TECH TRANSFER

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April 1981

Solar Thermal Energy Systems Research and Advanced Development Program Review

Oakland, California
April 8-9, 1981

Presentation Summaries

Prepared for
U.S. Department of Energy
by
Solar Energy Research Institute
Golden, Colorado

SERI/CP-633-1145
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Compiled by
W. A. Hunt
Conference Coordinator

Prepared for
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FOREWORD

The Solar Thermal Energy Systems Research and Advanced Development Program Review was held in Oakland on April 8-9, 1981. The two-day meeting was sponsored by the U.S. Department of Energy and was conducted by the Solar Energy Research Institute as a part of its program management responsibility. The meeting achieved its purpose of disseminating results of activities and presenting major accomplishments within the Research and Advanced Development Program since the previous meeting in December 1979.

The Research and Advanced Development Program seeks to stimulate the growth of solar thermal technology into a major energy source by 1995 through promotion within industry of a strong technological base for the development of advanced solar thermal systems.

This document contains the presentation summaries submitted by the speakers at the conference. The proceedings have been prepared by printing the papers made available to us by the individual authors. Readers are encouraged to contact the authors directly if more information is desired on any of the topics covered in the proceedings.

B. P. Gupta, Chief
Solar Thermal Program Branch
Conference Chairman

Barry L. Butler

B. L. Butler, Acting Manager
Solar Thermal, Ocean, and Wind Division

SOLAR THERMAL ENERGY SYSTEMS
RESEARCH AND ADVANCED DEVELOPMENT
PROGRAM REVIEW

TABLE OF CONTENTS

Page

SYSTEMS APPLICATIONS OVERVIEWS

FUELS AND CHEMICALS RESEARCH

SOLAR MATERIALS RESEARCH

APPLIED RESEARCH

ECONOMICS AND APPLICATIONS ASSESSMENT

Solar Thermal

SOLAR THERMAL
RESEARCH AND ADVANCED DEVELOPMENT PROGRAM
PROGRAM REVIEW
Oakland, California
April 8-9, 1981

AGENDA

TUESDAY, APRIL 7, 1981

7:00 - 8:30 p.m.	Registration - Oakland Room		

WEDNESDAY, APRIL 8, 1981

7:30 - 8:30 a.m.	Registration - Oakland Room		
8:30 - 8:40 a.m.	Meeting Announcements and Introduction	W. Hunt/ B. Gupta	SERI
8:40 - 8:45 a.m.	Welcome	R. Duvall	DOE/SAN
8:45 - 9:30 a.m.	Solar Thermal Program Overview	G. Braun	DOE/HQ
9:30 - 10:00 a.m.	Research and Advanced Development Program	K. Cherian	DOE/HQ
10:00 - 10:30 a.m.	Break		

SYSTEMS OVERVIEWS
Session Chairman - J. Thornton, SERI

10:30 - 10:50 a.m.	Central Receiver Systems	C. Yokomizo	SNLL
10:50 - 11:10 a.m.	Line Focus Systems	W. Schimmel	SNLA
11:10 - 11:30 a.m.	Point Focus System	A. Marriott	JPL
11:30 - 11:50 a.m.	Solar Ponds	S. Sargent	DOE/CH
12:00 - 1:00	Lunch - Alameda Room		
1:15 p.m.	Reconvene		

FUELS AND CHEMICALS REASEARCH
Session Chairman - P. W. Kaspar, DOE/SAN

1:20 - 1:40 p.m.	Solar Thermal Test Facilities Users Association	F. Smith	STTFUA
1:40 - 2:00 p.m.	Solar Thermal Derived Fuels	K. Ramahalli	JPL
2:00 - 2:20 p.m.	Fuels and Chemicals Market Survey	D. Grey	Black & Veatch
2:20 - 2:40 p.m.	Solar Oil Shale Retorting	D. Gregg	LLNL
2:40 - 3:00 p.m.	Solar Pyrolysis of Biomass	M. Antal	Princeton
3:00 - 3:20 p.m.	Solar Thermal Hydrogen	G. Parker	Westinghouse
3:20 - 3:40 p.m.	Break		

FUTURE R&D NEEDS OF THE SOLAR THERMAL ENERGY PROGRAM — PANEL DISCUSSION
Panel Moderator - A. Hildebrandt, U. of Houston

3:40 - 5:15 p.m.	Panel Members	J. Gintz A. Ignatiev S. Bomar G. Parker T. Cole	Boeing U. of Houston GIT Westinghouse JPL
6:00 - 7:30 p.m.	Mixer - No Host Bar - Oakland Room		

THURSDAY, APRIL 9, 1981

8:20 a.m.	Convene		
8:25 - 8:30 a.m.	Meeting Announcements	W. Hunt	SERI

SOLAR MATERIALS RESEARCH
Session Chairman - G. Gross, SERI

8:30 - 8:45 a.m.	Overview	G. Gross	SERI

THERMAL MATERIALS

8:45 - 9:10 a.m.	Slow Strain Rate Testing of Metal Alloys in Salt Environment	D. Dawson	SNLL
9:10 - 9:35 a.m.	Performance of 9 Cr/1 Mo Alloy	C. Pitts	U. of Utah
9:35 - 10:00 a.m.	Cermet Selective Absorber Coating	J. Thornton	Telic
10:00 - 10:20 a.m.	Break		

OPTICAL MATERIALS

10:20 - 10:40 a.m.	Polymer Development and Performance	M. Adams	JPL
10:40 - 11:00 a.m.	Polymer Metallization for Solar Concentrators	S. Brauman	SRI
11:00 - 11:20 a.m.	Thin Glass for Solar Thermal Applications	A. Shoemaker	Corning
11:20 - 11:40 a.m.	Optical Measurements	G. Gross	SERI
11:40 - 12:00	Materials Exposure Testing Results	T. Anderson	DSET
12:10 - 1:20 p.m.	Lunch - Alameda Room		
1:30 p.m.	Reconvene		

APPLIED RESEARCH
Session Chairman - J. Lefferdo, SERI

1:40 - 1:50 p.m.	Overview	J. Lefferdo	SERI
1:50 - 2:05 p.m.	Convective Heat Loss Analysis and Research Program Summary	R. Gallagher	SNLL
2:05 - 2:25 p.m.	Experimental Investigation of Convective Heat Losses from Cavity Type Central Receivers	J. Kraabel	SNLL
2:25 - 2:45 p.m.	Combined Experimental and Analytical Investigation of Convective Heat Losses from External Central Receivers	R. Moffatt	Stanford University
2:45 - 3:05 p.m.	High Temperature Ceramic Matrix Receiver Experiment	S. Davis	Sanders
3:05 - 3:25 p.m.	Fluidized Bed Solar Thermal Receiver Test Results	D. Archer	Westinghouse
3:25 - 3:40 p.m.	Thermochemical Transport Test Results	J. McCrary	NMSU
3:40 - 4:00 p.m.	Break		

ECONOMICS AND APPLICATIONS ASSESSMENT
Session Chairman - R. Edelstein, SERI

4:00 - 4:20 p.m.	Market Potential for High Temperature Process Heat	J. Iannucci	SNLL
4:20 - 4:40 p.m.	Review of Industrial Energy Use	B. Hamel	Gen. Energy Associates
4:40 - 5:00 p.m.	Utility Market Potential for Advanced Solar Thermal Systems	R. Witholder	SERI
5:00 - 5:15 p.m.	Closing Remarks	K. Cherian	DOE/HQ

SYSTEMS APPLICATIONS

OVERVIEWS

SYSTEM REVIEW: CENTRAL RECEIVER SYSTEM

C. T. Yokomizo
Energy Systems Studies Division
Sandia National Laboratories
Livermore, California

INTRODUCTION

During the last ten years, a concerted effort has been made by both the government and private industry to investigate the central receiver concept as a means of economically providing an alternate source of energy. The primary objective of the Department of Energy's program is to develop a sound technological and industrial base which will, with attractive economics, result in a wide-scale, self-sustaining commercial application of central receiver technologies. While results to date demonstrate technical feasibility, future work is necessary to prove economic viability through refined component designs. A number of excellent documents summarize the status of the program and the direction of future efforts [1-3].

GENERAL DESCRIPTION

The basic subsystems of the central receiver concept are illustrated in Figure 1. A field of individually guided mirrors, called heliostats, redirects the sun's energy to a receiver mounted atop a tower. From the receiver the energy is carried by a suitable heat transfer medium to a turbine/generator set (or an industrial process) or to thermal storage where it is retained for future use.

Some systems include a fossil fuel boiler to supplement the solar portion of the systems during periods when energy from the sun is not available. These hybrid plants allow greater plant usage. The desirability of building a hybrid plant vs. a stand-alone plant needs to be judged on economic and operational consideration of the industry in question.

There are two other generic uses of central receiver technology which have been studied in great detail. Repowering, where a central receiver system would be added to an existing facility, and cogeneration, where the energy from the system would be put to multiple use (i.e., generate electricity and provide process heat).

Inherent in the central receiver concept are a number of features that enhance its attractiveness as an economical alternate source of energy over other concepts. First, the energy from the sun can be greatly concentrated. This allows energy to be efficiently collected, even at relatively high temperatures (>500°C), since the magnitude of energy losses (directly related to receiver area) is relatively small. Another important feature is that energy is transmitted optically. This greatly reduces piping requirements for the systems. And finally, since energy is captured and converted to thermal

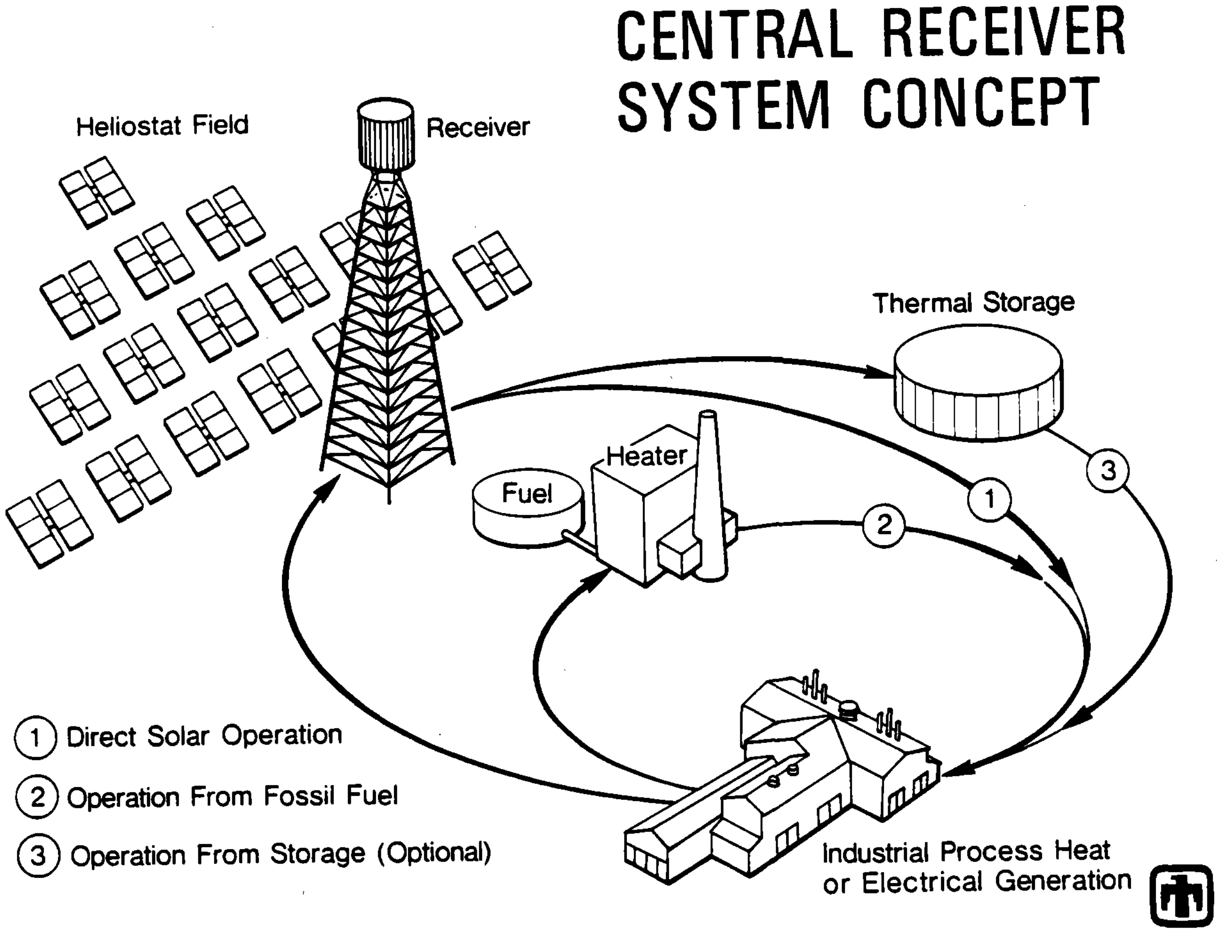


Figure 1. A schematic of central receiver system configurations and operating modes is shown. The solar energy may be used immediately, be stored for a period of time, or be supplemented by a fossil-fueled heat source depending on the design and operation of the plant. The end use for the solar thermal energy may be for industrial process heat or electric power generation.

energy, it is a form that can be easily stored allowing the system to be used when sunlight is not available.

STATUS

The central receiver concept is supported by a base of hundreds of studies and technical investigations. These range in scope from broad system optimizations and market analysis to highly focused investigations on technical issues such as materials compatibility and heat loss calculations.

To date, the program has achieved the following:

- Detailed system and component studies have been conducted investigating the economics of options for central receiver system configurations. These studies show that this technology should be competitive in the future. The options investigated use different media to transfer energy around the system.

These include molten salts (e.g., $NaNO_3$ - KNO_3), liquid metals (sodium), a number of water/steam (W/S) concepts, and air or helium. Figure 2 shows an example comparison of these alternatives for the production of electricity. Figure 3 shows how the "best" option, molten salt, might compete with future coal plants in the southwest. Similar studies show that favorable comparisons can also be made in the industrial process heat market.

- Operations at the 5 MW_t Central Receiver Test Facility (CRTF) at Sandia, Albuquerque, began in 1978. This facility is providing both valuable data testing new receiver concepts and operational experience for a large heliostat collector field.

- The Solar One Repowering Test Facility located near Barstow, California, is in the final stages of construction. The Solar One project is a joint undertaking of the DOE and the Utility Associates composed of the Southern California Edison Company, the Los Angeles Department of Water and Power, and the California Energy Resources Conservation and Development Commission. In the baseline concept sufficient steam is generated in the receiver to produce 10 MW of electric power. Current plans call for receiver steam to be delivered to the turbine generator by the end of this year. In the future, alternate receiver concepts can be added to the facility for testing repowering options.

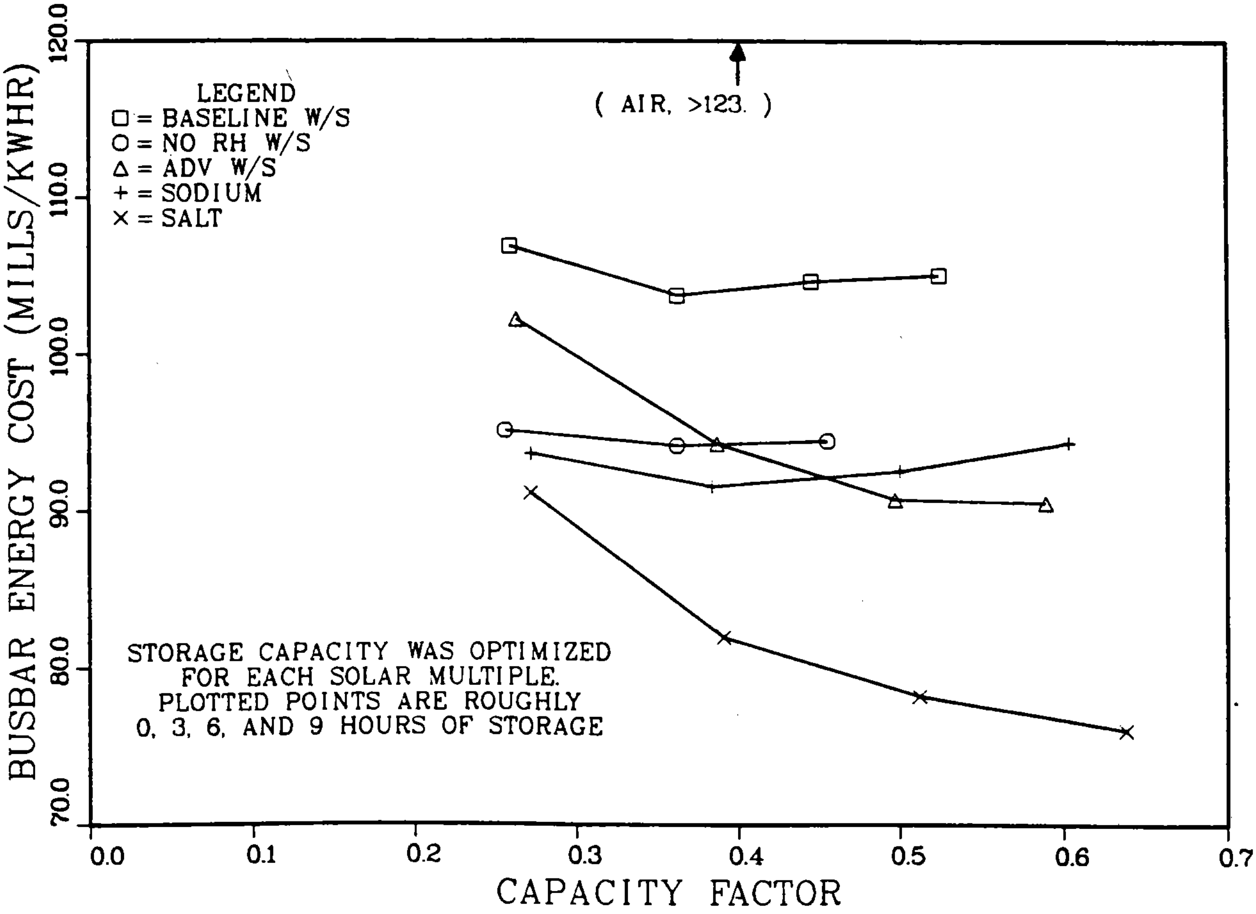


Figure 2. Solar central receiver busbar electricity cost as a function of capacity factor for nitrate salt, sodium, water/steam, and air heat transport technologies.

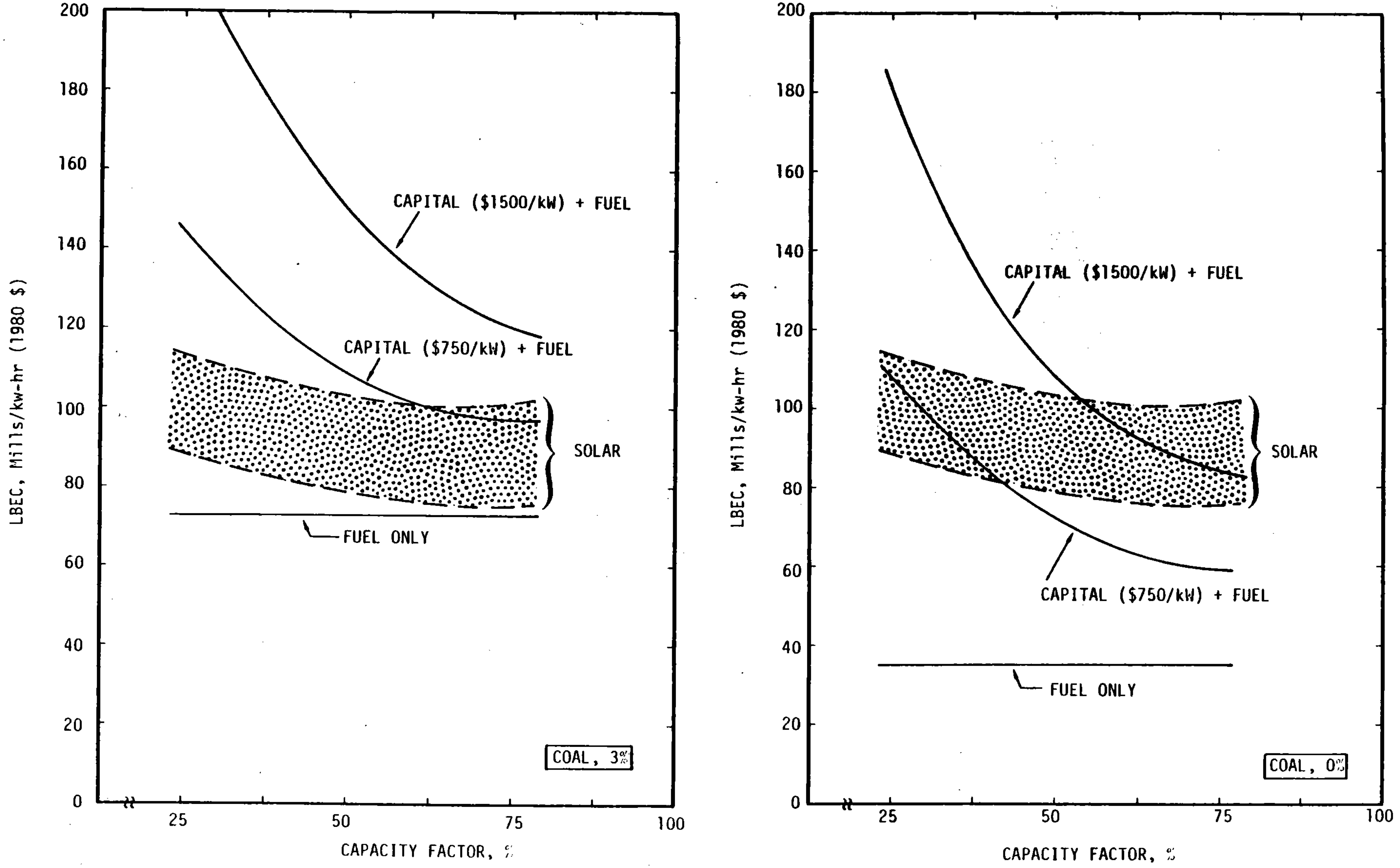
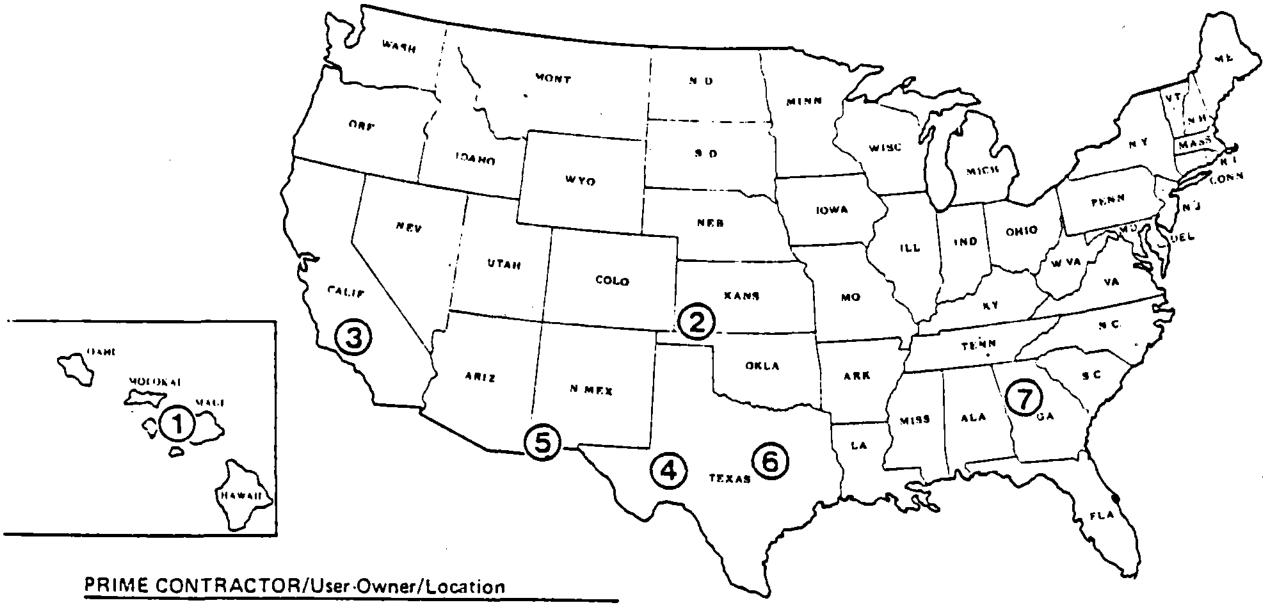


Figure 3. Energy cost comparison - solar vs. coal-fired plants with two different escalation rates assumed for coal. The range of costs from solar plants is based on the assumption that heliostat costs could range between $75/m^2 and $110/m^2.

- Detailed conceptual design studies have been conducted illustrating how the central receiver concept can be used with both utility applications and industrial process heat applications. Two major studies with site specific designs are the recently completed repowering investigations and the soon-to-be-finished cogeneration studies. Figures 4 and 5 show where these sites were located and who participated in the conceptual designs.

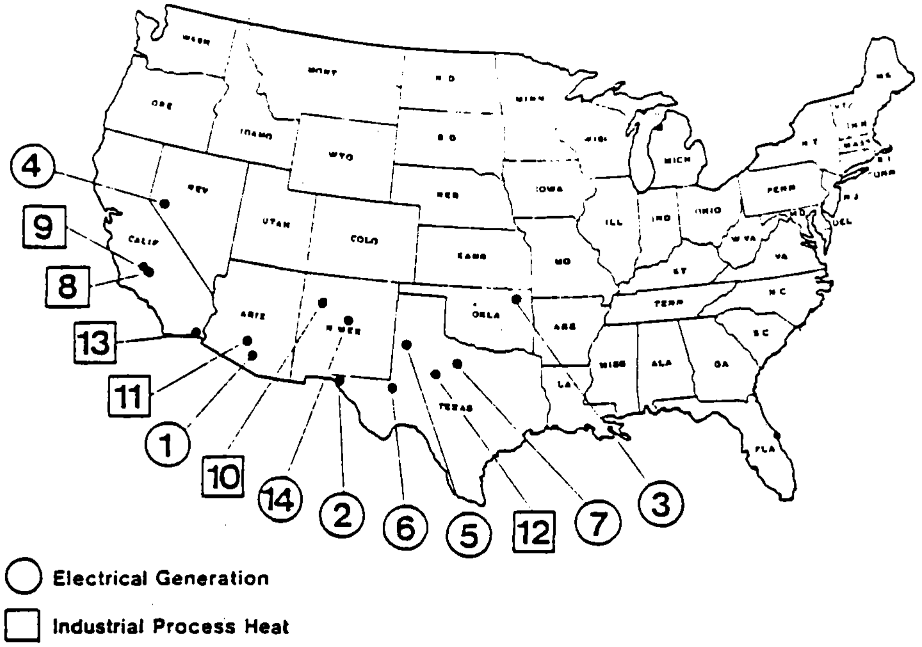
- In addition to projects sponsored solely with DOE funds, joint projects with other agencies have been undertaken to further development of central receiver technology. An assessment study with the Water and Power Resources Service, Department of the Interior, concluded integration of central receiver technology with a hydroelectric system offers an economical and flexible means of long-term storage. Along with eight European countries, the United States is participating in the International Energy Agency's Small Solar Power System Project under construction at Almeria in southeastern Spain. This project will include a 500 kW_e central receiver system that uses liquid sodium receiver and storage systems. While the DOE has concentrated on development of steam-Rankine systems for electrical energy production, additional work has been done supporting the Electric Power Research Institute's efforts to develop receivers to power advanced Brayton cycle (gas-turbine) systems. Examples of this cooperation include the successful testing of the 1500°F, one-megawatt hot-air receiver (built by Boeing Engineering and Construction Company) at the Central Receiver Test Facility and assistance provided to EPRI in the design review and planning process.



PRIME CONTRACTOR/User-Owner/Location

1. BECHTEL NATIONAL INC./Amfac Sugar Co./Pioneer Mill Co., Lahaina, Maui, HI
2. BLACK & VEATCH/Central Telephone & Utilities-Western Power/Cimarron River Station, Liberal, KS
3. EXXON/Exxon/Edison Field, Bakersfield, CA.
4. GENERAL ELECTRIC/Texasgulf/Comanche Creek Plant, Fort Stockton, TX
5. GIBBS & HILL/Phelps Dodge Corp./Hidalgo Smelter, Playas, NM
6. MCDONNEL DOUGLAS ASTRONAUTICS CO./U.S. Army/Fort Hood, Killeen, TX.
7. WESTINGHOUSE ELECTRIC CORP./U.S. Air Force Logistics Command/Robins AFB, Macon, GA.

Figure 4. Cogeneration design projects applications -- repowering.



Listed below are addresses for obtaining additional information on the solar thermal repowering projects.

(1) Arizona Public Service
Attn: Eric R. Weber
P.O. Box 21666
Phoenix, AZ 85036

(2) El Paso Electric Company
Attn: Jim E. Brown
P.O. Box 982
El Paso, TX 79960

(3) Black & Veatch Consulting Engineers
Attn: Sheldon Levy
P.O. Box 8405
Kansas City, MO 64114

(4) McDonnell Douglas
Attn: Robert Easton
5301 Bolsa Avenue
Huntington Beach, CA 92647

(5) General Electric Company
Attn: James A. Elsner
Energy Systems Programs Department
1 River Road
Schenectady, NY 12345

(6,7) Rockwell International
Attn: Tom H. Springer
Energy Systems Group
8900 De Soto Avenue
Canoga Park, CA 91304

(8) Northrup, Inc.
Attn: Roy L. Henry
302 Nichols Drive
Hutchins, TX 75141

(9) Martin Marietta
Attn: David N. Gorman
P.O. Box 170
Denver, CO 80201

(10) McDonnell Douglas
Attn: L. W. Glover
5301 Bolsa Avenue
Huntington Beach, CA 92647

(11) Foster Wheeler Development Corporation
Attn: D. R. Raghavan
12 Peach Tree Hill Road
Livingston, NJ 07039

(12) Boeing Engineering & Construction Company
Attn: Donald K. Zimmerman
P.O. Box 3707
Seattle, WA 98124

(13) PFR Engineering Systems, Inc.
Attn: Tzvi Roseman
4676 Admiralty Way, Suite 832
Marina Del Ray, CA 90291

(14) Public Service Company of New Mexico
Attn: J. P. Maddox
P.O. Box 2267
Albuquerque, NM 87103

Figure 5. Solar thermal repowering projects.

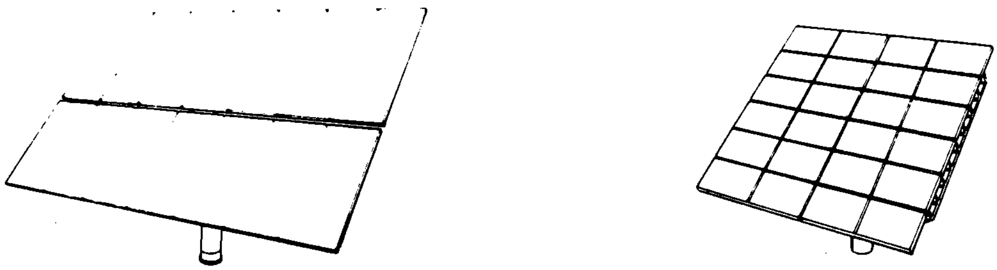
- Through their involvement in various conceptual designs, prototype design, construction and testing, many organizations have acquired experience and knowledge of central receiver technology. A partial list of participants is shown in Table 1.

- Components of the central receiver system have evolved through many design, construction and testing iterations. Although differing in design details, heliostats using conventional glass-steel construction have evolved into common structural philosophy as illustrated in Figure 6. Water/steam, molten salt, and hot air receivers have been tested. A sodium cooled receiver will be tested in the near future. In all areas, design refinements and improvements can be seen. The feasibility of central receiver technology is not in doubt, although the ultimate economics are yet to be proven.

TABLE 1

ORGANIZATIONS WITH SOLAR THERMAL CENTRAL RECEIVER EXPERIENCE

Aerospace Corp.
Amfac Sugar Co.
ARCO Oil & Gas Co.
Arizona Public Service Co.
Babcock & Wilcox Co.
Badger Energy, Inc.
BEI Electronics
Battelle Pacific Northwest Labs
Bechtel Group, Inc.
Beckman Instruments Inc.
Black & Veatch Consulting Engineers
Boeing Engineering & Construction Co.
Brown & Root Inc.
Brown-Boveri Corp.
Burns and Roe
Carolina Mirror Co.
Central Telephone & Utilities
Centrecon
Combustion Engineering Inc.
Dynatherm
EIC Corporation
El Paso Electric Co.
Electric Power Research Institute
Energy Systems Group-Rockwell Int'l
Exxon Research & Engineering Co.
Fluor Corp.
Ford Aerospace and Communications
Foster-Miller Associates
Foster Wheeler Development Corp.
Foster Wheeler Energy Corp.
Foxboro Co.
Franklin Institute Research Labs
GAI Consultants, Inc.
Gardner Mirror
General Atomic Co.
General Electric Co.
General Motors Transp. Systems
Georgia Institute of Technology
Georgia Power Co.
Gibbs & Hill Inc.
Grumman
Gulf Research & Development
Heery and Heery A/E Inc.
Honeywell, Inc.
Institute of Gas Technology
Kaiser Engineers
Lawrence Livermore National Labs
Los Angeles Depart. of Water and Power
Martin Marietta Corp.
Maui Electric Co.
McDonnell Douglas Astronautics Corp.
Mechanical Technology
National Helium Corp.
Neilsen Engineering
Northern States Power Co.
Northrup, Inc.
Okahana Shiegoka & Assoc. Inc.
Pacific Gas & Electric Co.
PFR Engineering
Phelps Dodge Corp.
Pittsburgh Corning
PPG Industries
Progress Industries
Provident Energy Corp.
Public Service Co. New Mexico
Public Service Co. of Oklahoma
Pyromet Industries
Rocketdyne Division, Rockwell Int'l
Rocket Research Corp.
Safeguard Industries
Salt River Project
Sanders Associates
Sandia National Laboratories
Sargent and Lundy Engineers
Schumacher and Associates
Sheldahl Inc.
Sierra Pacific Power Co.
Solaramics
Solar Energy Research Institute
Southern California Edison
Southwestern Public Service Co.
Springborn Labs
SRI International
Stanford University
State University of New York, Buffalo
Stearns-Roger Engineeering Co.
Stone & Webster
Sunpower Corp.
Texas Electric Service Co.
Texas Gulf Chemicals
Townsend and Bottum, Inc.
USAF Logistics Command
US Army Corp of Engineers
U.S. Gypsum
U.S. Naval Material Command
United Technologies
University of Houston
University of California, Berkeley
University of California, Los Angeles
University of Illinois
Valley Nitrogen Producers
VEDA, Inc.
Westinghouse Electric Co.
West Texas Utilities



MC DONNELL DOUGLAS

NORTHRUP

SECOND GENERATION HELIOSTATS

BOEING

MARTIN MARIETTA

Figure 6.

CONTINUING ACTIVITIES

Follow-on activities for the central receiver program include:

1. System Application Project Activities

The major on-going project activity involves completion of construction for the Solar One plant, its checkout, and acceptance testing. The plant will then be used in the acquisition of operational data for use in subsequent repowering, industrial retrofit, and cogeneration projects. Other activities include support to the International Energy Agency Project, the Electric Power Research Institute (EPRI) Brayton System Test Experiment, and the Water & Power Resources Service Solar-Hydro Integration Project. These types of projects are important for early acceptance of central receiver technology and to stimulate industries to produce solar components.

2. Development of Improved System Designs

System design activities will be continued in order to further identify configurations that improve the systems cost effectiveness. Several specific applications will be investigated (e.g., utility repowering, high temperature industrial process heat, cogeneration, and solar fuels and chemical production-sunfuels). Component and system hardware development for the most promising options will be pursued. With all system design activities, the main criteria is to provide the most cost effective system and not necessarily the most efficient.

3. Component and Subsystem Development

Projected efforts for this activity include completion of testing at the CRTF of second generation heliostats, receivers, and other subsystems, as well as development of designs and testing of the next generation components with lower costs, higher performance, and lower life cycle maintenance to match specific needs of the identified markets.

4. Market and Resource Assessment and Development

Electrical power generation, industrial process heat, cogeneration, and fuels and chemical production have been identified as the promising large energy consumption markets for central receiver technology. Projected activities for the next five years include continued characterization and understanding of these markets and analysis of the various central receiver system designs that best match specific market needs, to determine and enhance market penetration potential. Market development activities include extension of the current repowering commercialization plan to include IPH user requirements along with the utility requirements; detailed characterization of IPH application sites, temperatures, and geographic locations to provide guidance for follow-on hardware development efforts; and the development of appropriate incentive programs and technology dissemination to users and manufacturers to enhance commercialization.

In summary, the central receiver program is rapidly resolving the engineering feasibility questions. Current emphasis is on building user confidence by eliminating technical uncertainties and the establishment of system cost readiness.

REFERENCES

1. K. W. Battleson, "Solar Power Tower Design Guide," Sandia National Laboratories, SAND81-8005, April 1981.

2. "Department of Energy Solar Central Receiver Semiannual Meeting, Sandia National Laboratories, SAND80-8099, January 1981.

3. "Solar Thermal Central Receiver/Repowering Multi-Year Program Plan," San Francisco Operations Office, U.S. Department of Energy, March 1981.

OVERVIEW OF LINE-FOCUS SOLAR THERMAL COLLECTOR SYSTEMS*

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Albuquerque, New Mexico
87185 USA

ABSTRACT

An overview is given of progress being made toward commercialization by line-focus solar collector systems. The effort to characterize the various types of parabolic trough collectors is discussed and a trajectory for expected performance with time is presented for several temperatures. An indication is given of the total line-focus collector aperture arising from the several DOE-sponsored projects. Finally, the manner in which the installed capital cost divided by average energy provided by the system is decreasing with time is discussed.

Discussion

Because solar thermal systems are capital intensive whereas fossil-fuel-burning systems are largely fuel intensive, comparison of energy costs should only be made on a life-cycle basis. This permits the initial capital investment made in a solar thermal system to be spread over the system lifetime while accounting for the expected real increase in fossil fuel prices over the same period. A working group called the Solar Thermal Cost Goals Committee (STCGC) has been formed by DOE to establish the economic parameters to be used by the various solar thermal technology advocates in their life-cycle analyses. In addition, the Committee has enlisted the aid of several consulting groups to establish expected fuel escalation rates in excess of general inflation. Without going into specific details, the preliminary outputs of the STCGC has results in a series of graphs of the type presented in Figure 1.

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* This work was supported by the United States Department of Energy.

** Supervisor, Solar Systems Analysis Division.

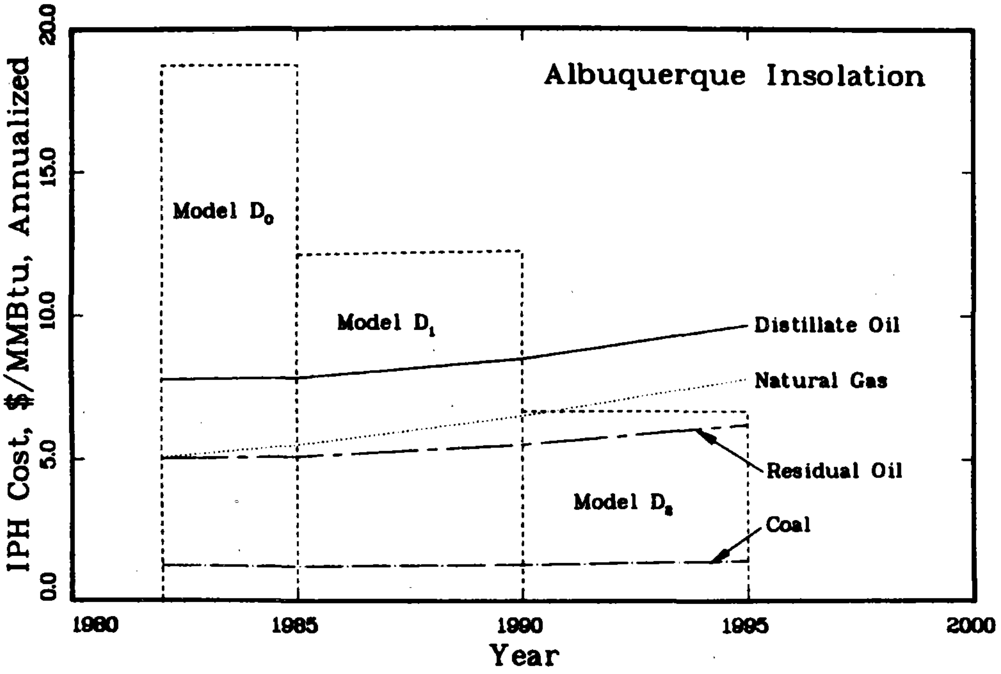

Fig. 1. Line-Focus Life Cycle Cost Comparison for IPH.

The lines labeled with fuel types correspond to the committee-recommended fuel price trajectories to be expected for the Albuquerque region. The ordinate of the figure represents the ratio of annual levelized system cost ($\$/m^2$) divided by annual system energy delivered to load ($MMBtu/m^2/yr$) at 600 F for Albuquerque, NM.

One can consider the upper horizontal lines for the various system models indicated to be the nominal values for the nominal STCGC-recommended economic parameters. It should be pointed out that the combination of all equity financing and rather high initial discount rate are largely responsible for the poor comparison of the model D_o system. Relaxing either of these assumptions will lower the solar system annualized cost as will an increase in investment tax credit or an accelerated depreciation schedule. Theoretically, any governmental incentive desired could be applied to this early system to accelerate market penetration for some non-financial reason such as national security, etc.

The model D_1 system fares better in the comparison because it enjoys a modest performance increase coupled with a substantial installed system cost decrease. This latter decrease comes as a result of reducing the field installed costs, especially in the area of plumbing and electrical wiring. The Modular Industrial Solar Retrofit (MISR) program of DOE is a necessary step in going from model D_o to D_1. The final model, D_2, can come about only as a result of mass production and the associated decrease in hardware costs. It is generally accepted that a sufficiently developed market for the collector systems could result in mass production manufacture. Again, the necessity for effecting intermediate time market penetration is indicated.

An effort to characterize the performance of trough collectors has been ongoing for several years at the Collector Module Test Facility (CMTF) in Albuquerque. This has resulted in an expression of the type indicated below:

$$\eta = \mathrm{ACos}\ \theta[1 + B(1 - \sec\theta)] + \frac{C\Delta T}{I} + \frac{D\Delta T^2}{I}$$

where:

η = Collector module instantaneous efficiency
A = Parameter indicating optical efficiency
B = Parameter indicating incident angle modifier
C = Parameter indicating linear thermal losses
D = Parameter indicating non-linear thermal losses
θ = Incident angle between collector normal and solar rays
I = Direct normal insolation
ΔT = Average collector temperature minus ambient temperature.

Using this expression, a systems analyst can estimate the annual performance expected from a given collector system at a particular location by using the Typical Meteorological Year (TMY) data tapes of weather and insolation. This has been done for a series of trough collectors in Albuquerque as indicated in Figure 2. The data indicated represent respectively polished aluminum, an acrylic film reflector, and silvered glass.

At first glance, it appears that the most recent data (glass) are well above the predicted trajectories, but in fact this is not the case. Collector performance development involves a set of three orthozonal axes representing time, annual energy delivered, and reliability (or lifetime). The particular collector module tested in the CMT which provided these data had a rather short lifetime and, consequently, its average annual performance over a system lifetime would be less. This involves an economic feedback loop between performance and cost which must be traded off by the systems analyst. One possible implication is that a lesser performance by a more reliable or substantially cheaper system would be preferred. In this case, the system designer might not look for the maximum performance system but take one of the other candidates.

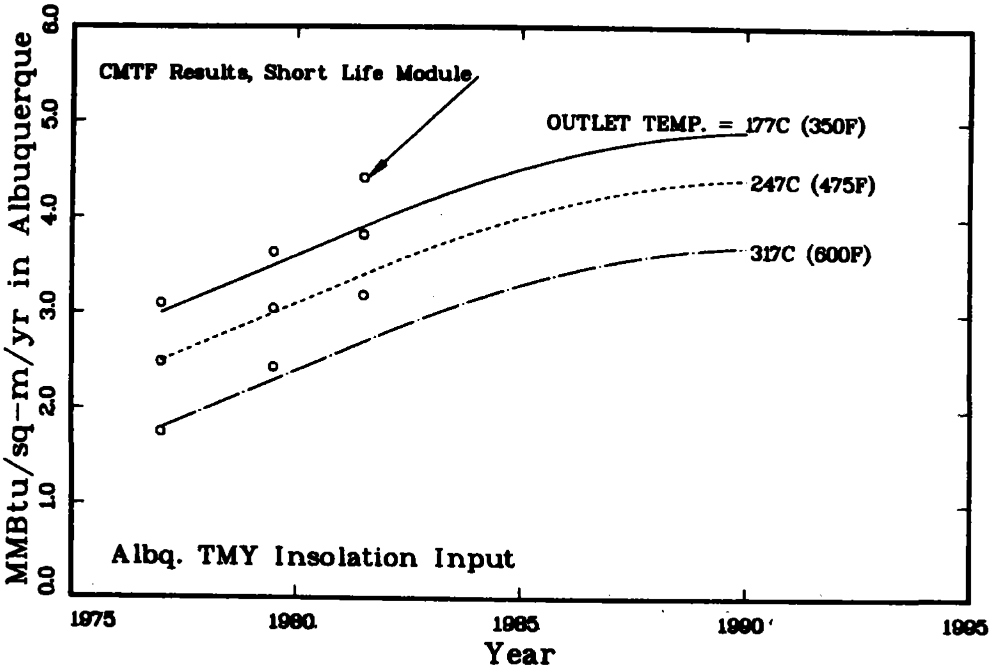

Fig. 2. Annual Trough Module Energy Delivered

The first demonstration units of line-focus collector systems were fielded in 1977 at Willard, NM, and Gila Bend, AZ. Both systems have since been decommissioned and are presently being dismantled. Data line-focus aperture due to these two systems was about 1100 square metres. Since that time, a series of additional demonstration units has been fielded by DOE as indicated in Figure 3.

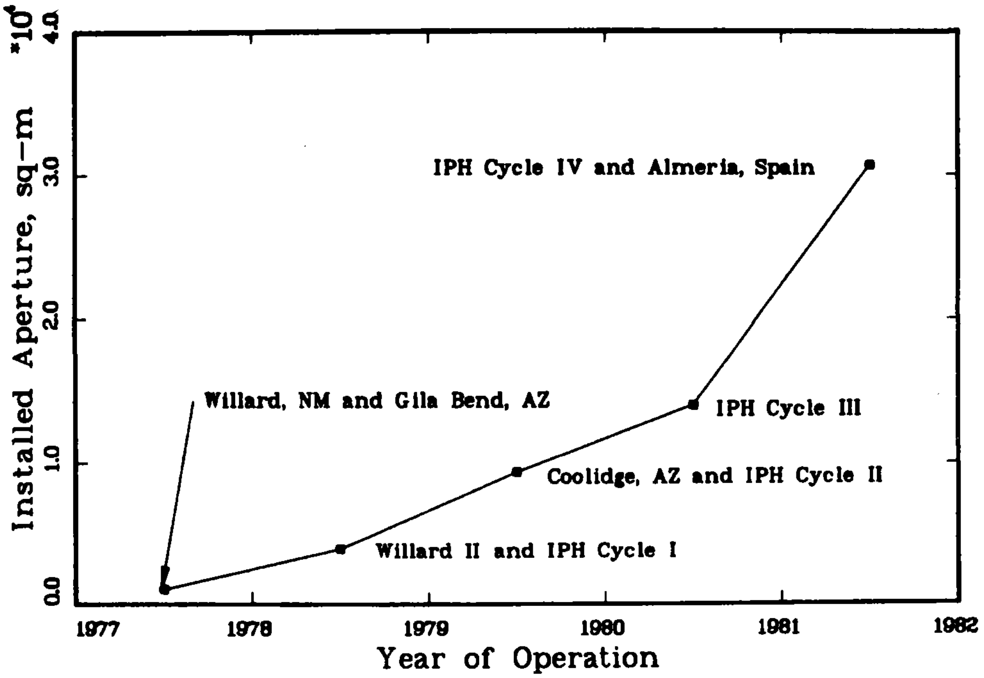

Fig. 3. DOE-sponsored Line-Focus Projects

The total installed aperture at the end of FY 1981 is expected to be about 30,000 square metres. Indicated on the figure are the names of the various projects. Note that the relative total apertures in square metres of the IPH Demonstration Projects are: Cycle I, 1440; Cycle II, 3290; Cycle III, 3630; and Cycle IV, 12,560.

Because all of these systems operate at different temperatures and different locations, it is extremely difficult to establish cost/performance trends from the system raw data. To overcome this problem, systems models were generated for the various projects and computer simulations were made at 177 C (350 F) using the Albuquerque TMY data mentioned above. If the expected range of values for both the MISR program and the long-range line-focus goals are also considered, the curve in Figure 4 results.

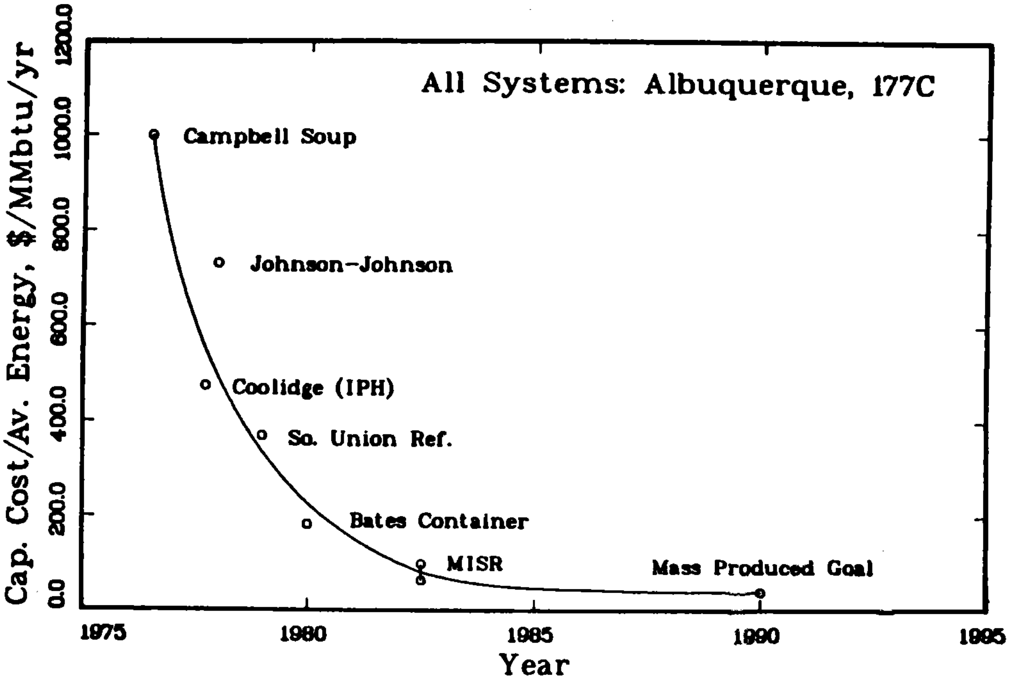

Fig. 4. Line-Focus IPH Systems

Note, that for this exercise, the Coolidge, AZ site was considered to be an IPH system rather than an electricity producer. Figure 4 should not be considered the bottom line but rather a trajectory for reaching the final horizontal line in Figure 1.

It appears that the expectation level associated with reaching the model D_1 level is very high provided that MISR continues to receive favorable funding priority by DOE. To reach the model D_2 level, the market must be stimulated through incentives to drive mass production and

and thus reduce capital costs. Because of the inherent uncertainty associated with predictions so far in the future one should assign larger error bars to both solar and fossil fuel system costs. If the line-focus program were to be prematurely truncated because of budgetary pressures, it is likely that only the model D_1 or D_2 levels would be reached. This point is especially important to remember when developing systems are assumed to be "ready for commercialization." Experience with flat plate collector systems indicates that the market for collectors (primarily residential) has produced collectors which are too expensive to compete without excessively high Federal and state incentives. Hopefully, this will not be the case for line-focus solar collector systems, and they will enjoy a rational development to commercialization.

PARABOLIC DISH SYSTEM DEVELOPMENT*

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INTRODUCTION

The Parabolic Dish Project at the Jet Propulsion Laboratory is approximately four years old and is now entering the stage when first-generation hardware is being tested for the first time. A significant effort has been underway to understand the applications that provide system-level requirements on which the technology development and design decisions are based. Several systems are now evolving to meet the needs of the applications deemed appropriate for dish technology. The system requirements, in turn, have provided subsystem and component design goals. The degree of success in meeting these goals is often predicated on a research and development activity in key areas. Since this process is continuous and cyclic, it is sometimes difficult for those not intimately involved in the program to know exactly where we stand with regard to the overall evolution of the technology. To help provide some perspective on the parabolic dish development program, this paper poses and answers three questions: (1) What requirements have influenced parabolic dish design decisions to date? (2) How has a specific design evolved to meet near-term system-level requirements? (3) What are the longer term requirements, and how will they influence the technology development program?

To answer the first question, the market assessment and applications analysis activities will be examined to provide a top-level summary of design requirements for first-generation technology now in production.

The second question will be addressed by an example of a completed design which is now being verified by testing components and subsystems before a complete system is implemented in the field. The example chosen is the Small Community Solar Thermal Power Experiment, a 1-MWe plant using organic Rankine power conversion technology.

Finally, some future development activities envisioned for second- and third-generation technology will be discussed, with emphasis on subsystem, component, and material requirements.

FIRST-GENERATION TECHNOLOGY: REQUIREMENTS AND DESIGNS

The ideal and rarely accomplished progression leading to a mature commercial product involves a market assessment, an analysis of a specific attractive

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

application from which certain requirements emerge, and then an evolution of a design in an iterative series of steps culminating in a product that meets the market needs. While it has seldom been in this ideal situation, the parabolic dish project has developed within a framework that has established design goals and requirements based on an understanding of attractive and appropriate applications for the technology. In addition, a technology development process has been defined in response to perceived near-term and long-term market needs.

The electric power market was assessed at JPL [1] to determine where dish technology can most readily compete. Figure 1 summarizes the results of the anticipated growth in levelized busbar electric energy costs by region and by industrial sector. One can see that to compete in the bulk electric market which uses coal-fired plants, costs must be in the range of 50 to 100 mills/kWhr, even beyond 1990. However, easier markets exist when smaller oil-burning plants and remote applications are considered. Parallel analysis of various technology options has led to the conclusion that at least two generations of technology would be required to achieve the lower cost, but that a first-generation technology could meet the cost of a number of nearer-term markets, if a sufficient production volume could be achieved (Figure 2).

Thus, two sets of information are needed to ascertain the probability of the dish technology meeting these costs. The first is a definition of cost goals that, if met, would permit the technology to compete in selected market sectors. DOE, with the assistance of SERI and the other laboratories involved in the Thermal Power Systems Program, has established such goals for each major technology. Table 1 lists the first-generation dish goals. The second set of data needed pertains to the potential market. When the technology is successfully developed, will the market be sufficient to support the required production levels? Two aspects are involved. First, the market must exist so the supply sector will invest the capital required to manufacture the hardware.

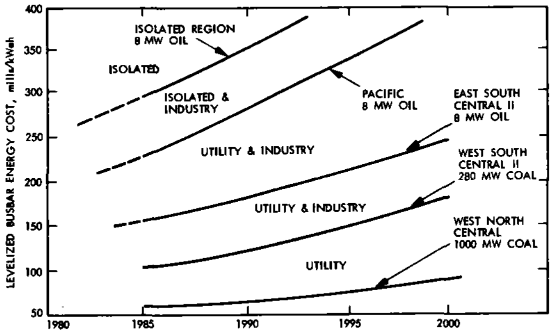

FIG. 1 ~~BBEC~~ FOR NEW CONVENTIONAL POWER PLANTS BY SECTOR AND REGION

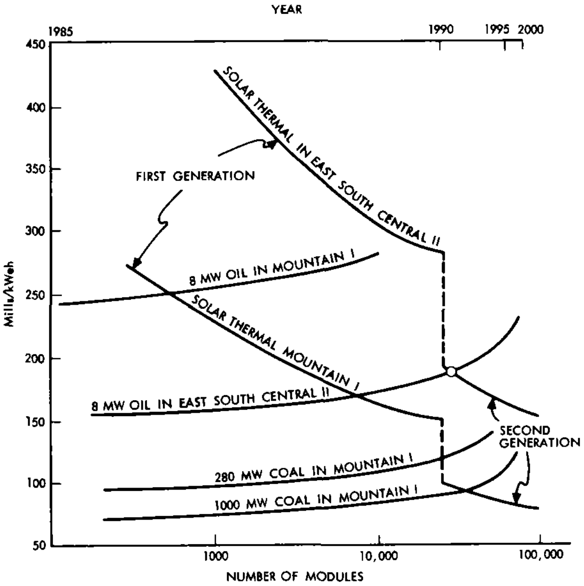

FIG. 2 BREAK-EVEN COSTS - SOLAR THERMAL PARABOLIC DISH SYSTEM AND CONVENTIONAL SYSTEM (1980 DOLLARS)

Second, the technology must compete with other sources for a necessary market share. Contractors [2] and JPL [3] have studied market opportunities for dish technology. From these studies evolved the definition of the Small Community Solar Power Program [4] that addresses a subset of the early opportunity markets for parabolic dishes. Important near-term small community markets include rural, small municipal, or agricultural communities which are either isolated from the grid or are located at the end of long transmission lines. In these cases, it is more economical to locate the power plant within the community than to transport electrical energy over long transmission lines from large central power stations. These communities will benefit greatly from a dispersed power source.

TABLE 1 PARABOLIC DISH TECHNOLOGY READINESS COST GOALS FOR FIRST-GENERATION TECHNOLOGY (1983)

	PERFORMANCE TARGETS	COST TARGETS
SYSTEM	20%	140-160 mills/kWhr
SUBSYSTEM		
CONCENTRATOR	78-90% REFLECTANCE	$\$120\text{-}170/\text{m}^2$
ENGINE	25-35% EFFICIENCY	$\$230\text{-}410/\text{kW}_e$
RECEIVER	82% EFFICIENCY	$\$45\text{-}70/\text{kW}_e$

NOTES: PRODUCTION RATE: 5,000 TO 25,000/YEAR
1980 DOLLARS
BASED ON SOUTHWEST LOCATION

JPL has conducted studies to characterize the small community markets in terms of size and potential for dish solar electric systems [5]. Figure 3 shows the anticipated new capacity required in 1990 for several such markets. Although these markets are intended to be representative of small community applications, and are not all-inclusive, for this sample alone, a new capacity requirement of 1600/MWe per year is projected for 1990. The largest annual increase occurs in small municipal utilities and in rural cooperatives.

The corresponding busbar energy costs in mills/kWhr are shown in Figure 4. This figure indicates that isolated loads found in island communities, for example, have the highest energy costs (projected to be over 300 mills/kWhr in 1990). Energy costs for municipal and rural cooperatives range between 100 and 300 mills/kWhr. As is illustrated in Figure 4, a production level of 1000 modules per year (20 MWe, or less than 2 percent of the aggregate market) would result in energy costs within the range of these markets.

Three major technology thrusts exist within the parabolic dish project with regard to achieving electric energy cost goals. These activities are centered around three engine developments: organic Rankine, Brayton, and Stirling power conversion subsystems. Each is undergoing development for first-generation application, but only the Brayton and Stirling engines have the potential for meeting the high efficiencies required for the second-generation goals. The organic Rankine engine was selected for early deployment because of the lower risk associated with its development, since this technology has been proven. The only remaining task is the engineering required to produce a power module capable of meeting dish requirements. Low-cost concentrators, receivers, energy transport, and control systems are also undergoing development. Because it is not possible to cover all of these activities within the constraints of this paper, an example of one specific system-level design will be given.

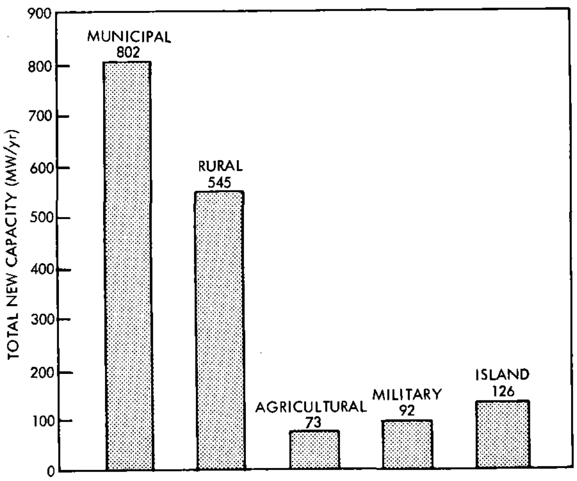

FIG. 3 PROJECTED DEMAND FOR NEW CAPACITY IN TYPICAL EARLY OPPORTUNITY MARKET SECTORS IN 1990

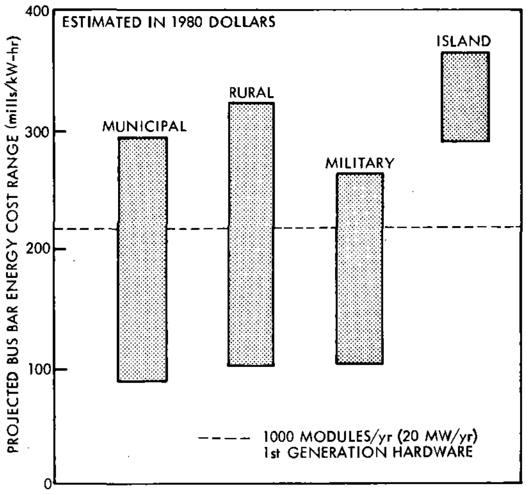

FIG. 4 PROJECTED ENERGY COST RANGES FOR SMALL COMMUNITIES IN 1990 (1980 DOLLARS)

A NEAR-TERM PARABOLIC DISH SYSTEM: THE SMALL COMMUNITY EXPERIMENT

An early experiment to be fielded is the Small Community Solar Thermal Power Experiment (SCSE). As the name implies, this experiment is being designed to support the electrical power demands of a small community. The power output, which will be selected from a range of 100 kWe to 1.0 MWe, will be conditioned and fed into the local utility grid. This concept evolved from the first phase of what is planned as a three-phase effort. A 1-MW plant is shown in Figure 5, while an example of an individual module can be seen in Figure 6. The hardware is presently being fabricated for demonstration at the subsystem and module level as Phase II, while Phase III will constitute the fully fielded experiment within the user environment.

As presently designed, the SCSE will consist of 56 individual modules clustered on approximately 10 acres of land, and will comprise four major subsystems. The first is the collector subsystem which consists of the two-axis, sun-tracking, 12-meter concentrator and the receiver into which the solar energy is focused. The concentrator collects and focuses this energy into the receiver, while the receiver absorbs and transfers this energy to the working fluid of the second major subsystem, the power conversion subsystem.

The power conversion subsystem converts the thermal energy acquired in the receiver to electrical energy by pumping the working fluid through the receiver where it is heated and subsequently expanded through a turbine. The turbine work is then converted to electricity by a permanent-magnet alternator that is coupled directly to the turbine wheel.

The third major subsystem, the energy transport subsystem, transports the power generated at each module to the central collection point. For the SCSE this includes the ac-to-dc conversion at each collector, the accumulation of the dc contributions from all of the operating collectors, the inversion of

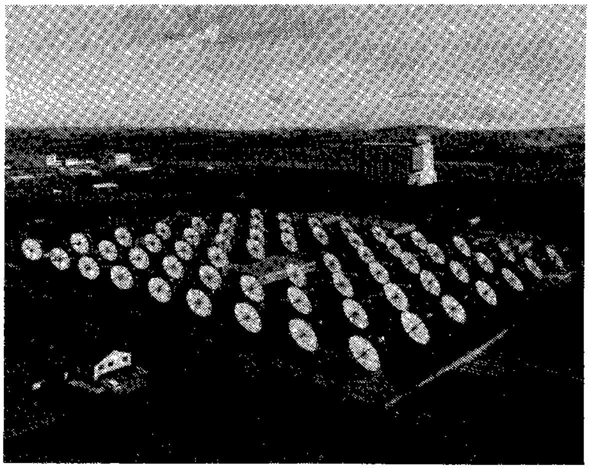

FIG. 5 EXAMPLE OF A 1-MWe SMALL COMMUNITY SOLAR THERMAL POWER EXPERIMENT

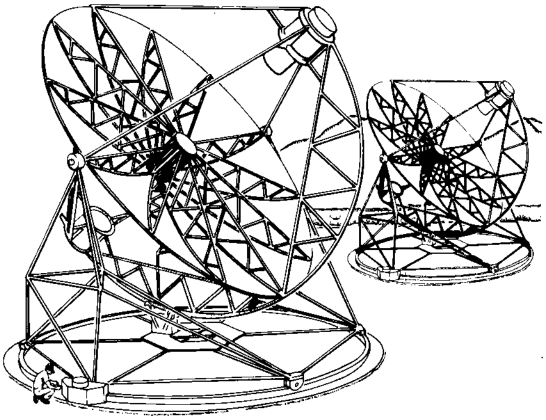

FIG. 6 EXAMPLE OF INDIVIDUAL SOLAR THERMAL POWER MODULES

the dc power to ac, and the conditioning of the power with the frequency and phase angle acceptable to the grid.

The last major subsystem is the system controls. This subsystem monitors and controls the experiment through all phases of its operation, including start-up, shut-down, normal operation, and intermittent operation. It must also handle emergencies in a manner that ensures safety to personnel and minimal damage to hardware. This subsystem encompasses the necessary hardware, software, and facilities required to conduct both the module-level and the plant-level functions either automatically or manually at the discrection of the experiment coordinator.

The specific design described above was developed to meet the need to provide a near-term alternative to rising fuel costs for the electrical power generation service to small communities. As this design evolved, several specific requirements imposed by the hardware needs were identified.

First, if this is to be a near-term alternative, then maximum advantage must be taken of proven technology, while recognizing that little or no "off-the-shelf" hardware generally exists within the desired sizes. Next, if the solar thermal power system is to be a viable alternative, it must generate power with high efficiency and high reliability. Additional constraints are the budget available for the hardware development and the projected cost of the developed units in mass-produced quantities. A synopsis of the influence of these requirements on the course of the SCSE design is presented below.

The contractor selected for the SCSE system integration is Ford Aerospace and Communications Corporation (FACC) of Newport Beach, California. An example of design tradeoff details for an earlier version of the SCSE can be found in

Reference [6]. At the time of the SCSE contract award to FACC, JPL already hadan ongoing contract with General Electric to produce an 11-meter-diameter concentrator of a low-cost design. (The diameter has since been increased to 12 meters). Because of funding constraints, FACC was directed to integrate the GE concentrator into their SCSE design and not to conduct further tradeoff analyses of concentrators. This concentrator constraint, in turn, imposed the further requirement that the engine mounted at the focal point be a nominal 20 kWe, which necessitated extensive engine tradeoffs.

The Rankine thermodynamic cycle was recommended from Phase I of this program as having the nearest-term proven technology within the size ranges of interest, and it was, therefore, selected for the SCSE. Given the premise that the engine was to operate on a Rankine thermodynamic cycle, the next question to be resolved was that of the working fluid. The obvious candidates were steam and an organic fluid of some kind. Steam turbines were eliminated from consideration relatively early, as their efficiency falls significantly for smaller sizes. For example, the projected efficiency of a 20 kWe steam turbine with 538°C (1000°F) inlet temperature is about 20%. The radial flow steam turbine, although a demonstrated technology, was felt to be insufficiently developed to be classified as truly near-term. The only competitive steam engines in the required size range were the steam piston engines, which were traded off against organic Rankine engines.

The additional requirement that the SCSE generate electrical power with high reliability necessitates that there be minimum "stress" on the hardware to ensure longer life with fewer failures. To meet this constraint, the temperature and pressure extremes and variations should be minimized to provide a more benign environment for the hardware. Since this requirement apparently conflicts with the need for highest efficiency, it was instrumental in tipping the engine trade-off balance in favor of the organic Rankine cycle engine.

The organic Rankine engines, meanwhile, have received considerable attention in the smaller sizes. Units have been built and tested at rated powers both greater and smaller than that required for SCSE. Although none existed in the size of interest, it was felt that the technology was proven and could be readily adapted to the SCSE needs. Because of the higher molecular weight of an organic working fluid, power is produced at higher efficiency and lower temperatures in the smaller kilowatt sizes than is typically possible even for piston steam engines. However, the choice of an organic working fluid became a critical issue, in support of which many candidates were traded off. The requirement of operating at the highest possible efficiency necessitates the highest tolerable operating temperature range: i.e., high engine inlet temperature and low condenser outlet temperature. However, because organic fluids are composed of relatively complex molecules, high temperatures can crack the carbon chains and generate both noncondensible gases and complex polymers, manifested as deposits of a gummy substance. Therefore, a working fluid with excellent thermal stability at high temperatures was needed, and during test operations the fluid could not be exposed to temperatures that might exceed the molecular bonding energy.

The candidate material which best fits the above criteria was toluene operating at a maximum of 399°C (750°F). At this temperature, toluene will experience a degradation rate of less than 10^{-2}%/hr. Yet, an organic Rankine engine with toluene as the working fluid can deliver a net efficiency of approximately

26% for a 399°C (750°F) engine inlet temperature. This efficiency includes all of the losses between the receiver inlet and rectifier outlet.

Organic working fluids like toluene typically have a low thermodynamic critical state. Hence, all high-temperature fluid handling can be accomplished while the fluid is in the supercritical state, thus avoiding the complications of two-phase flow. However, as mentioned above, the use of an organic working fluid means that the temperature limits for molecular dissociation must not be exceeded. This further constrains the receiver design to one with a minimum sensitivity to hot spots from the nonlinear solar flux incident upon its surface. The SCSE receiver is designed with a nominal 1/4-inch-thick copper liner between the surface exposed to the solar flux and the toluene heat exchanger tubes. Since copper has a very high thermal diffusivity, heat will be conducted very rapidly both axially and circumferencially, as well as radially. Thus, any potential hot spots will be quickly smoothed out.

Another requirement being investigated is the possible need for a short-term thermal buffer storage, located somewhere between the incident solar flux and the working fluid. As a reference as to what may drive the requirements for buffer storage, Figure 7 presents a histogram of the number and duration of cloud passages experienced in 1979 at the parabolic dish test site located at the JPL Edwards Test Station. It can be seen from this figure, for example, that nearly half of the cloud passages that reduced insolation to less than 200W/m^2 were less than two minutes duration. While two minutes of buffer storage are achievable with the present receiver design, the benefits of additional storage in terms of reduced engine stress are under consideration.

In summary, one can see from the above how the influence of the requirements has been felt throughout the SCSE design, and the ramifications of these requirements on the component tradeoffs. Although the SCSE case represents a specific example, it is, nonetheless, typical of the processes underway for the other experiments.

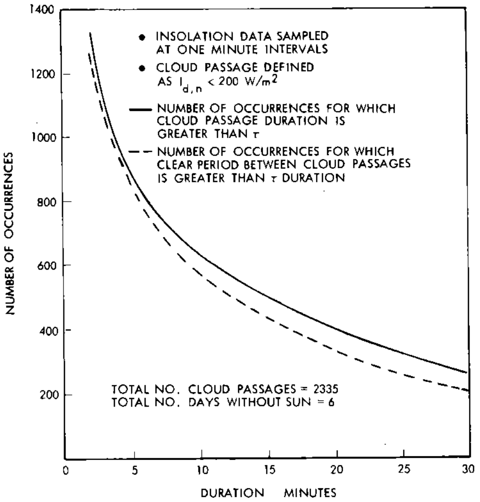

FIG. 7 HISTOGRAM OF CLOUD PASSAGES AT THE EDWARDS PARABOLIC DISH TEST SITE DURING 1979

FUTURE PARABOLIC DISH TECHNOLOGY DEVELOPMENT

Significant research and development effort is required to meet the long-term requirements of second-generation solar thermal systems such as low cost, high performance, long life, and dependability. Table 2 shows the second-generation cost and performance targets for the major subsystems of a solar thermal system [7]. These targets impose requirements on cost, performance and lifetime, which advanced research and development programs are aimed at meeting.

Analysis has indicated that increased system efficiency could significantly lower energy costs by reducing the number of concentrators that must be installed for a given power requirement. Savings in land and maintenance costs can also be realized. System efficiencies up to 20 percent are projected for solar thermal systems currently being developed. Advanced research and development is aiming at system efficiencies of 30 percent, resulting in approximately half of the collector area requirements of current systems.

The largest energy loss in a solar thermal electric system is the heat rejected by the engine. Thus, the greatest potential for improving system efficiency is through the use of high-performance, high-efficiency engines. Substantial improvement in the efficiency of small engines for solar thermal applications is possible [8]. The potential increase in small engine (25 kW mechanical output) efficiency compared with near-term performance is presented in Figure 8. It can be seen that the Stirling cycle offers the greatest promise for improved efficiency for temperatures between 550° and 950°C (1022° and 1742°F). The Brayton cycle also shows promise for high efficiency, but primarily at operating temperatures greater than 950°C (1742°F). Achievement of engine efficiencies greater than 40 percent will be a key step toward meeting energy cost targets. The temperatures associated with this goal imply the development of ceramic engine components, and significant efforts are underway in this area.

The use of high efficiency heat engines requires an advanced technology program in high-temperature receivers. Such receivers are also a key to the development of industrial process heat as well as fuel and chemical applications for thermal power systems. The requirement for increased receiver operating temperature must be balanced against an increase in thermal energy

TABLE 2 PARABOLIC DISH TECHNOLOGY READINESS COST GOALS FOR SECOND-GENERATION TECHNOLOGY (1987)

	PERFORMANCE TARGETS	COST TARGETS
SYSTEM	30%	80-100 mills/kWhr
SUBSYSTEM		
CONCENTRATOR	92% (REFLECTANCE)	$80-120/m^2$
ENGINE	35-45% (EFFICIENCY)	$120-230/kWe
RECEIVER	87% (EFFICIENCY)	$25-45/kWe

NOTES: 1. PRODUCTION RATE: 10,000 to 1,000,000/year
2. 1980 DOLLARS
3. SOUTHWEST LOCATION

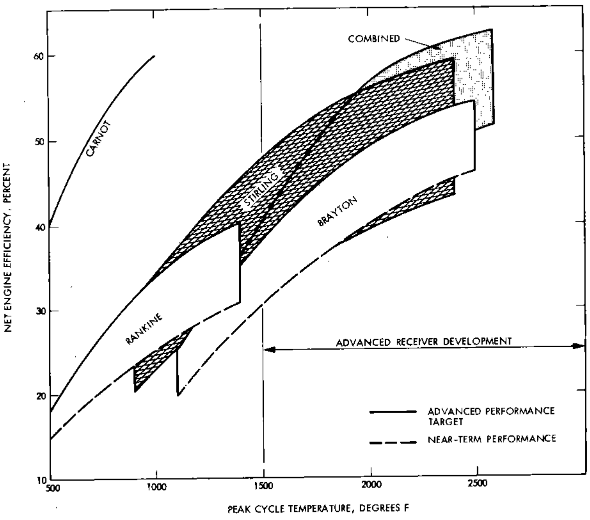

FIG. 8 ADVANCED ENGINE PERFORMANCE POTENTIAL FOR RANKINE, STIRLING, BRAYTON AND COMBINED BRAYTON/RANKINE CYCLES

losses - reradiative heat loss through the aperture, convective heat transfer through the aperture, and conductive/convective heat losses through the receiver insulation - at these higher temperatures. As operating temperatures increase, the reradiative heat losses increase most rapidly. Reduction of reradiative losses is a key factor in using high temperatures to achieve increased system efficiency. Second-generation receivers must be more than 87% efficient (ratio of heat to engine and heat to receiver) and cost \$25-45/kWe in quantities greater than 10,000/year.

The concentrator represents the greatest area for potential cost improvement in a solar thermal power system. The achievement of energy targets by advanced solar thermal power systems imposes requirements on concentrator cost and quality. The optical quality and reflectivity of the concentrator impacts the attainment of high system efficiency. The size of the solar image created by the concentrator is directly proportional to the concentrator surface error. Since the heat loss through the receiver aperture is proportional to the aperture size, the thermal performance of a receiver is directly related to the concentrator quality. To meet second-generation goals, concentrators will have to be at least 92% efficient in terms of reflectance and be producible at a cost between \$80 and \$120/m^2 when manufactured in quantities over 10,000/year.

The advanced technology research and development effort at JPL has been focused on meeting the second-generation requirements of solar thermal systems and components. Emphasis is being placed on improving system efficiency through the use of high performance heat engines, highly efficient receivers, concentrators with high potential for cost reduction, and long-life low-cost materials. Specific components which have been pursued are high-temperature receivers, high-efficiency engines, and low-cost concentrators.

Advanced receivers are being developed for applications with Brayton cycle and Stirling cycle heat engines, and for fuel and chemical production applications. The initial objective has been to prove the technology feasibility of receivers operating at high temperatures (800^o to 1400^{o}C; 1472^o to 2552^{o}F) and to test innovative features unique to high-temperature design applications.

Initial testing of a ceramic honeycomb receiver mounted on JPL's 11-meter-diameter test-bed concentrator has been completed at the parabolic dish test site, Edwards AFB, California. The ceramic receiver, developed by Sanders Associates, is shown in Figure 9. Concentrated solar energy passes through a quartz window where it is absorbed by the ceramic honeycomb which then transfers the heat to an air stream. Receiver outlet temperatures from 800^o to 1427^{o}C (1742^o to 2600^{o}F) were achieved. These conditions approximate the solar-powered operation of an advanced gas turbine (AGT) currently being developed for automotive applications and being adapted for solar thermal power conversion. Thus, the high-temperature receiver development represents an activity aimed at second-generation systems.

The feasibility of a dish-Stirling concept will be tested during the summer of 1981 at the parabolic dish test site. A near-term kinematic Stirling engine developed by United Stirling of Sweden has been adapted for use with a direct-coupled solar receiver. The Stirling engine/induction alternator will produce up to 25 kWe at a conversion efficiency of 35 to 40 percent.

After this demonstration, tests will be conducted using a heat pipe receiver with latent heat thermal energy storage.

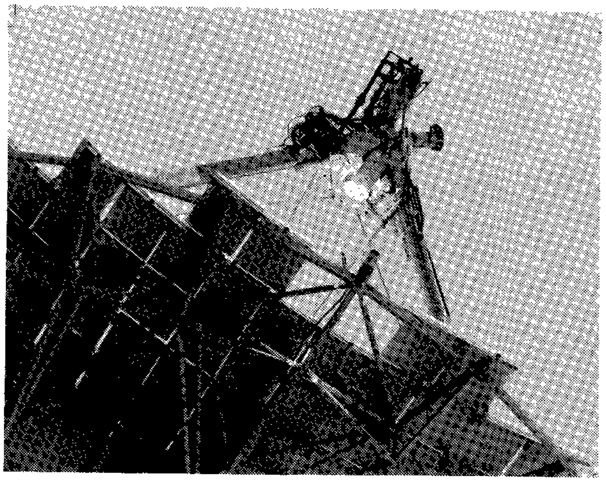

FIG. 9 CERAMIC HONEYCOMB RECEIVER MOUNTED ON 11-METER-DIAMETER TEST BED CONCENTRATOR

Advanced concentrator concepts which offer high potential for low-cost production have been under development. Novel concepts are being pursued for point focusing concentrators that utilize advanced materials or innovative design features which will allow mass-production at substantially lower cost than that of current design concepts. For example, a thin-film optical element concept by Boeing with good potential for low initial cost has been selected for evaluation and optical testing. A domed Fresnel lens concept with potential for very high concentration and low initial cost is being evaluated by E-Systems [9].

In conclusion, the advanced research and development programs at JPL can provide the improved efficiency and the low-cost materials and designs which will enable second-generation solar thermal systems to meet their goals.

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SOLAR PONDS: STATUS OF THE TECHNOLOGY AND NATIONAL PROGRAM

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ABSTRACT

The current state of the art in solar pond technology is described, further research and development requirements are surveyed, and the state of the national solar pond program is assessed.

I. INTRODUCTION

Solar ponds are now widely recongized as a promising low cost technology to collect solar radiation and store it as heat for a variety of low temperature applications, including space heating and cooling, hot water heating, industrial process heat, farm shelter heating and crop drying, ethanol production, and water desalination. Ponds may conveniently be classified into three main types: salt gradient ponds, shallow solar ponds, and innovative concepts. This paper will focus primarily on salt gradient ponds.

The theory and operation of ponds has been presented elsewhere [1,2] and will not be repeated here. The purposes of this paper are to present an overview of the present state of pond technology; to give a status report on the effort to develop a national solar pond program plan; to define further required research and development; to forecast future prospects for funding; and to discuss relevant problems and issues.

II. CURRENT TECHNOLOGY AND PROGRAM STATUS

A. Technology Status

Based upon experience in both the U.S. and Israel, it is reasonable to state at this time that ponds do "work", in the sense that they can deliver usable solar heat for either direct thermal applications or for power generation via a Rankine cycle. The Israelis have had the most visible success with their 7000 m^2 pond at Ein Bokek on the Dead Sea, which has generated over 150KW of electricity on an intermittent basis. Several experimental ponds in the U.S. have achieved operating temperatures over 65C (150F), and heat has been extracted for real or simulated thermal uses. The largest U.S. pond (2000m^2) at Miamisburg, Ohio, has produced useful heat for a municipal swimming pool, but a materials failure of the in-pond heat exchanger has prevented further heat extraction. The DOE-funded pond at the University of New Mexico achieved the highest recorded pond temperature in the summer of 1980, when the storage layer boiled at 108C (226F).

However, ponds can not yet be considered a proven technology, for a number of reasons. First, since ponds are most economical in large (multi-acre) sizes, at least one large scale field experiment must be undertaken to verify that scale-up from small ponds is feasible. Second, the actual measured collection efficiency of experimental ponds, approximately 9-12%, is substantially below the 20-30% efficiency predicted by thermal calculations [3]. Further, the performance of ponds over longer time periods (up to 20 years) must be measured, in order to determine long term effects from such factors as blowing dirt and debris, salt precipitation, brine or heat leakage into the soil, etc., as well as to establish routine maintenance procedures. Specific R&D needs are described in Section III.

Additional data is required on actual pond costs as well as performance. The Miamisburg pond cost approximately $70,000 to construct and fill, or about $35/m^2. A preliminary energy cost estimate is $9/GJ (about $9.50/MTU), which is below the cost of heating with fuel oil [4]. A study at SERI is currently evaluating several solar thermal technologies for industrial process heat, and while no definitive numbers have yet been obtained, it appears that salt gradient ponds will have favorable payback periods for sunny climates.

B. U.S. Program Status

Pond technology development is currently being supported by DOE and other state and Federal agencies. Within DOE, both the Active Heating and Cooling Division and the Division of Solar Thermal Energy Systems are supporting pond projects. The earlier pond projects have been described previously [1], most of which are still active. Selected salt pond projects initiated since that time are summarized in Table 1.

The primary thrust of these new projects is power generation utilizing naturally occuring salt water bodies, and supporting R&D. An additional project funded in FY1981 but not yet active involves a salt pond demonstration at the great Salt Lake, to be administered by the Water & Power Resources Service. As of this writing, the Office of Management & Budget has not released the funds to initiate the project.

A National Solar Pond Program Plan has been drafted to provide a focus for the DOE program, and coordination of pond work with other agencies. The Plan identifies both existing applications for ponds, such as space conditioning, power generation, and process heat, as well as new uses such as water desalination and alcohol fuel production. As of March 1,

TABLE 1. SELECTED RECENT POND PROJECTS

Investigator	Description
Jet Propulsion Laboratory Pasadena, California	1. Feasibility study of a Salton Sea power generating pond (with Southern California Edison and State of California) 2. Salton Sea brine Quality studies 3. National pond Regional Applicability Study
Solar Energy Research Institute Golden, Colorado	1. Direct contact heat exchange, thermoelectric generation, open-cycle desalination (funded by WPRS, Dept. of Interior) 2. Heat extraction experiments, side wall effects 3. Feasibility study of converting Boulder sewage treatment pond for space heating 4. Prototype IPH (chemical processing) pond in New Mexico
Argonne National Laboratory Chicago, Illinois	1. Numerical hydrodyramic modeling 2. Research pond (1100 m^2)
Los Alamos National Laboratory New Mexico	1. Hydrodynamic stability studies 2. Laboratory tank and research pond experiments
U.S. Army Corps of Engineers Tulsa, Oklahoma	Feasibility of converting Red River brine holding ponds for power generation
University of New Mexico Albuquerque	1. Saturated pond using KNO_3 2. Gel-stabilized saltless pond
Tennessee Valley Authority	Prototype pond (4000 m^2) for IPH and space heating
Mid-American Solar Energy Solar Energy Complex Minneapolis, Minnesota	National Solar Pond Plan preparation

1981, the Plan is being revised to incorporate reviewers' comments, and will probably have to be reduced in scope to correspond with the diminished solar budget projected under the new Administration.

C. Israeli Program Status

The ambitious Israeli Program to convert a large portion of the Dead Sea into salt gradient ponds for power generation has been described by Bronicki [5]. Although the proposed cooperative U.S.-Israel pond projects [1] were not put into operation, Israel is initiating the Dead Sea project on its own funding, and construction is expected to begin soon.

III. RESEARCH AND DEVELOPMENT NEEDS

A distinction can be made between "natural" and "constructed" ponds: natural ponds are those based upon a naturally occuring salt water body, such as the Dead Sea or the Salton Sea, while construcred ponds are usually excavated, lined, and filled with water and shipped-in salt. Most R&D problems are common to both, while the two types have some separate R&D requirements.

Common R&D needs include:

- Hydrodynamic studies - gradient layer stability, gradient layer erosion by top and bottom mixed layers, surface layer effect (wind, precipitation, evaporation, radiation), and wave control
- Evaporation control - by covers or surface liquid films
- Water clarity - methods to prevent clouding by dirt, blown debris, algae, mineral precipitates, organic matter
- Alternate salts - locally available, e.g., from mining wastes or stack scrubbers - low or zero cost
- Salt disposal - recycling methods, leak detection, emergency brine storage
- Heat exchangers - lower cost, corrosion and fouling prevention, direct contact alternatives
- Maintenance procedures - simple, standardized, low cost.

R&D needs for natural ponds, which tend to be larger in size include:

- Soil impermeability treatment - to eliminate need for liners
- Cheap, large-scale diking methods

- Prevention of organic matter decomposition under the pond, leading to bubbles
- "Floating Ponds" - for deep natural salt water bodies - no solid bottom.

R&D needs specific to constructed ponds, which tend to be lined and smaller, include:

- Liners - high temperature stability, UV resistance, reliable seam connections, repairable in place, lower cost
- Cheap excavation techniques
- Side heat loss effects
- Brine extraction without penetrating the liner.

Satisfactory answers must be found to most of these needs before ponds can be considered a proven technology.

IV. FUNDING OUTLOOK

The general outlook for the solar program is for substantially reduced funding in FY1982. The new Administration is re-defining the appropriate role of the Federal Government in solar energy development. According to backup narrative material to the FY82 budget submission, deregulation of oil and natural gas coupled with solar tax credits will promote a healthier environment for commercial solar technologies, such that "it is possible to shift the focus of the Department of Energy's solar activities away from costly near-term development, demonstration, and commercialization efforts and into longer-range research and development projects that are too risky for private firms to undertake."

The result for solar ponds is that proposed R&D activities for FY82 have been left in the President's budget, whereas field tests, demonstrations, market research and similar activities have been eliminated. While it is too early to predict actual FY82 pond funding, it appears that there should be a total of somewhere between 1 and 3 million dollars available for pond work, under both the Active Heating and Cooling and the Solar Thermal Technology programs. This is probably adequate for the R&D effort, but the lack of authorization for field tests will make it difficult to accumulate operating experience on actual ponds. One possible solution is to utilize existing or planned ponds funded by other sources, such as Miamisburg, Argonne, and TVA, for experiments and data acquisition.

V. CONCLUSION

Solar pond technology can provide cost effective low temperature thermal energy for power generation, industrial process heat, building space conditioning, and other applications. In order for the program to move ahead, a number of issues must be addressed:

- The extent to which the U.S. program should or can rely upon Israli experience
- Programmatic coordination between the DOE Solar Thermal and Active Heating and Cooling Programs
- Establishment of an Interagency Coordinating Committee for pond work
- Modification of the draft National Solar Pond Program Plan to reflect the new Administration funding priorities, and official DOE approval of the Plan
- How to utilize the limited R&D funding, perhaps in a cost-sharing arrangement with the private sector, to achieve overall program objectives
- How to establish a core U.S. personnel who are trained to design, build, and maintain ponds.

If these and related issues can be resolved, solar ponds can make a significant contribution to America's energy needs.

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FUELS AND CHEMICALS RESEARCH

RESEARCH AND ADVANCED DEVELOPMENT SUNFUELS PROGRAM

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INTRODUCTION

I am going to present a programmatic overview of the Research and Advanced Development (RAD) Sunfuels Program that was decentralized to the Department Of Energy, San Francisco Operations Office, for field management, last October. I hope to establish the relationship of the Sunfuels Program to the other Solar Thermal Energy Programs, such as the Central Receiver (CR), Dish, and Line-focus Programs.

But before I begin, I would like to tell you that DOE/SAN is looking forward to the challenge of managing the RAD Sunfuels Program. San perceives that the Sunfuels Program has great potential for providing F/C - STES for near term and long-term energy markets and that the program's end results will help to lessen our nation's dependency of foreign fuel imports.

I'm sure that most of the attendees are aware of the three-quad per year by the year 2000 goal assigned to the Solar Thermal Program. This means that the Central Receiver, Dish, and the Line-focus technology programs are each responsible a one-quad goal by the year 2000.

The quad is defined as 10^{15} BTU's or in layman's terms, approximately the amount of energy required to raise the temperature of a body of water the size of Lake Michigan, to a boil. With this definition in hand it is easier to relate to the largeness of the quad energy unit and to the formidable goal assigned to the Solar Thermal Program.

The RAD Sunfuels Program is a new thrust to support and expand the three-quad penetration by capturing new energy markets in the transportation and chemical intensive industry sectors. The Sunfuels Program is structured to lead to the development of Sunfuel systems that will provide an unlimited supply of clean, renewable, transportable fuels. The Sunfuels Program is designed to focus on early energy opportunity markets, provide maximum paricipation and feedback from industrial users and buyers and allows for innovative technology advances and breakthroughs by independent applied research.

This pie chart is a graphic representation of the energy that was consumed in the United States in 1980 at the point of utilization. The blue shading represents the portion of energy supplied by oil and gas. In 1980 the electrical industry used 25 quads of energy, the transportation sector consumed 20 quads, the industrial sector 19 quads and the commercial/residential sector 15 quads of energy.

The ellipses on this overlay indicate the potential energy available to the Solar Thermal Energy Programs. The small ellipses represent the potential energy markets available to the Cogeneration and Repowering Programs and the larger ellipse the potential energy markets available to the RAD Sunfuels Program in the transportation and chemical intensive industry sectors. These potential energy markets will be quantified when our initial market study, presently being conducted by Black and Veatch and the Ralph M. Parsons organizations, is completed.

The Goal Of The Sunfuels Program

The ultimate goal of the Sunfuels Program is to develop and implement technology that utilizes fuels and chemical processes integrated with solar thermal technologies that will affect the production of transportable fuels, industrial feedstocks, and chemicals by 1990.

The Objective Of The Sunfuels Program

To demonstrate the technical and economic feasibility of the Sunfuels systems based on domestic non-renewable and some renewable feedstocks by 1990.

Non-renewable feedstocks include coal, lignite, peat, oil shale and heavy crude. Renewable feedstocks include water, carbon dioxide, and biomass.

The next objective is to facilitate the commercial implementation of demonstrated Sunfuels systems during the decade of the 1990's.

Demonstrated systems have gone through a complete development cycle, from analytical, simulation, modeling, laboratory bench testing and through field testing at one of our Solar Thermal Test Facilities (STTF-UA) or tested under simular conditions.

The final objective of the program is to explore the unique capabilities of the solar thermal technologies for new industrial processes.

As the Sunfuels Program develops and expands it will utilize technology developed by other solar thermal programs such as the cogeneration and repowering programs and at the same time other programs like the coal, fossil, and synfuel programs will be monitored for potential processes, systems, and components that can be utilized within the Sunfuels Program and that have potential for integration with solar thermal technologies. The technology transfer methodology is used in the Sunfuels Program to cut program costs and to eliminate overlapping technology development between the differnt programs. The Sunfuels Program has the potential to support and expand the three-quad goal assigned to solar thermal program.

Sunfuels Program Strategies

Strategies that will be used in the Sunfuels Program to reach the objectives that will lead to the goal of commercialization, are:

Address both near-term and long-term energy markets.

For near-term energy markets, conventional F/C processes and existing solar thermal technologies will be screened, matched, and integrated into systems that have potential for development for near-term energy market options. For long-term energy markets a simular methodology will be used, innovative F/C processes, existing and advanced solar thermal technologies will be screened, matched and integrated into sytems with potential for development for long-term energy markets.

Focus development efforts on market/industry requirements.

This effort will be accomplished through the Technology Development Integrator Program element that interfaces with industry.

Secure early involvment of the supplier/user industry.

Coordinate and utilize technology developed by other programs such as the fossil, coal and synfuel programs.

Pursue development of the most promising F/C-STE systems.

The Sunfuels Program can be divided into six major activities:

1. Core Experiments
2. Market Survey Study
3. Special Analyses
4. Technical Development Integration (TDI)
5. Technical/Program Support
6. Solar Thermal Test Facilities (STTF-UA)

Below is a list of the RAD Sunfuels Program elements. Each program element has a specific function to perform.

Core experiments include basic and applied research for near-term and long-term energy market options.

JPL	Dish technology utilization for fuels and chemicals.
LLNL	Oil shale retorting and testing of reactor.
SNLL	Central receiver/reactor development for H.T. production of F/C.
Princeton Univ	Pyrolysis of biomass, reactor development.
University of NH	Coal gasification/fluidized bed reactor.
IGT	Hydrogen production for F/C.
Westinghouse	Hydrogen production/sulpur cycle.

Special Analyses.

Aeta	F/C-STE systems benefit/economic analysis.
SAI	Special through benefit/economic analysis.
ETEC	Technical development integrator.

Black & Veatch/ RMP	F/C -STES market/survey.
Aerospace	Technical/program support.
STTF-UA	Solar thermal test facilities

The Department Of Energy, San Francisco Operations Office is responsible for the overall management of the RAD Sunfuels Program. Below is a Program planning schedule for FY 81 and FY 82.

PROGRAM PLANNING SCHEDULE- Fred Corona 3/8/81

RAD Sunfuels Program FY 81

1. Program imlementation, negotiate new contracts, transfer existing contracts to DOE/SAN
2. Track Sunfuels Program core elements
3. Track STTF-UA H.T. experiments
4. Conduct F/C-STES market study/survey
5. Conduct special economic/benefit analyses
6. Develop criteria and implement an evaluation system to assess F/C-STE systems data for compatability with Sunfuels Program objectives and goals
7. Use evaluation system of (6) to assess (1), (2), (3), (4), and (5)
8. Prepare RAD Sunfuels FY 81 AOP
9. Prepare RAD Sunfuels Program Plan
10. Determine Sunfuels Program material requirements
11. Compile data available from (7) and establish an expandable RAD Sunfuels Program database matrix
12. Characterize and select F/C-STE systems for development for near-term energy market options
13. Characterize and select F/C-STE systems for development for long-term energy market options
14. Prepare draft RFP for specific-site conceptual design studies (4 to 8 studies)
15. Prepare FY 82 AOP
16. Select follow-on verification testing F/C-STE experiments
17. Select new innovative F/C-STE experiments
18. Prepare FY 82 budget
19. Select Technical Development Integrator (TDI)

RAD Sunfuels Program FY 82

1. Negotiate follow-on contracts
2. Award new contracts
3. Track Sunfuels core experiments
   - (a) verification
   - (b) lab bench tests
   - (c) STTF-UA or field tests
4. Update RAD Sunfuels Program Plan
5. Update RAD Sunfuels database matrix
6. Update RAD Sunfuels material requirements
7. Finalize RFP for site-specific conceptual designs
8. Initialize SEB process
9. Advertise and award site-specific design studies
10. Prepare FY 83 AOP
11. Prepare FY 83 budget

SOLAR THERMAL TEST FACILITIES USERS ASSOCIATION
SOLAR FUEL AND CHEMICALS

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INTRODUCTION

The STTFUA is involved in high-temperature solar thermal technology development using solar test facilities in Albuquerque, White Sands, Edwards Air Force Base, Atlanta, and Odeillo, France. It is a non-profit corporation with about 75 individual and institutional members from the US and abroad who are interested in advancing high-temperature solar technology. Membership is open to persons from educational institutions, commercial organizations, non-profit and government laboratories, and the public. Most of the Association's activities are funded by DOE via a contract to the University of Houston. It works closely with DOE Washington Headquarters, DOE's national labs (especially Sandia Albuquerque, Sandia Livermore, Los Alamos, Lawrence Livermore, JPL and SERI), the US Army solar furnace at White Sands, NM, and with the French CNRS. Organization of the UA in 1977 was based on earlier discussions between DOE (then ERDA) and the University of Houston. DOE wished to assure that solar developers in universities, commercial research labs, small businesses and national labs knew about and would have a means of using these facilities.

The Association's affairs are managed by an Executive Committee (university, industry, and national lab representatives) elected by the membership. Dr. Thomas H. Springer, Rockwell International, is Chairman of the Executive Committee. Mr. Frank Smith of the University of Houston is the full time Executive Director. The UA annual budget for 1981 is expected to be about $800,000, with $435,000 of that amount being spent in subcontracts for experimental work using the solar facilities.

USERS ASSOCIATION ACTIVITIES

The principal activities of the UA include technical workshops; solicitation, review and funding of proposals; management of research using solar thermal test facilities; and publication of newsletters and technical reports. UA Roles and Responsibilities, as mutually agreed upon by the UA and DOE/Washington, are:

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

The Association is authorized to fund and coordinate work done on:

- Sandia 5-MW Central Receiver Test Facility
- Georgia Tech 400-kW Advanced Component Test Facility
- JPL Parabolic Dish Test Site
- White Sands Solar Furnace
- CNRS 1-MW Solar Furnace and smaller Vertical Solar Furnaces at Odeillo, France

Specifications of these facilities are shown in Table 1.

Proposal Review

The UA proposal review system is unique in that proposals from universities, industry, nonprofit research institutions and DOE's national labs are all evaluated competitively by the same process and by the same reviewers. About one-fourth to one-third of the proposals are funded. Universities, industries, independent nonprofit and government labs have been funded.

Workshops

The UA runs two or three workshops per year, Table 2, at which solar experimenters from universities, industry, and government hear reports on results of solar experiments and make plans for future developments. Attendance at the workshops runs from 75 to 125 persons with participation from industries, universities, nonprofit laboratories, and government. Typical industrial participants include Boeing, Conoco, Exxon, General Electric, Martin Marietta, McDonnell Douglas, and Westinghouse. Participating universities include UNM, NMSU, U. of Houston, U. of California, U. of Washington, U. of Kansas, Princeton, and Georgia Tech. The workshops have also attracted participants and contributors from the foreign scientific community, including the French, German, Italian, Japanese, and Australian.

The first workshop, in November, 1977, brought together about 15 or 20 of the country's leading high-temperature research experts from universities and government laboratories with STTF operators, SERI and DOE personnel, and others. Much useful information was exchanged: UA, SERI, and DOE people learned a great deal about what is known--or not known--about traditional non-solar material and chemical processes at 1500-2000 K; and the high-temperature researchers learned a great deal about the characteristics and availability of the STTFs and solar furnaces.

I believe the September 1978 Solar High-Temperature Industrial Processes workshop in Atlanta can be identified as the beginning of the solar fuels and chemicals program. This workshop included participants from 9 universities, 43 industries or nonprofits and 11 government laboratories. Gerry Braun and Marty Gutstein discussed DOE's solar fuels and chemical plans, and other speakers discussed a variety of fuel and chemical processes that might be adopted (or new processes that might be developed) to use solar thermal energy. Subjects discussed included: solar reversible chemical reactions (SO_3/SO_2, ammonia and hydrogen sulfate, the EVA-ADAM methane/water system and methane/carbon monoxide systems); possibilities for solar production of ammonia or nitrogen fertilizers, hydrogen solar coal gasification and syngas from biomass. Other speakers discussed use of solar energy for metal ore reduction, metal heat treatment, secondary oil recovery, and gypsum production.

In 1980 it was becoming more painfully obvious that there existed an unacceptably high level of inconsistency among the solar data being used by various solar thermal energy developers. The UA therefore sponsored a workshop, STTF Testing for Long-Term Systems Performance, which served as a status report on the state of knowledge of baseline solar data such as available solar insolation, expected heliostat performance, current status of knowledge of air, steam, and molten salt solar receivers, etc. The workshop was well attended and well received.

The next meeting of the Users Association will be the Annual Meeting to be held in two weeks (April 22-24, 1981) at JPL. In addition to the technical sessions and the UA business meeting, a tour of the JPL Parabolic Solar Concentrator facility at Edwards Air Force Base is scheduled for April 24.

EXPERIMENTS

Some of the fuel and chemical experiments funded by the Users Association are shown on Table 3. Several experimenters are considering the possibility of using high-temperature solar energy available at the CRTF focal point to pyrolyze waste materials to produce hydrogen, carbon monoxide, and other hydrocarbon-rich synthetic gases such as methane and ethane. These reactions occur at around 500°-600°C. At higher temperatures the remaining char can be made to react with steam to form additional carbon monoxide and hydrogen.

Coal gasification is a similar process. If coal is heated to about 600°-800°C with steam, it decomposes to produce H_2, CO_2, CO, CH_4 with residual tars and char. At higher temperatures on the order of 1000°C the char can be further decomposed to produce additional H_2 and CO. Although the chemistry of these processes is fairly well known, the challenge is, of course, to develop continuous-process hardware to feed in powdered coal and take off the product gases--and to design systems that are cost effective.

Renewable Chemical Reactions

Other experimenters are working on various reversible chemical reactions where the solar thermal energy at the receiver is used to drive an endothermic chemical process to produce fuel gases which can then be piped to remote locations where they are reacted in an exothermic process to recover the thermal energy originally derived from the sun. For example, in the EVA-ADAM System, methane and water are combined in a 950°C steam/reforming reaction to produce H_2, CO, and CO_2. The gases can be transported by pipeline (at high pressure for good pumping efficiency) in a cold gas state and the H_2 and CO can be recombined to deliver thermal energy at 450°C. The methane is then piped back to the solar receiver to continue the process.

Other similar reactions being considered involve the endothermic dissociation of SO_3 at 950°-1000°C to produce SO_2 and O_2 and the exothermic synthesis of SO_3 at about 600°C at the delivery end.

Another proposed system involves dissociation of ammonia, NH_3, in the solar receiver at about 700°C to produce H_2 and N_2, and the subsequent exothermic recombination of the H_2 and N_2 to deliver heat at about 300°-400°C.

Solar Thermal Hydrogen Production

Other experimenters are working on the use of high-temperature solar energy to produce hydrogen. One proposal involves 850°C decomposition of sulfuric acid to produce H_2O, SO_2, and O_2 with a subsequent recombination of the SO_2 with the H_2O to produce hydrogen. Unfortunately, the SO_2 plus H_2O cannot be driven directly thermally so other schemes involving intermediate hydrogen iodide (HI) or Hydrogen Bromide (HBr) steps are being explored. For example, introduction of iodine, I_2, leads to an intermediate step producing HI which can be decomposed at about 450°C to produce H_2. The Laboratoire Des Ultra-Refractaires at Odeillo, France, has experimented with a process where solar energy at 2000°C is first used to break Fe_3O_4 to FeO and O_2 with a second FeO-steam reaction at about 700°C to produce Fe_3O_4 and H_2.

CONCLUDING COMMENTS

During the summer of 1980 the UA reviewed 37 proposals for experimental solar thermal work and came up with a list of 10 experiments which we feel to be very interesting and worth supporting. Unfortunately, those experiments total about $700,000; as of the date of this writing the UA has no FY 1981 funds for experiments support, but we do hope soon to have about $350-$400,000. If so, we then hope to support a few experiments, possibly including a study of zinc sulfate decomposition, an investigation of high-temperature black chrome surfaces, the behavior of pressurized quartz windows at high temperatures, further investigation of the photochemical aspects of coal gasification, investigation of possible use of solar thermal for curing tiles, and exploration of a couple of new central receiver concepts. To date, all STTFUA-supported experiments have been small-scale and have used mostly the smaller facilities at White Sands and Odeillo. We hope in the future, if sufficient funds are available, to begin supporting more larger-scale experiments which would be run at Georgia Tech or the Sandia 5-MW facility, and which would be more reliable indicators of the commercial feasibility of some of the solar thermal fuel and chemical processes.

TABLE 1

APPROXIMATE SPECIFICATIONS FOR STTFs AND SOLAR FURNACES

Facilities	SANDIA	GEORGIA TECH	WHITE SANDS	JPL	CNRS ODEILLO	
Configuration	CENTRAL RECEIVER	CENTRAL RECEIVER	HORIZONTAL FURNACE	TRACKING PARABOLA	HORIZONTAL FURNACE	VERTICAL FURNACES
Total Thermal Energy, kW	5000	325	30	85	1000	1.5 to 6.5
No. of Heliostats	222	550	1	NA	63	1
Heliostat or Parabola Size, m	6 x 6	1.1 D	11 x 12	11 D	6.0 x 7.5	1.5 to 4 D
Total Solar Collecting Area, m^2	8257	532	132	95	2835	1.8 to 12
Test Area Diameter, m	2-3*	0.5-1.0*	0.08-0.15*	0.09-0.17*	0.25-1.0*	.006 to .07
Peak Flux,** W/cm^2	240	125	400	1000	1600	1500 to 500
Maximum Temp., **K	2600	2100	2900	3600	4100	3200

*The first number is area receiving approximately 50% of total energy; second number is area capturing 95% of total energy.

**Small area at center of beam.

TABLE 2

SOLAR THERMAL TEST FACILITIES USERS ASSOCIATION WORKSHOPS

TITLE	LOCATION	DATE
Facility Operators/High-Temperature Sciences Workshops	Albuquerque, NM	November, 1977
Technical Sessions/Annual Meeting	Golden, CO	April, 1978
Solar High-Temperature Industrial Processes Workshop	Atlanta, GA	September, 1978
Facility Operators and Experimenters Workshop	Albuquerque, NM	May, 1979
Technical Sessions at ISES Meeting/ Annual Meeting	Atlanta, GA	May, 1979
Solar Fuels Workshop	Albuquerque, NM	November, 1979
Technical Sessions/Annual Meeting	Las Cruces, NM	April, 1980
STTF Testing for Long-Term Systems Performance	Albuquerque, NM	January, 1981

TABLE 3

TYPICAL STTFUA-FUNDED RESEARCH PROJECTS

PROPOSER	INSTITUTION	PROJECT	AMOUNT (K$)
Willem	NMSU	Weathering of Concrete Due to Solar Radiation	24
Cubicciotti	SRI	Solar Carbon Gasification	25
Skaggs	LASL	Solar Molybdenite Ore Processing	120
Schreyer	ORNL	Development of High-Temperature Solar Absorbing Coatings	10
Lenz	Colo State Univ	Ammonia Dissociation	21
Gilles	Univ Kansas	Thermodynamic Research on Oxygen Alloys of Electropositive Metals	25
Meinel/Zito	Univ Arizona	Thin-Film Materials Degradation Under High Solar Fluxes	5
Antal	Princeton Univ	Solar Biomass Pyrolysis	123
Ignatiev	Univ Houston	Solar Degradation of Black Chrome	10
Gregg	LLL	Solar Coal Gasification	23
Chubb/McCrary	Naval Res Lab/NMSU	CO_2-CH_4 Reforming	30
Archer	Westinghouse	Fluidized Bed Receiver	67
Bienert	Dynatherm	Heat Pipe Receiver	54
Foh	IGT	Solar H_2 Production	79
Duncan	IGT	Solar Calcium Carbide Production	37
Roberts	Solar Turbines Intl	Steam Loop Receiver	52
Besenbruch	General Atomic	Sulfuric Acid Decomposition	99

SOLAR RETORTING OF OIL SHALE

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INTRODUCTION

A systematic study was made to identify where solar thermal energy could have a significant impact on the production of fuels starting from a fossil feedstock. This study indicated four areas where large process energy losses occurr, and which also can be addressed with the use of focused solar thermal energy. These areas are: 1) Solar retorting of oil shale, 2) Solar coal gasification, 3) Solar Steam flooding of oil fields, and 4) Solar steam-reforming of methane.[1] This paper will address the basic logic of solar oil shale retorting, and present a preliminary technical and economic analysis of the process.

LOCATION OF OIL-SHALE RESOURCE

A basic requirement for retorting oil shale is that it can not be economically transported very far due to it being 90% inert material. Thus, if a solar oil shale retorting process is to be feasible, it is essential that there exist very favorable solar conditions at the location of the shale.

In the United States the oil shale of major commercial interest lies primarily in Colorado, with large additional deposits being found in Utah and Wyoming. Of these deposits, the one of greatest interest is the Piceance Basin, which contains in a relatively small area the majority of the oil shale resource. In this resource the concentration of oil in the shale ranges from 20 to 30 gal/ton. It is fortunate that the solar maps of the United States show exceptionally favorable solar conditions over these shale fields.

RETORTING CHEMISTRY

When the shale is heated at a rate of 2 ^{o}C/min the oil is essentially completely realeased by approximately 500 ^{o}C. The use of higher heating rates will cause this completion point to shift to higher temperatures.

Recent work has shown that the higher the heating rate, the higher the oil yield. As the heating rate increases from 1 ^{o}C/h up to 700 ^{o}C/h, the oil yield increases from approximately 75% of Fischer Assay up to 100% of Fischer Assay (Fischer Assay is a standard test where shale is heated at 12 ^{o}C/min). When even higher heating rates are used, oil yields can, under some circumstances, increase to as much as 110% of Fischer assay.

As the shale is heated above 550 °C, the mineral carbonates start to decompose. This decomposition is highly endothermic and thus reduces the energy efficiency of the process. Therefore, it is important to heat the shale just high enough to recover the oil (500-550 °C) but not any higher so that carbonate decomposition can be avoided.

Once the shale is heated to retorting temperature, the oil is not immediately released. There is a kinetically limited time which is required for the kerogen to decompose. This time in the retorting temperature range is 100-200 seconds (for 90% decomposition).

COMPARISON TO LURGI-RUHRGAS RETORTING SYSTEM

The Lurgi-Ruhrgas retort uses hot, spent shale to heat the raw shale to retorting temperature. The spent shale is heated in a lift pipe where char in the spent shale and some additional fuel (as needed) are combusted with air to provide the heat energy. The hot spent shale is then mixed with the raw shale in a screw mixer to perform the retorting function. The spent shale recycle loop has approximately six times the mass flow rate as the incoming raw shale. This rather complex heat transfer system is used in order to satisfy the retorting requirements as described in the retort chemistry section above. The shale must be heated as rapidly as possible to 500-550 °C, but no higher (to avoid carbonate decomposition). This heat transfer requirement is difficult to achieve with solids, and thus they have had to resort to a fairly complex system. However, as complex as it is, it still appears to be one of the best designed retort systems which is why we chose it to compare with.

We performed an energy analysis on the Lurgi-Ruhrgas retort to try to estimate the maximum possible fuel it could produce (after satisfying its own energy requirements) as a function of shale grade. The analysis predicted that the process could produce (deliver to a customer) an effective yield ranging from 75% of Fischer Assay with a shale grade of 12 gal/ton up to 100% of Fischer Assay with a shale grade of 36 gal/ton. This is to be compared with a predicted product yield (on the same basis) for a solar oil shale retort of 110% of Fischer Assay for all grades of shale (because no fuel is needed to heat the shale).

PROJECTED SOLAR ENERGY REQUIREMENTS AND COSTS

It is beyond the scope of this work to perform a complete economic analysis of a solar oil shale retorting plant. However, it is useful, for scoping purposes, to estimate the costs associated with the heliostat field and relate them to the incremental change in cost of the produced oil. When performing this analysis, it quickly becomes apparent that the cost of the product oil is relatively insensitive to the solar costs. This is because the oil production rate is approximately 10 times the solar energy input rate (in energy content). Thus, there is a great deal of "leverage" on the expensive solar energy. Changes in solar costs can be amortized over the much larger energy content of the produced oil. If one assumes mass production of heliostats, and cost numbers provided by Sandia Corp., one can calculate a cost of focused solar energy arriving at a point in space of approximately $2.30 per million Btu. Using this number and performing an energy balance over a hypothetical solar oil shale retort, the incremental solar costs are $1 to $3/bbl of produced oil. Thus, it appears that the cost of the solar energy alone will not be the determining factor in deciding on this system. These incremental costs could be more than compenstaed for by the increase in product yield.

EXPERIMENTAL RESULTS OBTAINED FOR SOLAR OIL SHALE RETORTING

A set of experiments were performed on solar retorting of oil shale at the White Sands Solar Furnace, N. M.. Shale particles, approximately 1/4 inch in diameter, were transported through the solar focus (in a windowed retort) where they were heated to retorting temperature by direct solar radiation. A number of difficulties were had with the retort which limited the number of runs that could be made in the time available. However, the one good run that we were able to perform showed that a oil yield of approximately 110% of Fischer Assay could be achieved with less than 15% of the mineral carbonates being decomposed.

PLANS FOR FY-1981

The primary effort for FY-1981 has been directed towards designing, fabricating and testing an improved solar oil shale retort. The retort is designed to match the White Sands Solar Furnace, and is far superior to the apparatus used for the last set of experiments. In the new solar retort, the normally horizontal solar flux is redirected downward just before the focus. The sunlight then passes through a quartz window at the focus (on the retort) and is absorbed directly on the shale particles. The shale is moved through the focus on a steel belt. This allows the shale to be heated very rapidly. The shale then falls into a rotary kiln (which is electrically heated) where the shale is maintained at retorting temperature for the kinetically limited time required for all the kerogen to decompose. In this design, 90% of the retorting energy will be supplied with focused solar energy, and 10% will be supplied electrically (to the rotary kiln). It is anticipated that the rotary kiln could be eventually solar heated in a commercial size plant. With this set of planned experiments which will be carried out in June, 1981, we hope to demonstrate reliable operation with high oil yield, with a retort designed that should be scaleable to commercial size.

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DESIGN AND OPERATION OF A SOLAR FIRED BIOMASS FLASH PYROLYSIS REACTOR

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ABSTRACT

The results of continuing research on the radiant flash pyrolysis of biomass as a source of fluid fuels, industrial feedstocks and chemicals are described in this paper. Bench scale sources of intense, visible radiant energy have been used to simulate the concentrated solar flux available at the focus of solar towers. Windowed transport reactors have been developed, which act as cavity receivers for the focused radiant energy and provide a means for direct use of the radiation to rapidly pyrolyze the entering biomass. Detailed results of both bench scale experiments and experiments using the Georgia Tech 400 kw_{th} solar furnace are presented. These results suggest the use of concentrated radiant energy as a selective means for the production of either a hydrocarbon rich synthesis gas or sugar related syrups from biomass by flash pyrolysis.

SOLAR THERMAL HYDROGEN PRODUCTION PROCESS

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INTRODUCTION

Westinghouse is currently under contract to DOE for technology development of the Sulfur Cycle, a hybrid thermochemical-electrochemical process for the production of hydrogen and oxygen from water. The development work has been co-funded by the Conservation (STOR) and Solar Divisions of DOE.

The process, in its most general form, consists of two chemical reactions. The production of oxygen occurs via the thermal reduction of sulfur trioxide obtained from sulfuric acid.

$$H_2SO_4 \rightarrow H_2O + SO_3 \rightarrow H_2O + SO_2 + 1/2\ O_2 \qquad [1]$$

A catalyst is used to accelerate the rate of sulfur trioxide reduction to sulfur dioxide and oxygen. The process is completed by using the sulfur dioxide from the thermal reduction step to depolarize the anode of an electrolyzer using dilute sulfuric acid electrolyte. The overall reaction occurring electrochemically is:

$$2H_2O + SO_2 \rightarrow H_2 + H_2SO_4 \qquad [2]$$

The net result of Reactions 1 and 2 is the decomposition of water into hydrogen and oxygen and the sulfur oxides are involved solely as recycling intermediates. Although electrical power is required in the electrolyzer, much smaller quantities than those necessary in conventional water electrolysis are needed.

The energy needs of the process are thermal energy, for the acid vaporization and sulfur trioxide reduction steps, and electrical energy for the electrolysis and auxiliary power (e.g., pumps, circulators, etc.). The temperature levels required for the thermal inputs are compatible with advanced high temperature solar receivers. The electrical power can be provided by a companion solar thermal electric plant, a solar photovoltaic plant, by fuel cells fed with a portion of the hydrogen and oxygen produced in the process, or by power from an available grid.

Process studies have been conducted to assess the potential viability of producing solar hydrogen as a feedstock for manufacture of synfuels or chemicals.

Several potentially attractive applications have been identified, including ammonia, methanol and direct reduction of iron ore. Operational studies have been conducted and have resulted in definitions of operating modes for solar/hydrogen plants and in assessments of the day/night and annual variations in performance that will influence the operating modes and the sizing of plant subsystems.

Conceptual design studies have been conducted for process components that interface with the solar receiver. From related tradeoff studies, a preferred configuration emerged that involves an intermediate working fluid (e.g., hot gas) between the solar receiver and the sulfuric acid decomposition reactor. The design of the reactor has been based on a shell and tube type heat exchanger configuration with catalyst placement on the shell side.

Technology development has proceeded in several areas: evaluation of high temperature structural materials, evaluation of catalysts for use in the acid decomposition reactor, and electrolyzer development for the hydrogen production step.

The present contract from DOE/Solar was initiated in January 1978. During 1980, a three year extension was executed for calendar years 1980-1982. Work under this contract has focused on technology development and supporting research for the thermochemical portions of the process, and on the interfaces of the process with solar heat. Development of the electrolytic system has proceeded under a companion contract from DOE/STOR.

PRESSURIZED TEST UNIT DEFINITION

A major milestone was attained during 1980 with the conceptual design definition of a pressurized test unit (PTU). The PTU configuration was chosen after comprehensive trade studies were performed and a rigorous selection process used to rank several candidate configurations. The selection process used a set of weighed criteria to rank six final PTU configurations that had been screened from a larger list of candidates.

The PTU has been sized for a nominal 85 kW(t)* rate of hydrogen generation that can permit the hybrid sulfur cycle to be coupled with a distributed solar collector (or simulated solar heat source) of reasonable size. A high temperature heat transport loop, e.g., helium at ∿1800°F, provides the thermal interface between the heat source and the sulfur cycle process.

When its design has been completed along with associated component development, the PTU will be constructed as a development test bed for the sulfur cycle. Subsequent operational testing of the PTU will

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*Based on hydrogen's HHV, ∿60,000 Btu/lb validate component and subsystem design approaches and provide a data base for follow-on developmental systems, e.g., a pilot plant.

CRITICAL COMPONENT RESEARCH AND DEVELOPMENT

The three year period 1980-1982 calls for substantial research and development work on critical components of the sulfur cycle. This component R&D is needed to ensure that the technology base is sufficiently mature before developmental systems, e.g., the PTU, are built.

After the PTU configuration had been selected, initial sizing and scoping studies for all of its components were made. Also the components were rated into one of four categories: (a) established technology; (b) near term technology; (c) developmental; or (d) speculative. None of the components was judged to be speculative and many were rated as established or near term. A few were judged to be developmental and therefore represent those critical components that will require substantial engineering development and supporting research. The sulfur dioxide electrolyzer is unique among these critical components because its development has been sponsored under a separate contract from DOE/STOR. The remaining critical components are two stages of sulfuric acid vaporization and a chemical reactor for cracking the sulfur trioxide in the acid vapor into sulfur dioxide and oxygen. This reactor is typically referred to as the acid decomposition reactor (or reduction reactor).

ACID VAPORIZER MATERIALS EVALUATIONS

During 1980, coupon tests with candidate materials continued with emphasis on a select group of materials exposed to boiling sulfuric acid at 450°C. Thirteen materials were exposed to the acid environment for periods up to 1000 hours; these samples included ceramics and metal alloys. By measuring weight changes in the materials and by visual examination, the most corrosion resistant materials have been judged to be silicon carbide, silicon nitride and metallic silicon. These tests, which were preceded by earlier screening tests during 1978-1979, have culminated in the selection of chemical vapor deposited (CVD) silicon carbide as a reference material for the acid vaporizer. During 1981, endurance tests for periods up to 6000 hours are planned with several SiC samples under an environment that simulates the acid vaporizer operating conditions.

REDUCTION REACTOR MATERIALS EVALUATION

During 1980, nine sets of candidate materials were tested for 1000 hours at either 870°C or 650°C under acid vapor conditions representative of the reduction reactor. These tests, taken with earlier tests that were performed in 1978 and 1979, have permitted a total of 42 candidate materials to be evaluated for periods up to 1000 hours. From the laboratory analyses performed on these material samples, several commercially available alloys have demonstrated good corrosion resistance: Incoloy 800, Inconel 625, Type 444 stainless steel, Type 20 Cb-3 stainless steel and Hastalloy G. When these alloys were alonized, their corrosion resistance was improved compared to bare samples. In addition, silicon, which can be used as a coating on metallic substrates, has displayed exceptionally high corrosion resistance. Two other ceramics, silicon carbide and silicon nitride, also have shown excellent corrosion resistance. During 1981, several of the attractive metal alloys will be subjected to endurance tests up to 6000 hours at 870°C and to short term tests at a more severe environment, ∿950°C.

REDUCTION REACTOR CATALYST EVALUATION

Tests on five candidate catalysts were conducted in 1980 using an experimental facility that permitted vaporized sulfuric acid to be passed through the catalyst bed. These tests, which provided a closer approximation to process conditions than had been possible in previous years, provided additional confidence concerning the selection of a reference catalyst, iron oxide on an alumina substrate. This catalyst, designated as ALFA-4, exhibited near equilibrium conversions of sulfur trioxide into sulfur dioxide and oxygen at temperatures above 850°C. At temperatures below 750°C, the tests indicated that a poisoning effect caused by sulfation phenomena occurred. However, the sulfation effects were observed to be reversible whenever the test temperature was raised above 750°C.

Based on these tests and earlier catalyst screening tests performed in 1978-1979, ALFA-4 has been selected as a reference catalyst for the sulfur cycle reduction reactor. A dozen commercially available catalysts have been evaluated over the three year period and, considering performance and cost, ALFA-4 has been judged to be preferable to a noble metal based catalyst (platinum on alumina substrate). This catalyst, designated MB-3, also has performed well and represents a viable alternative.

ELECTROLYZER DEVELOPMENT

Before 1980, electrolyzer development focused on evaluation of electrode kinetics and electrode catalysis, development of electrode fabrication techniques, and investigation of separator materials. Major objectives were to increase the understanding of the electrochemistry of depolarized anode electrolysis in sulfuric/sulfurous acid solutions and provide a foundation for the long-term development of the electrolyzer subsystem. This development was continued during 1980 with an emphasis on reducing the loadings of noble metal catalysts on the electrodes without compromising cell performance. The long-range performance goal for the electrolyzer is to obtain a stable cell voltage less than 600 mV at 200 mA/cm^2 while the electrolyzer is operated at ∿100°C and 20 atm, using 50-60 w/o sulfuric acid solutions.

During 1980, successful experiments were conducted to reduce the quantity of noble metal electrocatalyst used on electrodes by an order of magnitude without loss in cell performance. Loadings of 1 mg/cm^2 of platinum were attained on each electrode in conjunction with the use of sandwich type electrodes. An improved test cell configuration using Teflon structure was built and tested at 1 atm. The Teflon cell permitted cell overpotentials to be reduced via improved electrolyte flow patterns. The Teflon cell also demonstrated a capability to operate effectively at 75°C with current densities exceeding 400 mA/cm^2. Also an improved developmental separator between anode and cathode compartments was tested in the improved test cell. This separator, a cation exchange membrane, was very effective in preventing diffusion of sulfur containing species from the anolyte into the catholyte. Compared to a microporous rubber separator that had been used heretofore, the cation exchange membrane reduced the diffusion of sulfur dioxide by two orders of magnitude. Finally, the preliminary design was prepared for a pressurized cell and test loop intended to operate up to 20 atm so that adequate solubility of the anode depolarizer, sulfur dioxide, can be attained at temperatures up to 100°C. Pressurized operation is expected to provide further significant improvements in the voltage efficiency of the electrolyzer.

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SOLAR MATERIALS RESEARCH

ENVIRONMENTAL CRACKING OF CONTAINMENT ALLOYS IN MOLTEN SALTS

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INTRODUCTION

Molten nitrate salts have been shown to be a very attractive medium for absorber heat transfer and thermal energy storage applications for solar central receiver systems. Although there is a long history of successful industrial use of molten alkali metal nitrate salts, most of these applications have been isothermal and at lower temperatures from those proposed for solar thermal applications. As a result, the Department of Energy has initiated a comprehensive program to characterize the physical properties of molten nitrate salts, and their compatibility with potential containment materials.

Initial environmental compatibility tests have concentrated on evaluating the corrosion behavior of containment alloys at temperatures up to 650°C, using coupon immersion tests, convection loops, and pumped loops. The current results of these experiments indicate that corrosion rates for austenitic alloys such as Incoloy 800 and 316 stainless steel are acceptable up to 600°C, but that corrosion rates accelerate rapidly above that temperature. On the basis of moderately better corrosion resistance for Incoloy 800 compared to 316 stainless, the former alloy has been selected as a conservative baseline choice for many current central receiver system applications.

Absorber tube applications in solar receivers place severe operational demands on containment alloys. In addition to exposure to high-temperature absorber fluids such as molten salts, the tubes are subjected to fatigue cycling due to diurnal and variable insolation conditions, with superimposed sustained stresses (hold times) during periods of normal insolation. Thus, containment alloys used in the receiver must not only resist general corrosion, but also environmental cracking resulting from exposure to sustained stresses ("stress corrosion cracking") or fluctuating stresses ("corrosion fatigue") in the presence of the molten salt environment.

No evidence existed to indicate that environmental cracking would or could occur in molten nitrate salts. However, industry experience with environmental cracking failures has demonstrated that these phenomena can have a serious impact on the design and operation of engineering systems, should they occur. Many environmental degradation processes proceed at a fairly predictable rate, which permits reasonable prediction of component lifetimes and facilitates monitoring of the progress of the degradation. In contrast, environmental cracking processes often occur under unexpected conditions, with little or no warning or visible evidence of attack. Environmental cracking may occur on either a localized or widespread basis, and can result in complete penetration and structural failure of components even in the absence of severe generalized corrosion.

With these possible consequences in mind, the initial objective of the molten salt environmental cracking program is therefore early detection: with no prior evidence to indicate either susceptibility or immunity to environmental cracking in molten nitrate salts, tests are needed which can rapidly and aggressively screen a wide range of operating conditions relevant to solar thermal receiver service.

However, should any evidence of environmental cracking be detected in screening tests, there would also be a need to assess the scope of the potential problem. Detection of environmental cracking would not by any means rule out the development of solar receiver systems using molten nitrate salts. There are many cases in industry where alloy systems are used successfully in environments known to cause environmental cracking. The key to successful application of alloys under these circumstances rests with determining the bounds of the degradation process in terms of stress level, environment, and metallurgical variables, and designing accordingly. Thus, in the event that some evidence of susceptibility to environmental cracking in molten salts is detected during initial screening tests, greater emphasis will then be placed on determining the critical variables which affect the process. On the basis of that information, a sound judgment could first be made of whether environmental cracking would pose an unacceptable risk to the application of solar thermal systems based on molten nitrate salts; and if not unacceptable, what choices of containment alloy, design stresses, and environmental control would be required to assure successful operation.

The FY81 Solar Thermal Research and Advanced Development program for molten salt environmental cracking is oriented toward the first-phase objective, that of early detection of susceptibility (or immunity) to environmental cracking for containment alloys being considered for applications in the receiver subsystem. On the basis of both elevated temperature mechanical properties and corrosion resistance in molten nitrate salts, the current baseline material is Incoloy 800 (Fe-32Ni-20Cr), with 300-series stainless steels as the prime back-up materials. Initial molten salt screening tests are therefore concentrating on the evaluation of Incoloy 800 under a wide range of environments and stress states, the latter including both static and dynamic conditions. The test program and the initial results of some of these tests are presented below. Encouragingly, these first results show no evidence to indicate that a molten salt environmental cracking problem exists for central receiver applications.

ENVIRONMENTAL CRACKING TEST PROGRAM

A number of different environmental cracking test mehtods are included in the program. This reflects several factors: (a) the variety of forms of environmental cracking, (b) the desire to provide both rapid screening and (if required) an assessment of critical variables, and (c) the complexity of the actual receiver operating environment.

This actual service environment consists of thermally-induced strain cycling of receiver tubes, containing flowing molten salt which is itself being thermally cycled, i.e., thermal cycling creep/fatigue in a corrosive environment. Close simulation of these conditions are being considered as an ultimate goal of the test program, but one which will be difficult and costly to achieve, and not suited to rapid screening objectives. To meet these diverse objectives, several standard and non-standard test techniques of varying complexity are being utilized in different elements of this program to assess environmental cracking susceptibility:

a. Slow Strain Rate Test: the SSRT is performed under slow, constant extension conditions. Isothermal.

b. Stress Corrosion Cracking: a creep-rupture test performed in molten salt under constant load. Isothermal.

c. Corrosion Fatigue (Isothermal): Low Cycle Fatigue (LCF) and Fatigue Crack Growth (FCG) tests in which fatigue life and growth of pre-existing flaws, respectively, are measured in isothermal molten salt.

d. Corrosion Fatigue (Thermal Cycling): a closer simulation of the service environment, but experimentally much more difficult. Strain cycling is achieved thermally, rather than mechanically as in the isothermal tests.

Perhaps the most versatile screening technique is the SSRT, basically a tensile test conducted at a slow, constant rate of extension or strain in the molten salt environment. The technique provides a semi-quantitative measure of environmental cracking susceptibility by a comparison of fracture ductility (usually the Reduction in Area, RA) in the test environment and a reference environment, in this case molten salt and air, respectively. High values of RA indicate that ultimate failure occurs by processes which are essentially ductile in nature. A loss in RA for tests conducted in salt would be taken to mean that surface-initiated environmental cracking had truncated the normally ductile failure process. Additionally, metallographic and fractographic analyses are conducted to search for significant changes in fracture morphology which can be correlated with changes (if any) in RA.

Using relative changes in RA as a primary measure of environmental cracking susceptibility, Slow Strain Rate tests are run at a range of different strain rates, to determine the strain rate at which cracking (if it occurs) is most severe. When the SSRT technique is to be used for a screening evaluation of the effects of environmental or metallurgical variables, these subsequent tests are run at the strain rate showing the greatest degree of degradation. The continuous strain conditions of the SSRT can be considered to be a severe test of resistance to environmental cracking. The SSRT technique has been adopted as an important element of the molten salt program reported here, serving first as a screening method for detecting any evidence of cracking susceptibility; and then for assessing the critical metallurgical and environmental factors affecting the cracking process, if it occurs. The results of the first SSRT experiments are reported in the following section.

CURRENT STATUS OF TEST PROGRAM

An initial SSRT screening matrix for Incoloy 800 has been completed at Sandia National Laboratories, Albuquerque (SNLA) and additional slow strain rate experiments are in progress. A limited number of stress corrosion cracking (creep-rupture) tests have also been completed. Isothermal corrosion fatigue experiments have begun at General Atomics. San Diego (LCF-fatigue life) and at Sandia National Laboratories at Livermore, SNLL (fatigue crack growth).

The results of the SNLA slow strain rate experiments represent the first data reported anywhere on the environmental cracking behavior of materials used in molten nitrate salts at temperatures up to 630°C. In these experiments, specimens representing both as-received parent metal and weldments were machined from Incoloy 800 sheet. For these and all other tests currently being conducted, the molten salt environment was a commercially-available grade of draw salt with a nominal composition of 60% $NaNO_3$ - 40% KNO_3. The test matrix at SNLA has included air tests at 25 and 250°C (baseline data), and molten salt at temperatures from 300 to 630°C. Strain rates varied from 10^{-4} to 10^{-7} per second, with the majority of tests conducted at 10^{-4}, 10^{-5}, or 10^{-6} per second. At a strain rate of 10^{-7} per second, a single test required on the order of a month to run to completion. Tests at higher strain rates were proportionally shorter in duration.

The results of these experiments show no evidence to indicate that environmental cracking has occurred. The parent metal RA values for Incoloy 800 are between 52 and 72 pct. for all temperatures, environments, and strain rates, a range which is considered typical of normal scatter. The range in RA values for weldment specimens is even smaller, 65 to 71 pct. Within these ranges there are no apparent correlations or trends in RA values indicative of any significant environmentally-induced degradation. Fractographic studies do not show any evidence of changes in fracture modes for specimens tested in molten salt compared with those tested in air. The preliminary results of SSRT experiments conducted at SNLL show a similar lack of effect of molten nitrate salt on fracture ductility or fracture modes for Incoloy 800.

These results, while far from complete or exhaustive, are highly encouraging. There was initially no strong reason to suspect that environmental cracking would, in fact, occur in molten nitrate salts. However, the lack of supporting data was troubling in view of the possible consequences of a major cracking problem for solar central receiver systems now being designed to operate with that heat transport fluid. This initial round of screening tests has established that environmental cracking does not appear to occur over a wide range of strain rates and temperatures relevant to solar receiver operation, for a "typical" Incoloy 800 product form exposed to nominal-composition draw salt. Continuing SSRT screening studies at SNLA and SNLL will explore a wider range of variables, including environmental factors such as the effects of aged salt and salt chemistry variations; and metallurgical factors such as variations in Incoloy 800 product form, microstructure and composition, and the effects of prior sensitization heat treatments. Supplementing the Incoloy 800 baseline SSRT experiments, screening tests will also be performed on potential lower-cost, lower-alloy containment materials such as 304 and 316 austenitic stainless steel; and nickel-free, low-chrome ferritic and martensitic steels.

In addition to these SSRT screening experiments, the molten salt environmental cracking behavior of Incoloy 800 is also being explored with isothermal corrosion fatigue tests now in progress, to be followed by thermal cycling tests later in FY81. The balance between Incoloy 800 testing and alternative alloy testing in the SSRT and corrosion fatigue program elements will depend on whether (and to what degree) any evidence of environmental cracking appears in any of these initial screening experiments. Detection of susceptibility to environmental cracking would necessitate a greater effort devoted to scoping the extent and nature of the degradation process, while a lack of cracking susceptibility would permit a greater effort on alternative alloys.

SUMMARY

The environmental cracking behavior of containment materials in molten nitrate salts is being explored with a series of tests. Slow Strain Rate screening tests conducted at strain rates from 10^{-4} to 10^{-7} per second, over a temperature range from 300 to 630°C, do not show evidence of environmental cracking of Incoloy 800 exposed to molten draw salt (60% $NaNO_3$/40% KNO_3). The SSRT screening matrix will now be extended to include a wider range of environmental and metallurgical variables relevant to solar operation. Environmental cracking tests involving cyclic strain and temperature are also in progress. These studies will help to provide the basis for determining the direction and scope of further environmental cracking tests. At this point, there is no evidence to show that environmental cracking will cause any impediment to the development of molten salt-cooled solar receiver systems.

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CORROSION OF 9 CHROME 1 MOLY AND 316 L STAINLESS STEEL ALLOYS

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INTRODUCTION

Corrosion of metals and materials is an important factor in the economy of operation of most of our present day technologies. The ability to reduce loss by corrosion can in many cases determine the difference between success and failure of a given process.

In the solar thermal energy area one of the prime concerns with regard to corrosion is boiler tube corrosion. Much is known about corrosion of conventional boiler systems. However, a direct technology transfer from conventional systems to solar thermal systems cannot be made because of the continuous thermal cycling which occurs in these systems.

Consequently, research has been initiated in the Metallurgy Department at the University of Utah to study the effects of thermal cycling on the corrosion resistance of alloys which could be candidates for use in solar thermal energy boilers. The alloys chosen for study were 316 L stainless steel and an iron base 9 Cr 1 Mo alloy.

The corrosion resistance of these alloys is determined primarily by the formation of an extremely thin (2-10 nm thick) passive films on the surface of the alloy. The formation and stability of the passive film under boiler conditions and under cyclic thermal conditions is of prime importance in this research. One of the goals of the research is to mathematically model the kinetics of passive film formation on these alloys and to develop models which would predict the effects of thermal cycling on the stability and thickness of the passive film.

A number of techniques are possible for studying passive film formation. One of the best and the one chosen for this study is the use of potentiostatic and potentiodynamic methods to measure film formation and growth. Auxiliary techniques used to analyze the film composition are Auger spectroscopy and ESCA (electron spectroscopy for chemical analysis).

EQUIPMENT

Equipment used for the potentiostatic and galvanostatic measurements included two systems each having a Model 173D potentiostat, a Model 175 programmer, a Model 376 log converter, a 379 digital coulombmeter and X-Y recorder manufactured by Princeton Applied Research Company. Standard temperature baths and metallographic polishing equipment were also used. Auger and ESCA analysis equipment owned by the Solar Energy Research Institute at Golden, Colorado was also utilized.

ALLOYS

A 9% chromium 1% molybdenum alloy obtained from Oak Ridge Natinal Laboratories was used in the study along with a 316 L Stainless Steel Alloy obtained from G.O. Carlson, Inc.

EXPERIMENTAL ARRANGEMENT

The reaction cell consisted of a three necked flask which contained the working electrode which was the metal alloy being studied, a Luggin Capillary to measure the electrode potential and a counter electrode made of platinum to control the working electrode potential by current passage through the system. The reaction cell was immersed in a controlled temperature oil bath. Means were provided for stirring the solution in the cell and measuring its temperature. The specimens were prepared by mounting in cold setting plastic cylinders one inch in diameter and polishing with 0.05 alumina.

ANODIC POLARIZATION CURVES FOR 316L STAINLESS STEEL

The electrolytic solutions used in the cell were a mixture of 0.5 M Na_2SO_4 and 0.5 M H_2SO_4. The pH was adjusted by changing the ratio of these two chemicals. The solutions were deaerated prior to each experiment by bubbling purified nitrogen gas through the solution. At the beginning of the experiment the specimens were cathodically polarized at -900 mV (vs SCE) for five minutes to reduce any oxide film on the surface. Corrosion potentials were determined by allowing the electrode to come to equilibrium with the solution without any externally impressed current. Anodic polarization curves were obtained by increasing the potentials at a constant rate of 30 mV/min. Typical polarization curves are shown in Fig. 1 below. It can be seen from Fig. 1 that 316 L stainless steel has an active-passive transition and that the critical current density increases with decreasing pH. The current densities in the passive regions do not vary much with pH. Current maxima at 0.8 V were found to increase with decreasing pH. The effect of varying solution temperture was determined for pH values of 6.5 and 3.2. It was found that the critical current densities increase with temperature for a pH of 6.5 but decrease at the more acid pH. Bulman and Tseung [1] have reported an increase of critical current density in sulfuric acid solution (pH = 0).

By plotting the log of the current versus the potential, one obtains a Tafel plot which when extrapolated to the corrosion potential gives the exchange current density. The exchange current is the amount of current flowing at the interface in each direction at equilibrium potential. By plotting the log i (the exchange current density) versus the reciprocal of the absolute temperature for various temperaures an activation energy is obtained. The value obtained from a plot of this type was 10 Kcal/mole.

POTENTIOSTATIC CURVES FOR 316 L STAINLESS STEEL

In a potentiostatic experiment the potential of the electrode is held constant and the current required to maintain the potential is recorded. The current i_p determines the charge Q used to form the film on the metal surface through intregration of i_p over time (t). The data obtained fit an equation of the type

$$i_p = i_0 \exp(-BQ) \tag{1}$$

where B is a constant and a function of potential.

By plotting log i_p versus Q, two straight lines are obtained as is illustrated in Fig 2. This indicates that two different film building processes are involved in film formation.

GALVANOSTATIC EXPERIMENTS ON 316L STAINLESS STEEL

In the galvanostatic experiment a constant current is impressed on the electrode to cause film formation and the electrode potential change is measured. Since the current is constant with time it is directly proportional to the charge Q passed. An example of typical results obtained from this type of experiment done at different current densities is shown in Fig. 3. The straight line portions of the curves apparently represent the formation of different types of films on the metal surface.

AUJER ELECTRON SPECTROSCOPY MEASUREMENTS

The Aujer Electron Spectroscopy technique (AES) measures the depth profile concentration of elements. Standard specimen preparation techniques were used with the passivating potential being applied for 90 minutes after which the specimens were removed from solution and placed in the vacuum chamber of the AES equipment for examination. Fig. 4 shows the results obtained for potentials of -0.36 V, 0.18 V and 0.58 V at a pH 6.5 Chromium enrichment was observed at the surface and the enrichment was higher for the lower voltage. At a higher potential (not shown in Fig. 4) of 0.9 V (SEC) no enrichment of chromium or nickel was detected in the film. Since almost the same distribution of elements are observed between 0.18 V and 0.58 V by AES and different kinds of films are observed by potentiostatic and galvanostatic experiments it follows that the difference is likely due to valency and structural changes in the film.

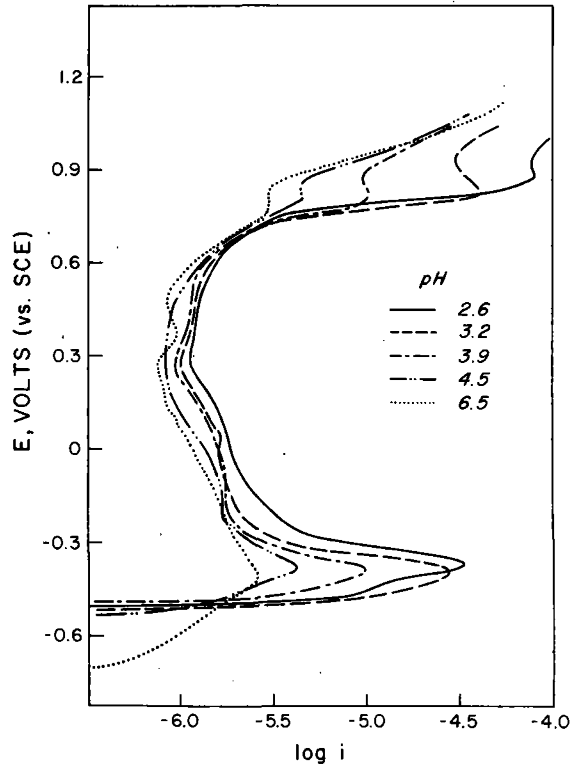
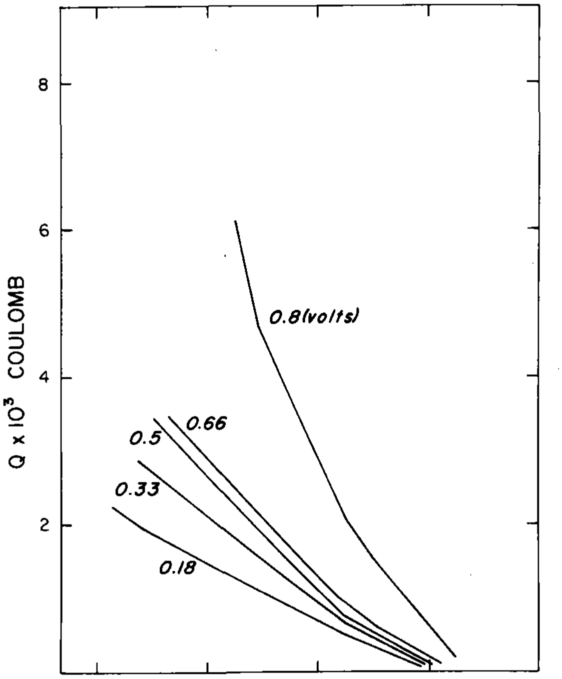


Fig. 1. Typical anodic polarization curves for 316 L stainless steel.

Fig. 2. Plot of total charge passed versus passivating current for 316L stainless steel as a function of passivating potential.



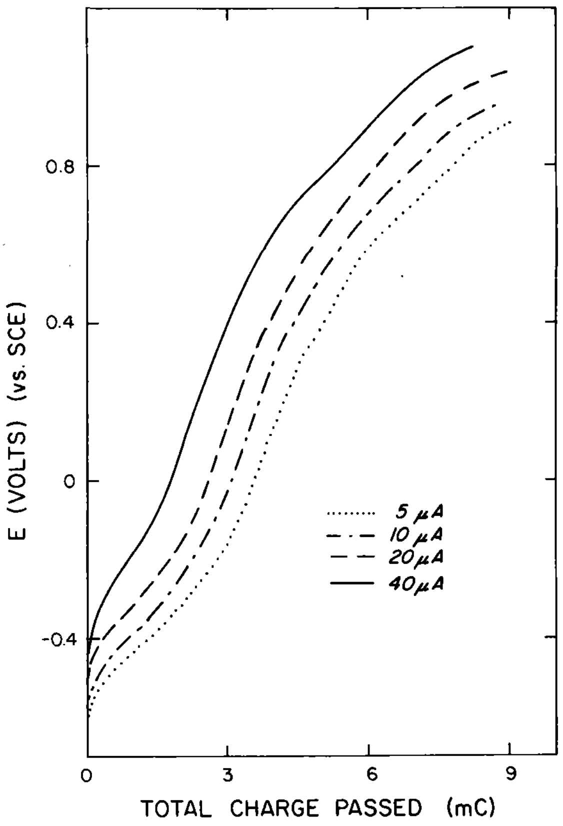


Fig. 3. Potential versus charge curves for galvanostatic treatment of 316 L stainless steel.

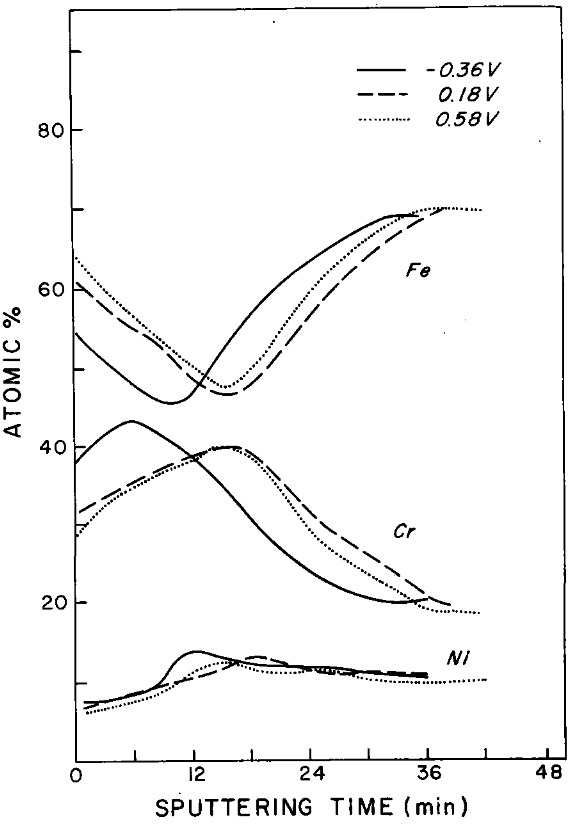


Fig. 4. Compositional depth profiles of 316 L passive films.

ANODIC POLARIZATION CURVES FOR 9 Cr 1 Mo ALLOY

Typical anodic polarization curves for the 9 Cr 1 Mo ferritic stainless steel used in this study are shown in Fig. 5 with pH used as a variable. Typical regions of passivity, transpassivity and secondary passivity can be seen on the curves. As the pH of the solution decreased the corrosion potential increased. This may be explained as due to the increase in the equilibrium potential of the hydrogen discharge reaction with pH. In the non deaerated solution of pH 6.2 the corrosion potential was higher than the equilibrium potential for hydrogen evolution in the solution. There was almost no change in corrosion potential with increasing temperature.

The critical current density increased with increasing temperature and decreasing pH. The active passive transition region exhibited two current maxima at high temperature and at low pH values. This phenomena has been noted for type 430 stainless steel in 0.1 M HCl solution at room temperature. The double peak in the critical current region indicates the likely formation of a second reaction product after the inital one has formed.

A secondary passivation peak is also found. This has been reported in the literature for iron chromium alloys in many instances.[2] It is known that the potential for the breakdown of primary passivity is nearly independent of the chromium content but the secondary passive current increases as the chromium content increases. As is shown in Fig. 5 the secondary passivation potential increases with decreasing pH and has been shown to increase with a decrease in temperature.

POTENTIOSTATIC CURVES FOR 9 CR 1 MO ALLOY

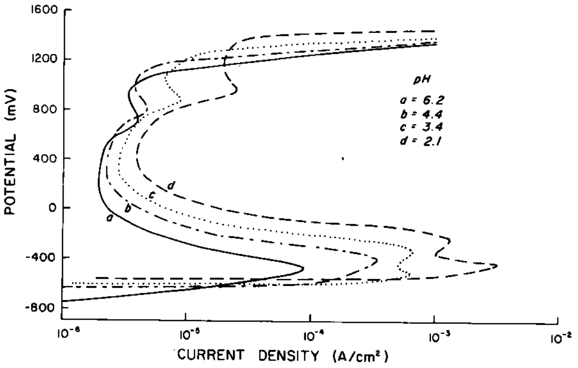
Potentiostatic experiments were carried out at various temperatures in the passive region. The dependence of the current density on film thickness which is proportional to charge (Q) passed at constant potential is shown in Fig. 6. In all cases thee was a high initial current which rapidly decreased. The high initial current is attributed to charging of the double layer at the surface. In general the curves in Fig. 6 are rather linear except for the initial part of the plot.

GALVANOSTATIC EXPERIMENTS ON 9 Cr 1 Mo STEEL

Constant anodic currents ranging from 5 to 70 A/cm^2 were applied to the specimens to induce passive film formation. In order to obtain good reproducability the specimens were given a preliminary anodic oxidation treatment for 10 minutes at a constant potential of -0.3V SCE).

Fig. 7 shows the curves obtained. The curves can be divided into four stages which may be attributed to anodic dissolution, first and second passive layer build up and finally the transpassive stage. In the steady film growth region the potential is a linear function of the amount of charge passed and the slope is independent of the applied current density.

Fig. 5. Anodic polarization curves of 9 Cr 1 Mo alloy as a function of pH.



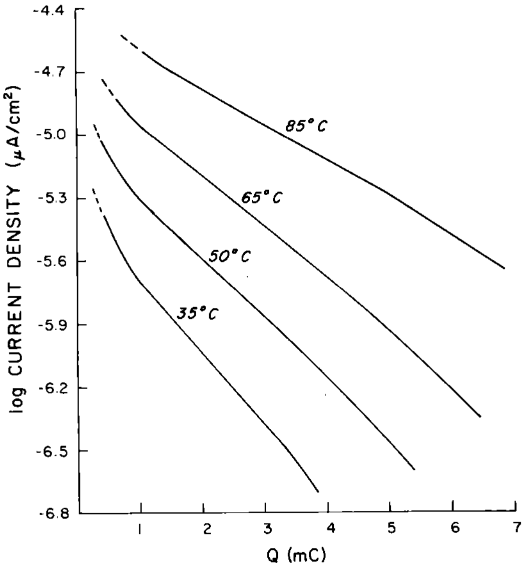
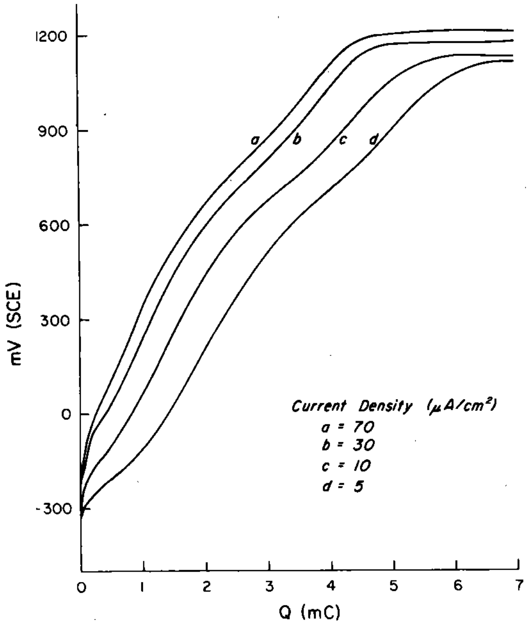


Fig. 6. Current density as a function of film thickness for 9 Cr 1 Mo alloy.

Fig. 7. Galvanostatic passivating curves for 9 Cr 1 Mo alloy.



ESCA ANALYSIS OF THE PASSIVE FILM

ESCA (electron spectroscopy for chemical analysis) was carried out in conjunction with argon ion sputtering to obtain composition depth profiles of passive films formed at constant potentials. The films were formed at constant potential for 90 minutes in a 0.2 M Na_2SO_4 solution of pH 6.2 at room temperature. The results obtained indicate that the composition of the film depends on the applied potential. Chromium enrichment occurred in the outer layers at a potential of -0.3V but further from the surface at potentials of 0.98 and 1.05 V. Oxygen was high at the surface and decreased more rapidly with depth in the sample treated at 0.3V as compared to the samples treated at 0.9V and 1.05V. The oxygen depth profiles were fairly similar to the chromium profile.

FUTURE RESEARCH

The nature of the passive films on the metal alloys studied has been sufficiently characterized that experimental work on the effect of thermal cycling on the stability and structure of the films can now be carried out.

Thermal cyling will be carried out by passing steam over the metal alloy held at various temperatures of up to 500^{o}C. The alloy temperature will be cycled from low temperatures to high temperatures numerous times. After temperature cyling in steam the passive films will be examined with the potentiostat for corrsion potential and the passive films will be removed by galvanostatic stripping. In this way the effect of thermal cycling in steam on the thickness, stability and structure of the passive film will be determined.

ACKNOWLEDGMENTS

Appreciation is expressed to the Mechanical Properties Groups, Metals and Ceramics Division, Oak Ridge National Laboratory for supplying the 9 Cr 1 Mo alloy and to G.O, Carson, Inc. for supplying the 316L stainless steel used in this research. Gratitude is also expressed to the Solar Energy Research Institute for financial support of this project under subcontract No. XP-9-8046-1 which made the research possible.

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CERMET SELECTIVE ABSORBER COATINGS

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This paper describes an investigation of Pt/Al_2O_3 cermet selective absorber coatings deposited by sputtering. The potential application is for medium and high temperature collectors. The investigation is based on recent work conducted at Cornell University which has shown that co-evaporated Pt/Al_2O_3 selective absorber coatings can possess remarkable thermal stability [1]. A coating on Pt-coated quartz showed no change in optical properties after being heated in air for 300 hrs at 600°C. By comparison, black chrome has been found to degrade at temperatures in the 300 to 350°C range.

The co-evaporation method used in the Cornell work is difficult to apply to the variety of substrate shapes (large flat panels, tubes, cylinders, hemispheres, and domes) that are of interest for high temperature solar collectors. Sputtering, by contrast, is applicable to such complex shapes; and magnetron sputtering in particular is capable of depositing uniform coatings over large surface areas [2]. This investigation is being conducted using cylindrical-post [3] and planar magnetrons [4]. The substrates are glass, quartz, and type 316 stainless steel plates.

Coatings with optical properties that compare favorably with the Cornell work, and with strong thermal stability, have been deposited using both direct rf sputtering of alumina and reactive sputtering to deposit the Al_2O_3. Guidelines have been established for selecting coating configurations (thickness, grading profile, and Pt content) to yield various combinations of absorptances and emittances. Particular attention has been given to examining coating configurations which can minimize the required platinum content. Multi-layer AMA-type coatings have been found to be very effective in this respect.

COATING DEPOSITION

Three sputter-deposited Pt/Al_2O_3 coating configurations have been investigated: (1) A cermet with a linearly graded Pt content, which varies from about 50 volume percent at the rear surface to zero at a point sufficiently below the top surface so that in effect an Al_2O_3 antire-

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Paper prepared for presentation at SERI Solar Thermal and Advanced Development Program Review, Oakland, California, April 8-9, 1981.

flection (AR) layer is formed. (2) A cermet, with uniform Pt content, which is overcoated with an Al_2O_3 AR coating. (3) An Al_2O_3-M-Al_2O_3 (AMA) type coating in which the M-layer is a uniform Pt/Al_2O_3 cermet with a high Pt content (~80% by vol.). The uniform cermet coatings were investigated for use in those applications, such as internal surfaces of cylinders and hemispheres, where co-deposition to form graded Pt contents would be impractical. The AMA coatings were examined as an alternative configuration which would require much less Pt. In addition, Mo and Cr were investigated as replacements for Pt in the low emittance base layer.

Pt/Al_2O_3 cermet coating having the three configurations described above were deposited by co-deposition from Al_2O_3 (driven rf) and Pt (driven dc) cylindrical-post magnetron sputtering sources arranged as shown in Fig. 1. Similar coatings were also deposited using the apparatus shown in Fig. 2, which is modeled after the apparatuses (Fig. 8) which are projected for coating flat panels in large volume production. In these apparatuses the cermet layers are formed by rotating the substrates alternately under the Al_2O_3 and Pt fluxes produced by planar magnetron sputtering sources. The Al_2O_3 has been produced both by direct rf sputtering of alumina and dc reactive sputtering from an Al target. Substrate temperatures of about 150°C and 500°C were used in both apparatuses.

COATING OPTICAL PROPERTIES

The coating optical properties were evaluated at the Lockheed Palo Alto Research Laboratory. Figure 3 shows the spectral reflectance of a graded sputtered cermet coating on a Pt coated glass substrate, compared to a typical black chrome coating. The grading of the cermet coating is shown by the Auger depth profile in Fig. 4. The absorptances and room temperature emittances of the cermet and black chrome coatings are seen to be comparable, although the sputtered cermet coating has a higher reflec-

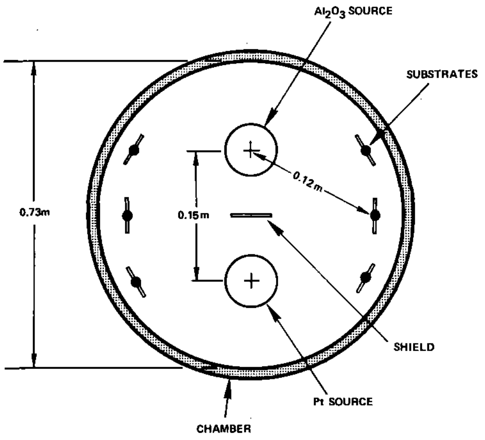

FIG. 1. DUAL SOURCE CYLINDRICAL-POST MAGNETRON SPUTTERING APPARATUS.

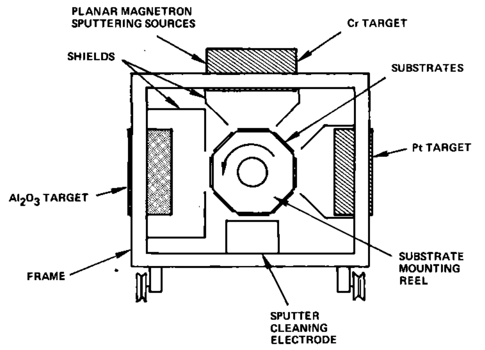

FIG. 2. MULTI-SOURCE PLANAR MAGNETRON SPUTTERING APPARATUS.

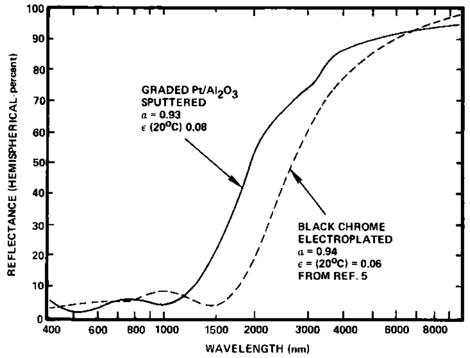

FIG. 3. SPECTRAL REFLECTANCE OF SPUTTERED CERMET COATING COMPARED TO BLACK CHROME.

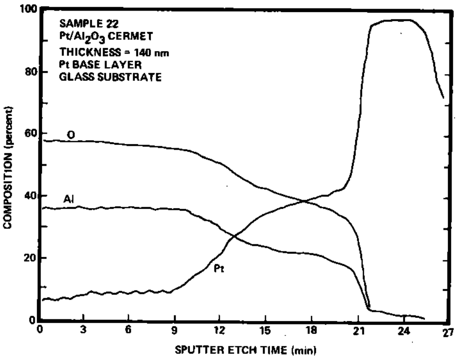

FIG. 4. AUGER DEPTH PROFILE SHOWING COMPOSITION GRADING FOR SPUTTERED CERMET COATING SHOWN IN FIG. 3.

tance in the near infrared and therefore a lower high temperature emittance (see Fig. 6).

Figure 5 summarizes the combinations of absorptances (α_H) and room temperature emittances (ϵ_H) that were achieved with the three different cermet coating configurations. The graded cermet layers were typically about 100 nm thick with a Pt volume fraction (F) of about 0.5 at the rear surface, and a 40 nm AR layer. See Figs. 3 and 4. The uniform cermet layers were typically about 60 nm thick with F∼0.65 and a 70 nm thick AR layer. The AMA coatings consisted typically of 25 nm of Al_2O_3, 5 nm of Pt/Al_2O_3 (F∼0.8), and 40 nm of Al_2O_3. The sputtered coatings with the graded Pt and AMA configurations are seen in Fig. 5 to have generally larger α_H/ϵ_H values than the uniform cermet coatings, or the evaporated coatings deposited during the preliminary Cornell studies. The effectiveness of the grading in producing high α_H/ϵ_H combinations is believed to be due to the nonlinear dependence of the cermet optical constants (n,k) on the Pt content at high F-values [6].

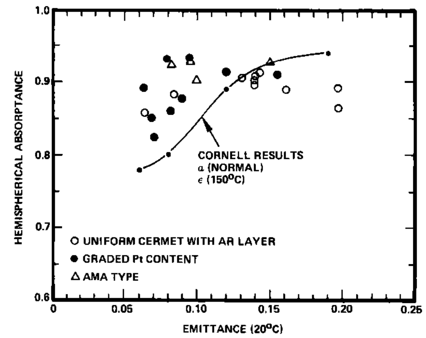

FIG. 5. ABSORPTANCES AND EMITTANCES OF SPUTTERED AND EVAPORATED CERMET COATINGS [1].

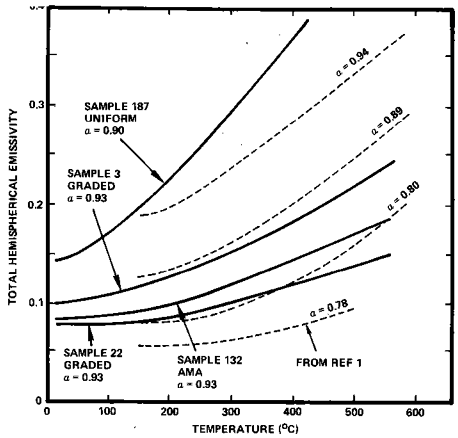

FIG. 6. EMITTANCE VERSUS TEMPERATURE FOR SPUTTERED AND EVAPORATED (DASHED LINE) CERMET COATINGS.

Figure 6 shows the projected temperature dependence of the emittances for several of the sputtered coatings. The high temperature emittances were calculated from spectral reflectance data of the type shown in Fig. 3. The graded and AMA type coatings are seen to undergo small increases in emittance with temperature and to compare very favorably with the evaporated coatings. The uniform cermet coatings are projected to undergo a rapid rise in emittance with temperature.

THERMAL STABILITY

Thermal stability and humidity tests are currently underway. Coatings with the graded, uniform, and AMA configurations deposited at ~500°C onto Pt coated glass by both direct rf or reactive sputtering have shown $<1\%$ changes in absorptance after 100 hrs at 600°C in air, thereby confirming the Cornell results. Similar stability was found for graded and uniform coatings deposited onto type 316 stainless steel with a 500 nm Al_2O_3 diffusion barrier. Coatings deposited at ~150°C were slightly less stable. The reflectance change for such a coating is shown in Fig. 7. Coatings deposited on Cr and Mo base layers were less stable than those on Pt, with Cr being superior to Mo. The results of preliminary failure temperature measurements are summarized in Table I.

SUMMARY-COST PROJECTIONS

Pt/Al_2O_3 cermet coatings with good optical properties and excellent thermal stability can be deposited by sputtering. Figure 8 shows a type of apparatus which is projected for coating large flat collector panels at high production volumes. The apparatus would coat about 10^6 ft^2/year of collector surface. The cost, based on Pt at $500/troy oz, is projected to vary from about $4/$ft^2$ for a graded cermet on Pt to $1/$ft^2$ for a Cr base layer. An AMA coating on Cr would be about $0.5/$ft^2$. Similar costs are projected for coating tubes. Thus the Pt/Al_2O_3 coatings show promise

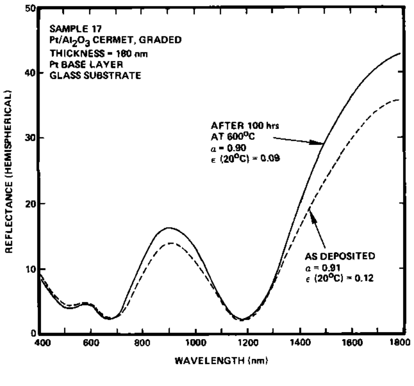

FIG. 7. CHANGE IN SPECTRAL REFLECTANCE DURING THERMAL TESTING IN AIR AT 600°C FOR 100 HRS.

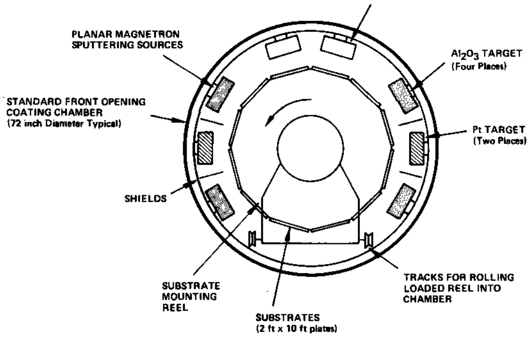

FIG. 8. PRODUCTION TYPE COATING APPARATUS FOR FLAT PLATES.

TABLE I
THERMAL STABILITY IN AIR*

Coating Type	Substrate Temp.	Pt	Cr	Mo
		Substrate Material		
Graded	~ 500°C	> 600°C	-	-
	~ 150°C	550°C	-	-
Uniform	~ 500°C	> 600°C	600°C	550°C
	~ 150°C	500°C	500°C	450°C
AMA	~ 500°C	> 600°C	500°C	500°C
	~ 150°C	400°C	450°C	300°C

*Temperature at which $\Delta\alpha_H > 1\%$.

for a wide range of medium and high temperature collector applications with the Pt content and cost being determined largely by the thermal stability required.

ACKNOWLEDGEMENT

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POLYMER DEVELOPMENT AND PERFORMANCE EVALUATION AT JPL

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Jet Propulsion Laboratory

INTRODUCTION

Since the last program review meeting, the polymer related activities in the JPL RAD Materials Task have concentrated on research and advanced development activities targeted at developing and evaluating low cost, polymeric films for use in solar thermal energy systems as mirror superstrate/substrates and for domes to enclose the concentrators (heliostats) in a protective envelope. While additional materials, processing and fabrication technology are required to assure success with polymer membrane mirrors or domes, the identification of a low cost polymer film material which possesses long term resistance to ultraviolet degradation is the first important step. In fiscal year 1981, the Materials Task is performing studies in areas including (i) the experimental study of polymer photoprocesses and mechanical behavior; (ii) the generation of preliminary criteria for the establishment and growth of a polymer materials data base for low-cost enclosure applications; and (iii) an assessment of polymeric materials for heliostat/dome applications.

The overall objective of the current work is to evolve polymer technology which is cost/performance effective in the identified Solar Thermal Energy Technology (STES) applications and which can be readily adopted and commercialized by industry. The output of this activity ranges from near-term, e.g. evaluation of the stability of solar transmittance in Kynar^R, to the long-term development of constituitive models of the mechanical behavior of selected polymers important to the STES Program. The nature of the work ranges from basic polymer engineering selection of available adhesives and films to in-depth research on the mechanisms of degradation which will enable short-term testing to be used for extended life prediction. The STES Polymer work funded at JPL is highly interactive and synergistic with ongoing polymer programs funded by NASA, DoD, and the DoE Photovoltaics program. This synergism results in the ability to carry out a much broader scoped program than would be possible with only STES funds.

POLYMER PHOTOPROCESSES

One of the promising approaches for developing low-cost solar energy systems is the cost-effective use of polymers for dome and mirror superstrate components. Although a variety of potentially suitable polymers are available commercially, these industrial products have not or cannot satisfy the rigorous functional requirements needed for solar energy applications. Importantly, in non-solar applications, polymers are only incidently exposed to damaging solar ultraviolet (UV); conversely, the exposure of transparent polymers to UV irradiation in solar system components is continuous during operation, maximizing the exposure and the requirement for UV stability. Although the incorporation of UV protective agents in low-cost materials is accomplished commercially, these agents are subject to loss by leaching or evaporation, leaving the polymer unprotected. Hence, the objectives of the photoprocesses study are to produce UV-induced failure in the candidate polymers and through identification of the failure mechanisms, develop life prediction models, accelerated testing technology, material modification concepts and nondestructive evaluation techniques for polymeric systems.

The significant accomplishments or findings of the photoprocesses activity to date are as follows:

1. A comprehensive photodegradation model has been developed for a formulated, UV-screening acrylic copolymer system.

2. The major conclusions from the experimental studies which led to the photodegradation model, are: a) the copolymer's matrix undergoes degradation by oxidative crosslinking, gelation, and chain scission at a slow rate which indicates acceptable performance of this material for 17 years of equivalent exposure (at one solar constant); b) the UV-screening agent is unaffected either chemically or physically over this exposure period; and c) a low molecular weight photoproduct has been identified by using a high-performance liquid chromotography technique.

3. A formulation has been developed for the UV-stabilization of polycarbonate material. Technical and patent disclosures are in preparation.

POLYMER MECHANICAL BEHAVIOR

The near-term polymer activities within the RAD Task support the field engineering work and the development of successful, potentially cost- effective prototype systems. From the design of these prototype systems requirements are identified for certain mechanical and optical stability characteristics in the polymeric components. Various functional material requirements, both generic and component specific, derive from the many proposed applications which range from thin-films for dome enclosures and reflector superstrates to structural, polymer composite panel configurations for reflector substrates or mounting supports. These system derived functional material requirements form the basis of the JPL program definition and the direction in which the work proceeds.

Polymers with intially acceptable mechanical properties (performance in the design) may, over time, degrade below the level required for acceptable, cost effective performance. It is critical to insure the long-term mechanical performance of the selected polymers over the operating lifetime in the particular application. For example, the "optical figure" and, hence, the performance of a pressure supported, polymer membrane mirror is strongly dependent on the dimensional stability of the membrane. The approach chosen in the RAD Task to insure success in such applications is that of predictive modeling studies. These studies use, as input, the functional requirements of the material in the component and data on the basic material behavior; the final output is the performance and limitations of the material in the design service environment.

The Task activities directed at understanding the mechanical behavior of polymers include both near- and long-term studies of selected materials which are candidates for low-cost solar concentrator systems. Near-term studies are in progress on Kynar^R, a polyvinylidene fluoride (PVDF), and polymethylmethacrylates (PMMA), including a commercial PMMA material available from 3M^R, which are candidate materials for dome components. The degradation mechanisms which occur in PVDF and PMMA are under study using the technique of producing thermally-induced, accelerated-aging while the material is biaxially strained. The objective of this study is to determine the kinetics of the mechanisms which lead to loss of specular transmittance in these materials by utilizing elevated temperature aging (50^o, 60^o, 70^o, and 85^{o}C) to induce accelerated degradation. Once the degradation mechanisms operative in the service environment are identified and their kinetics established, a long-term life prediction model will be available. After 2100 hours of exposure at 85^{o}C, PVDF was found to become translucent; the first measureable decrease in transmittance was noted after 1477 hours at 85^{o}C. However, the performance of PMMA showed an earlier, gradual degradation after only 600 hours under similar conditions. In another experimental study, with PVDF film under 3% constant strain at 60^{o}C and aged for 2400 hours, the initial decrease in integrated transmittance occured at about 1300 hours and in 2400 hours the decrease was 1.5%, as measured at 350 nm wavelength.

The summary of significant accomplishments in this study are as follows:

1. An initial model has been developed describing the Stress-Strain-Time-Temperature behavior of glassy polymers.

2. The experimental characterization of several engineering polymers has been completed and is being used in model validation and performance evaluations.

3. The major factors affecting dimensional stability (maintenance of optical figure) have been identified.

4. A contract has been established with Washington University, St. Louis for evaluation of the dimensional stability of a random glass fiber/polyester composite.

POLYMER FILM DATABASE

A plan has been developed for a polymer film database which can be structured to assist in the selection of candidate polymers for use in near-term hardware, in guiding polymer RAD task activities, and in the chain of studies leading to cost/performance evaluations. The structuring of the database requires that the engineering data collected for a specific material be characterized and based on the functional requirements of the system or component under study. The selection of polymeric materials for advanced components can, in this manner, be based on a quantitative comparison of the material's properties and the total set of design imposed material requirements. The lack of a qualifying parameter(s) in a particular material will be immediately identified to the polymer industry and the RAD polymer activity can be alerted to the particular hardware needs for short-term/long-term solutions. The database will also include the technical information necessary to support mathematical model prediction studies. The database is intended to be augmented by a microcomputer system making the approach economical and readily used by semi-trained personnel.

POLYMER DOME DEVELOPMENT PLAN

A preliminary plan was generated for the development and evaluation of plastic dome-enclosure components for use in low-cost solar thermal concentrator systems. The plan features a comprehensive approach for the development of advanced materials systems suitable for enclosure design, which are capable of being manufactured, and have demonstrated their cost-performance through a combination of performance data and laboratory verifications. In addition to using materials and components developed under previous DoE-funded feasibility studies, the overall plan was to achieve coordination through a systems task having the responsibility for integrating design requirements with potential user and industrial manufacturing interfaces. The development program was initiated in February, 1980 and terminated in April, 1980, due to a forecasted lack of programmatic resources in FY'81.

ASSESSMENT OF POLYMERIC MATERIALS FOR HELIOSTAT/DOME APPLICATIONS

Work has recently been initiated on a short-term study involving the assessment of polymeric materials for heliostat/dome applications. This study is evaluating both the near- and long-term potential of polymeric materials in these systems and identifying the specific needs for polymer development work. This assessment will be completed in June 1981.

REACTIVITY OF POLYMERS WITH MIRROR MATERIALS

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OBJECTIVE

The objective of this program is to establish the stability of polymeric materials that are under consideration as transmitting superstrates/substrates for solar mirror materials. Candidate polymeric materials (CPM) are being evaluated for the coating of silver and aluminum mirrors without a deleterious reaction occurring between the mirror surface and the coating. This paper summarizes results from screening studies designed to evaluate the interface stabilities of different polymer/mirror combinations. The objective of this initial screening is the selection of promising polymer/mirror combinations for subsequent long-term, semi-quantitative environmental evaluation.

EVALUATION

For screening stabilities at interfaces, polymer/mirror samples were exposed in an Atlas Weather-Ometer at 70°C and 50% relative humidity, using continuous radiation from a 6000-watt Xenon arc lamp with borosilicate filters. Exposed samples were removed periodically for evaluation that included analysis of the intact polymer/mirror (reflectance), the separated polymer (infrared) and mirror interfaces (scanning electron microscopy), and the polymer film (tensile properties, molecular weight).

MATERIALS

Table 1 identifies the candidate polymers and the polymer/mirror assemblies that have been both weathered and analyzed to date.

For EVA, PIB, EP, and PMMA, the polymer/mirror assemblies were prepared by solution-casting 2-4 mil (dry) polymer films over a silver mirror deposited on glass. These combinations are designated polymer/Ag/glass. PVDF assemblies were prepared by silvering a preformed commercial film (denoted by a subscript, f) of the polymer. In these first-surface PVDF assemblies, the mirror back was protected by a gasketed, glass cover, sandwich arrangement. All silver mirrors were prepared by wet deposition from commercial silvering solutions (London Laboratories Ltd., Woodbridge, CT). Llumar is Melinex O film (ICI) that is aluminized and sold by Martin Processing, Inc.

Table 1

POLYMER/MIRROR ASSEMBLIES STUDIED

Polymer	Assembly
Ethylene - (18%) vinyl acetate	EVA/Ag/glass
Polyisobutylene	PIB/Ag/glass
Polyisobutylene with 3% carbon	PIB_c/Ag/glass
Ethylene-propylene copolymer	EP/Ag/glass
Ethylene-propylene copolymer with 3% carbon	EP_c/Ag/glass
Poly(methyl methacrylate)	PMMA/Ag/glass
Poly(vinylidene fluoride) (Kynar)	$PVDF_f$/Ag/sandwich
Poly(ethylene terephthalate) (Llumar)	PET_f/Al

RESULTS

For comparison, the reflectance values (specular; 45° angle of incidence; mercury light source), relative to that of a standard mirror, for the weathering of the polymer/mirror combinations studied are given in Figure 1. (Systems with carbon black are not shown since the additive made little difference). Physical or chemical failure eventually occurred in these polymer-coated mirrors. Our results indicate, however, that both types of failure can be reduced or eliminated by proper selection of the polymer/mirror assembly and the additives in the polymer.

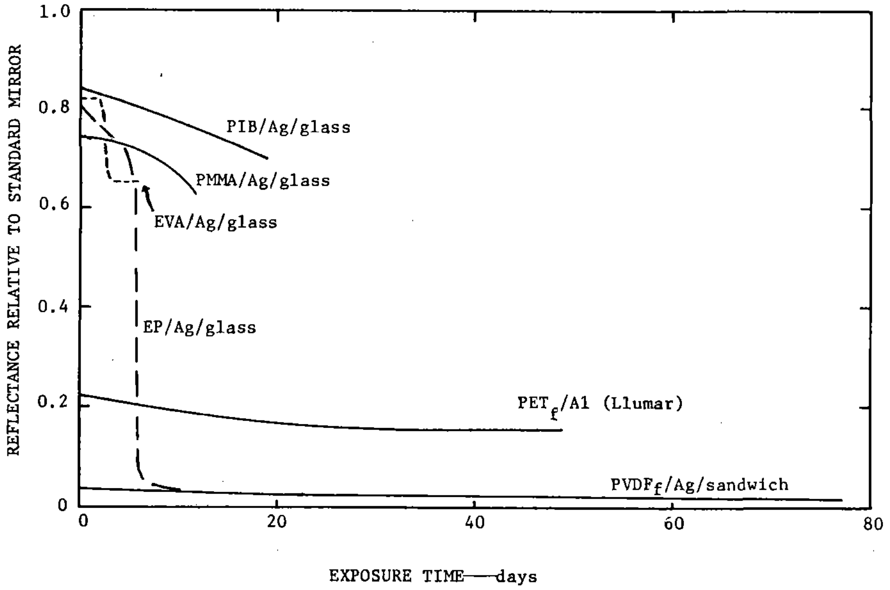

FIGURE 1 RELATIVE REFLECTANCE FOR WEATHERED POLYMER/MIRROR COMBINATIONS

Physical Failure: Delamination

Physical failure was evident as delamination of polymer and mirror during weathering of PMMA/Ag/glass. Because the polymer in PMMA/Ag/glass showed no detectable degradation during weathering, polymer degradation does not contribute significantly to delamination of PMMA. We believe, however, that the rigidity of this polymer probably causes physical delmination.

Various factors lessen or eliminate this delamination. For example, thinner PMMA films weather longer before delamination occurs. Furthermore, delamination can be reduced by changing the mirror assembly preparation so that silver is deposited directly onto a preformed polymer film instead of the polymer being cast over a mirror deposited on glass. An alternative approach to preventing delamination could be to make the polymer more flexible through copolymerization.

Chemical Failure: Interface Reaction

Chemical failure of polymer-coated mirrors has been detected (1) at polymer-silver mirror interfaces and (2) at the backs of first-surface mirrors (silver and aluminum) when the backs are not adequately protected. Reaction at the polymer/mirror interface, observed only for silver mirrors coated with EP, EVA, and PIB, was indicated by varying degrees of loss in reflectance and degradation of the polymer (EP/Ag/glass >> EVA/Ag/glass > PIB/Ag/glass best). The most noticeable change was selective yellowing only where the polymer was in contact with the silver. The color is associated with both the mirror and polymer, and its appearance is light-dependent. Interface degradation apparently does not result from any appreciable reaction of the mirror with corrosive gases permeating in from the atmosphere.

We suspect the antioxidants present in these polymers contribute to degradation of the polymer/mirror interface. Thus, extraction of most of the antioxidant BHT from PIB prior to mirror assembly fabrication significantly improved the stability (reflectance) of the mirror upon weathering. The three polymers that exhibit polymer-silver interaction and yellowing all contain related hindered phenol-type antioxidants; EVA and PIB contain BHT, and EP contains Irganox 1076. In general, BHT and other hindered phenolic stabilizers are ineffective in the light. Other more suitable stabilizers should be found.

Chemical failure of quite a different type was observed for the first-surface mirrors $PVDF_f$/Ag/sandwich and PET_f/Al (Llumar). The transparent, almost chalky, spots that these mirrors developed upon weathering appeared to account for the early, moderate losses in reflectance. The spotty nature of the mirror degradation, coupled with a general lack of polymer degradation, suggests that mirror deterioration results from reaction between the inadequately protected backside of the mirror and the surrounding atmosphere. We suspect that our sandwich assemblies did not give an adequate atmospheric seal. If atmospheric degradation of the mirrors is occurring, sealing the backs with a protective coating or paint should improve their weatherability.

CONCLUSION

Based on our findings, recommendations for polymer coatings for subsequent, semiquantitative environmental evaluation can be made. The PET-, PVDF-, PIB-, and PMMA-containing combinations were the most durable, and they should be studied further. However, the final polymer formulation and polymer/mirror assembly cannot necessarily be specified.

THIN GLASS FOR SOLAR THERMAL APPLICATIONS

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Corning Glass Works
Corning, New York

SERI funded runs of Corning's new 7809 Solar glass in 1979 and 1980. This glass had been developed from wants cited by various DOE personnel at SLL, SLA, and SERI. These wants were higher solar transmission, resistance to weathering and chemical attack, surface uniformity below 2 mr and cost-effective producibility. The thickness range contemplated ran from .25 to 3.17 mm (.010" - .125"). The principle of Corning's Fusion Process had the potential of meeting these targets.

The first run of this new glass was made in a small prototype fusion tank. The purpose of this run was to verify the properties of this new solar glass and to determine if the composition created any problems with fusion forming. From this run the glass properties were confirmed as well as its compatibility with the fusion process. Thicknesses from .9 to 3.17 mm (.035" - .125") were made in sample quantities. Surface quality goals were not achieved due to the lack of sophisticated controls on the small prototype equipment. The significant achievement was that at all thicknesses run, the solar transmission was in excess of 91.5%. This compares to the theoretical maximum of 92%.

The second run was made in the full scale fusion production facility at Blacksburg, Va.. The purpose of this run was to verify scale-up capability and production rates, also to determine how thin the glass could be made with the existing equipment. Thicknesses from .9 - 3.17 mm (.035" - .125") were demonstrated in widths to 1.22 m (48") and lengths to 3.35 m (132"). Shortness of available time and a mix of composition from a prior melt created conditions that prevented good surface quality from being produced. However, identification of the equipment modification needed to produce thicknesses down to .5 mm (.020") was made. Cutting and handling appear to be the only areas of concern for the production of large sheets below 1 mm (.040").

The purpose of producing thicknesses below 1.5 mm (.060") would be for the linear collector parabolic trough applications.

There are four methods by which glass can be adapted to the parabolic curvature.

1. Hot sagged.
2. Flat, .5 - .9 mm, composite structure - cold formed.
3. Flat, $\leqq$ .25 mm - cold formed.
4. Flat, .9 - 1.27 mm, chemical strengthened - cold formed.

Corning has concerns about items 1, 2, and 3.

1. <u>Hot sagged</u>

   Accuracy and consistency.
   Difficulty in mirroring curved shapes.

2. <u>Cold formed composite structure</u>

   Complexity of assembly.
   Bi-metalic strip effect.
   Long term fatigue at the bond line.

3. <u>Cold formed $\leqq$ .25 mm thickness</u>

   Glass production, handling and assembly problems.
   Mirroring of thin sheet.

As regards to item 4, tests run to date on this concept have demonstrated its ease of handling and assembly, toughness and high output efficiency.

In line with the above, Corning has developed another new solar glass, having the features of 7809 and being capable of deep case strengthening. This new solar glass would replace the existing 0313 chemical strengthened glass for trough applications as well as 7809 for the flat heliostat applications. This makes it possible to have one glass which could serve all of the solar market applications. This consolidation would create greater volumes for the production run resulting in better overall costs.

Finally, the use of thicknesses above .9 - 1 mm (.035" - .040") allows today's state-of-the-art techniques for cutting, handling, shipping and mirroring to be maintained. Historical learning curves could be used. Few, if any, new process developments or special equipment would be needed. Capital would only be required for expansion purposes.

EXPOSURE TESTING OF SOLAR MATERIALS

T. E. Anderson
DSET Laboratories, Inc.
Phoenix, Arizona 85029

INTRODUCTION

During the past year, DSET Laboratories, Inc. has been under contract to the SERI* to continue development of information for inclusion in a solar materials design handbook. The primary objectives of this program are to develop new materials information for a current data base and to validate the existing data base.

The scope of this program is to subject materials to both real-time and accelerated exposure tests. Optical and physical property measurements are made at periodic intervals, the goal of which will be to report the retention (or loss) of property as a function of exposure. This information will be furnished as data sheets in handbook format.

There are several features that distinguish this program from previous materials testing programs: 1) All materials are commercially available and were purchased from distributors or manufacturers without their knowledge of the purpose; 2) Exposure intervals are based on the total ultraviolet radiation deposited (specifically in the 300- to 385nm wavelength region); 3) Most of the test methods employed will simulate actual end-use conditions by utilizing special fixtures designed for that purpose.

Space limitations prohibit a complete discussion of all facets of the program. Therefore, emphasis will be limited to the test methods selected for absorber materials, and a review of the data obtained thus far.

DISCUSSION

The outdoor durability of most materials is generally determined by subjecting them to various real-time exposure tests in the Florida and Arizona environments, or to a variety of laboratory and outdoor accelerated test methods. Most of these exposure tests are applicable for a wide range of materials. In many cases the results will accurately predict the performance of the materials in an outdoor environment.

However, materials that are subjected to specific end-use conditions, such as interior automotive fabrics or solar absorbers and glazings, are generally not exposed to realistic conditions when subjected to current standard test methods (ASTM, SAE, etc.). Consequently, a need has developed for more severe exposure tests to more closely simulate the actual end-use conditions of the material in order to develop meaningful data.

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* SERI Contract XP-9-8215-1

For solar applications, temperature is a key consideration. To achieve realistic exposure conditions for absorbers, several different test fixtures were designed and constructed. During the past several years, DSET, the NBS, and ASTM Committee E44 have employed a variety of ersatz collectors for evaluating the outdoor durability of solar materials. Short of exposing a full-size collector, ersatz collectors afford an economical and realistic method for such testing. Ersatz collectors are defined as test boxes which have an optical (glazings and receiver) and thermal (receiver and insulation) environment that provides no cooling for the receiver, but which is otherwise identical to a flat plate collector.

PROCEDURE

A modification of the ersatz collector developed by ASTM Subcommittee E44.04[1] is presently being used in this program for evaluating the durability of solar absorber materials to real-time exposure conditions (Fig. 1). The collectors were constructed of 24-gauge galvanized steel with outside dimensions of approximately 673mm by 673mm by 83 mm deep (26-1/2 in by 26-1/2 in by 3-1/4 in). A 50mm (2 in) layer of Owens Corning SI 100 insulation was placed in the bottom of the collector, above which was mounted either a selective or nonselective absorber plate. In our tests, Olympic Plating BCO-91 on copper was used as the selective plate and Rustoleum Bar-B-Que Black on copper was used as the nonselective plate. The entire exterior frame of the ersatz collector was painted with Rustoleum Bar-B-Que Black. The removable cover plate is AFG Sunadex® tempered glass.

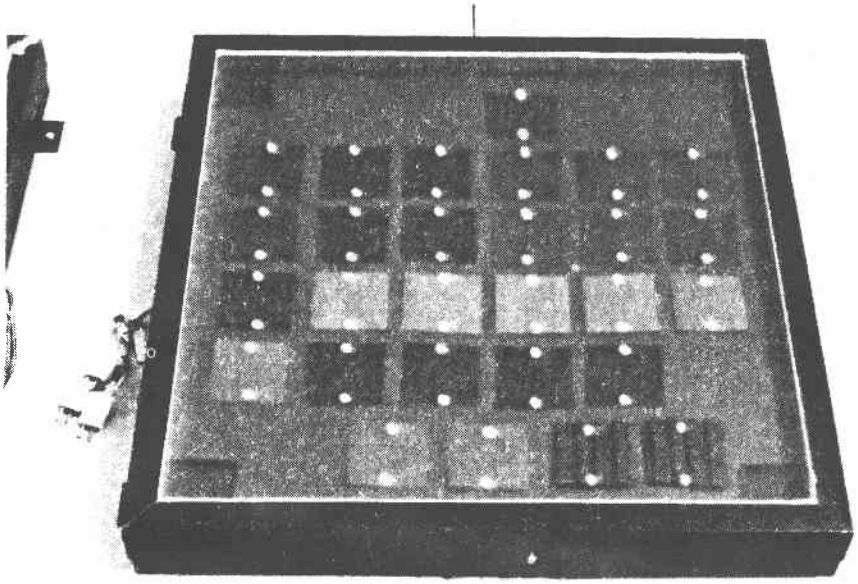

Figure 1. MODIFIED E44 ERSATZ COLLECTOR

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[1] ASTM E44.04.02, Draft Document 110R7; pages 7-11; January 24, 1980.

The test fixtures used for evaluating absorbers employing the EMMA® accelerated outdoor test method (Fig. 2) were constructed of 1.3mm (.050 in) aluminum. The collector covers the entire 127mm by 1397mm (5 in by 55 in) target area of the EMMA® test machine, and utilizes the same Olympic Plating and Rustoleum absorber plates that were used for the modified E44 collectors. No insulation was used in the EMMA® test collector. AFG Sunadex® tempered glass was mounted 25mm (1 in) above the absorber plates (Fig. 3).

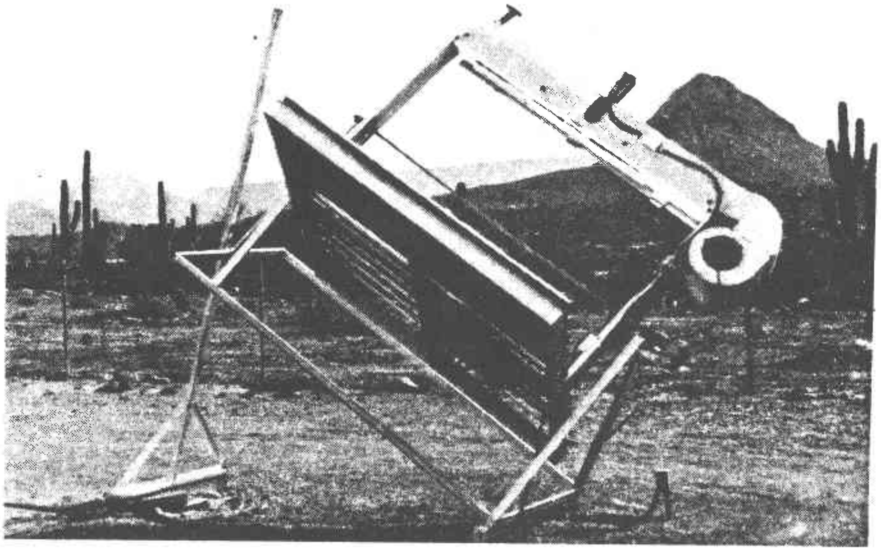

Figure 2. EMMA® TEST MACHINE

Selective absorber candidates were cut into 75mm by 75mm (3 in by 3 in) test specimens, and were mounted as received to the selective absorber plates in the ersatz collectors. The nonselective absorber candidates, most of which were supplied in liquid or aerosol form, were applied to primed 75mm by 75mm (3 in by 3 in) copper substrates following manufacturers' recommendations. After air drying for 48 to 72 hours, the specimens were baked at 163°C (325°F) for 24 hours. Dry film thickness for the test specimens was 0.04 to 0.05mm (1.5 to 2.0 mils).

Hemispherical spectral reflectance and total emittance measurements were made on the specimens prior to installation in the ersatz collectors. At-latitude exposure of both selective and nonselective collectors is being conducted at DSET's New River (Arizona) and Compton (California) facilities; at LASL in Los Alamos, New Mexico; and at South Florida Test Service in Miami, Florida. Exposure of the collectors to the EMMA® outdoor accelerated test method is being conducted at DSET's New River, Arizona facility.

Additional optical measurements will be made after approximately 3 and 6 months of at-latitude exposure and every 6 months thereafter. The

EMMA® specimens will be measured after the equivalent of 6 months and 12 months of exposure and the equivalent of every 12 months thereafter.

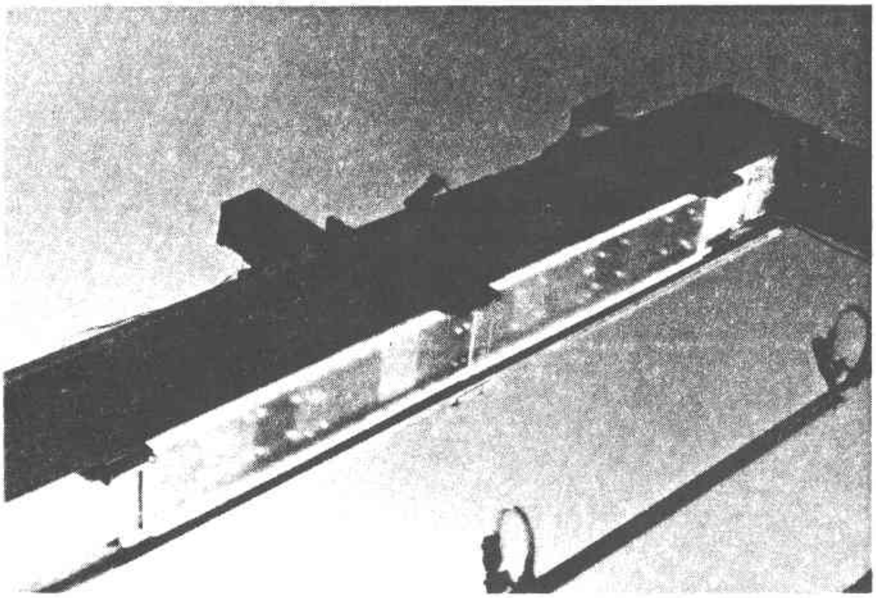

Figure 3. EMMA® ERSATZ COLLECTOR

RESULTS

Only limited optical measurement data is available at this time. Table 1 lists the reflectance and emittance data for some of the specimens after 3 to 4 months of at-latitude exposure at each of the four test sites.

Table 1

ABSORPTANCE/EMITTANCE DATA AFTER AT-LATITUDE EXPOSURE IN MODIFIED E44 ERSATZ COLLECTOR

ABSORBER NUMBER	INITIAL		AZ (4.4 mos)		FL (3.5 mos)		NM (4.0 mos)		CA (3.9 mos)	
	α	ε_T	α	ε_T	α	ε_T	α	ε_T	α	ε_T
09	0.940	0.80	0.906	0.74	0.908	0.75	0.908	0.77	0.908	0.76
10	0.935	0.81	0.916	0.77	0.915	0.79	0.913	0.79	0.913	0.76
11	0.946	0.80	0.925	0.75	0.928	0.77	0.926	0.80	0.928	0.77
14	0.936	0.11	0.920	0.11	0.922	0.11	0.919	0.11	0.914	0.11
20	0.939	0.10	0.929	0.08	0.919	0.11	0.924	0.07	0.930	0.11

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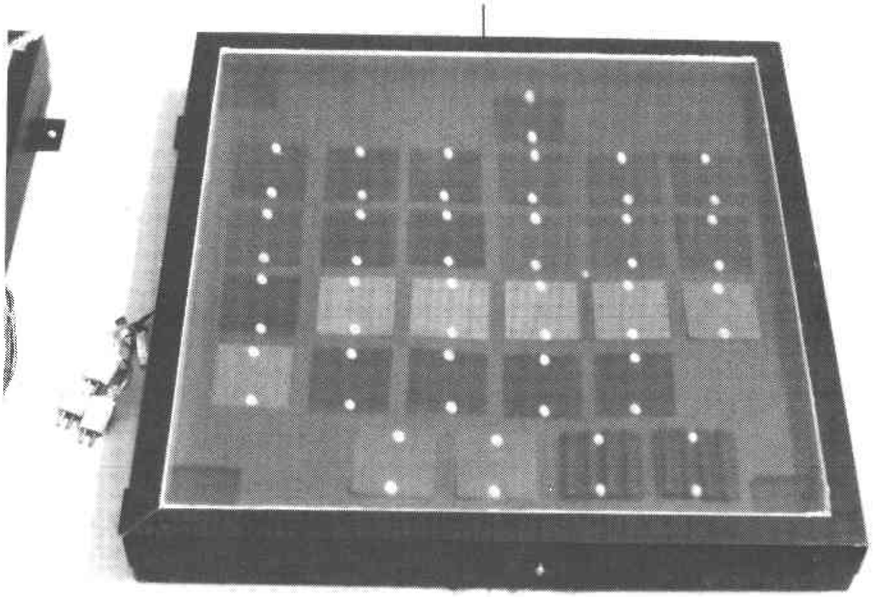

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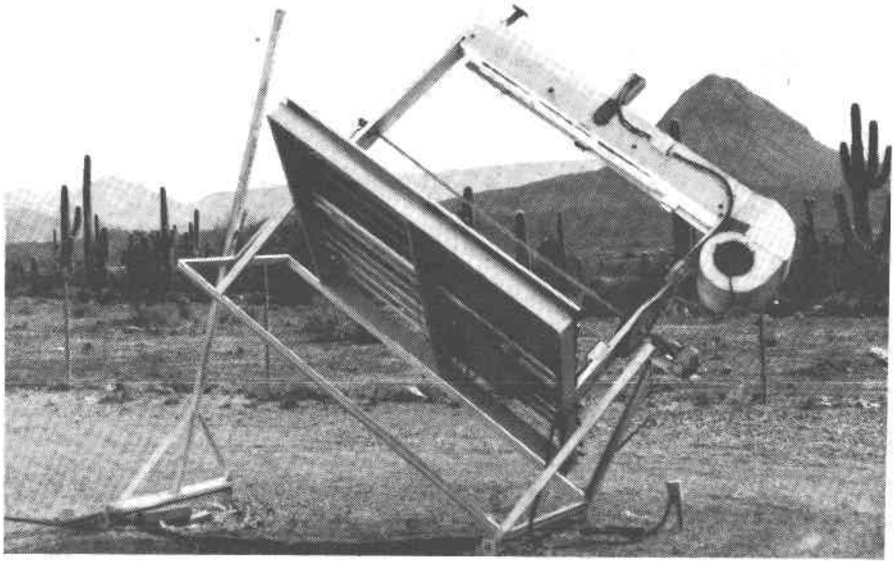

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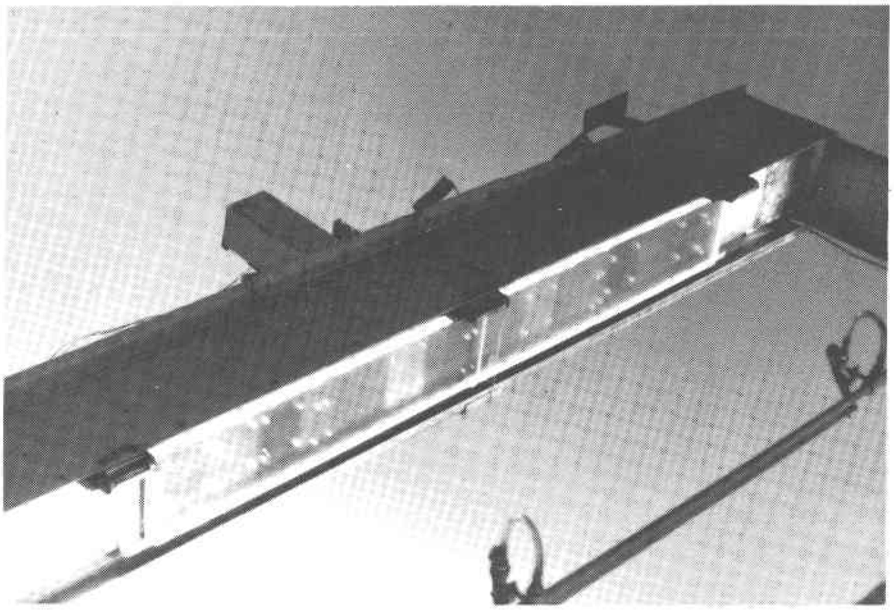

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20	0.939	0.10	0.929	0.08	0.919	0.11	0.924	0.07	0.930	0.11

Plate and specimen temperatures are monitored at each site as well as on EMMA® test machines. Table 2 lists the plate temperatures for each collector versus time-of-year at each site. Table 3 compares EMMA® specimen temperatures to at-latitude specimen temperatures for New River, Arizona.

Table 2

PLATE TEMPERATURES OF MODIFIED E44 ERSATZ COLLECTORS
VERSUS TIME OF YEAR AT EACH SITE - CLEAR DAY DATA

Site	October Sel-NonSel	November Sel-NonSel	December Sel-NonSel	January Sel-NonSel
New River, AZ	133°C-105°C	136°C-107°C	126°C-101°C	121°C- 93°C
Miami, FL	145°C-122°C	111°C- 91°C	117°C- 93°C	124°C-107°C
Los Alamos, NM*	133°C-111°C	115°C- 88°C	122°C- 94°C	126°C- 97°C
Compton, CA	101°C- 78°C	102°C- 82°C	91°C- 74°C	------

* Average monthly peak temperature

Table 3

COMPARATIVE SPECIMEN TEMPERATURES - EMMA® ERSATZ COLLECTOR
VERSUS MODIFIED E44 ERSATZ COLLECTOR AT 34° SOUTH

EMMA® ABSORBER NUMBER	Temp. °C @ I = 1.00 cal cm^{-2}	Temp. °C @ I = 1.33 cal cm^{-2}	Temp. °C @ I = 1.45 cal cm^{-2}
11	66	86	90
14	90	113	127
15	88	114	124

34° SOUTH ABSORBER NUMBER	Temp. °C @ I = 1.10 cal cm^{-2}	Temp. °C @ I = 1.33 cal cm^{-2}	Temp. °C @ I = 1.57 cal cm^{-2}
11	67	79	98
14	88	114	136
15	87	112	135

ACKNOWLEDGMENTS

The author wishes to acknowledge the support, advice and assistance of Mr. G. E. Gross of the SERI; Mr. S. W. Moore of LASL; Mr. W. F. Carroll of JPL; Ms. E. J. Clark and Dr. D. Waksman of the NBS; and Mr. G. A. Zerlaut, Mr. L. F. Bond, and Ms. K. R. Eoff of DSET Laboratories.

APPLIED RESEARCH

RAD APPLIED RESEARCH ACTIVITIES - AN OVERVIEW

J.M. Lefferdo, Project Manager
Solar Thermal Program Branch
Solar Energy Research Institute
Golden, Colorado 80401

Significant progress has been made during the past 1½ years in applied research in the Solar Thermal Energy Systems Program. The thrust of the effort has been to explore innovative concepts that will impact energy subsystems to deliver solar energy reliably and at costs that are competitive with conventional fossil fuel systems. This approach requires pursuing experimental and analytical programs from a technical feasibility stage to a point where the confidence gained will allow progression to the next step, technology readiness. In technical feasibility, small scale testing and/or analytical modelling characterize the primary activity. In technical readiness, having demonstrated proof of concept, greater consideration is given to performance improvement, component optimization and subscale production. Beyond technical readiness the activity progresses through additional stages of system feasibility, system readiness and finally, commercial readiness. The subject of the activities to be described today are limited largely to achieving the technical feasibility.

A number of high temperature solar thermal experiments were successfully completed during FY80. Within the constraints of a limited agenda, however, only a representative few will be reviewed today. In the following several paragraphs, those activities not being reviewed will be briefly highlighted.

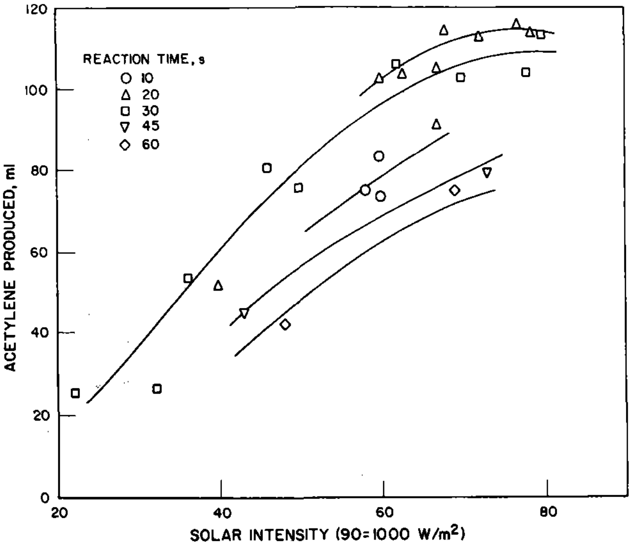

Figure 1 EFFECT OF SOLAR INTENSITY ON CONVERSION

Acetylene made from calcium carbide is a valuable raw material for plastics production which can displace currently utilized petrochemical cracking. Calcium carbide was successfully produced at Odeillo (CNRS) small-scale vertical furnace by the Institute of Gas Technology through conversion of a calcined lime-coke mixture. Reaction temperatures of 1980°C were achieved and valuable operating data on the effects of mixture, composition and heating rate were gathered. Figure 1 gives an indication of the amount of acetylene produced (from calcium carbide) as a function of solar intensity with reaction time as a parameter. The acetylene yield is shown to maximize at 20 seconds reaction time at the highest solar intensity.

A high temperature steam receiver was tested last year at the DOE/ Advanced Components Test Facility (ACTF) at Georgia Tech. One of the purposes of the experiment was to investigate the critical dry-out zone problem commonly associated with once-through steam generators. The experiment, carried out by Solar Turbines International, demonstrated the production of steam at 1500°F and 1500 PSIA under steady state conditions. Figure 2 illustrates the operating outlet steam condition as a function of time. The temperature is shown to remain steady at 1450°F while the pressure, more sensitive to insolation transients, fluctuates from 1100 to 1300 PSI.

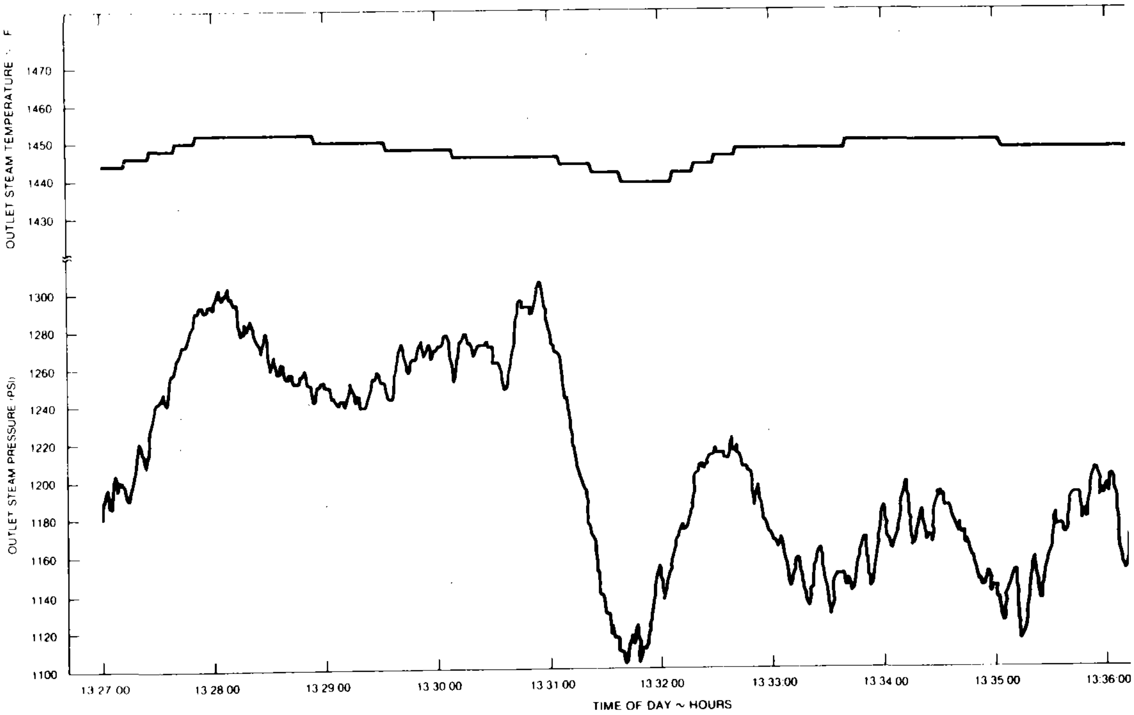

Figure 2 OUTLET STEAM PRESSURE AND TEMPERATURE

Another investigation recently completed at the ACTF was the sodium heat pipe experiment of Dynatherm Corporation. Heat pipes are currently being investigated for Stirling engine applications and as buffer storage devices. A bank of seven stainless steel sodium heat pipes were exposed to 11 kW_t load. Through a modulating calorimeter scheme, performance capability was assessed. Figure 3 shows the operating range of the heat pipes and the limit conditions controlled by the calorimeter operating with varying mixtures of argon and helium as heat transfer control media.

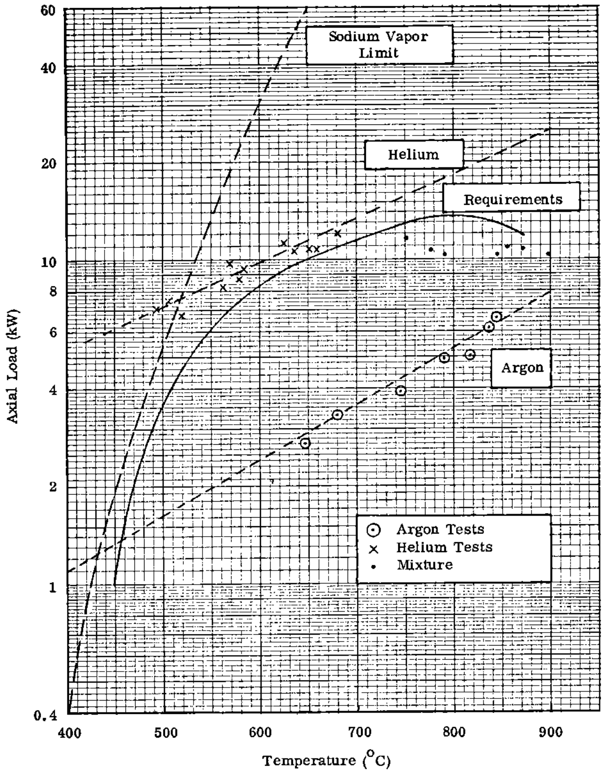

FIGURE 3
SERI EXPERIMENTAL HEAT PIPE TEST RESULTS

In two other experiments associated with high temperature processes, the feasibility of producing hydrogen as a fuel by decomposing cadmium oxide at 1500°C was demonstrated. In addition, an investigation of the rapid pyrolysis of biomass utilizing a solar environment at temperatures of 700°C was carried out. The cadmium oxide experiment was done at the White Sands Solar Furnace by the Institute of Gas Technology and the biomass pyrolysis research, at the ACTF by Princeton University.

Experiments that will be discussed in this session are those that have been recently completed at three test facilities. At the Parabolic Dish Test Site, operated by the Jet Propulsion Laboratory, a high-temperature ceramic matrix receiver was tested by Sanders Associates. Operation of a Brayton receiver at high temperature is potentially more efficient than at lower temperature levels. Preliminary testing concluded in January 1981 and the 1371°C operating temperature goal was reached along with the goal of 427°C temperature differential between input and output gases. Ceramics are required to withstand the severe thermal environment. The goals were exceeded during testing and the materials survived the extreme operating conditions.

Westinghouse Corporation demonstrated the operation of a fluidized bed heat exchanger at the ACTF in May 1980. The potential application for fluidized beds is for central receivers with increased heat transport efficiency. Several different fluidizing materials were tested under varying solar fluxes. A 122 cm long-30 cm diameter quartz tube contained the bed material. Due to abrasion and discoloration during the fluidization process a relatively high reflection of the solar flux resulted and therefore attenuated the energy incident on the bed. The experiment provided conceptual design information on bed height, containment considerations and bed material.

New Mexico State University successfully demonstrated the storage of high grade thermal energy as low temperature bond energy in a reversible chemical reaction at the White Sands Solar Furnace in January 1981. The application of this experiment is for efficient solar energy transport. Initial testing was done in December 1979 in which the feedstock ratio was 3 parts of CO_2 to 1 part of CH_4 with mass a flow of 3 gm/sec at 15 kW_t input. Conversion efficiency (solar to thermal energy) was approximately 33%. The January 1981 tests, utilizing a larger 6 coil reactor and similar feedstock composition ratios, resulted in a doubling of the efficiency to 67% with a power level input of 27 kW_t. Following an endothermic chemical reaction at the receiver end the gases can be transported long distances at near ambient temperatures thus minimizing thermal losses. At the user end of the transport line, an exothermic reaction releases energy for use in industrial heat application and electrical generation.

The means by which energy can be utilized following capture at, for example, a central receiver can be optimized to realize maximum efficiency of conversion. Fluidized bed technology, heat pipe applications, high thermal operations as well as low energy loss thermochemical transport have the potential to reduce costs of delivered solar thermal energy by allowing collector area to be minimized. The captured energy, however, will experience losses before it reaches the heat exchangers. The subject of the remaining presentation is the determination of convective losses for the two classifications of central receivers, cavity and external.

Experimental and analytical programs under the technical direction of Sandia National Laboratories in Livermore (SNLL) are underway to definitize convective losses in large size external and cavity receivers suitable for central receiver systems. A combined experimental/analytical effort at Stanford University and Nielsen Engineering will delineate and quantify external receiver convective loss mechanisms through wind tunnel data and computer prediction techniques. In addition, work at the University of California (Berkeley) is directed at defining the convective loss characteristics for cavity receivers using a similar combined approach of experiment and analysis.

A large scale model experimental program is also being conducted at SNLL using a heated 2 meter cubical cavity for the purpose of defining convective characteristics of a large scale central receiver geometry. Through this complementary approach large scale fluid flow problems can be addressed directly to establish increased confidence levels in the smaller scale work. Large scale effects is the primary complexity associated with central receiver convective loss assessments. Grashof numbers of 10^7 -10^{11} are typical for geometries envisioned for central receiver applications. The current literature in analytical modelling is lacking in this extreme regime.

A combination of better definition of energy loss mechanisms together with improved, innovative and reliable heat exchange components enhance the viability of the solar thermal system. Having defined those concepts that, following feasibility demonstration, have the potential to impact present technology, the follow-up activity involves making recommendations for the next phase, technology readiness. The ideas are carried to ultimate commercial readiness with the goal of providing solar energy delivered to the end user at costs which are competitive with conventional systems and which address reliability and extended lifetime.

AN EXPERIMENTAL INVESTIGATION OF THE CONVECTIVE HEAT LOSSES FROM CAVITY TYPE CENTRAL RECEIVERS

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INTRODUCTION

The thermal energy losses from solar central receivers may not presently be predicted with an adequate degree of certainty. The losses for a commercial size plant may range from 5 to 15 percent at the summer solstice design point. The effect of the reduced insolation that occurs for the remainder of the year may increase the percentage losses by a factor of two. Each percent of loss has been estimated[1] as costing $5.2M over a thirty year plant life. The uncertainties in the loss estimates make economic feasibility studies difficult; accurate knowledge of the losses would result in more accurate economic studies. Furthermore, knowledge of the losses could be used to evaluate the methods and the economic feasibility of actively controlling the losses.

Because of the above uncertainties, a program has been developed to study the energy losses from central receivers. The experiment described here is a portion of that program. It is a study of the convective and radiative losses from a cavity that simulates a cavity-type solar central receiver. The broad goals are two-fold: to provide information for modeling the losses, and to provide experimental data that can be used to check the resultant predictive schemes. The emphasis is on realistic simulation rather than scale modeling; the interior surface temperatures are in the same range as for actual receivers and the size is large enough to be in the same flow regime.

BACKGROUND

Natural or bouyancy-induced convective heat transfer is characterized by the Grashof number, Gr, where

$$Gr = \frac{g\beta(T_W - T_\infty)L^3}{\nu^2} \qquad [1]$$

It has been shown[2] that for high temperature surfaces, an additional dimensionless parameter related to the temperature, such as the ratio of the surface to freestream temperatures, is required to fully specify the similarity problem. This means that to study the convection from a central receiver, similar surface temperatures are required. The remaining variable, the characteristic length, L, in equation 1 must also be the same to insure that the value of Gr is the same. The characteristic height of the cavity experiment is sufficiently large so that the Grashof number is within an order of magnitude of several actual cavity receivers. Additional requirements included the Prandtl number, Pr, which is a function of the fluid properties, and geometric similarity.

EXPERIMENTAL APPARATUS

The experimental cavity is shown in Figure 1. Peripherals to the experiment include the electrical power controller, the operating console, the instrumentation traverse, and the data acquisition system.

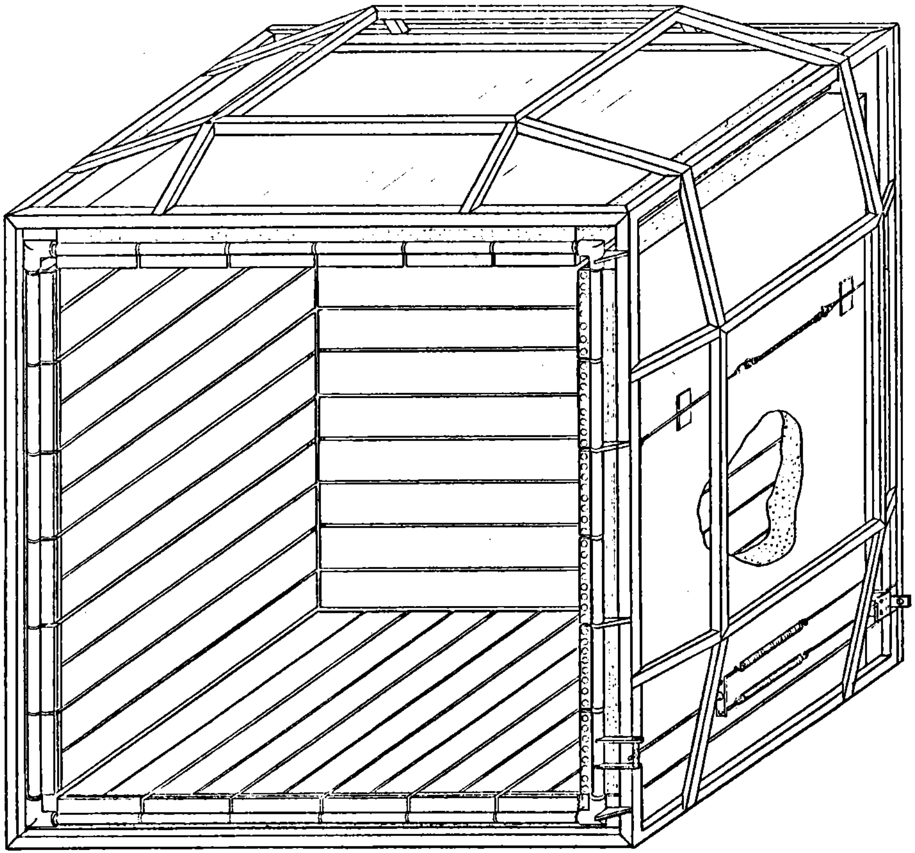

Figure 1. Cavity Isometric, Undercarriage Not Shown

The cavity geometry is that of a cube with one side open with an inside dimension of 2.15 m. The design temperature for all five interior surfaces is 815°C. The surfaces are heated electrically with a 500 kW power controller. Each surface is composed of twelve strips of 0.64 mm thick Inconel 600, 17.2 cm wide. The strips are electrically connected in series. The connecting bus bars on one end of each side rotate to absorb the 2.5 cm thermal expansion of the strips and to maintain enough tension to keep then flat. All of the bus bars are water cooled to prevent oxidation between the bus bars and the heater strips. If oxidation were to occur, Joule heating would take place in the Inconel between the bus bars. This phenomena was shown to be a problem in a prototype panel. The present design was also tested in a prototype and was found to be satisfactory in avoiding corrosion.

A 10 cm thick layer of rigid ceramic fiber insulation forms the walls of the cavity. The heater strips are pulled flat over the surface of the insulation. The insulation reduces thermal losses from the outside cavity walls due to conduction and provides a nearly airtight seal. The thickness is a tradeoff between minimizing conduction losses and minimizing the time necessary to reach steady-state. At design point, the conduction losses are nearly constant after three hours at about 1.4 kW/m^2. This represents about 6.5% of the input power.

The supporting frame surrounds the cavity and provides support for the insulation and for the bus bars. The undercarriage is wheeled and mounted on tracks so that the cavity can be moved into the building when not in use. A hinge connects the main frame and undercarriage and allows the cavity to be tilted to as much as 35° in a down-looking aperture orientation.

The cavity must be operated with the aperture outside the host building because of the large energy release. The operating position is in a 3.7 m x 3.7 m doorway. Large (4.5 m x 4.5 m) curtains on either side and a dirt embankment 7 m in front of the cavity should provide a quiescent environment for natural convection tests.

A traverse is mounted on the exterior building wall. It is water-cooled and provides 3.6 m x 3.6 m x-y motion in a vertical plane 0.6 m in front of the cavity aperture plane. The traverse is a horizontal beam, with an enclosed water channel on the side facing the cavity. In the back of the beam, sheltered from the radiation, a stepping motor drives the transducer mounting plate in the horizontal or x-direction. The beam is moved in the vertical or y-direction by a stepping motor/ball screw combinaton on either side. The transducer mounting plate has coolant water and air, mounting space, and fasteners for mounting a variety of transducers.

The power controller is a 480 V, 3ϕ, SCR, phase-angle controller. It is capable of controlling 1400 kW although the cavity will only use a maximum of 500 kW.

The operating console is in two sections; one provides for safe operation and monitoring of the cavity and the other provides control of the traverse and instrumentation. A variety of safety interlocks automatically remove power from the controller if water flow is sensed in the fire sprinkler system or if coolant flow to the traverse or power controller is below a set level.

EXPERIMENTAL APPROACH

There are two central goals for the experiment. The first goal is to conduct flow visualization experiments and make flowfield measurements to provide information for modeling the problem. The type of information obtained is essential to any new fluid dynamics problem such as this. The modeling information can be used to develop general predictive computer codes as well as simplified analytical estimating methods.

The second goal is to measure the energy losses. The results can be used in correlations to estimate the losses from receivers with similar geometry and to provide energy loss data that can be used to appraise the accuracy of predictive techniques.

Inherent in the above goals are measurements that are used to describe or define the boundary conditions of the experiment. These measurements include such parameters as surface temperatures, ambient air temperatures, and surface radiative properties.

The experimental approach emphasizes measurements in the aperture plane. The geometry is ideal for control volume measurements because the losses due to convection and radiation are confined to the cavity opening. The convective and radiative losses will be obtained by measuring the local loss distributions in the aperture and then integrating to find the total losses.

The convective heat losses will be determined by measuring the local enthalpy flux distribution in the aperture plane. The total convective losses are then given by

$$Q_{conv} = \int_A c_p \, (T-T_o) \, \rho\vec{V} \cdot d\vec{A} \qquad [2]$$

where the product $\rho\vec{V} \cdot d\vec{A}$ is used to specify the mass flux through the aperture plane. The specific enthalpy is $c_p(T-T_o)$. Measurements of the conduction losses through the insulation and of the power into the cavity will yield an energy balance closure, which may be used as an overall check.

INSTRUMENTATION

Velocity measurements in the aperture plane will be made with two different probes. A bidirectional probe developed for building fire studies by NBS (3) will be used to obtain directional information of the flow. The probe, used at NBS for velocity measurements under similar conditions to these, yields a pressure difference similar to the difference between total and static pressure. Unlike a pitotstatic tube, however, they do not measure a true static pressure and therefore must be calibrated. Calibration at NBS of the probes modified to provide self-cooling and built at SNLL showed that both viscous and directional effects were significant. These effects limit the usefulness of these probes in this application. The bidirectional probes are, however, best suited for determining the flow direction normal to the aperture plane.

Velocity measurements will be made with a pitotstatic tube. Calibration at NBS showed no viscous effects and subsequent studies have shown that errors due to angular fluctuations will be small. It is emphasized that the calibration included the entire measurement system: probes, pressure transducer, and electronics.

Temperature measurements in the aperture plane are made with a 0.16 cm diameter sheathed type K thermocouple. It is shielded, aspirated, and the sheath and shield are gold-plated. Studies have shown that the air temperature fluctuations in the aperture may be as high as ± 125°C. The temperature measurement is sampled over a time interval and averaged to find the mean temperature at each measurement location in the aperture.

Surface temperature measurements are obtained by placing sheathed, ungrounded thermocouples between the inconel heating elements and the insulation. This approach minimizes the problems of electrical noise and high voltage affecting the thermocouple signal or measuring electronics.

Radiant heat fluxes will be measured with thin foil calorimeters or radiometers. Calorimeter measurements require correction for convective heat transfer errors and radiometers require correction for limited field-of-view errors. This instrumentation task has not yet been fully evaluated.

Preliminary visualization of the flow has been made with smoke and by shadowgraph techniques. Although neither approach has produced useful movies, they have illuminated the flow patterns for observers. Both show promise for both still and moving pictures.

FUTURE EFFORT

The cavity and traverse construction and check-out phases are complete, both are operational and perform as designed.

The near-term emphasis is on the aperture measurements. The mean air velocity and temperature measurements are difficult to obtain; the mean velocities are low, the transducers are in a high radiant flux field, and both the velocity and temperature are fluctuating. High confidence in these measurements will come from knowledge of the fluctuating portion of the flow combined with careful uncertainty analyses. Radiant flux measurements will begin with calorimeters corrected for convection errors.

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OVERVIEW OF THE STANFORD/NEAR PROGRAM
CONVECTIVE LOSSES FROM SOLAR CENTRAL RECEIVERS

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INTRODUCTION

This paper introduces the Stanford/NEAR program and gives some of the background which led to its inception. The program has two parts. Nielsen Engineering and Research is conducting a series of large-scale experiments on heat losses in mixed convection (a heated vertical surface in a grazing cross wind), and Stanford University is developing a three-dimensional boundary layer code to predict heat transfer under such conditions. Results from the experiments will be used in developing the computer program.

Plans for large-scale electric power generation using solar energy envision an array of heliostats focusing sunlight onto a high-temperature receiver. The receiver heats a working fluid (air, water, molten salts, or liquid metals) which is subsequently used in a thermal power plant cycle.

The high-temperature receiver loses heat to its surroundings both by radiation and by convection. These losses are significant to the economics of power generation, and accurate prediction of the losses is necessary if accurate predictions are to be made of the future cost of solar electric energy. Roughly speaking, each 1% loss will cost the consumer about $5 million over a 30-year lifetime for a 100 MW solar power plant (Siebers, D., "Natural Convective Heat Transfer from an External Receiver," Sandia report 78-8276, Dec. 1979).

Receivers currently proposed for solar central power plants can be divided into two categories, "cavity" and "external"; each has its own characteristic mechanism for losses, and both must be understood. The present program is related to the convective losses from external receivers and does not address cavity receivers.

A representative external receiver might be a cylinder mounted on top of a tower and heated more or less uniformly around its perimeter. The cylinder might be from 10-30 m in diameter and 10-30 m in height. Its external surface may be made of flat panels, or tubes of perhaps 2 cm in diameter. The surface temperature may be between 500 and 650°C. The system may be expected to operate in winds of up to 10-15 m/s. Under these conditions there will be a complex flow field around the heated cylinder, with regions of boundary layer flow and separated flow, driven both by free convection and by the incident wind, as indicated in Figure 1.

The surface-attached zones of this problem can be characterized as mixed-flow convection with the buoyant force orthogonal to the free-stream velocity. Reynolds number and the Grashof number are two important descriptors in this problem. A typical receiver will operate at Reynolds numbers (based on cylinder diameter) up to 10^7 and Grashof numbers (based on cylinder height) of up to 10^{13}.

Figure 1 shows four zones of the flow: a stagnation region, a laminar boundary layer zone, a turbulent boundary layer zone, and a region of detached flow. All four zones are affected by end effects. In addition, there are two important boundaries: the transition zone and the separation zone.

The flow field around an external receiver, complicated as it is by the end effects, becomes even worse with heat transfer. The high surface temperature will induce significant buoyancy effects and will cause large changes in fluid properties. In the laminar regions, the stagnation zone and laminar boundary layer zone, these effects could likely be dealt with by present computer codes, at least as far as the steady-state behavior is concerned. The transition location is likely to be significantly affected, and present transition criteria may not acknowledge this. If there is a saving grace for this aspect of the problem, it is that transition is so poorly understood, even in simpler situations, that one more complication (buoyancy) is not the principal problem. As the boundary layer moves around the surface, it is subject to the effects of pressure gradients, convex curvature, and surface roughness, as well as to the effects of buoyant forces orthogonal to the boundary layer shear force. Of these four effects, the effect of the orthogonal body force is least well understood. There have been several studies published within the past ten years, at Stanford and elsewhere, concerning the effects of pressure gradients (both favorable and opposing), of surface curvature (both convex and concave), and surface roughness. This is not to say that these problems have been solved completely, far from it, but there do exist enough data to support some reasonable conjectures as to the mechanisms by which these boundary conditions alter the response of the boundary layer. By contrast, however, there has not been any study reported concerning the effect of the orthogonal body force due to buoyancy on the heat transfer characteristics of a turbulent boundary layer. Given only one experimental program to do, it seemed most important to address this new problem area.

The objective of the present program, then, is to conduct a set of experiments which will provide enough data to support development of a predictive model for heat transfer through a turbulent boundary layer subject to orthogonal buoyancy forces, and to incorporate these results into a computer code which will accommodate the other conditions which exist in an external receiver configuration.

The ideal situation for studying the orthogonal body force problem is a heated, vertical, flat plate, parallel to an incident wind. This would produce the simplest boundary layer and would most clearly reveal the changes induced by the orthogonal body forces. Such a boundary layer could be studied in detail. With both the surface heat transfer and the boundary layer structure available, it would be possible to develop a turbulence closure model for this new situation, with minimum uncertainty.

The results of these experiments will be interpreted in terms of mixing length and turbulent Prandtl number, as a first modeling effort. There exists a well-documented library of mixing length models covering the separate effects of curvature, roughness, and pressure gradient. Expressing the buoyancy effects in this same form would facilitate combining the new results with the old. Once a predictive model is working, with the combined effects accounted for, future modeling efforts could investigate other turbulence closures.

It is also necessary, however, to obtain a check on the validity of the prediction of the final computer code. For this reason, a second test was proposed: a short cylinder, of reasonably large scale. The results of the short-cylinder test would not only reveal the overall degree of agreement between predictions and reality, but would also produce data on the effect of the buoyancy forces on the transition and separation regions, mainly through flow visualization and examination of the surface heat transfer. These are the two principal experiments proposed: a large vertical, heated flat plate parallel to the wind, and a large, short cylinder.

THE PROGRAM

A three-year effort has been begun with the objective of developing a computer code and a supporting experimental data base which can be used to predict the convective losses from an external receiver.

The computer code is being developed at Stanford University, under the direction of Professor Joel Ferziger. The experiment is being constructed and will be operated by Nielsen Engineering and Research, Inc., under Dr. Richard Schwind's direction. Professor Robert J. Moffat, Stanford University, serves as Technical Director, coordinating the two programs. The overall effort is monitored for Sandia Laboratories, Livermore, California, by Dr. John Kraabel and Dr. Robert J. Gallagher.

The predictive program is being developed for the case of a temperature-dependent body force in the vertical direction, with a horizontal flow along the surface. It will require, as input, information about the distribution of velocity and temperature along each upwind boundary and in the far field, and will calculate the velocity and temperature field over the region, including the surface-heat-transfer coefficient. Different turbulence models will be tested, as well as different criteria for transition and separation in response to pressure gradients and buoyant forces. Pending acquisition of the new experimental results, it will be assumed that the responses of the mixed-convection boundary layer to the pressure gradients, surface curvature, and surface roughness can be anticipated, based on results from forced-convection flows, by incorporating these effects into the turbulence closure model.

The overall experimental program must provide three things: (1) sufficient boundary layer structural detail for guidance in turbulence modeling, (2) identification of the locations of the transition and separation regions, and (3) measurement of surface heat-transfer rates on the flat plate and the cylinder to check the final predictions. It was agreed that surface heat-transfer rate, mean-velocity distribution, and mean temperature distribution would provide sufficient structural information and that no turbulence data would be sought.

A large-scale test approach was adopted, to minimize the extrapolation required between experimental data and probable field conditions. It would obviously be less expensive to test a smaller model at conditions aimed at scaling the Reynolds/Grashof effects, and one might ask: Why such a large-scale test? The answer, in part, lies in the high cost of uncertainty in the results: approximately $5 million per percent. It is difficult to assure the validity of any substantial (i.e., factor of two or more) extrapolation of a data set. The more nearly full-scale the test is, the more confidence can be held in its validity. A second consideration is that one large-scale experiment, carefully conducted and accepted by the research community, will establish a benchmark against which future scaled-down experiments can be judged. Another important point is that the receiver problem displays strongly variable properties through the boundary layer, as a consequence of the large temperature drop across the boundary layer. It is difficult to scale a variable properties problem with any significant reduction in size and assure that a valid scaling has been accomplished. For all of these reasons, a large-scale experiment was proposed.

The first flat-plate tests will use a 3m × 3m test plate whose surface is composed of thin, stainless-steel strips, electrically heated to 600°C and exposed to a grazing wind up to 9 m/s. Surface heat transfer coefficients will be measured and detailed traverses made of the boundary layer to determine mean temperature and mean velocity. These data will be used to develop a turbulence closure for the predictive program.

The cylindrical model tests will incorporate flow visualization, as well as measurement of the local surface heat-transfer coefficient, and some boundary layer traverses. The main objectives will be to locate the transition and separation regions, as functions of the Reynolds number and Grashof numbers and to check the heat loss predictions. This information will provide criteria for transition and separation.

These are large-scale experiments, yet the data must be of laboratory quality. This poses severe problems in the design and quality control of the experiment. The guiding principal has been "a priori uncertainty analysis," a technique pioneered at Stanford, whereby the choices of technique, of instrumentation, and of operating procedures are guided by consideration of the required precision of the final data, following strict analytical rules for the evaluation of uncertainty.

PRESENT STATUS

A prototype, 2 1/2 × 1/2 m, was built and tested to develop design criteria. Following this, the test facility and 3m × 3m plates were designed.

The test facility and 3m × 3m test plate have been finished and the plate installed in the tunnel. Flow-quality tests have been completed, and preliminary operations have been made. As of April 8, the system is ready for instrumentation shake-down. Following those diagnostic tests, baseline and qualification tests will begin. Production data taking is expected to begin before the end of April.

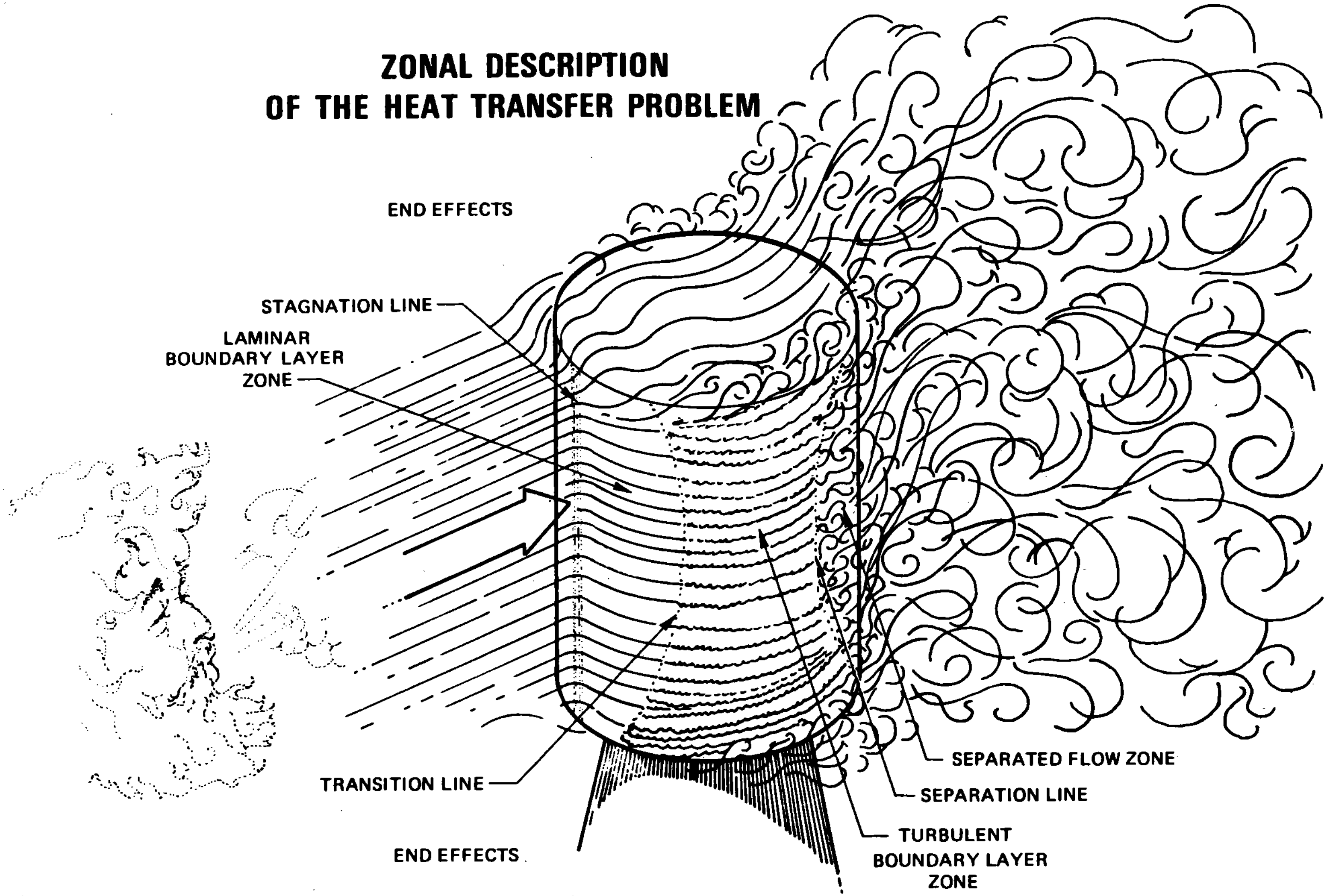

Figure 1. Zonal Description of the Heat Transfer Problem.

FLUIDIZED BED SOLAR THERMAL RECEIVER: TEST RESULTS

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INTRODUCTION

A bed of solids particles becomes fluidized when suspended in an upward flowing gas stream. At higher flow rates, vigorous bed mixing occurs in the wakes of gas bubbles which rise in the bed, making it suitable for use as a receiver because:

- The high solids-gas interfacial area results in excellent heat and mass transfer between these two phases.
- The excellent mixing results in a bed of very uniform temperature (very high effective thermal conductivity).
- The solids movement acts to disturb boundary layers on containing walls and immersed heat transfer surfaces, reducing film heat transfer resistance, and causing rapid heat transfer between these items and the bed.

A gas, a solid, or a secondary fluid can be used as the heat transfer medium, so the receiver can be a gas heater for gas turbine power or for process heat; a heterogeneous chemical reactor for fuel conversion or synthesis, or for mineral processing, a particulate solids heater for thermal energy storage, or a steam generator via heat transfer surfaces submerged in the bed.

RECEIVER DESIGN

Westinghouse, in cooperation with Georgia Tech, has investigated the suitability of a fluidized bed as a solar thermal receiver that might one day be applied to some of these processes (DOE contract through SERI No. XP-9-8321-1). A fluidized bed atmospheric pressure air heater (Figure 1) was designed and built to be simple, representative of a specific application, and yet to provide information relevant to other applications. In this design concentrated solar energy is transmitted by a transparent vessel containing a bed of particles that absorb the

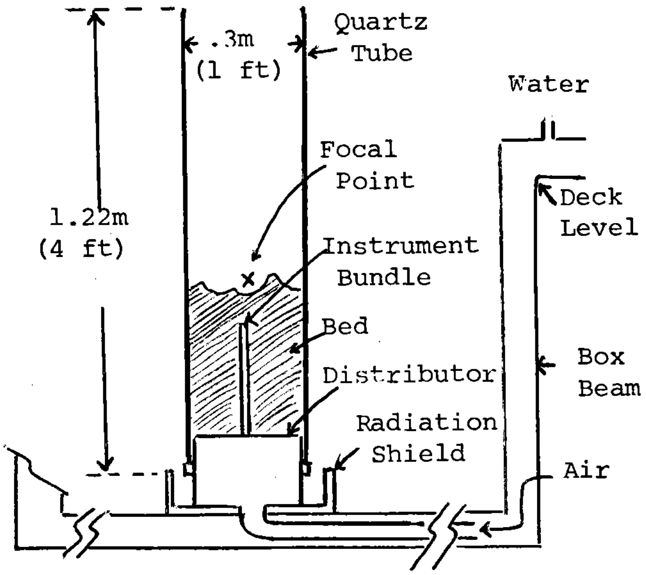

FIGURE 1 RECEIVER SCHEMATIC

energy, are mixed, and transfer heat by convection to the gas stream. The bed is large enough that scale-up can be carried out with confidence.

The fluidized bed was contained in a 0.3 m (1 ft) OD by 1.2 m (4 ft) long by 2.5 mm (0.1 in.) wall transparent fused silica cylinder. The bed was supported on a gas distributor/air plenum assembly made of stainless steel. An instrument tube containing thermocouple and pressure sensor leads penetrated the distributor into the bed. The receiver was supported on a single water-cooled steel beam running across the deck opening, about 4 ft below the deck. Fluidizing air was supplied via a pipe running within the support beam. The air cooled band clamp and instrument line bulkheads were protected by a coiled water-cooled barrier.

TEST PROGRAM AND RESULTS

Over 75 hr of exposure of the receiver to focused solar energy in 75 tests at the Advanced Components Test Facility at Georgia Tech. A variety of bed materials were tested (Table 1). In each run steady state data was recorded at each of a variety of gas flow rates. Included was a flux map and integration generated by a cylindrical geometry scanning flux calorimeter provided by Georgia Tech.

Mechanically, the receiver and its components performed well. The window was durable, but became discolored when silicon carbide or copper (only) were used as the bed material. The discoloration did not cause mechanical damage or identifiably impair receiver performance, but did mask the expected differences in radiation properties of the bed materials.

Table 1 summarizes the test results, absorptances being rough estimates based on a heat balance analysis given in our final report. As anticipated darker materials were generally better absorbers and effectiveness declined at higher temperatures. Performance can be readily maximized at the proper point in the development process by placing the receiver within a cavity (considered not cost effective in the current program). A frequent and surprising result was a non-uniformity in bed temperatures at some conditions, a result attributed to poor mixing at the low gas velocities required to prevent excessive carryover of bed material. This limitation can be readily avoided by providing a larger disengaging height, using a cyclone collector, or continuously feeding solids.

CONCLUSION

The use of a large fluidized bed as a solar thermal receiver has been demonstrated. Standard fluidized bed design techniques are suitable for receiver preliminary design. These techniques, and the use of a cavity, can be used to maximize receiver effectiveness at the appropriate point in the development process, as the most promising applications for these versatile devices are identified.

ACKNOWLEDGMENT

We are grateful to D. H. Neale and C. T. Brown of Georgia Tech for their valuable partnership in this program, and to J. M. Lefferdo of SERI for his continued support and guidance. L. M. Thomas was responsible for the successful construction and operation of the receiver.

TABLE 1. TEST MATRIX AND RESULTS SUMMARY

Material	Run time hr	Bed Temperature Range K (°F)	Incident Power kW	Energy to air kW	Mean bed absorptance
Copper beads	6.2	449-562 (348- 552)	36-42	14.7-19.1	0.50
Silicon carbide	15.1	433-749 (319- 888)	32-72	11.7-29.5	0.58
Alumina	7.6	495-663 (431- 733)	45-58	13.7-17.4	0.43
Fused Silica	2.2	583-597 (589- 615)	51-54	17.8-24.9	0.54
Sand-large	8.5	404-457 (267- 363)	34-43	13.3-18.0	0.49
-medium	7.0	455-752 (359- 894)	37-79	10.9-18.9	0.38
-small	10.7	475-836 (395-1045)	42-80	8.1-15.9	0.47
-fine	5.4	738-817 (868-1011)	28-36	5.9- 8.6	0.50
Steel mill slag	1.8	496-506 (433- 451)	50-58	23.9-30.5	0.58
SiC/sand mix	5.0	542-661 (516- 730)	34-49	16.2-20.6	0.64
SiC/silica mix	2.4	539-560 (510- 548)	44-39	24.2-25.6	0.70
SiC/lava mix	2.2	590-626 (602- 667)	48-54	20.1-25.9	0.58

THERMOCHEMICAL TRANSPORT TEST RESULTS

by

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Thermochemical receivers are being developed for use in the Solchem energy collection and delivery system [1 - 6]. These receivers use concentrated solar flux to heat a 3 CO_2 + CH_4 working fluid to approximately 900°C and to catalytically convert the inflowing gas mix to an outflowing energy-rich synthesis gas. At a user's site the synthesis gas is converted back into 3 CO_2 + CH_4 with the release of process heat. The use of a closed circulation gas loop with heat exchangers at both the receiver and user ends permits high temperature heat to be delivered through low temperature lines.

Current thermochemical CO_2 reformers are cavity receivers. They are assembled from a stack of converter-heat exchanger receiver elements operated in parallel. These receiver elements are flat, spiral coils containing a tube-in-tube heat exchanger and a single pass catalytic converter section. During the past two years a large number of receiver elements has been tested in an effort to optimize their performance. Two solar power receivers have been operated in the focussed beam at the White Sands Solar Furnace.

At the NMSU Solchem Test Facility single coil reforming receiver elements are individually tested in an environment similar to that encountered in a solar furnace. The reactor under test is housed in a furnace fabricated from slabs of high temperature insulating material. The converter and heat exchanger are positioned within the insulating material around a heated cavity. Eight 750 watt electrical resistive heaters are suspended into the cavity. The radiant heat from these elements simulates the focussed solar beam. In a solar power receiver a stack of perhaps six of these helices would form a cavity whose interior would be illuminated by rays diverging from the focal spot.

Electrical power to the heaters is supplied through a large variable transformer which permits accurate control of the converter temperature from ambient to 1100°C. The test facility does not utilize closed-loop operation. Gaseous feedstock, drawn from commercial cylinders of premixed compounds, is introduced into the reactor at controlled temperature, pressure, and flow rate. Stainless steel tubing and swaged fittings are used throughout the test loop.

Test stand instrumentation permits the measurement of inlet gas temperature, pressure, and mass flow, of the effluent gas temperature, pressure, and composition, and of the temperature of as many as 25 points on the reactor being tested. All temperature measurements are made with sheathed chromel-alumel (Type K) thermocouples. These data are automatically recorded as frequently as once per minute. Inlet gas temperature is maintained constant in the 15 to 25°C range. Inlet gas pressure can be held constant at any value in the range of 100 to 500 kPa (absolute). In most of the work reported here, the inlet gas pressure was held at 404 kPa. Mass flows of 0.1 to 3 gm/sec are measured with a turbine flowmeter located in the feedstock line. Mass flow rates are controlled with a regulator valve in the effluent line. A small fraction (~1 l/min) of effluent gas is routed through two infrared absorption gas analyzers. One of these instruments measures the molar fraction of CH_4 in the effluent, the other measures the molar fraction of CO. From the measured composition of the effluent gas and its flow rate, the power converted to chemical heat of reaction can be calculated. Conversion powers of 3.5 kW with conversion efficiencies of greater than 60% have been observed in single coil tests. Most reforming reactor tests are made with the converter opeating at 900 to 1000°C. The maximum electrical power available to the furnace heaters is 5.4 kW. This furnace constraint is the limiting factor in the testing of high efficiency receiver elements.

Two solar energy receivers have been assembled and operated. These two units were tested at the White Sands Solar Furnace in December 1979 and January 1981 respectively. At this facility, the full power of the furnace is concentrated within a conical envelope with a half angle of 45° and a focal spot of less than 10 cm diameter. In December 1979 the full power capability of the Furnace was 30 kW; in January 1981, 26 kW was the maximum power available. Tests at the solar furnace involved exactly the same plumbing system and instrumentation described above for the laboratory work.

The two solar receivers operated at the White Sands Solar Furnace are designated as the Mark I and Mark II receivers. Both were designed to operate in the 900 to 1000°C converter temperature range with a $3\ CO_2 + CH_4$ feedstock mixture. Results from the Mark I receiver tests were reported previously [7]. Results from the Mark II receiver tests will be shown and discussed in this presentation.

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ECONOMICS AND APPLICATIONS ASSESSMENT

MARKET POTENTIAL FOR HIGH TEMPERATURE PROCESS HEAT*

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1. INTRODUCTION

The potential penetration of solar thermal energy into the industrial process heat (IPH) market depends upon many factors, important among these are the energy use characteristics of industry. Although the overall IPH market is large, there is presently little known about typical facility size and temperature combinations. These questions rarely arise in the context of electrical generation for two reasons: (1) utilities tend to build as large a plant as is practicable, distributing the output to many locations; and (2) electricity is a standard commodity easily transformed to satisfy various end uses. IPH requirements, on the other hand, must be provided on-site and at specific temperatures.

Using recently published data of 1972 United States industrial energy consumption (grouped by Standard Industrial Classifications, SIC) and the number of energy consuming establishments[1], estimates can be made of average consumption rate (megawatts thermal) of energy per site. Incorporating temperature requirements for those industries [2,3], the power consumption ratings required at various temperatures can also be estimated. Combination of these data yields distributions of energy consumption facility sizes at various temperatures. These end use distributions are presented in two forms: (1) the number of facilities of a given size and temperature and (2) the amount of energy consumed annually in facilities of a given size and temperature.

To provide a complementary perspective on the U.S. IPH market, an analysis is done on the types of process heat currently used. All process heat (even at a given temperature) is not equally easy to replace with solar energy. A breakdown of the process heat market by detailed type (steam, direct heat, indirect heat, etc.) is presented.

2. SIZE AND TEMPERATURE DISTRIBUTIONS

2.1 Data Bases

A large number of industrial energy consumption data bases have been compiled for various purposes [1,2,4,5,6]. The energy consumption data base used in this study is taken from Reference 1. Prominent among the sources of information used in Reference 1 are (1) the

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U. S. Department of Commerce, Bureau of the Census, (2) FEA's Major Fuel Burning Installations, and (3) the Department of the Interior's Bureau of Mines. It not only provides the energy consumed by thirty nine of the largest energy using industries, but also the numbers of establishments in each of those industries. The annual energy consumed (in 1972) for these selected industries summed to 14.1 quads (one quad is equal to 10^{15} BTU's) and ranged in size from 31 milliquads (ethylene oxide) to 3.4 quads (steel) in size.

The same reference gives total manufacturing energy consumption as 21.1 quads and the total industrial energy consumption as 25.8 quads in 1972. The Industrial Sector is taken to include manufacturing, agriculture, mining, construction, and transportation. The 39 selected industries in the manufacturing sector should be fairly representative of that sector since they account for two-thirds of its energy requirements. The only alteration of this raw data was the subtraction of roughly 2.4 quads of reducing coke in the iron and steel industry and .8 quads from ethylene for chemical feedstock. For the purpose of deriving combined size and temperature data, the temperature distributions are taken from references 2 and 3.

2.2 Assumptions

Certain definitions are required in order to clearly describe energy consumption patterns by both temperature and size. An industry is the entire collection of all producers of a given product (e.g. all petroleum refineries). An establishment is a single location at which a given product is made (e.g. a specific refinery). A facility is a specific process or group of processes within a plant which require a specific temperature.

Starting from the total energy consumed in each industry, industry-wide assumptions were made concerning the energy use at each establishment to obtain a lower bound on their power consumption ratings:

1. All plants operate 24 hours/day, 365 days/year at full thermal rating.
2. No backup facilities are installed (boilers, burner, etc.).
3. Each establishment is made up of separate facilities, each facility having specific temperature range requirements.
4. The sum of the thermal ratings of the facilities is the rating of the establishment.

Thus, the average establishment thermal rating in an industry is the annual energy consumption of that industry divided by 8760 hours divided by the number of establishments. The average facility thermal rating is some fraction of that establishment rating. That fraction is taken to be the fraction of the industries energy required in a given temperature range as reported in References 2 and 3.

Representing an industry by its average plant size probably presents a lower bound for the plant sizes which solar might penetrate, since newer plants tend to be above average in size (e.g. for ethylene [3]). The facilities present a lower bound for solar plant ratings (energy at temperature) also, since energy cascading, cogeneration, and colocation were not treated. While the total installation energy consumption may be reduced using such techniquies, such multiple uses of a single thermal plant would require larger facility sizes.

2.3 Combined Size and Temperature Distribution Results and Discussion

The distribution of number of facilities as a function of facility size (megawatts thermal) and process end use temperature is shown in Figure 1. More than 60% of the facilities in the U.S. are of sizes less than 3 MW_t and at temperatures below 450°F. Figure 2 which gives the size and temperature distributions by energy consumed (rather than by number as in Figure 1), present a completely different view of this same industrial energy consumption data. If the objective were to impact the largest number of installations, the smaller size, lower temperature ranges would be the principal targets. If, on the other hand, one wished to significantly impact the energy consumed by industry as process heat, the larger (30 to 300 MW_t), higher temperature systems must be targeted. The detailed distribution of industrial energy consumption by facility size and temperature is broadly peaked in the 30 to 300 MW_t range, but the temperatures required appear to increase somewhat as facility size increases. Little energy is required at low temperatures (250°F and below), and that only at the smaller size facilities.

Previous works with which to compare this study are sparse. Dow [7] presented a size analysis of the process steam market only. The same general distributional shape as Figure 2 is in evidence in their steam only market survey. This should be of no surprise since steam is a large part of the industrial process heat sector. More recent work on the IPH market by Gresham shows a similar trend toward larger facilities for industrial process heat up to 100 MW_t, the size where his study ends [8] as does the work of PEDCo.-Environmental [9].

3. SURVEY OF PROCESS HEAT TYPES AND FUELS CONSUMED

Knowing the average size and temperatures of IPH installations is not sufficient to determine which solar thermal technologies may be most generally applicable. The "type" of heat required is just as important. By type, we mean direct heating, process steam, hot water, etc. and also what the current fuel sources are.

In a recent study [11] we detail the U.S. energy consumption patterns with special emphasis on the manufacturing sector. The ECDB [12] and ORAU [13] data bases were found to be especially useful in illuminating the current IPH types used. The total amount of process heat in the former survey is 9.7 quads. There it is shown that sectors 28 and 29 (chemicals and fuels respectively) comprise roughly 5 quads of the fuel required. The IPH temperature requirements for these two sectors are about 60% direct heat above 600°F and 40% process steam.

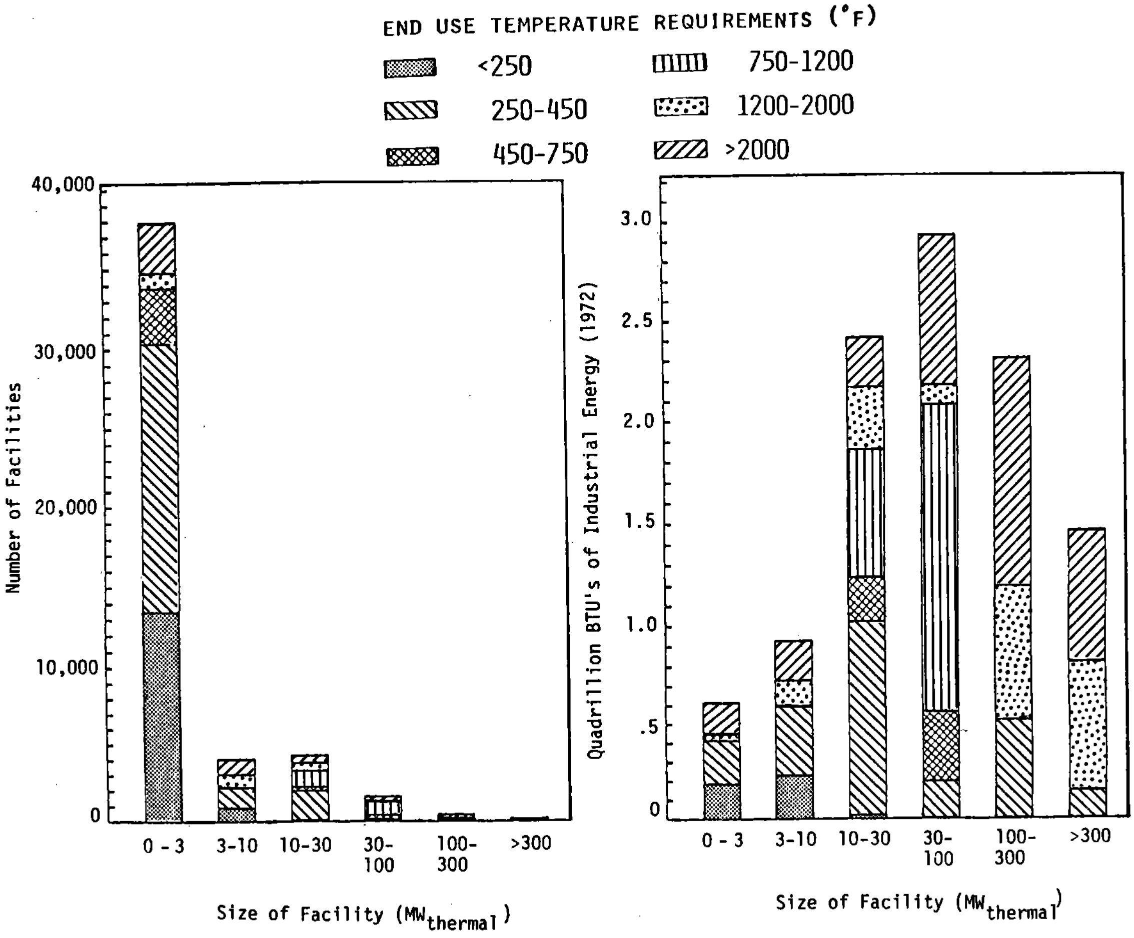

Figure 1. Distribution of <u>Number</u> of Facilities by Size and Temperature. A facility, as defined in the text, is an energy consuming process at a given temperature (or range). Several facilities may be at one location. The majority of the facilities are seen to be small (but see also Figure 2).

Figure 2. Distribution of <u>Energy Consumed</u> at Facilities by Size and Temperature. Most of the energy is consumed at the larger size facilities despite their smaller number (see Figure 1).

Reference 11 also gives summary data on fuel types used in these SIC categories (unfortunately not for IPH end uses only). In all of the SIC categories (except 26, paper, and 33, metals) natural gas is the fuel of choice followed by petroleum derivatives (distilate, residual, etc.). SIC 26 uses mainly its own wood waste products and SIC 33 is dominated by coal feedstock purchases. However, even SIC 33 uses a large amount of natural gas.

4. COMMENTS UPON THE PROCESS HEAT MARKET AND APPROPRIATE SOLAR THERMAL TECHNOLOGIES

We have seen in the previous discussions that (1) the majority of the IPH energy consumed is at large installations, 10 MWth and larger; (2) almost all of the IPH energy consumed is above 200°F with the vast majority at 600°F and above; (3) the chemical and fuel industries dominate the IPH market; (4) natural gas is the current fuel of choice especially in these large, high temperature installations. This is not to imply that large, high temperature installations are the only ones which should be of interest to solar thermal, only that they dominate the quads of energy consumed. While the fuels and chemicals sectors provide the most attractive target, much IPH energy is consumed in other sectors.

These general patterns of energy consumption in the IPH marketplace still only present a part of the picture. Economics must play a major role in the selection of an appropriate solar thermal technology.

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REVIEW OF INDUSTRIAL ENERGY USE

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INTRODUCTION

This brief review endeavors to address three principal areas

- the basic approach used to construct General Energy Associates (GEA) industrial data system,
- some general observations about energy use in the industrial sector at the national level, and
- some specific examples of the rather specific definition of industrial process heat requirements for a given industry and geographic region, such as petroleum refineries in the Southwest.

In the next section,Industrial Data System Concepts, the work of GEA in developing large industrial data systems is briefly reviewed. In the following sections, results on national and regional use are described.

INDUSTRIAL DATA SYSTEM CONCEPTS

In examining the problem of market definition for industrial process heat (IPH), it is perhaps instructive to look at this problem in the broader context of industrial marketing approaches.

In Table 1 the two mainstream approaches generally used in industrial marketing are presented. The first involves case studies and test marketing; the second attempts to use statistical data at the SIC level with an input/output matrix approach to provide a broader definition of the market. The great advantage of the second approach is that in a complex market it provides an opportunity to examine the market in the broadest possible terms. The limitations of this approach heretofore have been that the coefficients used were national, SIC wide averages determined by linear regression over some past time period. This has meant that the results from such an approach were difficult to translate into market potential for a given class of potential users.

Over the past five years, GEA has pursued the development of approaches in market definition that have significantly augmented the input/output matrix approach. This is critical for energy related products such as solar process heat. The advances made by GEA have involved the integration of a process encyclopedia and actual plant process/production information to provide a very detailed picture for the top 7000 plant sites. For the remaining plant sites a sophisticated input/output matrix approach has been applied with appropriate energy and production control totals from the Bureau of Census and trade associations.

This entire data system is called the Industrial Plant Energy Profile Data Base (IPEP).

In the construction of IPEP for each industrial sector three key steps are necessary:

- Definition of all relevant processes used in the sector to include energy intensity, temperature, and waste for each process (Table 2).
- Definition of generic plant types in the sector. In general the operations within a plant will be determined by the nature of the feedstock and the end product ("degree of finishing"). It is on this basis that the generic plant types are choosen. For example a rolling mill would be a generic steel mill type. A model is developed for each plant type with associated input parameters (Table 3).
- Use of trade association data to identify, for each plant, the production level (tons/year,etc.), and generic plant type with associated input parameters.

For 7000 major plants (78% of U.S. industrial fossil energy), this data has been collected and the capability to make direct plant estimates is in place. For the remaining plant stock, as noted earlier, the remaining energy and production is apportioned using a sophisticated input/output matrix based on sales and employees for each company. The coefficients in this matrix have been developed at the State and utility level - so that all relevant control sums are retrieved.

This data system now serves as the basis of any market identification effort since it provides breadth across the market as well as depth at the plant level. In the following sectors some representative data from IPEP are shown.

PATTERNS OF NATIONAL PROCESS HEAT USE

In Tables 4 and in Figures 1 through 3, aggregated results from the IPEP data base on process heat use are presented. Given the nature of the data system, arbitrary aggregations are possible by SIC, temperature, use type and region.

- Aggregated fuel use by 2-digit SIC are presented in Table 4. These represent data with significant corrections to the Census of Manufacture.

- A breakdown of process heat use by temperature is show in Figure 1.
- High temperature and low temperature segments of the market are shown by SIC in Figure 2.
- Percentage of steam use is shown by SIC for both national and regional (Southwestern states) in Figure 3. This shows the dangers of using national distributions at the regional or state level.

The thrust of these remarks is that quite complex cuts through the data can be taken. The above information within the space available here is illustrative of process energy use.

In the next section the capability of the data system to analysis of plants at a quite local level is shown.

PATTERNS OF END USE IN OIL REFINERIES IN THE SOUTHWEST

Oil refinery thermal process use in the Southwestern States is shown in Tables 5 and 6. These have been obtained by summing the refinery flows for each unit operation in each refinery in the relevant states. Again it is interesting to note in Table 6 that the differences in energy intensity by state and region. These differences are primarily caused by the differing mix of processes in the refineries in each of the states. The ability to create these aggregations are but one of the many cuts through the data base that can be performed.

TABLE 1 CONVENTIONAL APPROACHES IN INDUSTRIAL MARKETING

APPROACHES:	o QUALITATIVE:	Case studies, non stratified sampling of market.
	o QUANTITATIVE:	o SIC, census of manufactures' data, input/output matrix approach. o Mailing lists in relevant SIC, using state directory.
PROBLEMS:	o QUALITATIVE:	Gives insight into consumer behavior, but impossible to deal with large, complex market.
	o QUANTITATIVE:	o I/O approach gives a more general approach; coefficients are usually constants based on linear regression, deals with entire SIC in a non-differentiated manner, and also does not provide potential client lists. o Mailing lists give potential client list, but impossible to determine if these are best sites, can be very expensive to follow-up non-qualified buyers.

TABLE 2 BLAST FURNACES AND STEEL MILLS PROCESS FLOW

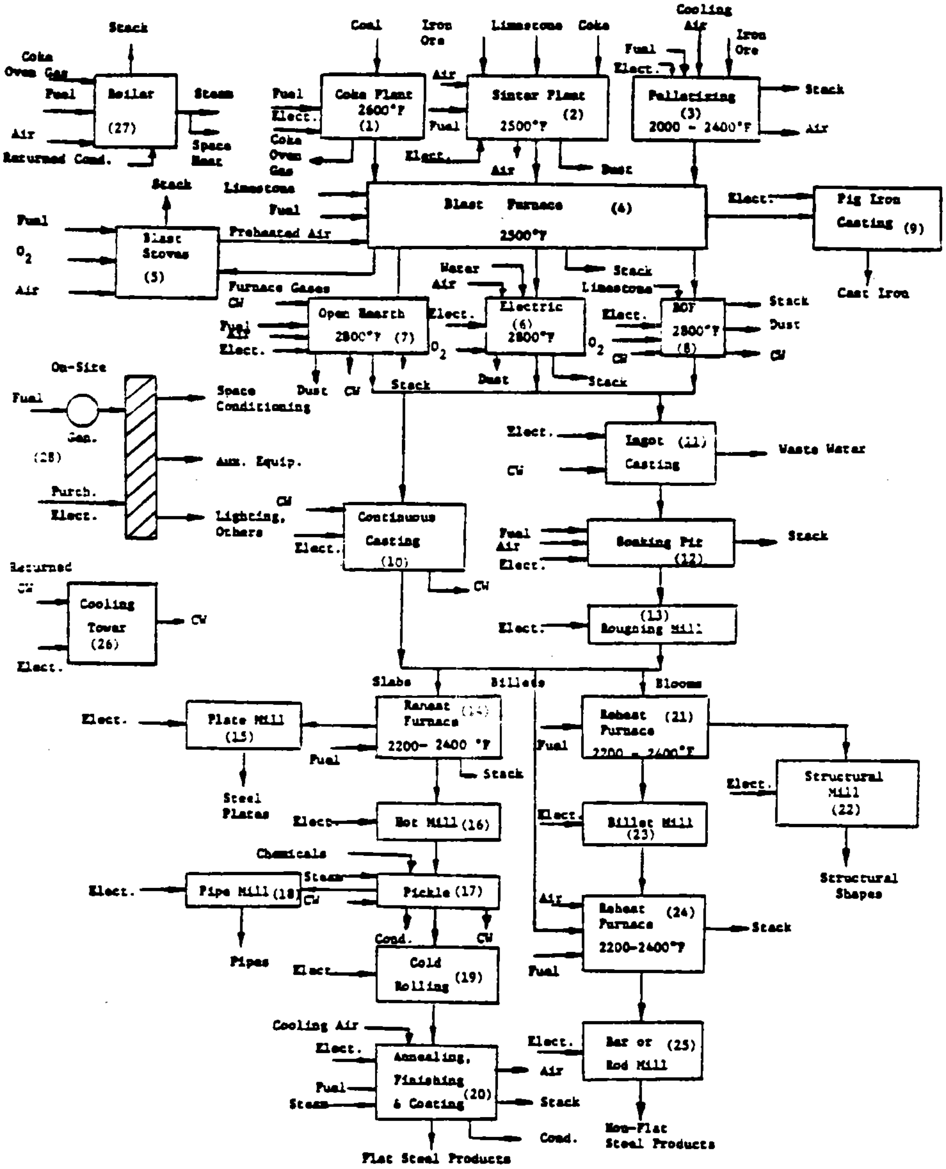

TABLE 3 GENERIC PLANT TYPES

1. Fully Integrated: Coke to rolling mill.

2a. Partially Integrated:
  o Coke to B.F.
  o Coke to steel furnace
  o B.F. to rolling mill

2b. % steel in each furnace type.

3. Minimills:
  o Electric arc
  o Electric arc to rolling mill

4. Rolling Mills: Rolling mills only.

5. Product differentiation.

TABLE 4 NATIONAL ENERGY TOTALS AS MODIFIED BY GEA
(10^{12} Btu/Yr)

SIC	Coal	Oil	Nat. Gas	Other Fossil Fuel	Other Internal Fuels	Electricity
20	86.50	195.79	567.85	105.60	19	136.82
21	10.46	7.08	2.36	.28		4.23
22	30.34	102.15	120.52	52.51		94.90
23	3.41	8.68	38.45	6.18		22.59
24	1.70	48.86	103.14	160.05	346.00	55.02
25	2.80	8.07	33.48	7.73		14.30
26	217.78	524.28	342.00	24.19	649.20	170.71
27	0	8.75	57.12	23.19		36.00
28	352.18	567.07	2013.12	575.89	194.07	508.87
29	405.13	403.64	1019.27	78.11	1193.90	102.88
30	22.89	65.72	133.59	21.64		76.96
31	1.12	7.44	12.34	3.09		4.83
32	340.28	164.48	672.23	107.21	1.21	105.51
33	2061.89	322.59	1018.94	296.43	514.76	538.20
34	12.06	49.47	265.07	67.70		90.03
35	20.58	41.57	203.73	55.25		97.04
36	14.09	31.31	123.25	47.93		85.24
37	51.81	51.79	167.09	100.05		105.72
38	15.25	12.72	42.42	9.28		18.88
39	2.89	9.67	25.80	8.50		14.07
	3653.10	2642.13	6961.77	1925.59	2918.14	2282.92

TABLE 5 THERMAL PROCESSES IN SOUTHWEST OIL REFINERIES (1979)
TOTAL SOUTHWEST REQUIREMENT: 1.329×10^{15} Btu/yr.

		Thermal Energy (10^9 Btu/day)									
States	bbl./d $\times 10^6$	Atm. Distill.	Vac. Distil.	Thermal Crack.	Lube	Cat. Crack.	Cat. Reform.	Coking	Hydro-Treat.	Alk.	Hydrogen
California	2.374	391.	106.	45	5.	73	191.	57	135.	54	405
Colorado	.065	10.7	1.14	1.6	-	2.76	4	-	2.5	-	-
N. Mexico	.116	19.	1.16	-	-	2.	6.2	-	1.1	1.8	-
Texas	4.597	758.	140	32	24	193	407	70	250	137	110
Utah	.158	26.	4.2	.85	-	7.8	7.3	2.	2.5	5.8	-

TABLE 6 AVERAGE THERMAL PROCESSING REQUIREMENTS PER BBL. OF OIL IN SOUTHWEST

	Calif.	Colo.	N. Mex.	Texas	Utah	S.W.	U.S.A
$\frac{\text{Btu}}{\text{bbl.}} \times 10^5$ Thermal Processes	616	350	270	461	357	505	571.

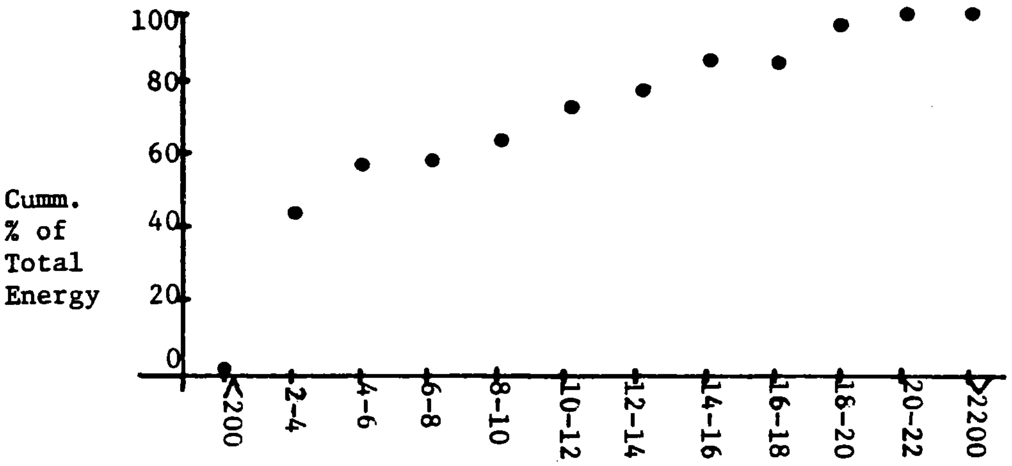

FIGURE 1 DISTRIBUTION OF PROCESS HEAT BY TEMPERATURE (°F)

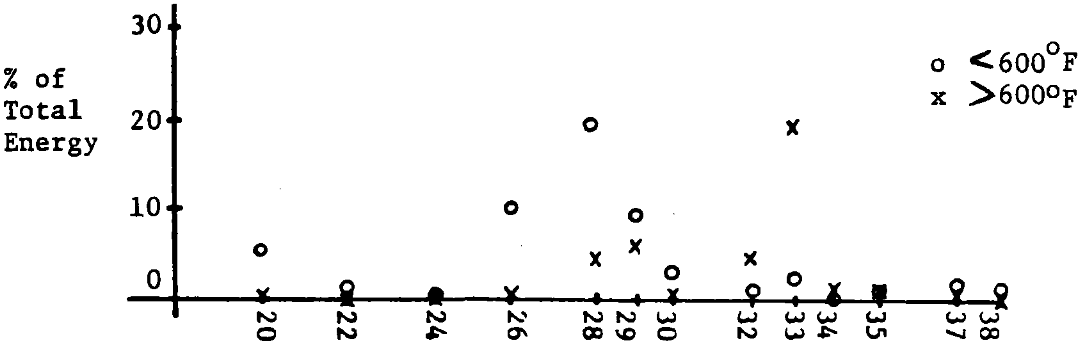

FIGURE 2 DISTRIBUTION OF NATIONAL PROCESS HEAT BY 2-DIGIT SIC

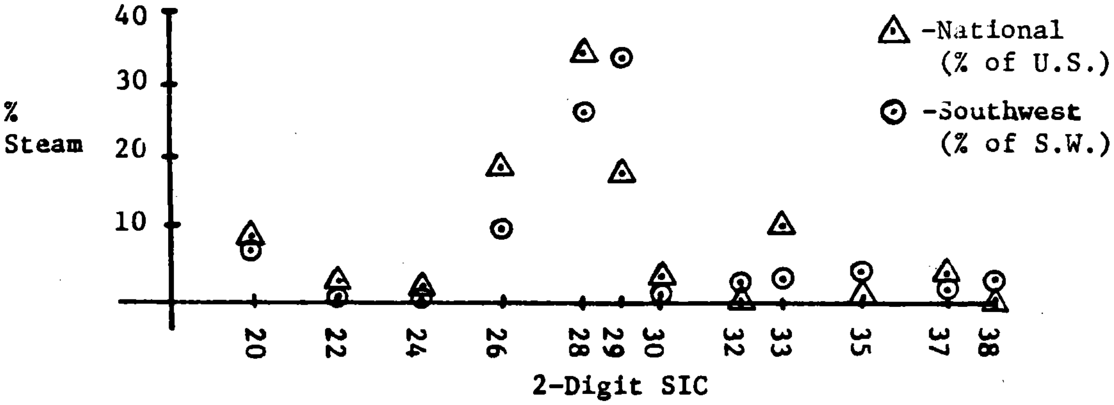

FIGURE 3 DISTRIBUTION OF STEAM USE BY 2-DIGIT SIC

Regional Assessment of Solar Thermal Energy

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INTRODUCTION

The Department of Energy and the Solar Energy Research Institute sponsored a series of three regional assessment studies (covering the South Central, North Central and Northwest regions of the United States) aimed at identifying the potential for solar electric technologies (Solar Thermal, Biomass, Wind, OTEC, PV) and identifying applications that represent the best potential for early commercialization. This paper is based on the work done for these Regional Assessment Studies, and it focuses on the results obtained for Solar Thermal Electric (STE) centralized applications and utilities in these regions.

METHODS OF ANALYSIS

For both utility and distributed applications*, the basic approach (see figures 1) and 2) was to determine what it costs to produce or purchase the electrical energy required for one year. Then STE Systems (and other solar electric technologies) were added to the system and a year's operation was simulated by a computer model that utilized hourly resource data. The difference in production cost (for the utility) or in the annual electric bill (for distributed users) after adding the STE system is an annual savings that can be used to derive a value for the STE System. Through application of an appropriate present-value analysis, a breakeven value for the installed capital cost can be determined which is the amount that could be paid for the solar system such that there would be neither loss nor gain over the systems' life. The breakeven value can, in turn, be compared to projections of STE costs in the future to estimate when the systems may begin to be economically viable.

SOLAR ENERGY RESOURCES

The solar energy sites investigated in the studies are shown in figure 3. There is great variation in the insolation one site to the other.

RESULTS

Figures 4, 5, and 6 compare the breakeven value to the cost determined as a function time in each of the three regions studied for the centralized application. For the results displayed the annual solar insolation available shown in table 1. Principal differences in value

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*The regional assessments included centralized and distributed applications.

amongst the regions are accounted for by differences in solar energy resources, match between solar output/load curves, regional fuel cost, and generation mix. The optimum situation (value greater than cost) is seen in the South Central region. The other regions appear to have applications potential beyond year 2000. The cost shown for the Solar Thermal Systems are based upon central receiver technologies and engineering estimates of the cost. On the figures (4, 5, 6), the cost are the installed cost of the systems (note the $/m are for the heliostat cost).

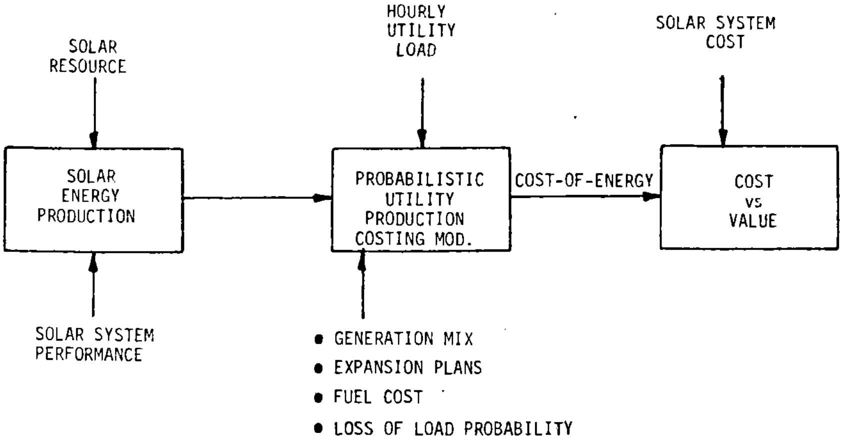


FIGURE 1 - VALUE ANALYSIS FOR CENTRALIZED SOLAR ELECTRIC SYSTEMS

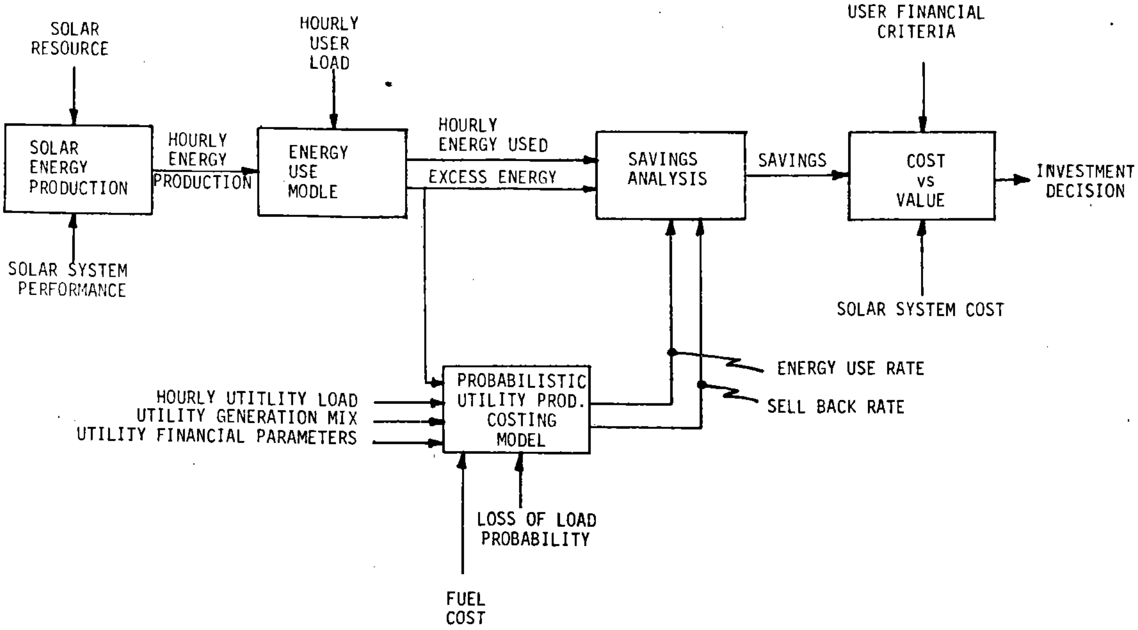
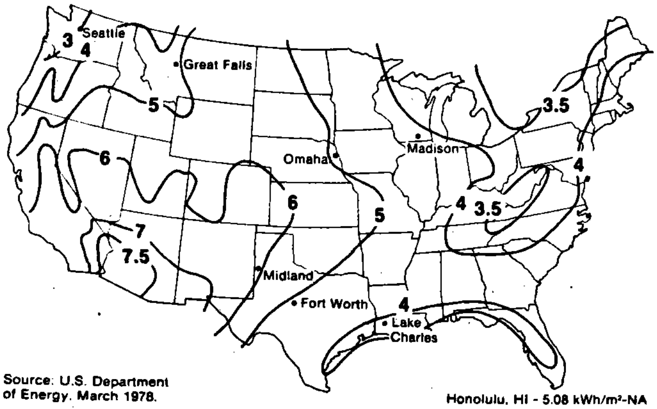


FIGURE 2 - VALUE ANALYSIS FOR DISTRIBUTED SOLAR ELECTRIC SYSTEMS



Source: U.S. Department of Energy, March 1978.

Honolulu, HI - 5.08 kWh/m²-NA

Figure 3. The Site. Investigations Using Direct Normal Solar Radiation (kWh/m²-day)

FIGURE 4 - SOUTH CENTRAL REGION - VALUE vs COST

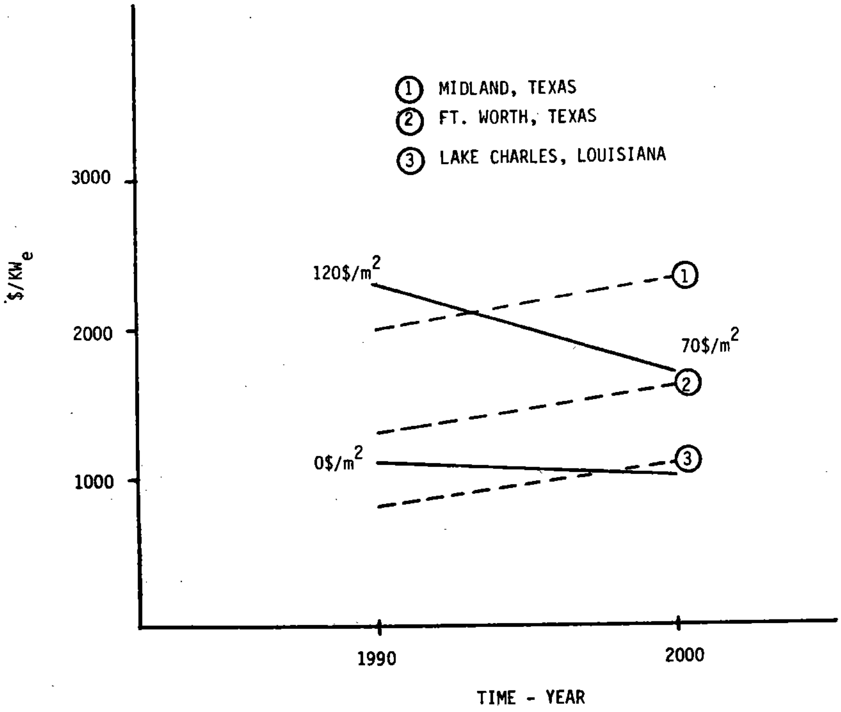


FIGURE 5 - NORTHWEST REGION - VALUE vs COST

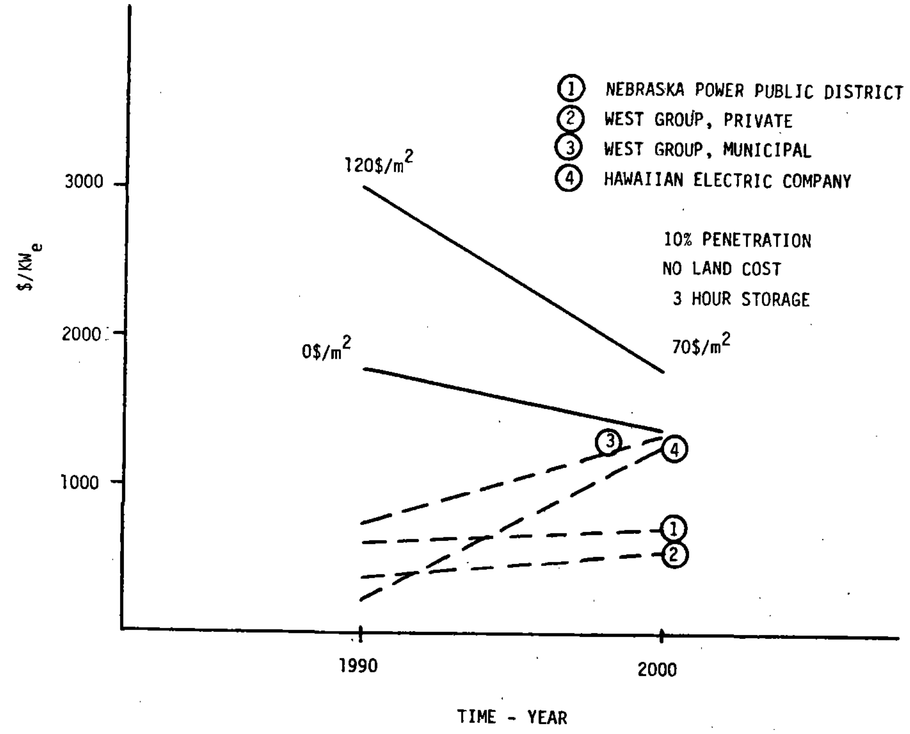


FIGURE 6 - NORTH CENTRAL REGION - VALUE vs COST

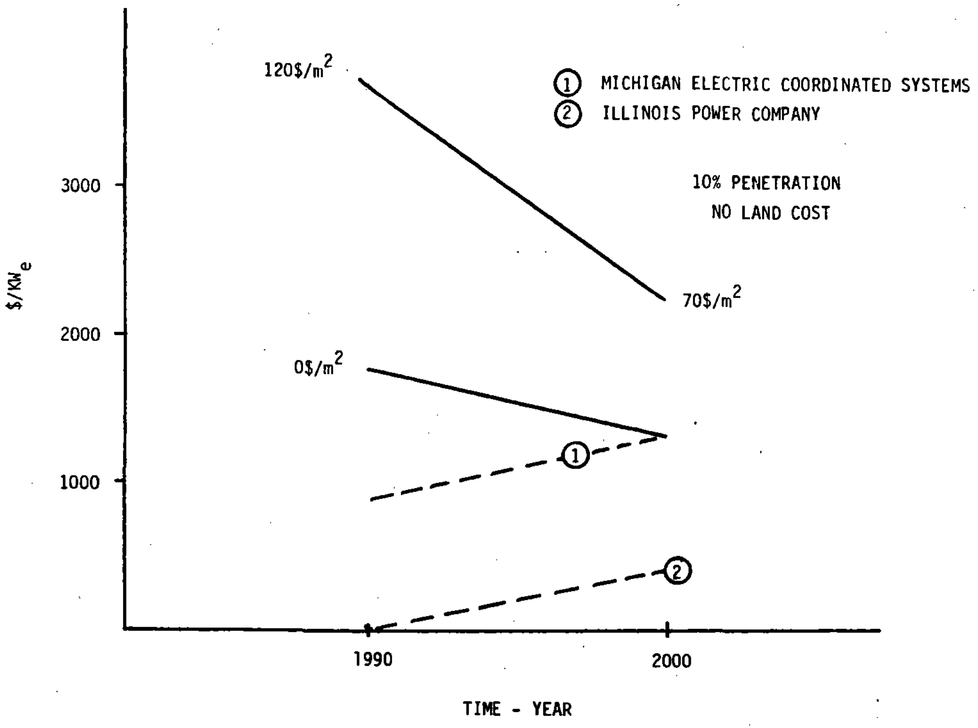


TABLE 1. ANNUAL INSOLATION

	ANNUAL INSOLATION $\frac{\text{KW HR.}}{\text{M}^2\text{ YR.}}$
OMAHA, NEBRASKA	1680
MADISON, WISCONSIN	1330
FT. WORTH, TX.	1763
MIDLAND, TX.	2350
LAKE CHARLES, LA.	1285

*BASED UPON SOLMET DATA.

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