maximum thermal performance. The difficulties associated with inhibiting density-induced flow in a horizontal-flow type of pond limits the thermal performance potential of this alternative. Also, the construction cost per unit of stored volume for the horizontal-flow pond is estimated to be higher than that of a stratified pond. Correct design of the flow inlet and outlet devices at the top and bottom of the vertical-flow pond should result in a good approximation to ideal stratified flow thermal behavior. It has also been determined that conventional techniques for the construction of "cut-and-fill" water storage reservoirs can be utilized for the construction of a thermal storage pond. Currently available membrane lining and covering materials may be applied to minimize seepage and evaporative water losses.

The final task in the concept assessment has been the evaluation of the system cost. The combined dry cooling tower and thermal storage pond concept for waste heat rejection from solar-thermal steam-electric plants has been found to have a significant cost advantage in comparison to conventional dry cooling. This result has been obtained by examining the detailed thermal performance and cost of cooling systems for a nominal 100 MWe second-generation type of solar-thermal plant with 6 hours of thermal energy storage capacity sited in arid Southwest locations. In each case the cost of heat rejection is computed as a present-worth sum of capital investment, system operation, and loss of capacity and energy production penalty costs and is presented as an incremental cost of power production due to heat rejection requirements. All costs related to thermal performance of the cooling system are developed through the simulation of the system thermal behavior for a one year operating period which is represented by a correlated set of meteorological and steam condensing load data.

Importantly, the economic analysis has shown that the pond-tower cooling concept is cost effective in maintaining the plant conversion efficiency (i.e., condensing temperature) at levels similar to that achieved with conventional evaporative cooling systems. With the pond-tower system, it is not necessary to compromise the plant efficiency to reduce, to acceptable levels, the investment in dry cooling heat exchange capacity. This result holds even for a site at which the maximum ambient temperature is 112°F. The total cost of heat rejection with the combined pond-tower system has been determined to be between about 5 to 7 mills/KWhr depending on the site and amount of thermal energy storage in the solar plant. The cost of simple dry cooling systems of equivalent cooling performance is in the range of 10 to 16 mills/KWhr, again depending on the site and plant. Thus, the potential cost reduction is large, especially if one considers that the cost of conventional evaporative cooling with low-cost water would be about 3 mills/KWhr.

For the nominal 100 MWe solar plant considered in the economic analyses, the optimum size thermal storage pond was found to be in the range of 4 to 8 acres with an average depth of 25 feet. The optimum size of the dry cooling towers coupled with these ponds were determined to be only 20 to 50% of the size required for conventional dry cooling.

A SURVEY OF INDUSTRIAL INPUT TO R&D PLANNING FOR USE OF HIGH-TEMPERATURE SOLAR ENERGY IN CHEMICALS AND FUELS PROCESSING

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The purpose of this study was to obtain input to the planning of R&D in this area from industrial firms who would be expected to reduce to practice and use commercially any new technology for high-temperature solar energy in the processing of chemicals and fuels. Interviews with technical executives in such firms were conducted by eight Emeritus Members of the Industrial Research Institute, each of whom had occupied a top technical position in a major American company prior to retirement.

Data from the interviews were analyzed by the Principal Investigator for the project.

Fifty-four industry R&D executives, representing twenty-nine companies selected as important potential users of solar technology, were interviewed to obtain their perceptions and suggestions for R&D programs in this area. Each interviewer was provided with extensive background material on the status of this technology and was trained in the methodology and techniques of interviewing.

Interviews were preceded by an introductory letter, providing information on the purposes of the project and background information on it.

SUMMARY

Responses were constructive and candid. Quite uniformly industry regards solar technology as far from ready to provide high-temperature thermal energy for practical application in the processing of fuels and chemicals. Cost, intermittent availability and lack of practical storage and transmission systems are cited as disadvantageous, for which no satisfactory solution can be predicted

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Paper for presentation at the Session on Solar Fuels and Chemicals, Semi-Annual Review of Advanced Solar Power Systems, Long Beach, CA 21 June 1979.

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with reasonable probability for the foreseeable future.

While a number of potential applications were suggested, there was general agreement that work in this field should be concentrated on relatively small-scale R&D, at least until breakthroughs can be achieved in overcoming the disadvangages cited, including cost reductions of roughly an order of magnitude, and that the temptation to proceed prematurely to large-scale experimentation and demonstration should be resisted.

Research of a basic nature is needed particularly in the area of chemical reactions directed at new routes to chemicals and basic fuels.

Hydrogen appears especially attractive as an intermediate for chemicals production, as a fuel, and as a means of providing buffer storage for solar systems.

Many in industry feel that the status of solar technology is being overstated by its proponents to the point of misrepresentation, and that if this is allowed to continue, it will destroy credibility, already damaged, and impede the sound development of this potential alternate energy source.

A cooperative approach to the planning and monitoring R&D in this area, with representation from industry, government, contractors and academia, is recommended.

RESULTS

The introductory letter sent to each company was followed by a telephone call requesting an appointment for the interview. The results were as follows:

Companies Contacted	32
Companies Interviewed	29
Personally	27
By Telephone	2
Companies Declining Interview	3
Individuals Contacted	58
Individuals Interviewed	54

As noted, five companies declined personal interviews but two consented to be interogated by telephone. Three companies declined any participation. Reasons cited for refusal were (a) no knowledge of the subject, hence unable to comment on it, and (b) well acquainted with the subject and convinced that the program is unsound; not willing to be involved with it.

A. Summary of Responses

Responses have been aggregated into coherent issues or groups of issues. The responses congruent with each issue expressed are shown as a percentage of all companies interviewed. In doing this, no distinction was made between personal interviews and telephone interviews. This probably biases the percentages on the low side, since personal interviews inherently last longer, give more opportunity for dialogue and are more complete.

Not every issue was mentioned by every respondent. This biases the reported percentages on the low side; absence of a comment on an issue does not mean that the response is negative but only that the issue was not addressed by that particular respondent.

The issues and responses are reported without attaching any significance to the order in which they appear.

1. <u>Processes require 24-hour, dependable availability of energy.</u> 66%

   Respondents almost unanimously emphasized the necessity that energy be available uninterruptedly, even for batch processes. It follows that some form of storage, either of the thermal energy itself or by way of an intermediate fuel or transfer agent, will be an essential component of a useable solar energy system.

2. <u>Transmission systems will be required.</u> 24%

   Respondents could visualize few cases where solar energy could be utilized directly at the point of collection and concentration, and emphasized that transmission for distances up to a mile in a contiguous plant site,and for hundreds, or even thousands of miles in many cases would be required. Development of suitable transmission systems obviously is related to the development of storage systems.

3. <u>Solve storage and transmission problems before trying to apply to specific processes.</u> 45%

   This response obviously relates to the two preceding ones, as well as to the three which follow. High-termperature heat transfer systems are under development, notably in connection with nuclear systems, but these are rather exotic and none are suitable for transmission beyond quite short distances. Suggestions for study included production, storage and transmission of hydrogen, methane or CO as an energy carrier, development of a "chemical heat pipe system" (as visualized by IGT and General Electric), and concentration on a steam-electric system, utilizing turbine output for process heat.

4. <u>Develop processes for pipeline-grade gases.</u> 34%

   Hydrogen, methane and carbon monoxide were cited as examples of fuels which could be stored and transported, with suggestions that work be done on the basic chemistry of reactions which could be developed into processes for their production at suitable solar sites.

   Several respondents cautioned that other sources of process heat probably always will be more economical than solar for this purpose.

5. Ignore direct thermal application and concentrate on development of photovoltaic, thermoelectric or thermomechanical generation of electricity. 24%

Four respondents expressed conviction that direct application of solar thermal energy as a direct source of process heat never would be practical but that conversion to electricity, for optimizing production and distribution in a major grid might be. In effect, they recommend against the concept which is the subject of this study.

6. It is premature, at this time and for the near future, to study specific processes or reactions. 38%

Those respondents argue that until the economics of solar concentration and collection, storage and transmission can be improved by orders of magnitude there is no point in studying specific reactions or considering processes for using solar heat in chemicals and fuels processing. This conclusion also obviously is related to several which follow it.

7. Applications for high-temperature solar energy are limited. Should concentrate on low-temperature uses. 28%

Respondents argue that high-temperature applications amplify the problems of economics, storage and transmission, but that there are many more applications for lower temperature sources, typically via steam, which would be more adaptable. Examples cited included drying, dehydration, distillation, dissolving and crystallization.

8. Present programs should be limited to basic research on new concepts. Support in this area should be increased. 45%

Related to issues 3, 4 and 5, this response reflects a widely-held perception that the state-of-the-art is far from ready to support specific process development efforts and should be held to a research basis until a more solid scientific basis is established.

9. Energy costs in the chemicals and fuels industry are important but only in perspective relative to the total picture including capital and overall operating costs. 45%

and

10. Acceptance of any energy source in these industries will be conditional upon economic viability. 100%

Without exception, respondents emphasized that no energy source would achieve acceptance, no matter how attractive its other attributes might be, unless it would result in a processing system whose overall cost was competitive with available alternates. The two perceptions which follow derive from or relate to this issue.

11. <u>Alternates available in the forseeable future are and will remain economically more attractive than solar.</u> 45%

Liquid fossil fuels are predicted to remain more economic than solar at least through the middle of the next century. This leads to the conviction that work beyond basic research on solar is premature for the near future. Several respondents cited experience that comparative economic relationships are affected roughly the same by inflation, and that only technological break-throughs alter comparative economics. This in turn leads to recommendations for concentration on new technology. Other respondents expressed a conviction that future supply situations would affect all components of the economy equally, hence an individual company could compete equally with all others for basic supplies.

12. <u>Solar heat is, and for the foreseeable future, will be, non-competitive for process applications.</u> 45%

and

13. <u>A "quantum jump" in efficiency will be required.</u> 31%

and

14. <u>Reliability and maintainability, very important for an individual system, must be greatly improved.</u> 24%

These expressions all relate to a perception that the degree of development of the optical thermo-mechanical systems required is at an early state, and far from ready for specific applications. There is a strong feeling that major R&D should be concentrated in these areas and that order of magnitude improvements will be necessary before industrial applications can be seriously considered. (Interestingly, among the strongest proponents of these views were companies who have been or are participating in government-financed programs in solar thermal utilization).

15. <u>Solar is a dilute source of low grade energy.</u> 18%

The implication is that recovery of low-grade resources always is disadvantageous economically, requiring high capital investment, to be undertaken only when no viable alternative is available.

16. <u>Demonstrations are counter-productive at this stage.</u> 24%

Unless economic viability can be reasonably assured, demonstration projects will discourage potential users. The implication is that solar thermal demonstrations in the foreseeable future will be counter-productive and should not be considered until technological break-throughs have been achieved. Available resources should be concentrated on laboratory scale R&D and on prototype systems development.

17. <u>If the economics are favorable, no government input to specific applications is needed.</u> 17%

These respondents felt strongly that a technically and economically viable resource would be picked up and developed by industry without any involvement by government. An implication was that such government involvement tends to inhibit the investment of industry resources in such exploitation.

but

18. <u>Economic incentives (e.g., accelerated tax write-offs, etc.) will be necessary to offset high incremental capital costs.</u> 5%

The following responses relate to the questions concerning the specific company's willingness to participate in the program.

19. <u>Would the company be willing to participate in future studies and demonstrations?</u>

Yes	21%
Yes, with reservation	14%
No	38%
No opinion	27%

Several of those stating that they would not participate in government-funded programs in this area cited shortage of capable engineers and the necessity to use those they have and can recruit on company projects of more urgency and with more promise of success. Other reasons cited were government policies regarding patents and know-how, frustrations over dealing with Government contracting policies, practices and personnel, and basic conviction that the program is unsound and a waste of talent and resources. When the latter opinion was encountered, it always was expressed very forcefully. There was much criticism of DOE's management of its solar programs, particularly with respect to coordination, organization and technical quality.

Of those who expressed willingness to participate but with reservations, all stipulated that participation would be contingent on 100% government funding. Other reservations were that the specific project would have to be one pertinent to the company's interest, that the company must have something specific to contribute and that personnel be available. The implications were that participation would be either very specific or limited.

The necessity of allocating professional talent and other resources to projects of highest priority for the specific company was mentioned by 17% of the respondents.

It is worth noting that these responses all are from companies who would be directly involved in applying energy to real world commercial processes. Different responses undoubtedly would be received from professional research organizations or architect-engineer type organizations.

20. Would the company be willing to participate in critical reviews of the program?

Yes	31%
Yes, with reservation	14%
No	21%
No opinion	34%

There was general expression of desire to be helpful, but doubt often was expressed that any attention would be paid to or use made of industry's suggestions and recommendations. Reasons for the negative responses and for the reservations were essentially the same as for the preceding question.

Some general conclusions stand out from the responses to the questions and from the elaborating comments which were made.

1. Energy costs are extremely important for chemicals and fuels processing, and the potential cost of solar heat needs much better definition before its use can be considered seriously in planning for the future. Sensitivity to energy costs varies widely, depending upon the particular process, but always is an important factor, and increasingly so. One respondent pointed out that "The energy component of most of our - - - products is higher than the net profit component" and "If we can cut our energy costs in half, it is more than likely that we can raise our profits by 50%".

   That "sunshine is free and non-depletable" is an attractive idea, but in reality the collection and utilization of solar energy at today's state-of-the-art (and even for the foreseeable future) involves such high capital investments as to make the delivered cost unattractive.

2. Continuity and dependability of heat supply is extremely important if solar is to be more than an auxiliary source of energy.

   Most respondents opined that solar thermal energy should only be considered as an auxiliary, or peak-shaving source for the process industries. Even batch processes require predictability, and reasonable continuity of process heat. The necessity of investing in supplementary or stand-by heat sources greatly reduces economic viability of solar thermal energy projects.

3. The above input leads to the conclusion that efficient

energy storage of some kind must be a critical component of any solar heat system. The interviewers could visualize very few processes which could tolerate interruptions. Particularly, large-scale chemicals and fuels processes must operate continuously and at near steady-state conditions, once start-up has been achieved. (Three companies made specific suggestions for storage systems.)

In the same vein, effective and efficient energy transfer systems are required for practical utilization of solar energy. Only rarely can a system be devised to utilize solar heat at the point of collection. Means are required to transmit it to where it is to be used and to distribute it to the surfaces where it is needed. Other than via conversion to and transmission as steam or electricity, such systems generally do not now exist, and most respondents feel strongly that much research and engineering development must be accomplished before solar high-temperature technology can be defined well enough for use in planning and engineering design. 80% of those commenting on this issue feel that it will be 1990 or beyond before enough information will be available to permit serious consideration of its practical uses for other than limited applications.

4. These perceptions lead to the widely-held conclusion that D.O.E.'s R&D programs should be concentrated on development of collector, receiver and heat-transfer technology, on basic research on storage systems and on defining the chemistry of new reaction systems which, developed into processes for chemicals and fuel production, might be better adapted to utilization of solar heat than would be today's processes.

B. Specific Responses to Questions

Responses reported against the questions posed in the letter introducing the project are summarized here. Detailed comments on each question, providing much specific information, are contained in the final report on the project, available on request.

1. What processes and what specific reactions would you suggest be studied?

   As reported above, a significant number of respondents feel that it is premature to study specific processes and reactions, suggesting instead that available resources be concentrated on R&D for concentration, collection, transmission and storage of solar thermal energy until practical systems can be defined. 48% of those interviewed strongly recommended that no specific process should be studied at this time. 38% of those interviewed, however, made specific suggestions in response to this question. These fell into two broad categories, - those involving only physical transformations and not involving chemical reactions (e.g., evaporation, drying, fusion, etc.), and those involving chemical transformations.

(a) Physical Transformations

Specific suggestions included:

Metal working; soldering, brazing, welding, melting - suitably with heat recovery.

It was suggested that near-time energy applications will include such things as evaporating potable water from sea water, uranium recovery mill, bio-treatment plant, steam for heavy oil flooding in California, and perhaps in situ shale.

Casting: E.g., metallic glasses (1300-1400°C) on cooler surfaces (200°C), with heat recovery for other uses or for preheating.

Plastic Working: E.g., injection of molten plastics into cold molds or extrusion through dies.

Zone Refining and Crystal Growth. Concentrated heat, with close control of temperature, required.

Calcining: I.e., heating for dehydration but without other chemical changes. Examples include phosphate rock processing, lime manufacture, alumina dehydration, gypsum manufacture, fusion of borax, clays.

Dehydration: Examples include drying of aluminum hydrate trona process for soda ash, drying of sewage sludge, drying of cellulose board and paper, borax processing, drying of clays.

Distillation: Systems involving solvents, especially could benefit.

Crystallization: Dissolving and crystallization or recrystallization of many inorganic and organic compounds was suggested.

Oil Recovery: Solar heat is being considered seriously for production of steam or other injectants for enhanced recovery of petroleum from difficult formations. Four respondents suggested this as a valid possibility for solar heat.

Frasch process: Heating water for melting sulfur.

Glass: Auxiliary heat source for melting.

(b) Chemical Transformations

Specific suggestions included:

Ammonia Synthesis: Several unconventional systems suggested.

Formic Acid from CO_2 and H_2O (University of Texas).

H_2S Reduction to sulfur and hydrogen.

Hydrogen: Production from water, or by less conventional processes deserves high priority, both as a fuel source and as an energy transfer medium. This was mentioned more frequently (35%) than any other item; hydrogen is more desirable, both as a fuel and as a chemical intermediate.

Methane)
Methanol) also desired as fuels and as intermediates.

Char, Tars, Gas and Chemical Products, from carbonization of wood wastes and other bio-mass.

Coal Gasification; Coking: However, one respondent was most emphatic that this is <u>not</u> a valid candidate for solar.

Water Gas ($CO + H_2$): Again, one respondent feels strongly that solar is not applicable here.

Acetylene: Thermal processes from methane or other short-chain hydrocarbons.

HCN: Synthesis from ammonia and methane.

Aromatic Hydrocarbons: Synthesis from aliphatics.

Metals, by reduction from ores or intermediates.

Vinyl Chloride) Not considered to
Carbon Bisulfide) be promising
Cracking of Hydrocarbons) candidates.

Black Liquor Processing: Recovery of sulfur values by thermal processing of pulping residue.

Styrene: By cracking of ethyl benzene.

Ethylene: By cracking of ethylene.

Aromatics: By thermal reforming of petroleum fractions.

Digestion: Alumina refining in the Bayer process was suggested as an example. Processing of borax was another, as was phosphate rock processing.

Pulping: E.g., in the Kraft processes.

Among those who commented directly on the subject (21% of those interviewed), there was unanimous agreement that solar energy, now and for the foreseeable future, is totally unsuited for processing of petroleum hydrocarbons or for coal gasification.

2. <u>What kinds of systems - batch vs. continuous integrated process or unit operations - would you suggest?</u>

No one interviewed could cite a single exception to the statement that <u>all</u> large-scale, high-throughput chemicals and fuels processes operate on a continuous, usually steady-state basis and are intolerant of interruption. Only three suggestions were made for possible operations which might be adaptable to intermittent, batch operation; (a) steam generation for enhanced oil recovery, (b) digestion or dissolution and (c) melting for casting or other processing.

17% of the respondents could visualize possible applications for solar heat in batch processes. 34% felt that only continuous processes could be considered. 28% felt (usually strongly) that solar energy cannot be adapted to either batch or continuous processes, and 21% expressed no opinion on this issue.

Practically without exception those who could suggest either batch or continuous process applications introduced the caveat that systems for thermal storage and transmission would be essential, and 21% qualified their suggestions with the opinion that solar could only be considered as an auxiliary heat source, to be used when available but only in addition to a more dependable source.

Almost all respondents who commented on this issue pointed out that the qualifications cited above would result in very high and intermittently productive capital investment as compared to a more conventional facility, with resultant unacceptably high product cost.

3. <u>What criteria would you suggest for project selection?</u>

There was uniform agreement that economic considerations, according to accepted standards for engineering evaluation and venture analysis, should be the basis for project selection decisions.

Quite detailed suggestions for selection criteria were made and these are shown in the final report.

4. <u>What criteria would you suggest for evaluating progress of the research?</u>

Technical and economic feasibility, determined according to usual standards for project evaluation, were cited unanimously. Methods for such evaluation, as routinely employed by industry are well known and should be used without exception.

Again, detailed suggestions and comments are given in the final report on the project. The importance of utilizing industry experience and personnel in evaluation was emphasized.

5. What is the commercial susceptibility of chemicals and fuels commodities and product line mixes to energy costs?

As would be expected, the estimates varied with respect to the importance of energy cost relative to total costs, depending upon the industry and its product mix. A general comment was that cost and availability of any particular energy source would affect everyone alike, hence the relative costs of available energy sources would be the important issue.

Detailed comments are quoted in the final report.

6. What is the adaptability of production processes to alternate energy supplies?

For many of the industries interviewed, energy is supplied to the point of use as high pressure steam. For such cases adaptability generally is high. For many other industries (or processes), however, energy is supplied directly by combustion of fossil fuels. Adaptability to such process, in general, is relatively low.

7. Under what circumstances would the chemical and fuels industries participate with the Department of Energy (DOE) to conduct alternative studies and/or demonstrations?

Answers to this question showed a general and genuine desire of industry to be helpful and to cooperate to the extent of its ability toward solution of the Nation's energy problems. However, they also showed a widespread and deep-seated feeling of frustration and futility with respect to any dealings with DOE. The agency's image with the industry generally is one of incompetence and disorganization.

At the same time, respondents almost unanimously stressed the desirability of industry participation in the early stages of planning and evaluation of energy R&D programs.

8. Would you (your company) be willing to participate in critical review of plans for this program and in progress reviews?

Again, most respondents expressed a sincere desire to cooperate and to be helpful, but with qualification.

CONCLUSIONS

General conclusions are as follows:

A. Those interviewed were genuinely cooperative and made sincere efforts to contribute to the objectives of the study. Responses were frank and, in most cases, in appropriate detail.

B. Industry generally regards solar technology as far from ready to provide high-temperature thermal energy for process use. Many feel that the status of the technology is being over-stated by its proponents, to the point of misrepresentation, and this, if allowed to continue, may seriously impede sound development of this potential alternative by destroying credibility.

C. While many potential applications are suggested, there is general agreement that attention to these should be confined to relatively small-scale R&D for the foreseeable future, to develop a knowledge base for future applied work.

D. Lack of continuous availability and of practical transmission systems are formidable - and in some cases insuperable - barriers to industrial application of solar energy. These, plus cost of collection, prevent serious consideration of this source for the near future.

E. The available resources for R&D in this area should be concentrated on basic research related to applications and on the development of cost-effective systems for collection, storage and transmission. Such work should not be pushed prematurely beyond engineering evaluation stages.

F. Hydrogen production appears to be one of the most promising potential applications for energy production, for storage and for use as a chemical intermediate.

G. Many of those interviewed question the emphasis on high-temperature solar energy, pointing out that the most significant applications are in the low - or intermediate - temperature ranges.

H. A number of respondents expressed the opinion that primary usage of solar thermal energy should be for generation of electricity, via steam or gas turbine cycle, with utilization of exhaust steam or gas for direct thermal process energy.

I. Photovoltaic conversion to electricity was cited as the most practical use for solar energy by several respondents.

J. Conversion to electricity with pumped storage was advocated by two respondents.

K. There is evidence that DOE in general, and the solar program in particular, have a severe credibility gap to overcome with industry. It is especially interesting that, without exception, those who have participated in DOE contracts for work in this area are among the most severe critics of the Department and its programs.

L. Despite this handicap, a significant sector of industry is willing to cooperate with DOE and its contractors in the planning and evaluation of R&D in this area. A smaller portion is willing, under the proper circumstances, to participate in the conduct of such R&D.

FUTURE PLANS

No further work of a survey nature is recommended. It is believed that the results of this study, as reported in detail in the final report for the project, gives a broad and deep insight into the perceptions and recommendations of industry with respect to development of solar energy as an alternative source for chemicals and fuels processing. It is unlikely, in our opinion, that extension of the survey to a larger number of companies would yield any significantly different results.

Further efforts should be directed to involving experienced industry personnel in the planning and evaluation of R&D programs in this area. The Federal Science and Technology (FST) Committee of the Industrial Research Institute is available to assist in the recommendation and recruitment of suitable candidates for participation in such efforts.

MATERIALS CONSIDERATIONS RELEVANT TO SOLAR HEATING OF CHEMICAL REACTIONS*

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INTRODUCTION

Materials for use in solar process heat systems (either a central receiver or heat exchanger) must meet certain performance criteria. First, a candidate material must be stable in the chemical environment required for the process. This includes phase stability in the presence of the reactants, any intermediate compounds, and final products characteristic of the process. A usable material must also have predictable mechanical and thermal properties under steady state and transient mechanical loads required by the process and system. In conjunction with these constraints the material must be able to perform in the system long enough so as not to impair the economics of the system. Lastly, the material must be fabricable into the required system structures with acceptable economics.

Structural alloys are logically the first materials choice considered for use in solar process heat systems because of their established engineering property data base, economics, and available fabrication technology. However, the high temperatures envisioned in some solar heated chemical processes (>1000°C) are clearly beyond the recommended upper use temperatures for all conventional structural alloys because of their low melting points and the degradation of mechanical properties which occurs in these materials well below their melting or solidus temperatures. Thus, alloys are limited to relatively low temperature use in solar heated systems, especially in oxidizing atmospheres. At elevated temperatures their application is also limited due to mechanical creep and fatigue. High alloy corrosion rates can occur in the presence of many chemical species such as those containing sulfur, chlorine, etc.

DISCUSSION

Because of the relatively high melting points of many ceramic materials, they offer potential advantages for some high temperature applications. Certain ceramic materials are very stable in oxidizing atmospheres and inert to many chemical species at elevated temperatures. However, the mechanical properties of ceramic materials are not highly predictable especially at high temperatures and their mechanical behavior is controlled by flaws of the order of 1 μm in size (compared to hundreds of μm for ductile alloys). The flaw distribution in a structural ceramic

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can be strongly dependent upon the fabrication process used to fabricate a ceramic component and this characteristic requires use of design methodologies quite different than that used for alloy structures. Depending on the material, ceramics may also be very difficult to fabricate into the shapes conventionally used in structures by the structural design community.

An assessment of materials for use in solar ceramic chemical process heat receivers based upon published mechanical and thermal property data was recently completed at ORNL.[1] A number of candidate materials were compared for their potential applicability, including SiC, MgO, corderite ($2MgO \cdot 2Al_2O_3 \cdot 5SiO_2$ or MAS), Al_2O_3, Si_3N_4, silicon aluminum oxynitrides known as SIALONS, BeO, stabilized ZrO_2, CeO_2, CaO, and ThO_2. An evaluation of the important material properties led to the following conclusions. On the basis of the available data base for tensile strength, thermal expansion, thermal conductivity, fabricability, and high temperature stability, the leading candidate ceramic materials for process temperatures below 1300°C in decreasing order of preference were: (1) SiC, (2) MgO, (3) MAS, (4) Al_2O_3, (5) Si_3N_4, (6) SIALONS, and (7) BeO. Selection of candidate materials for very high temperature process applications (1300–2200°C) was restricted because of the insufficient property data and operational experience considered relevant to solar system applications. Potential candidates identified for very high temperature process system application in decreasing order of preference were: (1) ZrO_2 (Y_2O_3 stabilized), (2) MgO, (3) CeO, (4) BeO, (5) CaO, (6) ThO_2 or UO_2.

Other work recently completed at ORNL[2] has identified several possible chemical processes of potential interest for use in solar thermal process heat systems. In the present study, we chose three of the most promising identified chemical processes for critical examination in regard to materials which may be suitable for use with these systems. The processes were:

1. <u>Hybrid Bismuth Sulfate Cycle for H_2 Production</u>. This cycle includes heating a $SO_3/SO_2/O_2$ gas stream to temperatures from 750 to 1250°C. Currently this cycle is being investigated by workers at LASL.[3] The series of reactions are:

$$\begin{array}{ll}
3SO_2 + 6H_2O \longrightarrow 3H_2SO_4(aq.) + 3H_2(g)^* & (350\ K) \\
3H_2SO_4(aq.) + Bi_2O_3 \longrightarrow Bi_2O_3 \cdot 3SO_3 + 3H_2O & (350\ K) \\
Bi_2O_3 \cdot 3SO_3 \longrightarrow Bi_2O_3 + 3SO_3 & (1000\text{–}1500\ K) \\
3SO_3 \longrightarrow 3SO_2 + 3/2\ O_2 & (1000\text{–}1500\ K) \\
\cline{1-1}
H_2O \longrightarrow H_2 + 1/2\ O_2 &
\end{array}$$

---

*electrochemical step

2. Cadmium Oxide Cycle for H_2 Production. CdO is decomposed by inert gases in the temperature range 750 to 1250°C. This cycle was identified by IGT as a high efficiency thermochemical cycle. The series of reactions are:

$$\begin{array}{ll} Cd(s) + 2H_2O \longrightarrow Cd(OH)_2(s) + H_2(g)^* & (300\ K) \\ Cd(OH)_2(s) \longrightarrow CdO(s) + H_2O(g) & (600\ K) \\ CdO(s) \longrightarrow Cd(g) + 1/2\ O_2(g) & (1500\ K) \\ \hline H_2O(\ell) \longrightarrow H_2(g) + 1/2\ O_2(g) & \end{array}$$

---

*electrochemical step

3. Nitrogen Fixation from Air for Fertilizer Production. This process requires temperatures at 2200°C. The direct oxidation of nitrogen from air was demonstrated in the 1950s[5] and is currently being investigated by the Kettering Research Institute. The pertinent reactions are:

$$\begin{array}{ll} N_2 + O_2 \longrightarrow 2NO & \\ 2NO + O_2 \longrightarrow 2NO_2 & (2500\ K) \\ \hline N_2 + 2O_2 \longrightarrow 2NO_2 & \end{array}$$

RESULTS

The tendency for chemical interaction between a given material and various chemical species is determined by two basic factors. The first is the thermodynamic free energy change associated with all possible chemical reactions which can occur between the components in the material and the chemical species peculiar to the particular process under consideration at the temperatures and concentrations of interest. For a material to be inert for all the species present in a given chemical cycle from a classical thermodynamic view, all of the potential reactions which involve the candidate structural material must have positive free energy changes. This condition is rarely if ever achieved completely for any engineering system in use in process heat systems. If the calculated free energy changes are negative, but relatively small, the driving force for the reaction is small and this condition is favored over large driving forces.

If a given material/chemical process system includes negative free energy changes for some potential reactions, the second basic factor which can limit degradative reactions between a given material and the process species includes reaction kinetic limitations. This type of limitation is very difficult to estimate thermodynamically, because these processes are usually nonequilibrium in nature and the stability of a given material in a certain environment is usually dictated by a complex set of competing reactions, some of which tend to impede other reactions between the material and its environment. Most structural alloy applications at high temperature are possible because of such kinetic limitations. For example, stainless steels are usable in air at high temperatures because at high oxygen potentials an oxide film is formed on the metal which effectively impedes rapid oxygen transport to the underlying alloy and thus greatly reduces the kinetics of the oxidation reaction.

Determination of the details of the rates of reaction between materials and various chemical species where the degradative reactions are nonequilibrium in nature usually must be done experimentally where the test conditions are as close to the anticipated application conditions as possible.

In this work, we have made a preliminary assessment of the equilibrium thermodynamic stability of a number of materials which could be considered as candidates for containing the three chemical cycles cited previously. This assessment was made using available high temperature mechanical property data for the candidate materials and thermodynamic data for both the species in the chemical cycles and for the materials. The chemical interaction conclusions are based, therefore, primarily upon calculational results which indicated either nonnegative or relatively small negative free energy changes for all of the anticipated material degradation reactions.

The computer program[6] used in this analysis calculates the system composition, within certain constraints, which contains the minimum free energy. The constraints are the preservation of the masses of each element present and either constant pressure or volume.

Results of assessing the structural and corrosion property data base for alloy candidates which may be considered for use with all or in some part of the three subject chemical cycles indicated that either the anticipated use temperatures were too high or that some of the chemical species in a given cycle were known to cause high alloy corrosion rates. Candidate materials examined further included selected ceramic materials.

The potential chemical inertness of the three candidate cycles and the three leading candidate solar structural materials (i.e., SiC, stabilized ZrO_2, MgO) was analyzed using the computer code to calculate the thermodynamic equilibrium compositions for each combination. These calculations, as noted previously, are indicative of possible chemical interactions which could occur with the chemical species available in a given cycle and the materials. The nitrogen fixation cycle-SiC combination was not investigated because 2200°C is beyond the temperature normally considered suitable for structural application of SiC, even in a relatively non-oxidizing atmosphere.

A search of the literature provided information needed to perform calculations between the various species in the hybrid bismuth sulfate cycle and SiC and MgO. However, no thermodynamic data could be found on any Zr (or Y)-sulfur compounds. Results from the calculations with SiC, showed that oxidation of Si by the $SO_3/SO_2/O_2$ gas stream at 1000°C would take place. The extent of this reaction may be such that a protective film of SiO_2 is formed over the SiC but in any event some of the SiC will be oxidized. Calculations based on MgO as the containment material showed the MgO to be relatively stable in the $SO_3/SO_2/O_2$ gas environment. Other researchers[7,8] have recently had some success in MAS compatibility tests in a $SO_3/SO_2/O_2$ environment.

Obtaining results for the cadmium oxide cycle was very difficult. Cadmium does form some zirconium, magnesium, and silicate compounds, but no thermodynamic data on Cd and any possible reaction products from the candidate receiver materials could be found.

Because of the oxygen present in the high temperature CdO decomposition portion of this cycle, it is unlikely that ceramic SiC could be used if the presence of cadmium significantly fluxes the protective SiO_2 film. While formation of compounds of Cd and either Mg and Zr(or Y) are possible, it is doubtful whether they are more stable than the oxides at high temperatures. Thus, MgO and stabilized ZrO_2 such as with yttria may be quite stable with all of the chemical species anticipated in this chemical cycle, but confirmatory testing will be required to demonstrate if this is the case.

Calculations for the nitrogen fixation cycle and either MgO or ZrO_2 (stabilized with Y_2O_3) indicated one of the materials should work well and one is tentative. The MgO was calcualted to remain relatively unaffected by very high temperature air and is predicted to be stable. On the other hand, calculations for ZrO_2 (stabilized with Y_2O_3) showed that at equilibrium some ZrN is formed (∿2% of the original ZrO_2 is converted). The effect of the ZrN formation on the mechanical properties of the ZrO_2 ceramic or the receiver structure is unknown. The calculations showed that yttria used as the stabilizer in the ZrO_2 would have no tendency for chemical reaction with the nitrogen in high temperature air.

CONCLUSIONS

As shown in Table 1, MgO appears to be the best material for use with the hybrid bismuth sulfate and nitrogen fixation cycles, although the ZrO_2 (Y_2O_3) ceramic could possibly be used with the hybrid bismuth sulfate cycle. Confirmatory testing of these predictions are planned at ORNL. Since no appropriate thermodynamic data were available for the cadmium cycle, no equilibrium reaction predictions could be made. Testing of candidate materials with components of the cadmium oxide cycle are required and such tests are scheduled for initiation during FY 79.

ACKNOWLEDGEMENTS

Advice and assistance of C. E. Bamburger, G. W. Weber, J. M. Besmann, and T. B. Lindemer of ORNL were significant in the accomplishment of this work.

TABLE 1

SUMMARY OF RESULTS ON EQUILIBRIUM REACTIONS OF VARIOUS CANDIDATE CHEMICAL PROCESSES AND RECEIVER MATERIALS

	Candidate Processes		
Receiver Material	Hybrid Bismuth Sulfate	Cadmium Oxide	Nitrogen Fixation
SiC	Not recommended due to SiC oxidation	*[a]	Not recommended due to very high temperatures
$ZrO_2(Y_2O_3)$	*	*	Tentatively recommended, possible ZrN formation
MgO	Appears acceptable	*	Appears acceptable

[a] Because of oxygen present, it is questionable that SiC would have sufficient stability for use with this cycle.

*Insufficient thermodynamic data available for equilibrium phase assemblage predictions.

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8. Personal communication with J. Nemecek, Naval Research Laboratory (May 1979).

SOLAR COAL AND BIOMASS GASIFICATION

R. W. Taylor, D. W. Gregg, J. H. Campbell, J. R. Taylor, A. Cotton

Contract No.: AD-03-01-05
Start Date: 10/01/78
Completion Date: 09/30/79
Amount: $100,000.00
Contractor: Lawrence Livermore Laboratory
P. O. Box 808
Livermore, California 94550
Project Manager: David W. Gregg

The use of focused solar energy for gasifying coal has been identified as a process that should be technically and economically feasible.[1] This paper will present the plans for a demonstration solar coal gasification experiment to be carried out at White Sands, New Mexico, on June 18-30, 1979. The purpose of the experiment is to show technical feasibility as well as obtain some quantitative evidence as to the efficiency of the process. It is expected that at the time of this talk, June 21, 1979, we will be able to present some preliminary experimental results.

In this planned experiment the sunlight will be focused through a fused silica window into the coal reactor. The coal will be in the form of a packed bed (in contrast to a fluidized bed) with a vertical standpipe of coal to provide a coal feed. Both steam and CO_2 will be used in separate tests for gasification with sunlight providing the necessary energy to drive the following endothermic reactions:

$$\text{C(char)} + H_2O \rightarrow CO + H_2 \quad - 31.4 \text{ kcal/g-mol}$$

$$\text{C(char)} + CO_2 \rightarrow 2CO \quad - 41.2 \text{ kcal/g-mol.}$$

In addition to pure coal, blends of coal and biomass will be gasified.

A diagram of the coal reactor is presented in Figure 1, the White Sands Solar Furnace in Figure 2, the placement of the coal reactor and the gas vent system in the White Sands Solar Furnace facility in Figure 3, the steam and CO_2 supply system in Figure 4, a more detailed view of the steam and CO_2 supply system in Figure 5 and the gas analysis and sampling facility in Figure 6. In addition to the gas analysis diagnostic capability, there will be 12 thermocouples distributed in the reactor and printed on a strip chart. Solar blind infrared pyrometer measurements will be made to monitor window temperature and visible color pyrometer measurements will be made to monitor the temperature of the coal face.

The details of the experimental design will be discussed as well as the preliminary performance of the various components of the system. The product gas compositions will be compared to those predicted by our coal gasification computer code.

Reference

1. D. W. Gregg, W. R. Aiman, H. H. Otsuki, and C. B. Thorsness, "Solar Coal Gasification," Lawrence Livermore Laboratory Report No. PREPRINT UCRL-81853, November 1978.

SOLAR GASIFIER

Showing Inside Details

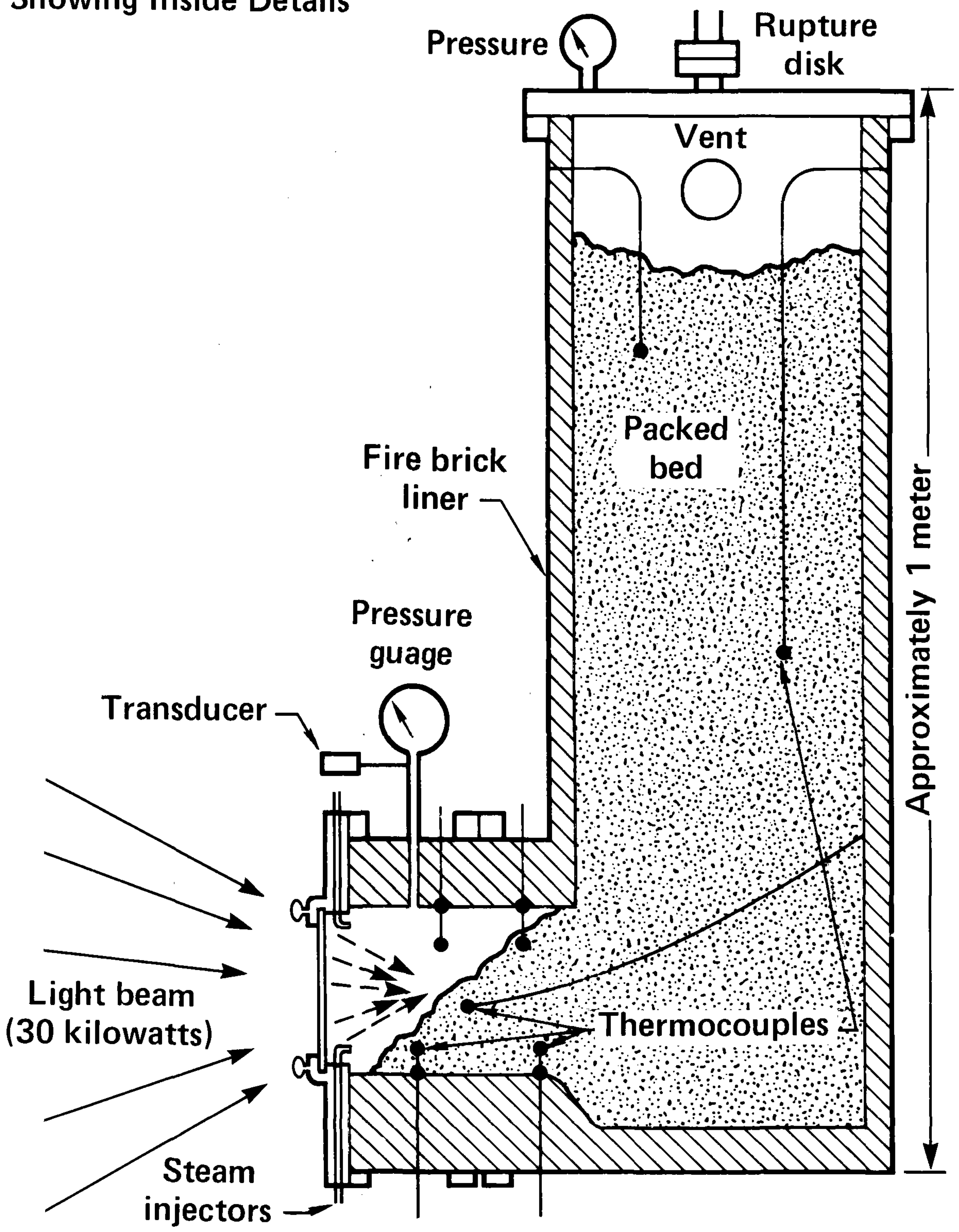

Figure 1

FOCUSED SOLAR FURNACE (30 kW WHITE SANDS N.M.)

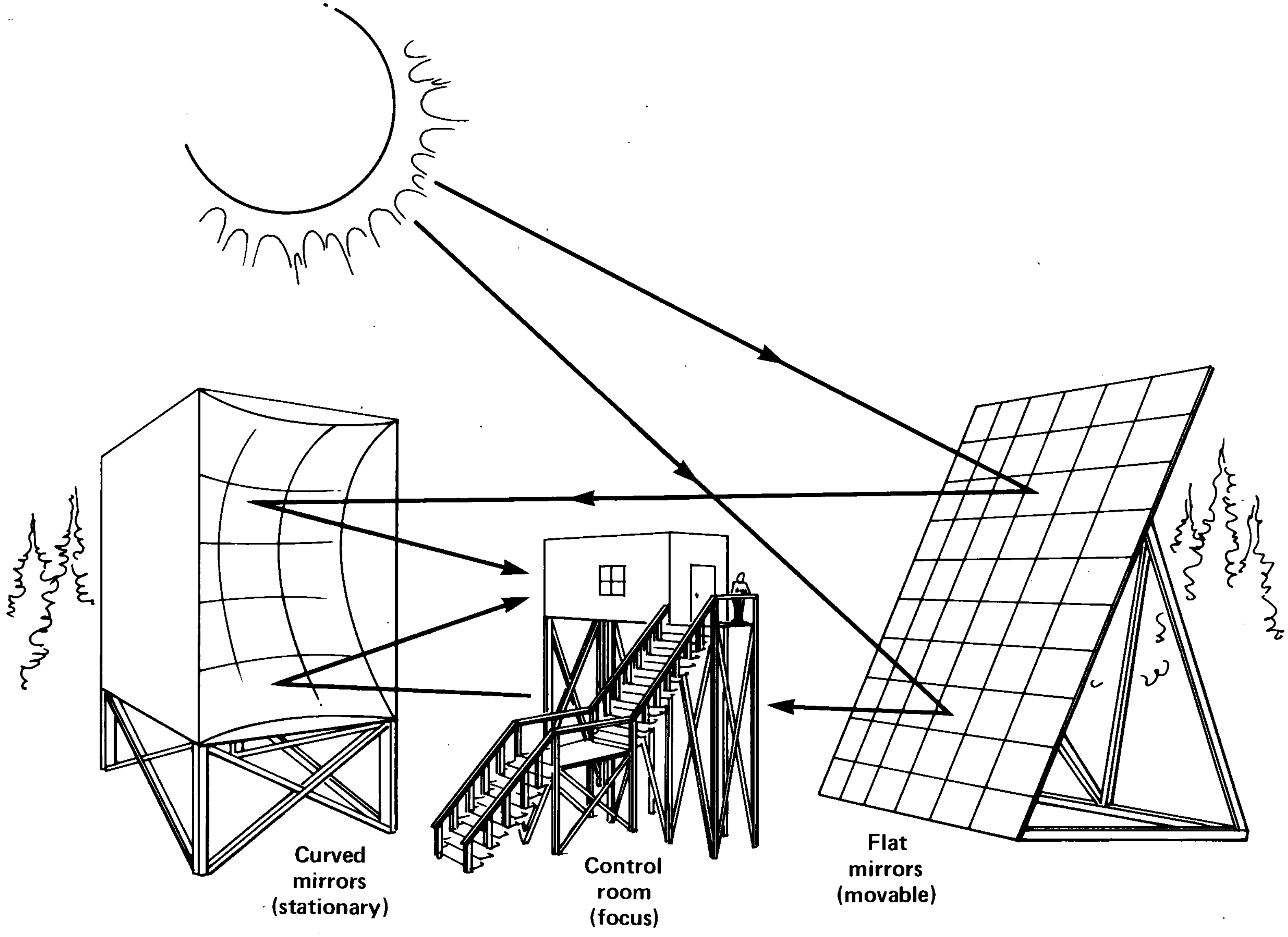

Figure 2

GASIFIER IN CONTROL ROOM (SHOWING VENT SYSTEM)

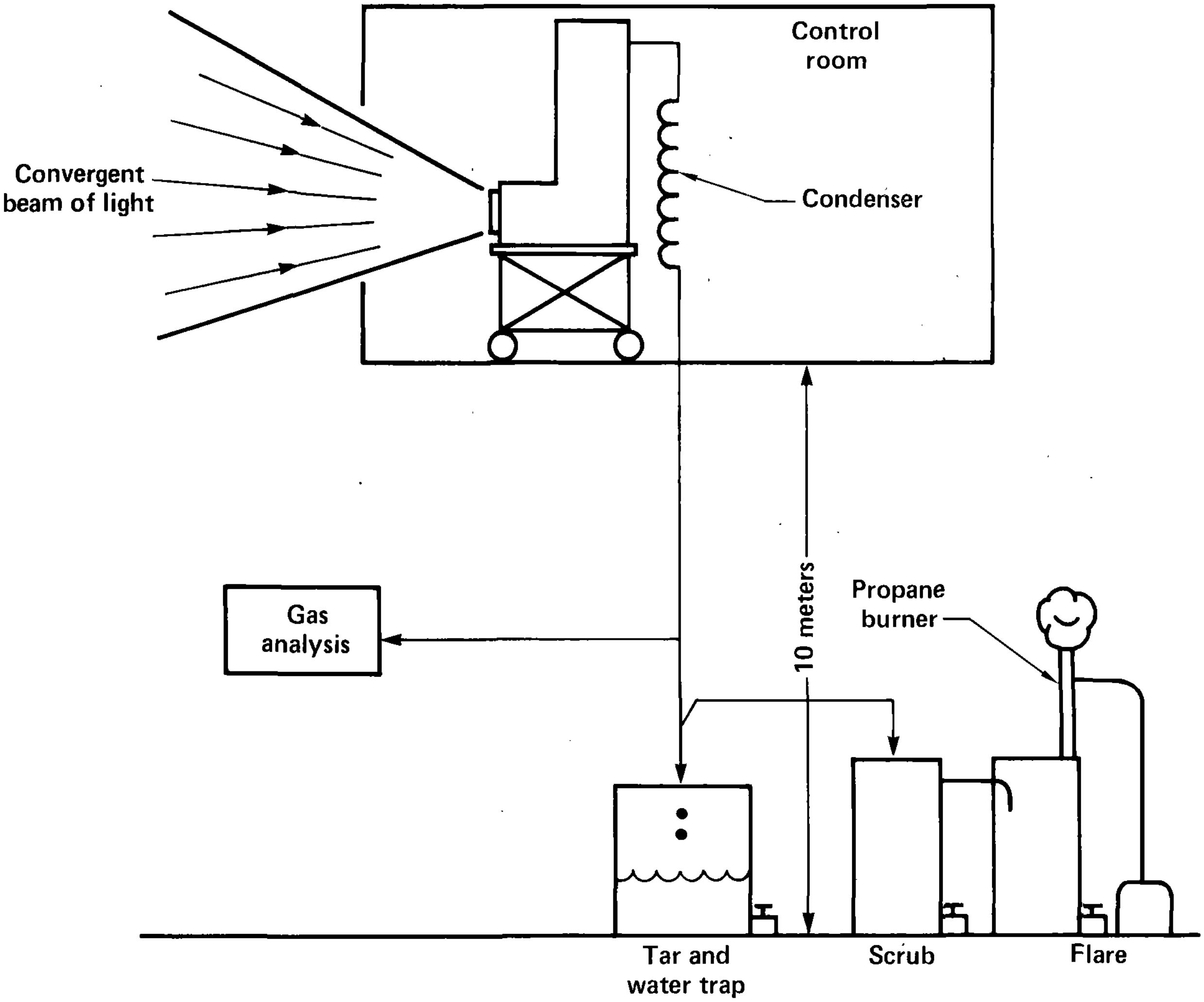

Figure 3

STEAM WATER AND CO_2 SUPPLY

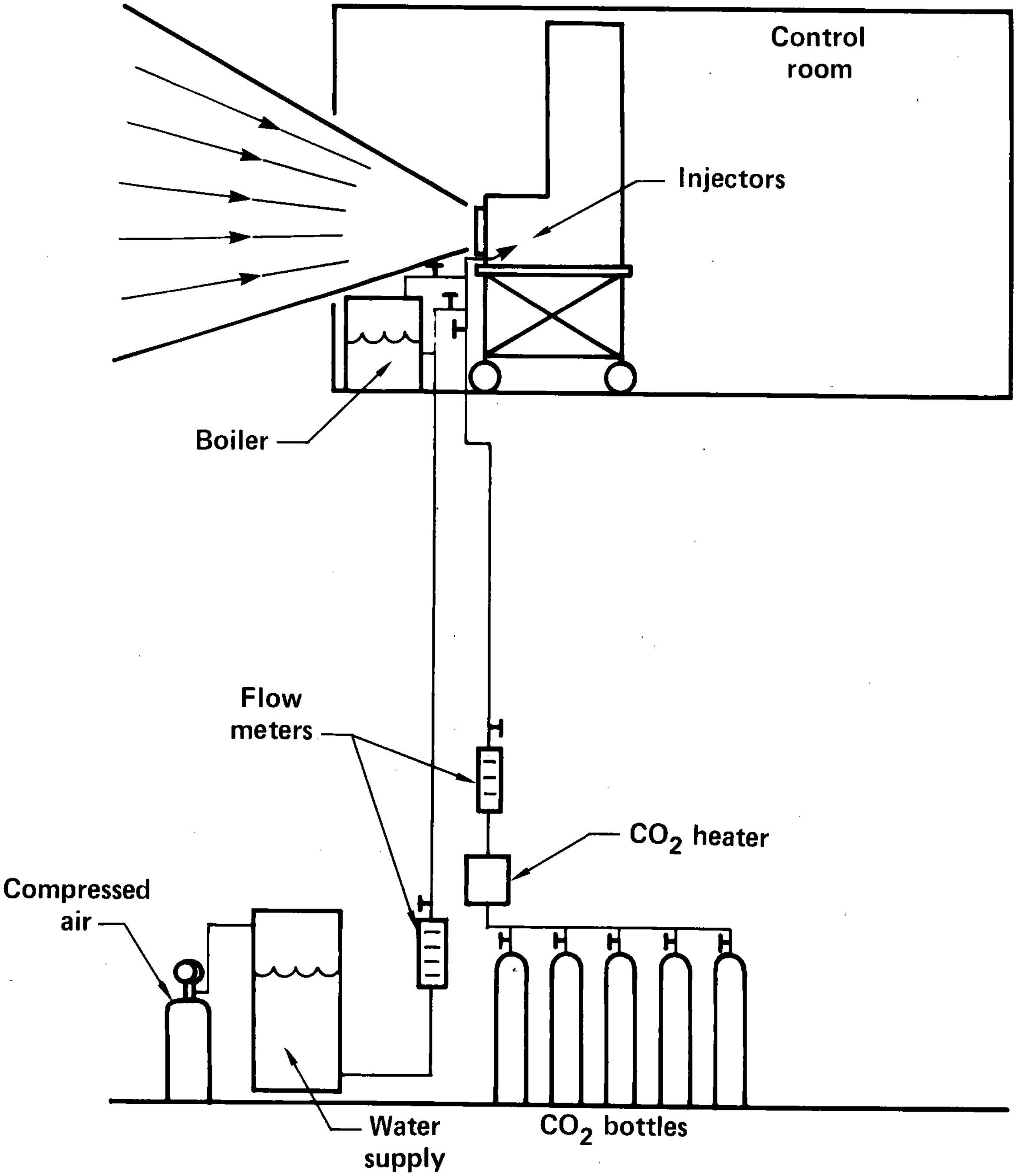

Figure 4

WATER STEAM AND CARBON DIOXIDE SUPPLY (DETAILS)

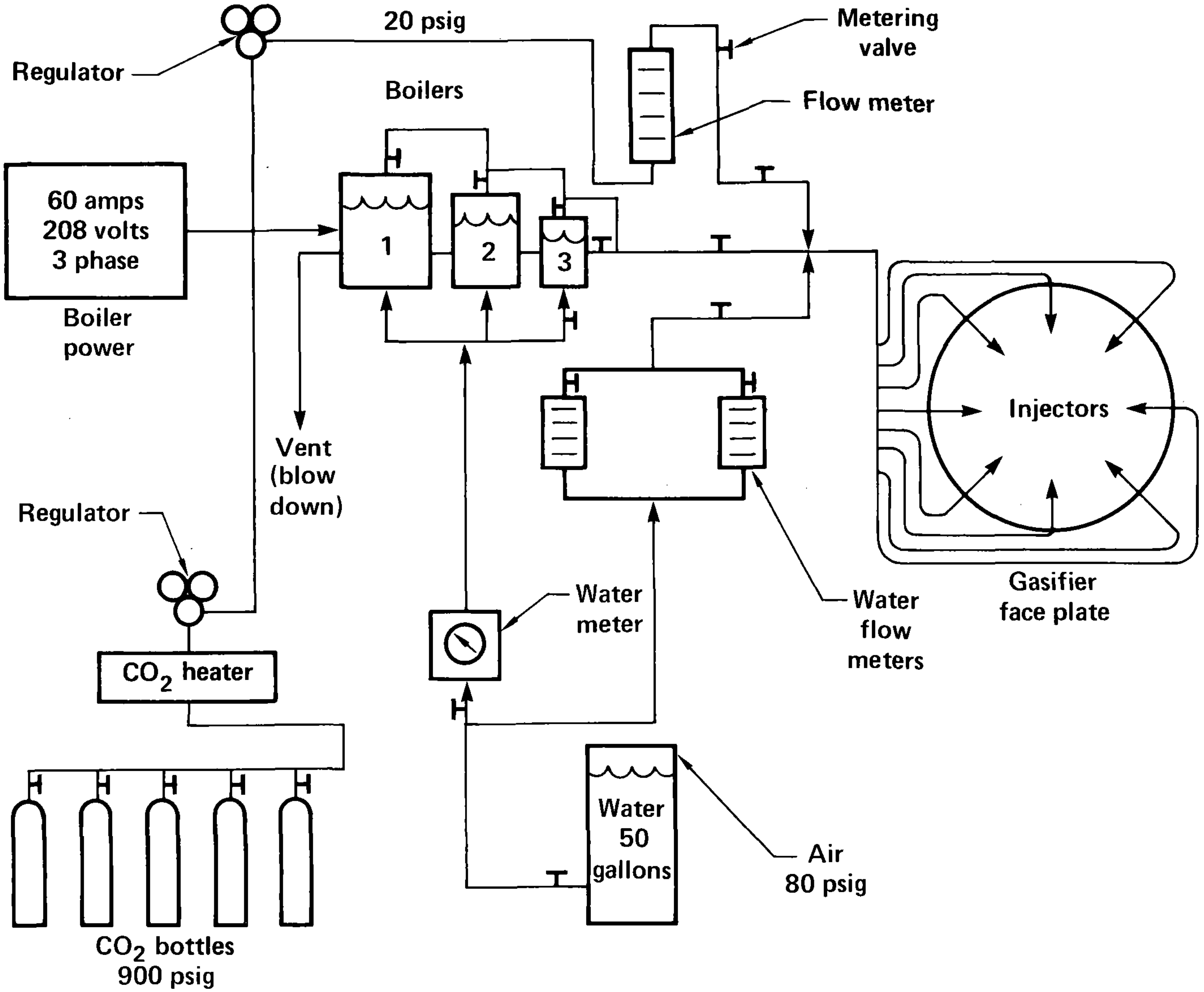

Figure 5

GAS ANALYSIS AND SAMPLING FACILITY

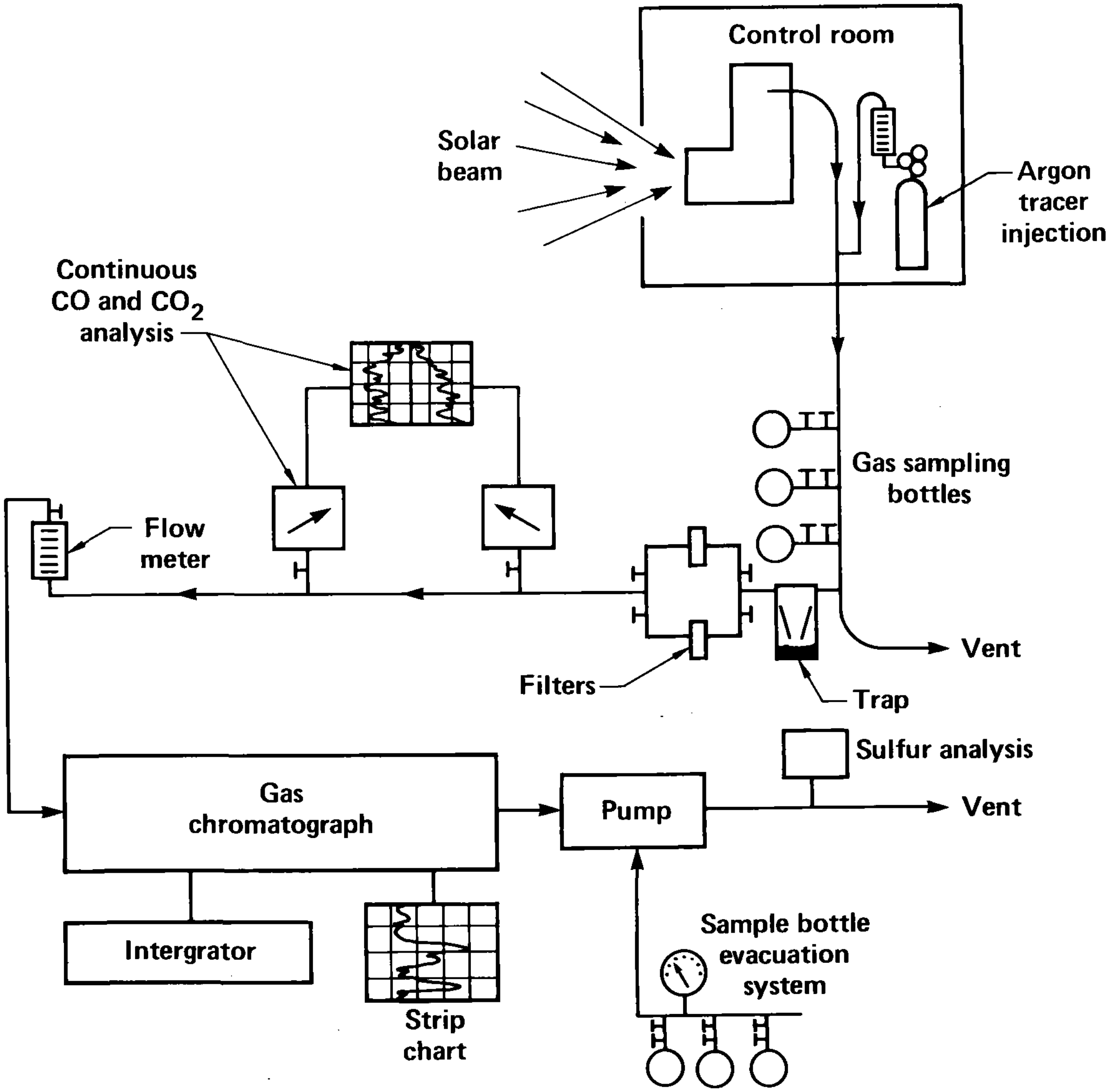

Figure 6

High Temperature Industrial Process Heat

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ABSTRACT

Industrial process heat constitutes the largest major consuming sector of U.S. energy demand -- approximately 37% or 15 quads in 1976. While low and intermediate temperature applications (< 300°C) have been the primary focus of DOE-sponsored solar applications studies and experimental projects to date, the off-quoted report by Intertechnology Corporation [1] suggests that nearly 75% of the process heat demand lies in a process temperature range from 300-1800°C.

The size of this energy-use sector and the fact that it represents a relatively flat seasonal demand necessitates a serious examination of the potential for solar systems to supply this energy. Only a few such studies have been carried out to date, and little has been done to determine the true value of solar energy compared to fossil fuels in high temperature applications. This is not an easy task, for it requires a thorough knowledge of the solar systems required in a large number of diverse applications, cost data on future high temperature solar technologies, and an understanding of the important economic factors for the industries in question.

Cursory examinations of selected high temperature processes have been carried out to evaluate the <u>technical</u> feasibility of solar substitituion. These include petroleum refining, drying and calcining of Fullers earth, annealing of flat glass, reactivation of bone char in cane sugar refining, drying in beet sugar refining and wet corn milling, blast furnaces and steel mills, hydraulic cement calcining, casting foundries, glass melting, and some processes for synthetic fuel production. The solar technologies needed to supply energy to these processes include parabolic troughs, two-axis tracking dishes and central receivers. The technical necessity or economic value of thermal storage is expected to be strongly process-dependent.

These early process studies have shown that in general the problems of utilizing solar thermal energy directly in high temperature industrial applications are formidable, and these problems may significantly limit the future extent of such direct solar substitution. To some degree, this conclusion derives from the obvious problems of retrofitting solar to industrial processes designed to utilize existing energy forms (fossil fuels, electricity). On the other hand, large industries generally produce a sizable percentage of their own electricity and all their process steam, so that cogeneration is a viable option. In the 300-500°C range, solar could also be utilized in several processes to supply high temperature air or to provide air preheating, but this represents only a small fraction of the total energy usage. Perhaps more important is the potential for indirect impact of solar via synthetic fuel production, which can be utilized in existing process equipment with only minor modifications. A tentative conclusion is that competitive solar-produced synthetic fuels appear to offer the most promising mechanism by which solar energy could satisfy a significant portion of high temperature industrial process heat needs.

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INTEGRATED FUELS AND CHEMICALS CONCEPT

- SUMMARY -

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Severe capital intensity and discontinuous energy availability are two factors that will challenge development of solar-fired fuels and chemicals processing. One response to those challenges is to consider integrating into a single complex several processes that are traditionally sited and powered separately, in such a way as to significantly increase efficiency of resource use.

We have been engaged in a study of the solar fuels and chemicals integration concept for some time, supported by JPL and DOE funds. This study has been aimed at synthesizing conceptual integrated facilities, evaluating their potential, and identifying areas where R & D activities are most likely to accelerate implementation. System synthesis and evaluation is accomplished by application of two modeling techniques. The first of these is a flexible, time dependent system performance model that can be applied to a wide range of systems and allows easy examination of options within systems. This model yields mass and energy flows into, within, and out of an integrated complex as a function of diurnal cycle and system parameters including process mix, process characteristics, and integration strategy (or facility configuration). The second methodology is used to determine economic potential over the life cycle of system options; it provides sensitivity to financing costs and tax and inflation rates.

This combined methodology has been exercised on one test integrated facility concept to produce diurnal performance parameters for one process mix with one set of process characteristics, looking at two variants of operational strategy within one facility configuration. The test case is a complex that produces gasoline and light hydrocarbons, urea, and ammonia from coal, air, and sea water. Fuel output (from a Fischer-Tropsch process) was used as the controlling parameter. Urea production was sized to use a variable fraction of the CO_2 produced; the ammonia plant was postualted to match the urea requirement in winter while producing excess in other seasons. Hydrogen is formed by the Westinghouse sulfur cycle with electrolysis decoupled from sulfate decomposition. That thermal decomposition is the only process subjected to diurnal cycling. Internal energy production and demands are matched so that the solar source provides only high temperature thermal input to sulfate decomposition. Application of economic evaluation to this non-optimized facility reveals some promise of economic potential, and provides a mapping of cost sensitivity.

CONCEPTUAL STUDY ON THE ECONOMICS OF USING SOLAR ENERGY IN THE PRODUCTION OF FUELS AND CHEMICALS

JPL Contract No. 955215
November 1978 Through June 1979

John Sinnott
The Institute of Gas Technology

INTRODUCTION

In 1976, U.S. manufacturers' energy consumption was approximately 12 quadrillion Btu's. Chemicals and fuels manufacturers were responsible for about one-third of this consumption. Because current direct solar thermal energy (DSTE) technology can produce heat at temperature levels high enough to meet the process heat requirements for most fuels and chemicals production processes, these industries are important targets for the initial commercialization of high temperature DSTE systems.

The rate of commercialization for these systems will depend on their ability to meet process heat requirements, their reliability, and their economics. Assuming that the performance and reliability requirements can be met, the commercialization will ultimately depend on economics — specifically, what is the cost of using a DSTE system compared to that of using a conventional fuel system?

In comparing the economics of these systems, a number of factors play dominant roles. These factors are —

1. The process heat requirements,
2. The current and projected economics of using conventional systems,
3. The production location,
4. The level of conventional fuel displacement,
5. The costs and performance of the DSTE system,
6. The ownership and capitalization structure for financing the DSTE and conventional fuel systems, and
7. The incentives provided by Federal, State, and/or local governments.

Each of these factors consist of a number of variables which have individual influences on the resulting user economics. Some variables will be independent of any federal or private action. An example variable would be the insolation pattern for a plant site. Others can be directly or indirectly affected by federal or private action. Examples would be receiver performance (by R&D funding) and tax credits (by lobbying and legislation). Knowledge of the relative effects of the variables on the user economics can be an important resource to research funding, research, and legislative agencies — particularly those whose charter it is to champion DSTE technology. For example, through predictions of the effects of different development projects on user economics, a funding agency can better allocate its hardware R&D monies to maximize their impact on bringing DSTE commercialization closer.

GOAL AND OBJECTIVES

The goal of this project has been to develop a better understanding of how the different variables affect the user economics. Toward this goal, two principal objectives were specified for this research. The first objective was to identify the dominant economic variables. The second was to determine the potential impact of each of these variables on the economics of substituting DSTE for a conventional energy system.

Two sub-objectives of this research were (1) to develop a computer model which can be used to analyze the substitution economics on a conceptual basis or for a particular fuel or chemical manufacturing process and (2) to use the model to analyze the substitution economics for using a DSTE system in two specific cases. The model has been designed to simplify the economic analysis process and to provide an upgradeable tool which could be used in the future to analyze specific substitution opportunities.

The variables to be considered were chosen prior to the start of the research. These variables were —

A. Process heat requirements
B. Conventional fuel costs
C. Conventional fuel efficiency
D. Weather profile
E. Land costs
F. Level of conventional fuel displacement
G. Solar collector performance
H. Solar collector costs

I. Thermal storage performance
J. Thermal storage costs
K. Heat Transfer performance
L. Heat Transfer cost
M. Capitalization structure
N. Incentives
O. Inflation rates

As the research proceeded, several of these variables were found to be too general. Others were added. The process heat requirements variable was split into two, differentiating between the heat rate requirement and the temperature requirement. The heat transfer performance and costs variables were likewise split to differentiate between the pipefields tranferrring the heat from the collectors and the heat exchangers in direct contact with the process. Added variables were the costs related to the capital structure such as debt interest and the required rate of return for the system owners. The inflation rate variable was expanded to include both inflation and escalation rates. As a result, quite a number of variables have been considered.

PROGRESS TO DATE

At the time of the submission of this summary, the project was 95% complete. Remaining are final review of the economics results, documentation of the model, and submission of the final report. The work on this report has consisted of the following efforts:

- Design of the conceptual DSTE system
- Definition of the intra-component relationships for the DSTE system
- Definition of the external influences and their relationships with the DSTE system
- Development of the model
- Creation of a "base case" chemical process for the conceptual economic analysis
- Analysis of the key variables using the "base case"
- Analysis of the key variables with two processes — methanol production and vinyl chloride monomer production.

The DSTE System developed contains all the major subsystems necessary to provide solar thermal energy to a fuel or chemical production process on a 24 hours per day basis. The system includes the following subsystems:

- Collector/receiver subsystem
- External heat transfer subsystem
- Thermal storage subsystem
- Conventional fuel subsystem
- Internal heat transfer and control subsystem.

Each of these subsystems consists of major components with important cost and performance characteristics which can ultimately influence the economics of using a DSTE system. These components have been approached on a generic basis rather than on a manufacturer specific basis. For the analysis, the performance or cost of Manufacturer X's central receiver is less important than the range of costs or performance that could be achieved for central receiver technology.

The system has been designed to work with a wide range of process heat requirements and component capabilities. Component sizing, and thus cost, is determined by using the process heat requirements as a base. Each manufacturing process is broken into thermally discrete subprocesses. For instance, an integrated process that can use a heat source for one subprocess and then use waste and lower quality heat expelled from that subprocess to meet all other needs in a cascading mode would be treated by the system as having only one subprocess. Likewise, if there were a number of subprocesses, each needing a separate, different temperature heat source with no usable waste or lower quality heat, each would be treated separately.

The system works on a requirement basis. Starting with the process requirements, the size, performance, and cost requirements are determined for the internal heat transfer and control subsystem. Based on an externally determined "use strategy" and the input needs of the internal heat and control subsystem, output requirements from the thermal storage, conventional fuel, and external heat transfer subsystems are calculated. The input needs of the thermal storage subsystem are determined and added to the output requirements of the external heat transfer subsystem. The input requirements of the external heat transfer subsystem are then calculated and used to determine the size and performance needs of the collector/receiver subsystem. This calculation flow is integrated with the external influences such as weather, local conventional fuel and land costs, financing costs and structure, escalation rates, and available government incentives. The precise relationships are included in the final report.

The model was developed to duplicate the calculation process for the DSTE system so that the end cost per Btu delivered to the overall chemical or fuel process and to each subprocess could be determined and compared against that of a conventional system. Further, the model was given the capability of using one of a number of options for each subsystem category and to compare the results when using each option. Finally, the model was given a sensitivity analysis capability so that a single variable within a subsystem could be varied through three positive and three negative increments and the results compared. This sensitivity analysis capability is the critical component necessary to determine the effects of various research and incentive possibilities.

The "base case" production process contains three subprocesses: one low temperature requirement at 250°F, one mid-pressure steam requirement at 445°F, and one high temperature requirement at 1000°F. The results of our analysis have been summarized. They are not suprising. As with any capital intensive system, the financial structure and costs, the life of the system, and the availability of economic incentives are critical if a DSTE system is going to economically replace, or displace a conventional fuel system. Second, the availability of clear skies is critical for a high temperature DSTE system. Again this is a reflection on the capital intensity of the system. Third, maximizing the percentage of heat provided by the DSTE system is not normally the most economical way of using DSTE. As a corollary to this, found indirectly in the analysis, hybrid systems which use conventional fuels to provide peak temperatures are more economical in the near future than pure DSTE systems which provide heat through the peak temperatures. Fourth, the economic feasibility will be dominated by the cost and availability of different fuels. Perhaps the most important result of this research is that any one of these major influences can prevent a DSTE system from being economically feasible. To this point, the process of bringing DSTE systems to commercialization must not forget to address each of these influences.

The details of this analysis will be found in the final report for this project. The results for the methanol and vinyl chloride monomer processes are not presented here.

FUTURE PLANS AND EXPECTED RESULTS

The analyses to date show potential for using the model on an individual process basis in addition to the generalized/conceptual basis. Prospects here will be pursued.

Hybriding, in the preliminary analysis, shows substantial potential for speeding up the commercialization of DSTE. In high temperature processes, the use of conventional fuels to provided the high quality heat may be the additional impetus needed to make a DSTE system economically feasible. This potential should be followed up carefully.

APPLICATIONS OF THE WESTINGHOUSE SULFUR CYCLE

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ABSTRACT

This paper highlights results of one of the tasks performed during 1978 for DOE/Solar Energy under Contract No. ET-78-C-02-4705. Westinghouse is developing, with DOE support, a hybrid electrochemical/thermochemical process for hydrogen production. The process, known as the Sulfur Cycle, has the potential for generating hydrogen and oxygen with substantially smaller energy requirements than are needed in normal water electrolysis.

Recent process studies have focused on driving the Sulfur Cycle with solar heat and using the resulting hydrogen as a feedstock for chemicals or synthetic fuels. Figure 1 schematically illustrates this general approach. Scoping studies have been performed to identify specific chemical or synthetic fuel processes that could be integrated with a solar/hydrogen plant. Five processes were selected for concept evaluation: ammonia synthesis, methanol synthesis, hydrogen peroxide manufacture, direct iron ore reduction, and coal liquefaction. The major characteristics of solar plants for the first four processes are summarized in Table 1. The coal liquefaction process was evaluated on a qualitative basis only.

The studies were based on the use of heliostat fields and solar central receivers to absorb the concentrated solar flux. To illustrate, a sketch of a solar/hydrogen/ammonia plant arrangement is shown in Figure 2. A "conventional" solar receiver is used to generate steam for electric power generation, while a high-temperature (1600°F) receiver is employed for the thermochemical step of the Sulfur Cycle (i.e., sulfuric acid vaporization and decomposition). Energy storage systems are used to permit continuous operation of the chemical process. Thermal energy storage (oil/rock sensible heat) is used for electric power generation at night. Chemical storage in the form of sulfur dioxide is used for the thermochemical step by decomposing surplus acid during periods of insolation to charge the storage tanks.

Single solar central receivers are limited in capacity by the physical constraints of heliostat distance from the receiver and by tower dimensions. "One-module" capacities for each process were estimated using a single high-temperature

receiver and a single steam receiver. Larger capacities could be obtained by using multiple modules. Although relatively small, the ammonia and methanol plant capacities may represent attractive plant sizes for market areas such as the southwestern United States. The hydrogen peroxide plant capacity is larger than necessary, and a scaled-down plant could be designed. The capacity for direct reduction of iron ore is comparable to medium-sized fossil-fuel direct reduction plants. Since the sponge iron product can be processed in an electric furnace, there are no overriding scaling factors similar to those that determine the capacities of conventional steel making facilities.

Each of the concepts was judged to be technically feasible and environmentally attractive. The ammonia and hydrogen peroxide plants require only solar energy, air and water to function. The methanol plant requires a carbon source, which could be carbon dioxide recovered from flue gas, calcining operations, air or sea water. The direct iron ore reduction plant is particularly attractive from an environmental standpoint. It uses solar energy and water to reduce iron ore to sponge iron, which can be made into steel in an electric arc furnace, thus eliminating the need for coke ovens, blast furnaces, and basic oxygen furnaces.

In summary, several potentially attractive solar fuel and chemical plant concepts have been identified using the Sulfur Cycle as an intermediate process for producing hydrogen. These concepts offer attractive alternatives for producing synthetic fuels or hydrogen-rich chemicals without the need for fossil fuels to produce hydrogen. Preliminary economic estimates indicate product costs somewhat greater than costs with plants that use fossil fuels. As anticipated, the dominant capital costs are associated with the solar energy and energy storage subsystems. However, this trend is consistent with numerous evaluations of solar electric power plants that use comparable technology, i.e., central receivers and heliostat collector fields. Since the solar collection and storage portions of the plants represent almost two-thirds of the total estimated capital investment, this is the area where the greatest reduction in costs can be obtained. DOE's programs for advanced heliostat design, high-temperature solar receivers, and advanced storage systems are aimed at reducing these costs. In addition, continuing development on the Sulfur Cycle should permit reduction of the hydrogen production costs. It would be premature at this point to make projections of breakeven fossil fuel prices or plant payback periods. The results to date in effect represent scoping studies aimed toward identifying potential candidate solar fuels and chemicals processes, and determining first-cut approximations of technical performance and economics.

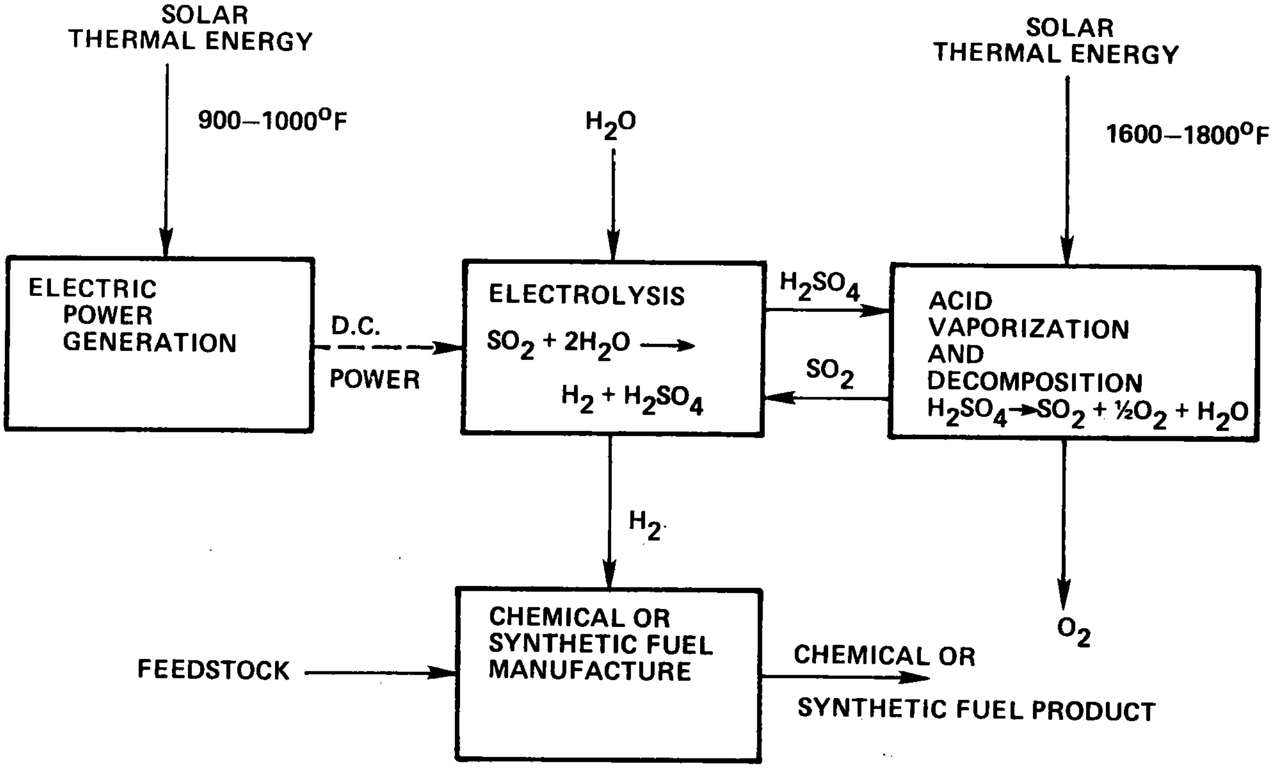


Figure 1. Solar/Hydrogen Fuels and Chemicals Production

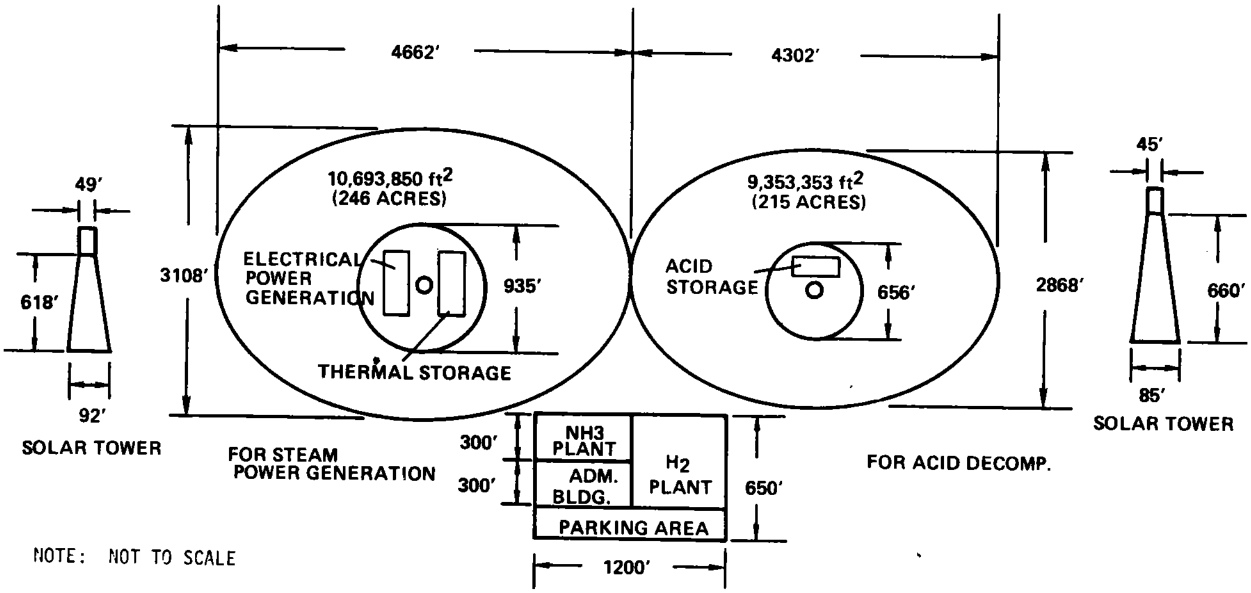


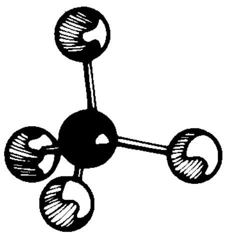
Figure 2. Solar/Hydrogen/Ammonia Plant Arrangement

TABLE 1

MAJOR CHARACTERISTICS OF SOLAR/HYDROGEN/CHEMICAL PROCESS PLANTS

	Ammonia	Methanol	Hydrogen Peroxide	Direct Reduction of Iron Ore
Product	NH_3	CH_3OH	H_2O_2	Iron Ore
Production Rate (tons/day)	190	215	490	625
Solar Power (MWt)	1000-1500 Typical ← fossil plant	→ 1000 tons/day	✓	Z
• For Electric Power Generation	224	156	159	155
• For Sulfuric Acid Decomposition	177	177	177	177
Total Reflective Surface (Thousands of m^2)	690	573	578	572
Electric Power Generated (MWe)	29.2	22.2	22.5	22.1
Hydrogen Production Rate (Millions of SCFD)	12.7	12.7	12.7	12.7
Total Energy Consumption (Millions of Btu per ton of product)	64.8	47.6	21.1	16.3

Advanced Carbon Cycle Applications



PRESENTED AT

DOE SEMI-ANNUAL REVIEW OF

ADVANCED SOLAR THERMAL POWER SYSTEMS

SOLAR FUELS AND CHEMICALS SESSION

JUNE 21, 1979

L. R. SITNEY

ADVANCED CARBON CYCLE APPLICATIONS

Abstract

Results obtained to date on both DOE and Aerospace sponsored research on thermochemical carbon cycles and their applications are described. The DOE work deals exclusively with the identification, through thermodynamic calculations, of potential carbon cycles to reduce CO_2 or CO to carbon and oxygen. Closed cycles are shown for the reduction of the oxides of carbon by means of cadmium, nickel, and zinc. Experimental validation of one or more carbon cycles will be attempted on a current DOE contract. The Aerospace sponsored research has been concerned primarily with the identification of chemical and power applications of thermochemical carbon cycles, examples of which are given. A concept is shown for using a solar-driven carbon cycle to achieve higher temperatures than solar thermal technology would permit for commercial applications involving large masses of materials. Various combined power cycles, which utilize a thermochemical carbon cycle for regeneration of the combustibles, are identified. In particular, a combined CO_2 cycle, which incorporates MHD, a CO_2 turbine, and a steam turbine with an overall efficiency of approximately 60 percent, is described.

ADVANCED CARBON CYCLE APPLICATIONS

L. R. Sitney
The Aerospace Corporation

The work reported in this paper was sponsored in part by the Department of Energy and in part by The Aerospace Corporation. The material dealing with the thermochemical carbon cycles themselves is based upon a study carried out under DOE sponsorship in late 1977 and early 1978. Work is currently in progress under DOE sponsorship to validate one or more of the thermochemical carbon cycles experimentally and to identify additional carbon cycles. The current DOE effort also includes an experimental study of the reduction of CO_2 by various carbonaceous materials, including coals and coal chars, by means of the Boudouard reaction. At present, no experimental data are available since the experiments are just being set up. The information presented on user's cycles for the production of power and chemicals is based on work sponsored by The Aerospace Corporation, which is still in progress.

Work on thermochemical carbon cycles was initiated as an offshoot of a study for the DOE Assistant Director for Thermal Power Systems to identify markets for high temperature industrial process heat based on the use of solar thermal power technology. It was realized that CO_2, which was emanating from fossil-fueled power plants and contributing to the "Greenhouse Effect", could be reduced to CO by a solar-driven Boudouard reaction, and that the resulting CO could then be used to produce hydrocarbons and other organic chemicals by means of suitably catalyzed Fischer-Tropsch reactions. While an external source of carbon, such as coal, could be used to accomplish the CO_2 reduction, it would be desirable to develop a closed thermochemical carbon cycle to provide the carbon for the CO_2 reduction. The work described in this paper is based upon that premise.

A number of potential thermochemical carbon cycles were identified in the initial DOE-sponsored study on the basis of thermodynamic calculations. Some were found to be infeasible when they were analyzed in more detail. At the present time, three cycles reported by The Aerospace Corporation on the basis of thermodynamic calculations only, still appear to be feasible. The experimental verification must still be carried out. A fourth cycle is under investigation, but will not be reported until experimental validation is demonstrated.

The three potential carbon cycles identified to date are designated as the cadmium and zinc cycles for the reduction of CO_2 to carbon and oxygen, and the nickel cycle for the reduction of CO to carbon and oxygen. In the nickel cycle, a Boudouard reaction is used to reduce the CO_2 to CO by means of the carbon produced in the nickel cycle. The three cycles are shown below, along with the temperatures at which the individual reactions should occur and the estimated overall theoretical efficiencies for the cycles, including allowances for the energy required to separate products by chemical processing.

$2Cd + CO_2 = 2CdO + C$ (600^{o}K) 46%
$2CdO = 2Cd + O_2$ (1900^{o}K)

$2Zn + CO_2 = 2ZnO + C$ (1300^{o}K) 37%
$2ZnO = 2Zn + O_2$ (2400^{o}K)

$C + CO_2 = 2CO$ (1000^{o}K)
$2Ni + 2CO = 2NiO + 2C$ (600^{o}K) 49%
$2NiO = 2Ni + O_2$ (2850^{o}K)

Of the three cycles, the cadmium cycle is the most attractive because the decomposition temperature of its oxide is lowest. However, even that temperature (1900^{o}K) is much higher than is believed acceptable for a long duration commerical operation. A preferred upper limit for the temperature in a thermochemical carbon cycle is of the order of 1400^{o}K in order to keep equipment lifetimes at reasonable levels. Of course, the specific operating temperatures of a practical system will depend upon the results of materials testing and other engineering tests. Reduction of the pressure may permit the upper temperature limit to be lowered as a result of the enhanced decomposition of the metal oxide at lower pressure. These effects will be examined during the experimental phase of the study.

Work accomplished with Aerospace Corporation funds has dealt primarily with applications of the carbon cycles. The greatest portion of this effort has been devoted to power applications rather than chemical applications because it was felt that significant fuel savings could be achieved as a result of the high efficiencies of some of the combined power cycles.

One chemical application which has been examined in a cursory fashion has been the production of ammonia by means of the following reaction sequence:

$C + CO_2 = 2CO$ (from closed carbon cycle)
$CO + H_2O = H_2 + CO_2$
$3H_2 + N_2 = 2NH_3$

This process would be an alternative to reforming methane to obtain the hydrogen, as is currently the case. The advantage of the solar-driven carbon cycle is that no carbon is consumed in the process; only water and nitrogen are used.

One of the uses to which the carbon cycle can be applied is "temperature amplification". In this concept, the carbon monoxide and oxygen formed in the carbon cycle are combusted to form CO_2 with the release of the heat of combustion. The heated CO_2 can then be used, either directly or by means of a heat exchanger, to raise the temperature of the material of interest. After the heat has been removed from the CO_2, it is recycled using solar energy to generate CO and O_2. The advantage of this concept is that it can be used to raise the temperature of large quantities of the material of interest to as high as 2500°K, much higher than would be achievable with solar energy alone for such quantities of material.

The power cycles involve the carbon cycle to form CO and O_2 from CO_2. The CO and O_2 are reacted to form CO_2 and heat. The hot CO_2 can then be passed into a power cycle, such as MHD, followed by passage through a CO_2 gas turbine and a steam turbine, and then back to the carbon cycle for regeneration. The overall efficiency of such a cycle is calculated to be 58-62 percent, based on cycle efficiencies reported by other organizations for each of the separate power stages. No work has been reported in the literature on a CO_2 MHD cycle, but such a cycle should be feasible at a lower efficiency than for an air cycle. Work has been reported by General Electric on the design of a CO_2 gas turbine as part of the Energy Conversion Alternatives Study (ECAS) for DOE; however, no large-scale hardware exists for such a gas turbine. On the other hand, the technology associated with a CO_2 turbine should be straightforward.

A second power application passes the CO from the carbon cycle through a CO fuel cell at approximately 1000°K, the temperature at which the CO would be formed. Such a cell is under development by Westinghouse and is expected to give efficiencies of the order of 58-68 percent in combination with a steam turbine. The CO_2 exiting from the CO_2/steam heat exchanger of the turbine is recycled through the carbon cycle to form CO and O_2.

Based upon a power cycle efficiency of approximately 60 percent, the actual efficiency of the carbon cycle must be at least 64 percent to be competitive with a conventional solar thermal power system.

ADVANCED CARBON CYCLE APPLICATIONS

Contractual Data

CONTRACT No.	PERIOD OF PERFORMANCE
EY-76-C-03-1101	11/1/77 - 4/30/78
DE-AI-01-79ET-21036	1/15/79 - 1/14/80
AEROSPACE SPONSORED RESEARCH	7/1/78 - 9/30/79

ADVANCED CARBON CYCLE APPLICATIONS

Objectives

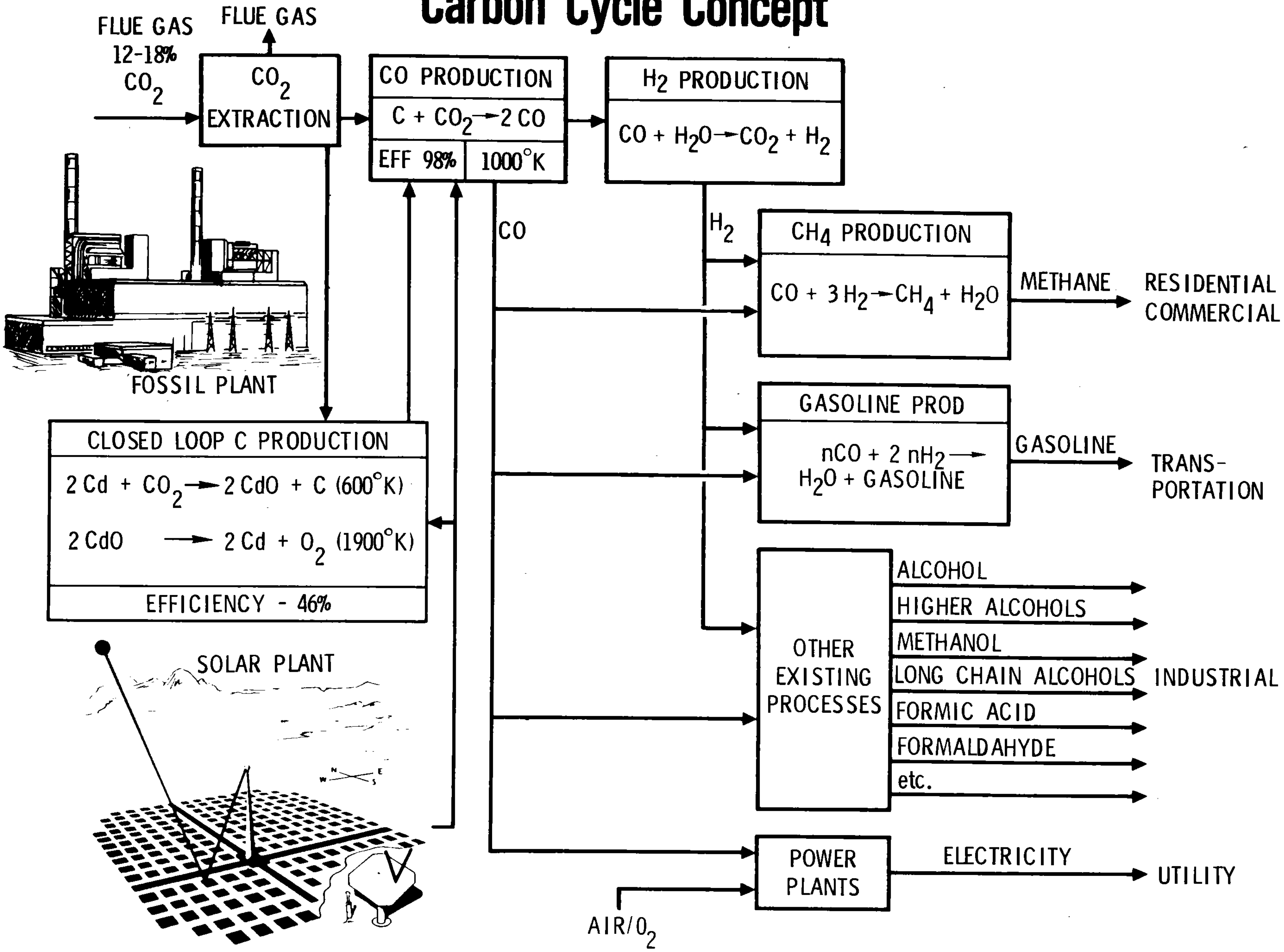
- DOE
  - ASSESS THE POTENTIAL APPLICATION OF SOLAR THERMAL POWER TECHNOLOGY TO PROVIDE A SOURCE OF HIGH TEMPERATURE TO DRIVE KEY REACTIONS FOR THE PRODUCTION OF TRANSPORTABLE FUELS AND CHEMICALS, USING CARBON AND/OR HYDROGEN CYCLES
- AEROSPACE SPONSORED RESEARCH
  - IDENTIFY POTENTIAL APPLICATIONS OF THERMOCHEMICAL CARBON CYCLES FOR THE PRODUCTION OF FUELS, CHEMICALS, AND POWER

ADVANCED CARBON CYCLE APPLICATIONS

Approach

- THERMOCHEMICAL CYCLE SELECTION
  - IDENTIFY POTENTIAL THERMOCHEMICAL CYCLES BY THERMODYNAMIC CALCULATIONS
  - VALIDATE PROMISING CYCLES EXPERIMENTALLY
- APPLICATION STUDIES
  - IDENTIFY ATTRACTIVE APPLICATIONS
  - CONFIGURE SYSTEM CONCEPTUALLY
  - DETERMINE PERFORMANCE

SOLAR FUELS AND CHEMICALS
Carbon Cycle Concept



FLUE GAS 12-18% CO_2

FLUE GAS

CO_2 EXTRACTION

CO PRODUCTION

$C + CO_2 \rightarrow 2\,CO$

EFF 98% | 1000°K

H_2 PRODUCTION

$CO + H_2O \rightarrow CO_2 + H_2$

CO

H_2

CH_4 PRODUCTION

$CO + 3H_2 \rightarrow CH_4 + H_2O$

METHANE → RESIDENTIAL COMMERCIAL

GASOLINE PROD

$nCO + 2\,nH_2 \rightarrow H_2O + \text{GASOLINE}$

GASOLINE → TRANS-PORTATION

FOSSIL PLANT

CLOSED LOOP C PRODUCTION

$2\,Cd + CO_2 \rightarrow 2\,CdO + C$ (600°K)

$2\,CdO \rightarrow 2\,Cd + O_2$ (1900°K)

EFFICIENCY - 46%

SOLAR PLANT

OTHER EXISTING PROCESSES

- ALCOHOL
- HIGHER ALCOHOLS
- METHANOL
- LONG CHAIN ALCOHOLS
- FORMIC ACID
- FORMALDAHYDE
- etc.

INDUSTRIAL

POWER PLANTS

AIR/O_2

ELECTRICITY → UTILITY

ADVANCED CARBON CYCLE APPLICATIONS

Results

- IDENTIFIED POTENTIAL THERMOCHEMICAL CARBON CYCLES
  - CADMIUM

    $\mathrm{2\,Cd + CO_2 \rightleftharpoons 2\,CdO + C}$ (600°K) 46%
    $\mathrm{2\,CdO \rightleftharpoons 2\,Cd + O_2}$ (1900°K)

  - ZINC

    $\mathrm{2\,Zn + CO_2 \rightleftharpoons 2\,ZnO + C}$ (1300°K) 37%
    $\mathrm{2\,ZnO \rightleftharpoons 2\,Zn + O_2}$ (2400°K)

  - NICKEL

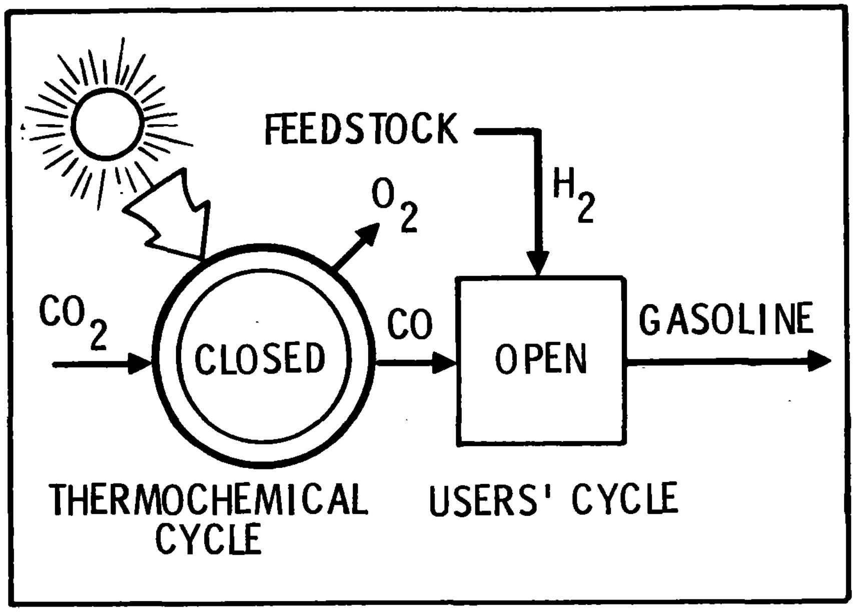
    $\mathrm{2\,Ni + 2\,CO \rightleftharpoons 2\,NiO + C}$ (600°K) 49%
    $\mathrm{2\,NiO \rightleftharpoons 2\,Ni + O_2}$ (2850°K)

- IDENTIFIED METALLURGICAL APPLICATIONS FOR PRODUCTION OF Al AND Mg BY REDUCTION OF OXIDES BY CARBON

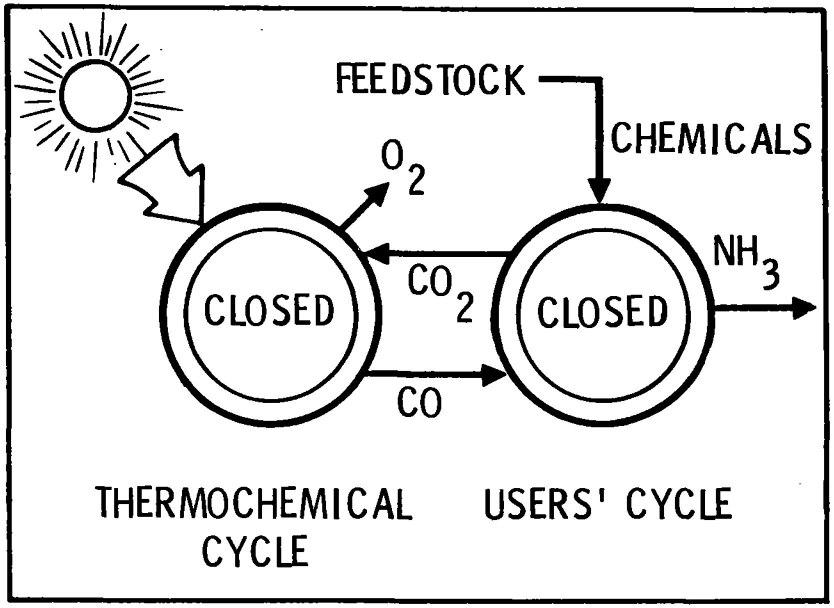
- IDENTIFIED DUAL SYSTEM ENERGY STORAGE
  - GASES FOR TRANSMISSION ($\mathrm{CH_4 + H_2O \rightleftharpoons 3H_2 + CO}$)
  - LIQUIDS FOR STORAGE ($\mathrm{NaHF_2 \rightleftharpoons NaF + HF}$)

SOLAR FUELS AND CHEMICALS

Carbon-Based Users' Cycles



- ENDPRODUCT BASED ON CO FEED IS NOT RETURNED TO CHEMICAL CYCLE



- CO_2 FORMED IN USERS' CYCLE IS RETURNED TO CHEMICAL CYCLE

- APPLICATIONS (Open or Closed)

CO AS FEEDSTOCK

- FUEL SYNTHESIS
- FUEL CELLS
- H_2 PRODUCTION
- REDUCING AGENT

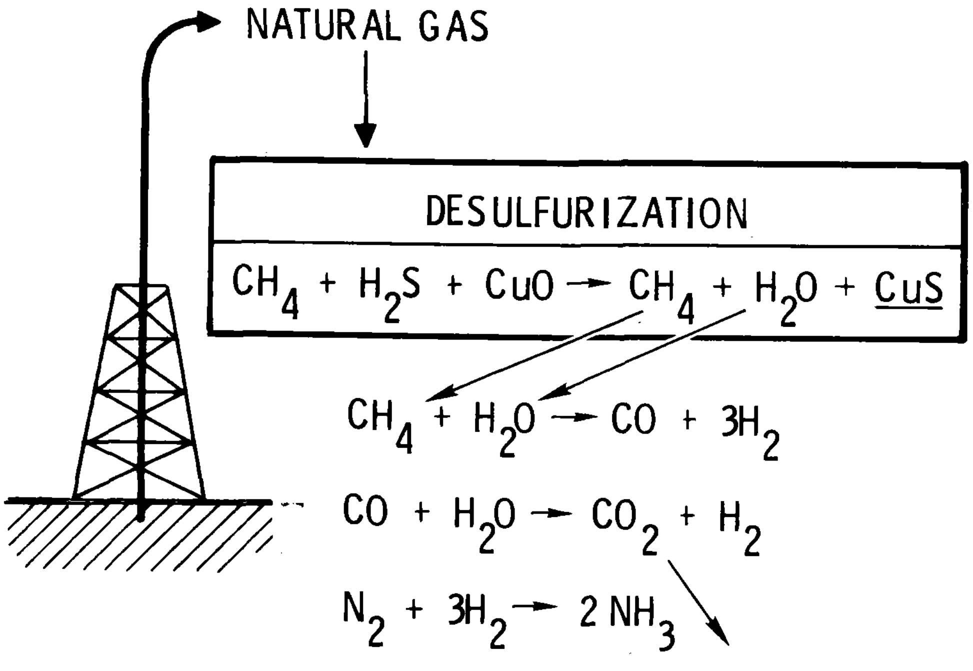
TEMPERATURE AMPLIFICATION

- COMBUSTION OF CO PRODUCES HIGHER TEMPERATURES THAN DIRECT SOLAR
  - HIGHER CARNOT EFFICIENCY
  - CO_2 SUITABLE AS WORKING FLUID

SOLAR FUELS AND CHEMICALS

Closed Users' Cycle - Chemical Production

CONVENTIONAL AMMONIA PROCESS



$CH_4 + H_2S + CuO \rightarrow CH_4 + H_2O + \underline{CuS}$

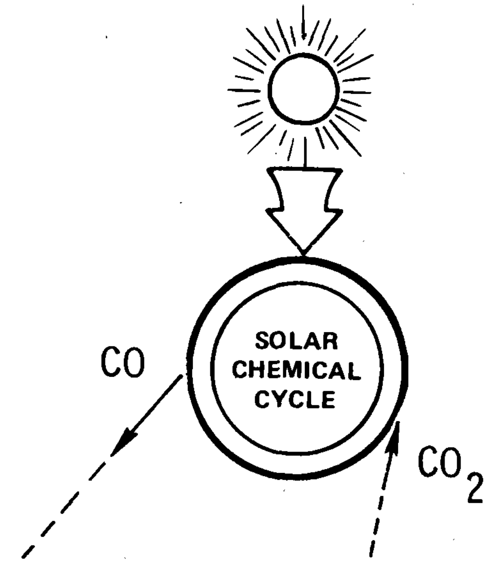
$CH_4 + H_2O \rightarrow CO + 3H_2$

$CO + H_2O \rightarrow CO_2 + H_2$

$N_2 + 3H_2 \rightarrow 2\,NH_3$

- CO_2 IS SOLD OR WASTED

SOLAR CHEMICAL APPLICATION



$CO + H_2O \rightarrow H_2 + CO_2$

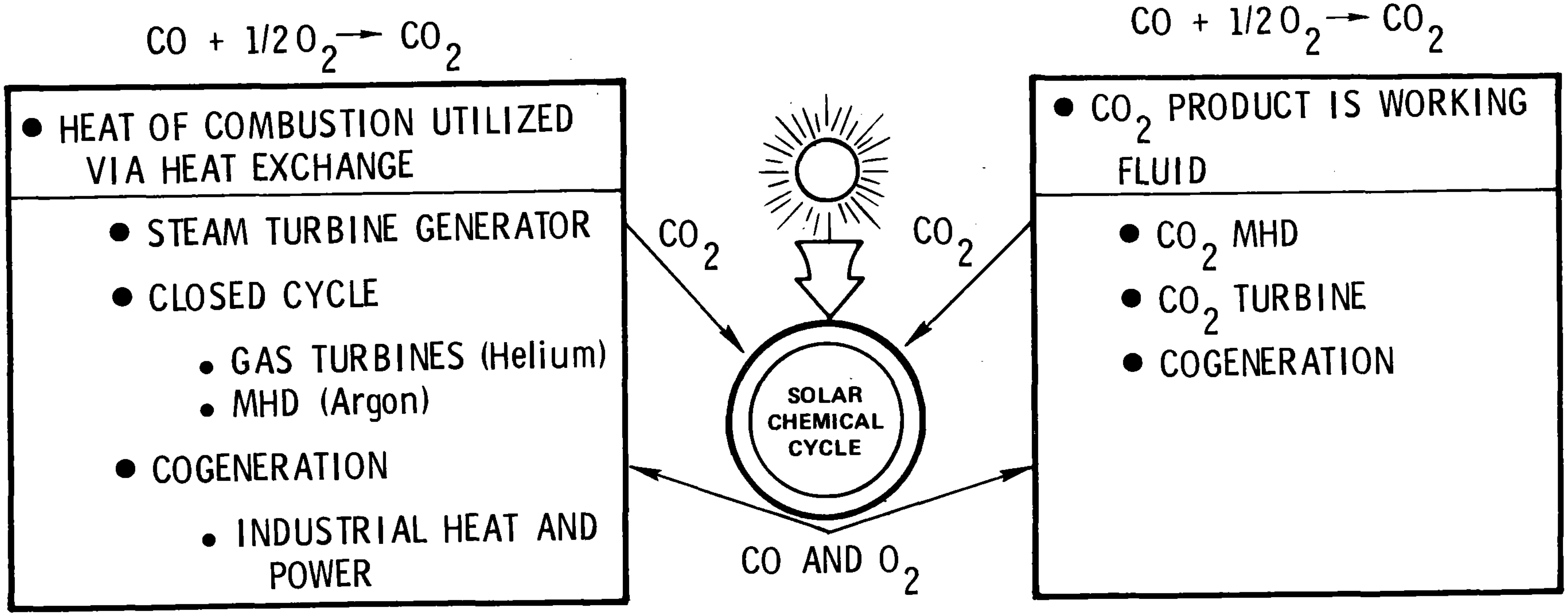
$N_2 + 3H_2 \rightarrow 2NH_3$

- CO_2 IS RETURNED TO CHEMICAL CYCLE

SOLAR FUELS AND CHEMICALS

Closed Users' Carbon Cycle - Temperature Amplification

- CO IS BURNED WITH OXYGEN TO PRODUCE HIGHER TEMPERATURES THAN ATTAINABLE IN SOLAR RECEIVER



$CO + 1/2\,O_2 \rightarrow CO_2$

- HEAT OF COMBUSTION UTILIZED VIA HEAT EXCHANGE
  - STEAM TURBINE GENERATOR
  - CLOSED CYCLE
    - GAS TURBINES (Helium)
    - MHD (Argon)
  - COGENERATION
    - INDUSTRIAL HEAT AND POWER

$CO + 1/2\,O_2 \rightarrow CO_2$

- CO_2 PRODUCT IS WORKING FLUID
  - CO_2 MHD
  - CO_2 TURBINE
  - COGENERATION

SOLAR FUELS AND CHEMICALS

Carbon Cycles

- EXAMINATION OF COSTS AND AVAILABILITIES

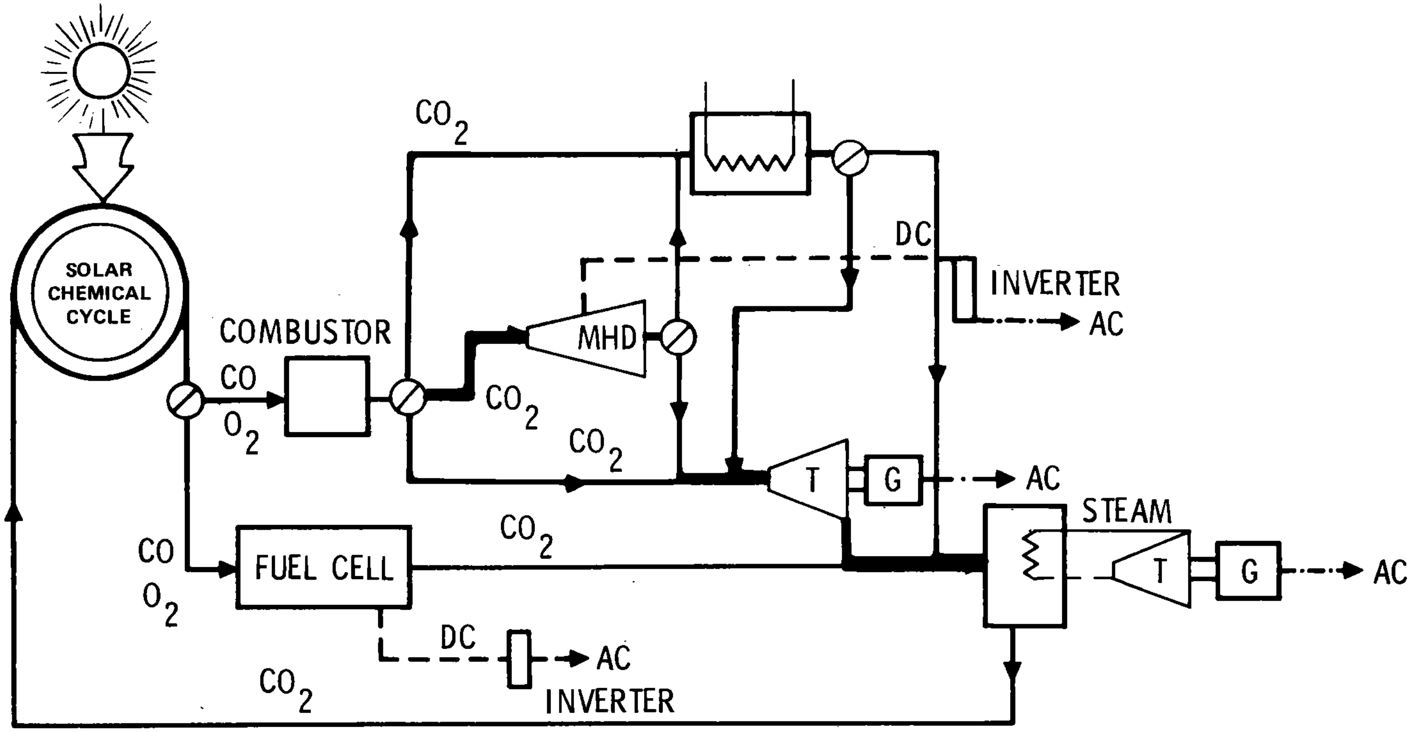
	SOURCE	POTENTIAL AVAILABILITY	COST, $/MSCF
• CARBON DIOXIDE	FLUE GAS	HIGHEST	0.90 TO 1.10 (Purification)
	NATURAL GAS	LIMITED	0.65 TO 1.00 (Purification)
	BY-PRODUCT, e.g., NH_3 PRODUCTION	LIMITED	UP TO 2.75 (Market Price)
• CARBON MONOXIDE	COAL GASIFICATION	UNLIMITED	0.90 TO 1.60 (Production)

- PURIFIED CO_2 FOR FEED TO THERMOCHEMICAL CYCLE WILL COST ~$1.00/MSCF
- CO FROM COAL GASIFICATION WILL COST UP TO ~ $1.60/MSCF
- THE THERMOCHEMICAL CYCLE TO MAKE CO FROM CO_2 CANNOT COST MORE THAN $1.60 - 1.00, OR ~ $0.60/MSCF (difficult to attain)

THEREFORE,

- CLOSED USERS' CYCLES, WHICH RETURN PURE CO_2 TO CHEMICAL CYCLE, APPEAR MORE PROMISING

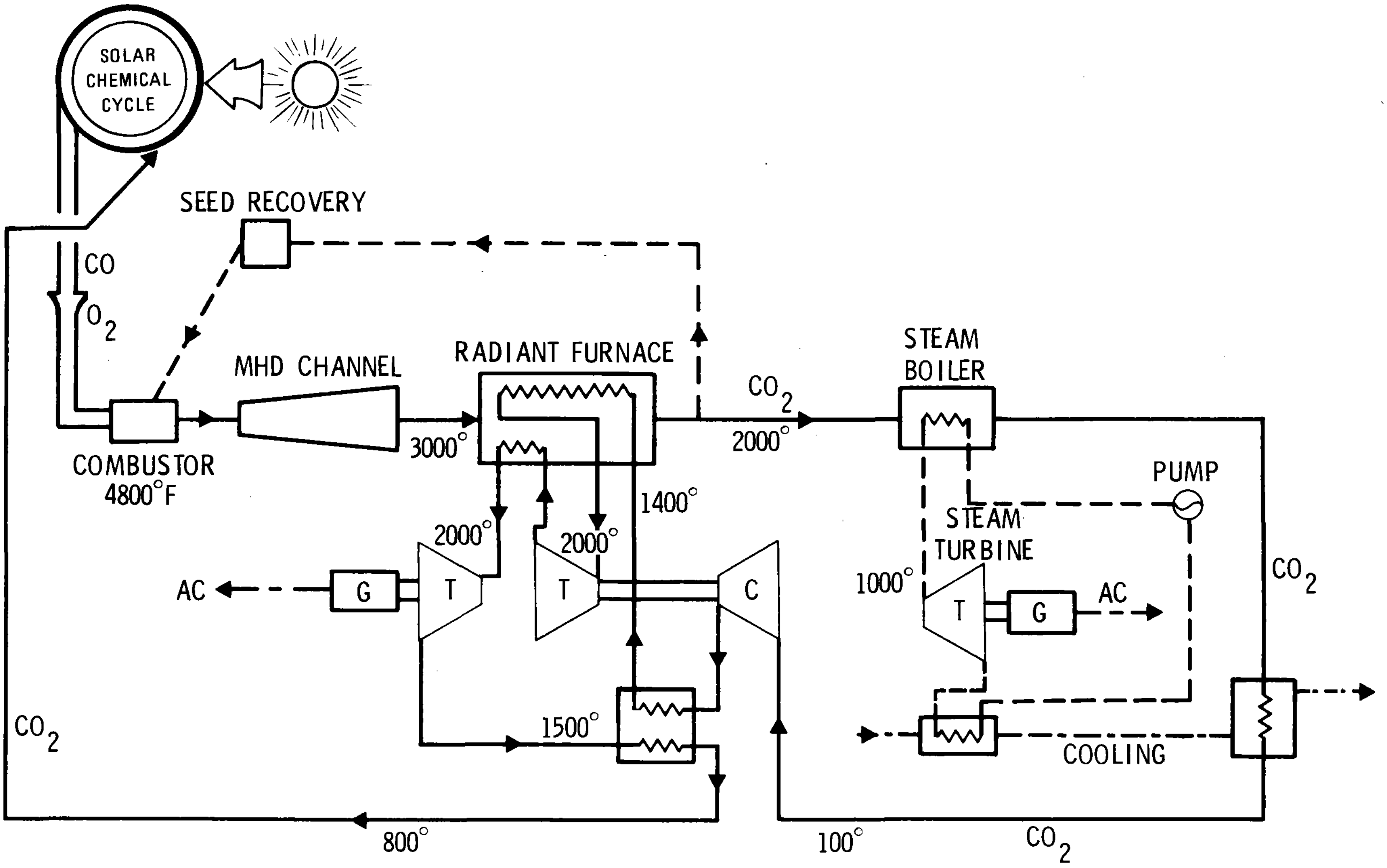
Closed CO/CO_2 Cycles



		POWER CYCLE THERMAL EFFICIENCIES
CO + O_2	COMBUSTOR $\xrightarrow{4800^\circ F}$ MHD → CO_2 TURBINE → STEAM TURBINE	58-62%
	COMBUSTOR → MHD → INDUSTRIAL HEAT → STEAM TURBINE	44-51 (power only)
	COMBUSTOR → INDUSTRIAL HEAT → CO_2 TURBINE → STEAM TURBINE	40-45 (power only)
	COMBUSTOR → CO_2 TURBINE → STEAM TURBINE	60-68 (supercritical CO_2)
	FUEL CELL $\xrightarrow{1400^\circ F}$ STEAM TURBINE	58-68

POWER GENERATION ALTERNATIVES

MHD/CO_2 Turbine/Steam Combined Cycle



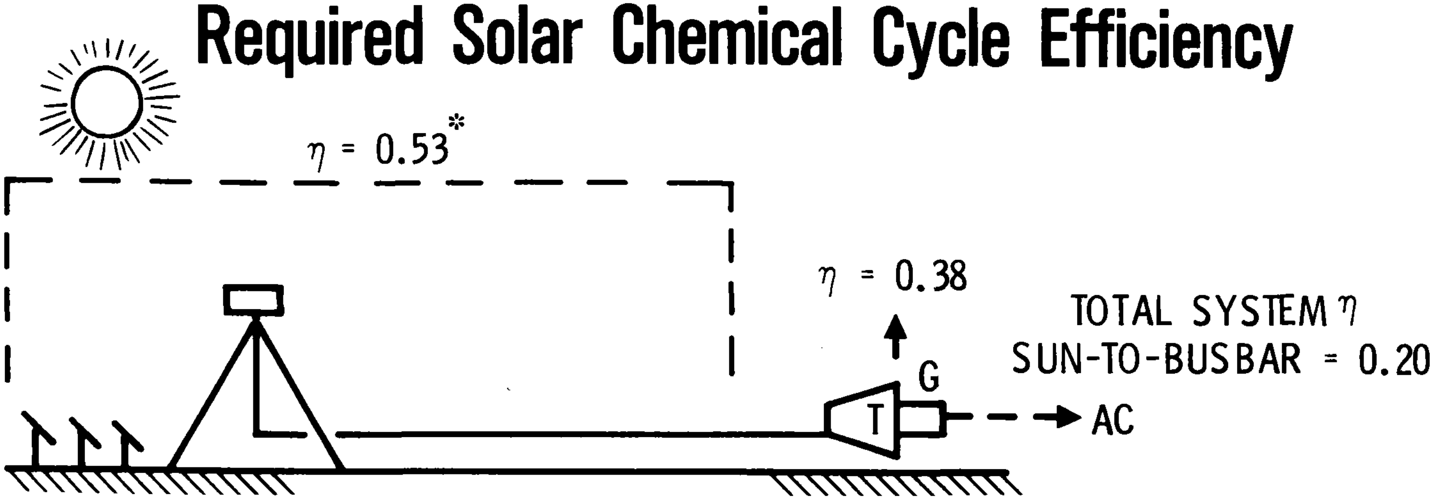
SOLAR FUELS AND CHEMICALS

CO_2 Combined Cycles - Technology Status

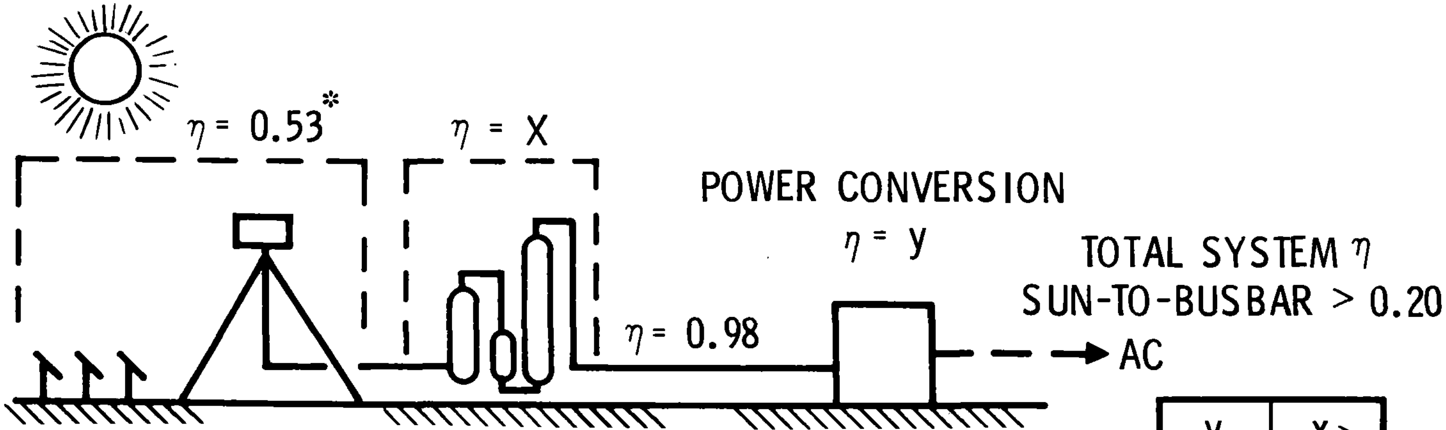
CO_2 MHD GENERATOR	CO_2 TURBINE
● STATUS • COAL-AIR MHD SYSTEM UNDER DEVELOPMENT • CO_2 MHD CONCEPT NEW • REQUIRES R&D	● STATUS • ONLY CONCEPTUAL DESIGNS DEVELOPED IN ECAS STUDY • REQUIRES R&D
● COMPARISON WITH COAL-AIR SYSTEM: • NO COAL PREPARATION • SIMPLER COMBUSTOR • NO ASH OR SLAG • NO SEED PURIFICATION • NO REGENERATIVE HEATER • FEWER ENVIRONMENTAL PROBLEMS • NO FOSSIL FUEL USED BUT: • CO_2 PLASMA LESS CONDUCTIVE • HIGHER GAS PRESSURE DESIRED • MAY REQUIRE LONGER, HEAVIER CHANNEL • HIGHER EQUIPMENT COSTS • DEVELOPMENT REQUIRED	● COMPARISON WITH GAS TURBINES / STEAM TURBINES • NO ASH / SLAG • SMALLER TURBINES / COMPRESSORS • LESS PARASITIC LOSS • FEWER ENVIRONMENTAL PROBLEMS BUT: • HEAT EXCHANGERS LARGER / MORE COSTLY • MATERIALS PROBLEMS • TEMPERATURE • CARBURIZATION • DEVELOPMENT REQUIRED

SOLAR FUELS AND CHEMICALS

Required Solar Chemical Cycle Efficiency



TOTAL SYSTEM η
SUN-TO-BUSBAR = 0.20



TOTAL SYSTEM η
SUN-TO-BUSBAR > 0.20

y	x >
0.50	0.77
0.60	0.64
0.70	0.55

CHEMICAL CYCLE EFFICIENCY = x
POWER CONVERSION SYSTEM EFFICIENCY = y

*Parasitic Power Excluded

- INTEGRATION OF USERS' CYCLE AND CHEMICAL CYCLE IMPORTANT TO ACHIEVEMENT OF HIGH TOTAL SYSTEM EFFICIENCIES

SOLAR FUELS AND CHEMICALS

Preliminary Conclusions

- CLOSED USERS' CYCLES MOST ATTRACTIVE FOR COMPETING FOR FOSSIL FUEL APPLICATIONS
- TEMPERATURE AMPLIFICATION VIA SOLAR THERMOCHEMICAL CYCLE, WHEN DEVELOPED, MAY BE MORE PROMISING THAN DIRECT SOLAR HEATING FOR
  - POWER GENERATION
  - HIGH TEMPERATURE PROCESS HEATING
- SOLAR CHEMICAL CYCLES AND USERS' CYCLES SHOULD BE CONSIDERED AS SYSTEMS IN IDENTIFYING EFFICIENT APPLICATIONS
- CARBON MONOXIDE FUEL CELLS MAY OFFER SPECIAL OPPORTUNITY FOR SOLAR CHEMICAL CYCLE APPLICATION
  - HIGH EFFICIENCY
  - GOOD TEMPERATURE MATCH

EXPERIMENTS IN THE SOLAR THERMAL TEST FACILITIES

F. B. Smith
STTF Users Association
Albuquerque, NM 87108

Introduction

The Users Association was organized in 1977 to expedite the use of the Sandia and Georgia Tech solar central receiver facilities by potential solar researchers in universities and industries. Shortly after organization, we also reached agreements to cooperate with the US Army solar furnace at White Sands, New Mexico, and the French CNRS solar furnace in Odeillo, France. Since most of you are well-informed on the four facilities (Figures 1, 2, 3, and 4), I will not discuss details except to note that the Sandia and Georgia Tech facilities are solar central receivers, whereas the White Sands and Odeillo facilities are solar furnaces. Unlike the central receiver units, the solar furnaces are double-reflecting systems which give horizontal rather than upward-slanted solar rays. The specifications of the four facilities are shown in Figure 5.

Operation of the Users Association is funded via a Solar Energy Research Institute (SERI) contract to the University of Houston (Contract #XD-8-0637-1, June 27, 1978 to September 31, 1979, $306,364). This contract provides for: operation of a three-person Association office in Albuquerque; running of workshops related to use of the solar facilities for high-temperature chemistry, physics, materials, and surfaces experiments; provision of information to potential experimenters on the facilities and their availability; solicitation and evaluation of proposals from potential experimenters; and funding and monitoring of approved experiments.

The UA annual operating budget runs about $175,000 with an additional $500,000 to $550,000 allocated to support of STTF experiments approved by the Association.

UA Role and Objectives

The Association's role and objectives, as approved by DOE and SERI are:

1. To act as the point of contact for users of the STTFs and as primary access link between users and STTFs.
2. To solicit and review proposals and make recommendations to DOE regarding utilization of the STTFs.
3. To disseminate STTF information on a regular basis.
4. To provide funding for STTF users, subject to DOE program approval.

The Association has no direct responsibility for the large solar central receiver systems being developed for DOE by Boeing, EPRI, Martin Marietta, McDonald Douglass, Sanders, or Black & Veatch, et al, but it does have primary responsibility for accepting and reviewing proposals from all other experimenters who want to use the facilities. For the Sandia and Georgia Tech facilities this includes those who expect to fund their own experiments as well as those who seek UA funding. We also review STTF experiment proposals originating in DOE's national laboratories.

Approved Experiments

The Users Association thus far has funded (or approved for SERI funding) ten high-temperature solar experiments:

- S. R. Skaggs of Los Alamos Scientific Laboratory ($22,000) in collaboration with J. P. Coutures, CNRS, France, used the Laboratory-Scale solar facililties at Odeillo to investigate the use of solar heat to reduce molybdenum ore.

- A. B. and M. P. Meinel, University of Arizona ($5,000) investigated a reconcentrator for use with one of the heliostats at the Sandia CRTF to provide a high-temperature solar test facility for smaller scale experiments.

- T. G. Lenz and J. H. Wright, Colorado State University, and T. A. Chubb, Naval Research Laboratory ($20,000) made an engineering design study of hardware for the conversion of solar energy to chemical energy through the dissociation of ammonia.

- R. A. Willem, New Mexico State University ($24,000) will use the White Sands Solar Furnace to study changes in the compressive strength of concrete resulting from exposure to high levels of solar flux for various periods of time.

- P. W. Gilles, University of Kansas ($25,000) is doing fundamental thermodynamic research on the oxygen alloys of electropositive metals.

- J. M. Schreyer, Oak Ridge National Lab ($10,000) used the White Sands Solar Furnace to measure absorptivity-reflectivity properties of plasma-spray coatings.

- Alex Ignatiev, University of Houston ($10,000) also used the White Sands solar facility to investigate the degradation of black chrome under high-temperature solar radiation.

- Daniel Cubicciotti, Stanford Research Institute ($25,000) is exploring use of solar energy to react carbon and carbon dioxide to produce carbon monoxide, which is then used for the carbothermic reduction of iron ore.

- Richard Zito and A. B. Meinel, University of Arizona ($5,000) are studying the temperatures at which deterioration by agglomeration occurs in selective surfaces on metallic films after sustained high temperatures.

- M. J. Antal, Princeton University ($24,000) this summer will be running a series of experiments on the Odeillo 1-MW furnace to investigate use of high-temperature solar energy for flash pyrolysis of biomass to produce synthetic fuel gases.

Proposals Under Review

Many new possibilities for use of the solar central receiver technology were discussed during a Solar High-Temperature Industrial Processes Workshop[1] sponsored by the Users Association in Atlanta, on September 28-30, 1978. As a result of this workshop, and in response to the UA's High-Temperature Solar Research Program Announcement issued January 15, 1979, the following proposals were received:

PROPOSER/AFFILIATION	SOLAR FACILITY	TITLE
Materials/Surface Test		
J .C .H. Li/Rocket Research	SERI/JPL	SO_2-SO_3 Corrosion
Clements/Texas Tech	WSSF	H.T. Fluids
Schreyer/ORNL	WSSF	Metal Surface Treatment
Knasel/SAI	CRTF	Optical Trapping Coatings
Hull/Mulholland/NMSU	WSSF	H.T. Alloy Test
Coal Gasification/Liquification		
Gregg/LLL	WSSF	Coal Gasification
Beattie/Sullivan/LASL	WSSF & Odeillo	Coal Gasification
Zenty/SOLARCO	ACTF	Coal Gasification
Paquette/Atlantic Research	N/A	Hydroliquefaction
Chemical Products		
Duncan/IGT	WSSF or Odeillo	Calcium Carbide
Whaley/IGT	ACTF	Zinc Oxide
Skaggs/LASL	WSSF Or Odeillo	Ore Processing
Wartes/Ecothermia	WSSF	Gypsum-Limestone Calcination
Mukherjee/Battelle	CRTF	Refractory Glasses
Knasel/SAI	CRTF	Flash Roaster
Central Receiver Designs		
Archer/Westinghouse	ACTF	Fluidized Bed
Jarvinen/MIT	WSSF	Fuel/Chemical Receiver
Hertzberg/U of WA	WSSF	Molten Bed Receiver
Bienert/Dynatherm	WSSF	Heat Pipe Receiver
Thayer/MSNW	WSSF	Metal Vapor Receiver
B .P. Roberts/Solar Turbines	ACTF	Steam Loop Receiver
Besenbruch/Gen Atomic	ACTF	H_2SO_4 Decomposition

PROPOSER/AFFILIATION	SOLAR FACILITY	TITLE
Reversible Chemical Reaction		
Chubb/NRL & McCrary/NMSU	WSSF	CO_2 - CH_4
Gutterman/Foster Wheeler	N/A	Steam Reforming
Hydrogen		
Veziroglu/U of Miami	N/A	H_2 Production
Foh/IGT	WSSF	H_2 - CdO
Zenty/SOLARCO	ACTF?	H_2 - Silicon
Pyrolysis		
Bazan/Foster-Wheeler	N/A	Pyrolysis
Antal/Princeton	Odeillo	Flash Pyrolysis
Other		
Weekes/Mt. Hopkins	CRTF	Astronomical Research
Hoye-JHU/Navy	CRTF	Radome Test
Knasel/SAI	CRTF	Soil Test
Grams/GIT	ACTF	Atomsphere Observation
Toth/CETHEL, France	CRTF	Heliostat Test

These proposals which cover a variety of high-temperature solar processes are still under review and will not be discussed in detail. Note, however, the list includes proposals from universities, commercial and not-for-profit firms, government laboratories and DOE national laboratories. It also includes two proposals from researchers who wish to make night-time use of the Sandia and Georgia Tech facilities, and two others which are being funded by DNA and the US Navy. The total cost of all the proposals is just over $2 million, but only about $1/2 million is allocated for experimental support this year; it is therefore obvious that not all proposals will be funded, but we do hope to fund the more promising ones.

Proposal Review Procedure

We use a two-phase proposal review procedure (Figure 6). Since most proposals present something less than a totally clear understanding of just what the proposer intends to do, we make a preliminary review and send reviewers' questions and comments (suitably edited) back to the proposer to give him another opportunity to clarify any uncertain aspects or to modify his proposal as appropriate. After that, an Assessment Committee reviews the proposals and makes recommendations to the UA Executive Committee, which in turn recommends to SERI which proposals should be funded. Approved proposals from those now being reviewed should be funded in September or October 1979, and another High-Temperature Solar Research Program Announcement will then be issued.

Concluding Remarks

The Users Association has been in operation for about two years now and I believe its unique role is becoming clearer and better appreciated by more people. Although we engineers too often assume that information about new technology somehow automatically reaches interested people across the country, it simply does not happen that easily--especially high-temperature solar central receiver information. However, the Users Association is succeeding thorugh newsletters, workshops, program opportunity announcements, technical presentations, and hundreds of personal contacts in identifying persons throughout the country who are not associated with large-scale solar government contracts but who have a potential for developing and exploring possibilities for new uses of high-temperature solar central receiver technology. To date, about 50 of those people have become interested enough to write proposals to do experiments on or related to solar central receivers.

It should be understood that we are still in the early stages of development of most of the ideas which have been proposed and that the practicalities of using solar energy for hydrogen production, coal gasification, fertilizer manufacture, etc., have not yet been established. The Users Association's outlook is that many of these ideas should first be explored on a small scale so that those which show real promise may later be funded more substantially by the UA, or by SERI or DOE. If it turns out that even relatively few of the proposed new solar processes are successful, our efforts will have been amply rewarded.

References:

1. Proceedings of Solar High-Temperature Industrial Processes Workshop, September 28-30, 1978, SERI/0637-4; Available from NTIS or STTFUA Albuquerque Office.

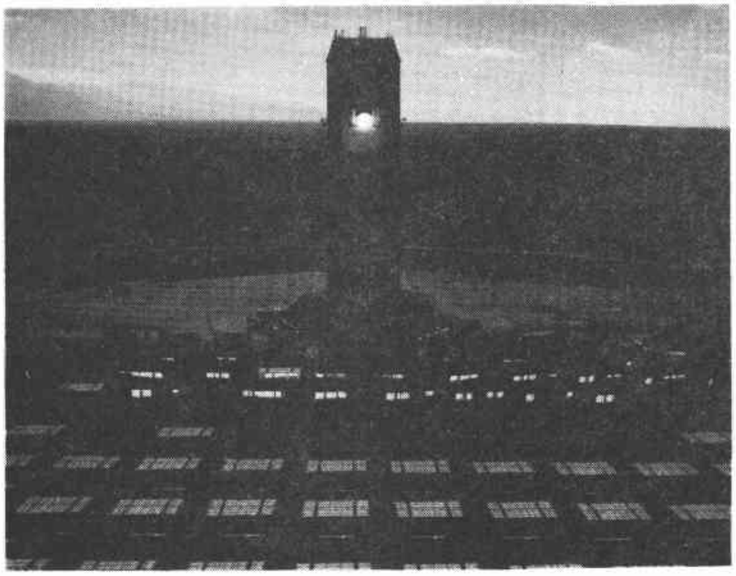


Figure 1
Sandia 5-MW Central Receiver Test Facility

Figure 2
Georgia Tech 400-kW_t Facility

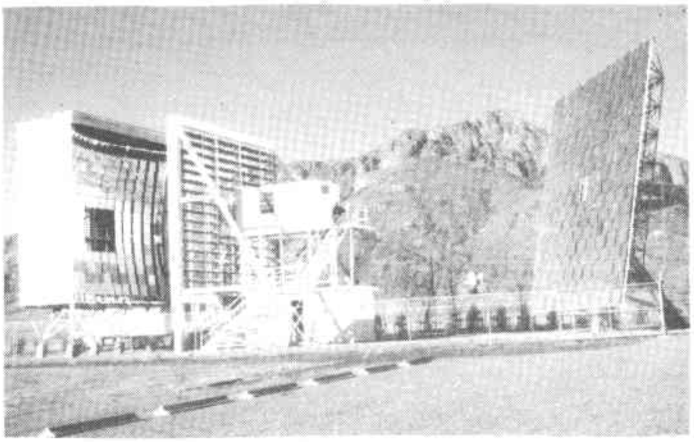


Figure 3
White Sands 30-kW_t Furnace

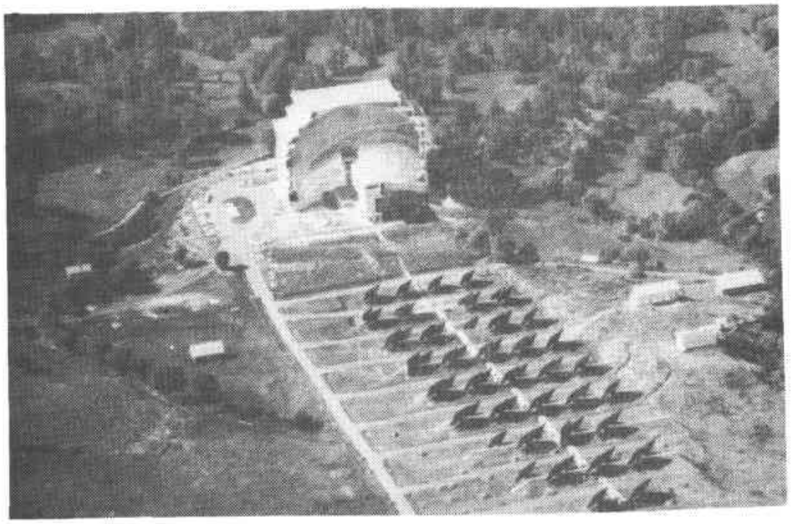


Figure 4
French CNRS 1000-kW_t Furnace

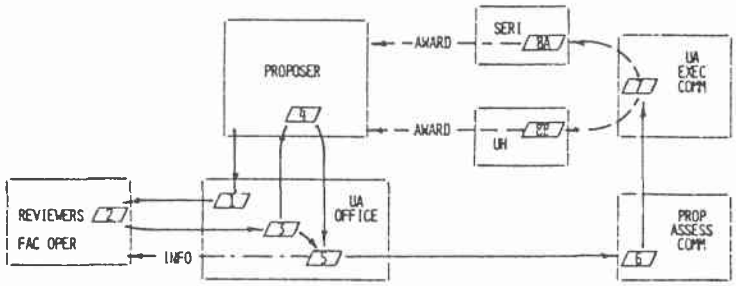
APPROXIMATE SPECIFICATIONS FOR STTFs AND SOLAR FURNACES

Facilities	SANDIA	GEORGIA TECH	WHITE SANDS	ODEILLO
Total Thermal Energy, kW	5000	400	30	1000
No. of Heliostats	222	550	1	63
Heliostat Size, m	6 x 6	1.1D	11 x 12	6.0 x 7.5
Total Heliostat Area, m^2	8257	532	132	2835
Test Area Diameter,* m	2-3	0.5-1.0	0.08-0.15	0.25-1.0
Peak Flux,** W/cm^2	250	200	400	1600
Maximum Calculated Equilibrium Temperature,** K	2600	2500	2900	4100

*The first number is area receiving approximately one-half of total energy;
**second number is area capturing 95% of total energy.
Small area at center of beam.

Figure 5

PROPOSAL REVIEW FLOW CHART



1. PROPOSAL REC., LOGGED, FORWARDED TO REVIEWERS
2. REVIEWERS REVIEW, SEND QUESTIONS & COMMENTS
3. UA OFC EDITS QUESTIONS & SENDS TO PROPOSER
4. PROPOSER RESPONDS WITH FURTHER INFORMATION (OPTIONAL)
5. RESPONSE ADDED TO FILE & FORWARDED
6. COMMITTEE REVIEWS & RECOMMENDS TO EXEC COMM
7. EXEC COMM PRIORITIZES, RECOMMENDS AWARD, NOTIFIES PROPOSER
8. SERI OR UH ISSUES SUBCONTRACT TO PROPOSER

Figure 6

POINT-FOCUSING DISHES

John W. Lucas

Assistant Manager for Point-Focusing Distributed
Receiver Technology

JPL

The solar point-focusing distributed receiver (PFDR) concept is briefly described. A number of detailed talks given the previous two days on PFDR is summarized. Much of the PFDR technology is under development for production of electricity and will be available as a direct spinoff for heat production. Each module for heat production consists of a concentrator, receiver, heat transport and associated controls, and, later, storage and will typically produce 50 kWth or 3500 BTU/hr. The current technological status of concentrators and receivers is summarized. Cost targets and activities underway to meet them are described. For concentrators, detailed design is, or soon will be, underway on a test bed concentrator, on the first-generation low cost concentrator, and on conceptual designs and associated advanced component development for the second and third generations. For receivers, detailed design is underway on both first generation steam and air receiver to provide heat at temperatures of 1000°F respectively. Design is also underway on second generation receivers to provide gases at temperatures of 1600 to 1900°F and contracts for 2500°F are being negotiated.

Key to the achievement of designs to meet the cost targets is the utilization of the modularity characteristic and features mass production. The relation of the hardware cost targets to cost of produced energy is provided. Projected energy costs are compared with projected fossil fuel costs to the end of the century.

The Point-Focusing Distributed Receiver (PFDR) Technology Project has contracts with industry for developing first generation subsystems. The Advanced Solar Thermal Technology (ASTT) Project is developing components for the second and third generations; results from this ASTT Project will be transferred to the PFDR Technology Project for subsequent development of second and third generation subsystems. Both projects are being implemented by the Jet Propulsion Laboratory for the Department of Energy through an agreement with the National Aeronautics and Space Administration.

AGENDA

Roundtable Discussion on Industry Input High-Temperature Solar Energy For Processing Of Chemicals And Fuels

Semi-Annual Review of Solar Energy Programs
Long Beach CA 21 June 1979

Participants:

Harry L. Craig, Co-Investigator & Consultant
Eli M. Dannenberg, Co-Investigator & Consultant
Donald P. Krotz, Co-Investigator & Consultant
James A. Reid, Co-Investigator & Consultant
Howard K. Nason, Principal Investigator

15:10 P.D.T.	I.	Purpose of the Study and Methodology Employed. H. K. Naso
15:15	II.	Principal Issues Report. H. L. Craig
15:20	III.	Typical Industry Perceptions. D. P. Krotz
15:25	IV.	Conditions for Industry Participation. E. M. Dannenberg
15:30	V.	Summary of General Conclusions. H. K. Nason and J. A. Reid
15:35	VI.	Discussion of Future Work. All present
15:40	VII.	Recommendations to JPL and DOE. All present
15:50	VIII.	Adjourn