Solar Thermal Test Facilities
USERS ASSOCIATION

STTFUA/81-13

PROCEEDINGS OF ANNUAL MEETING TECHNICAL SESSIONS

April 21-23, 1981

Pasadena, California

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WELCOME

Dr. Thomas H. Springer
President
Solar Thermal Test Facilities Users Association

Welcome to the 1981 Annual Meeting of the STTF Users Association. I would like to express our appreciation to Gottfried Besenbruch, program chairman, and to Marylee Adams and the Albuquerque staff who planned the meeting. I also wish to thank members of the JPL staff, including Terry Cole and Darrell Ross, who have contributed considerably to what we hope will be a successful meeting.

This is one of our most important meetings because it affords members the opportunity to discuss their work and to express their thoughts regarding the direction solar thermal test facility work should take.

With that in mind, we encourage comments which can be carried back to DOE in an attempt to influence the direction of solar thermal work in the way that we from industry, universities, and other members, might think best.

I'm sure all of us are very much interested in the status of the Users Association contract. We do have the contract, although there are a couple of minor problems to be worked out yet. It would be especially appropriate to recognize Frank Smith's accomplishments in this area. Funding for experiments is $435,000.

Again, welcome to all of you.

Geoff Robillard
Jet Propulsion Laboratory

I would like to welcome all of you to JPL this morning on behalf of Bruce Murray, our Director, and hope you will have a very successful meeting. I understand the tour of the Parabolic Dish Test Site yesterday went well and that the sun even shone. It usually doesn't when we're trying to demonstrate solar engineering to someone from outside.

The Lab has been in the energy business for quite a few years. Our interest in solar energy in particular was a natural outgrowth of the need to provide electric power to send spacecraft through the planetary system. Only the energy of the sun is available to supply the necessary energy to operate the spacecraft. Therefore, photovoltaics, solar thermal energy, and radio thermal isotope technologies have been of interest. They were also particularly adaptable for supplying terrestrial energy when that became an important problem.

Quite some years ago we decided we had to do something about the people who kept saying, "If you can land a man on the moon, why can't you solve 'X' problem." So, we began a small amount of work on earth-based problems. That led naturally to the energy activity which has grown into quite a large fraction of the Laboratory's present effort, or at least was until the beginning of this year.

Like everybody else, we suffered a fairly radical cut in our budget. However, we're getting ourselves consolidated and back on our feet so we can start up the slope next year. Hopefully, we will be back to where we were at the beginning of this year within a short time.

I understand that this evening you'll be hearing a little about the Laboratory's other work, which is exploring the planets--the "gee whiz" side of the operation. I hope you will enjoy that presentation and your tour on Friday of the space center.

Again, I wish you a good meeting. Thank you very much.

OVERVIEW OF JPL SOLAR PROGRAM

Marshall E. Alper

Jet Propulsion Laboratory

Pasadena, California

This paper was unavailable for publication. For further information, please contact the author

PARABOLIC DISH TEST SITE

Darrell Ross
Jet Propulsion Laboratory
Pasadena, CA

The Parabolic Dish Test Site (PDTS) was established for the Department of Energy in 1978 at JPL's Edwards Test Station (ETS). Its purpose is to test and evaluate solar thermal systems and subsystems. ETS was originally established as JPL's rocket engine test facility in 1945, and it is still used for that purpose.

The PDTS has three main objectives: 1) evaluation of DOE-developed hardware; 2) acceptance testing of prototype solar thermal systems before full-scale production commitment is made; and 3) evaluation of industry-developed hardware, as time and funding permit, with feedback to industry on test results.

A number of site capabilities will be discussed briefly. Because JPL has had experience since 1945 in working with rocket engines, we can draw upon the expertise of a number of personnel who are experienced in working with high-pressure and high-temperature fluids.

At the PDTS we have a high insolation level, excellent meteorological conditions, and a small amount of down-time because of bad weather. Among the supporting services at the Test Site are a computerized data acquisition and reduction facility and a weather station. An instrument calibration laboratory exists at ETS, as well as electrical, machine, welding, and carpenter shops. Photographic services are also available. Office space is available for experimenters, and there is a cafeteria.

With regard to some of the items previously mentioned, the data acquisition and processing capability is minicomputer-based with magnetic tape storage for all test data, including weather data. Typical data acquired are temperatures, voltages, pressures, and flows. The weather station, located right at the Site, enables us to record a number of different things. We record the direct component of radiation, total sky radiation, ambient temperature and dew point (from which relative humidity is calculated), wind speed and direction, and barometric pressure.

A circumsolar telescope is also in operation, which completes the complement of equipment at the weather station.

Recent test activities at the PDTS include the following: 1) testing of the Garrett Steam Rankine Receiver up to 1300° F, at 2000 psi; 2) generation of furfural (using the Garrett Steam Rankine Receiver mounted at the focal plane of a Test Bed Concentrator) which was later used to power an automobile; 3) testing a Sanders High-Temperature Solar Receiver, with receiver exit temperatures up to 2600° F.

Future activities on the Test Bed Concentrators include the testing of Carter 5-hp and 25-hp steam engines. We expect to begin testing both of these engines in late April or early May, 1981.

The Garrett Air Brayton Receiver is under test, and some preliminary results have been obtained, but we are still a month away from finishing that test program. The Organic Rankine engine and alternator and the Stirling engine and alternator will be tested this summer.

Figure 1 is a view of the PDTS, showing three concentrators. The smaller of the three is an OMNIUM-G unit, which is a 6-meter diameter, parabolic concentrator. It is not presently operational since it is being refurbished. The other two units are the test bed concentrators which are 11 meters in diameter, and they produce about 82 kilowatts thermal at the focal point. Each is composed of 224 individual mirrors which focus the energy at the focal point to approximately an 8-inch diameter circle.

The building in the photograph is the control room in which all of the data acquisition and control equipment is located. All test activities at the PDTS are controlled from this building under the direction of one or more test chiefs.

Figure 2 is an on-sun photograph of the Test Bed Concentrators, one with a Garrett Steam Receiver located at the focal point, and steam is being generated. Figure 3 is a closeup of the Garret Steam Rankine Receiver which was shown at the focal point in the previous photograph. This gives an idea of size. The receiver weighs about 500 pounds.

Figure 4 is a photograph of the Sanders Air Brayton Receiver giving a view of the front where a quartz window exists, and showing a combuster at the rear of the receiver.

To give you an idea of the schedule, at the module level, we expect by the end of May to be generating electricity with the Steam Rankine Receiver and the two previously mentioned Carter engines. The Organic Rankine Module will begin generating electricity in late summer, and that program will probably carry through the end of the calendar year.

The Stirling Module will be generating electricity at almost the same time as the Organic Rankine Module, sometime in the late summer.

We expect to get an automotive advanced gas turbine from the Garrett Corporation sometime toward the end of this year, or possibly early next year. We would expect to begin testing that unit at the PDTS in the spring of 1982.

Question - What is the diameter of the parabola?

Ross - The Test Bed Concentrators are 11 meters in diameter, with a focal length of 6.6 meters. The OMNIUM-G unit is 6 meters in diameter, with a focal length of 4 meters.

Question - Is the quartz window on the Sanders receiver actively cooled?

Ross - The window is air-cooled.

Question - The Carter engines are steam turbines, not reciprocating steam engines?

Ross - No, both of the Carter engines are reciprocating engines.

Silverstein - If you didn't include any performance data on the tests of the Sanders or the Garrett receivers, do you have any? Could you tell us roughly what the receiver efficiencies were for those tests.

Ross - The Sanders objectives were to operate the receiver at exit temperatures up to 2500°F--we actually achieved 2600°F. The inlet temperature from the combusters was designed for 1700°F, and we actually achieved 1700°F. The design mass flow rate was .25 lb/sec, and 0.2 lb/sec was achieved. The design point efficiency was 62.2%, whereas we achieved 45 to 80% over a temperature range of 1600°F - 2600°F at the receiver exit. These data are shown in Figure 5. For the Steam Rankine Receiver we achieved temperatures of 1300°F, at 2000 psi with a flow rate of 175 lb/hr. The efficiency ranged from 80 to 92% over a temperature range of 300 - 1300°F.

Question - Why is the input to the Sanders receiver as high as 1700°F?

Ross - It was designed as a high-temperature receiver, up to 2500°F, and so we would expect the temperature from the Air Brayton engine to be on the order of about 1700°F.

Question - So it is a very highly recuperated engine?

Ross - Yes.

FIGURE 1

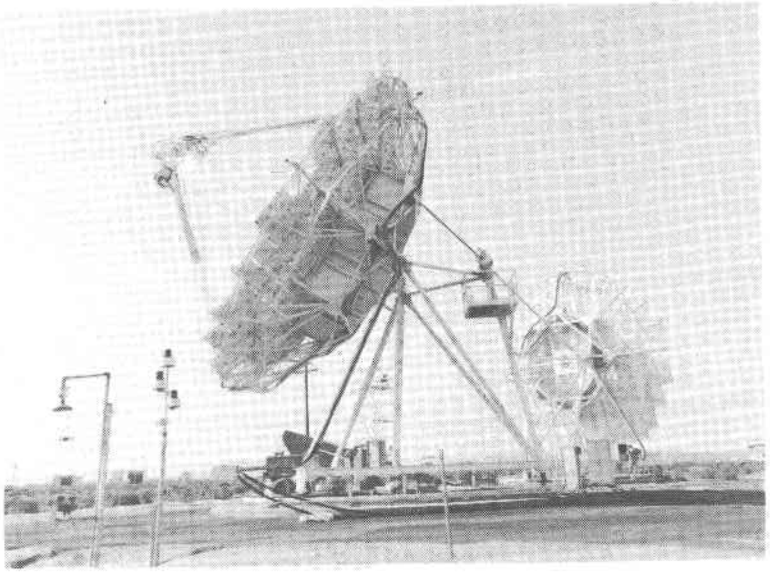


FIGURE 2

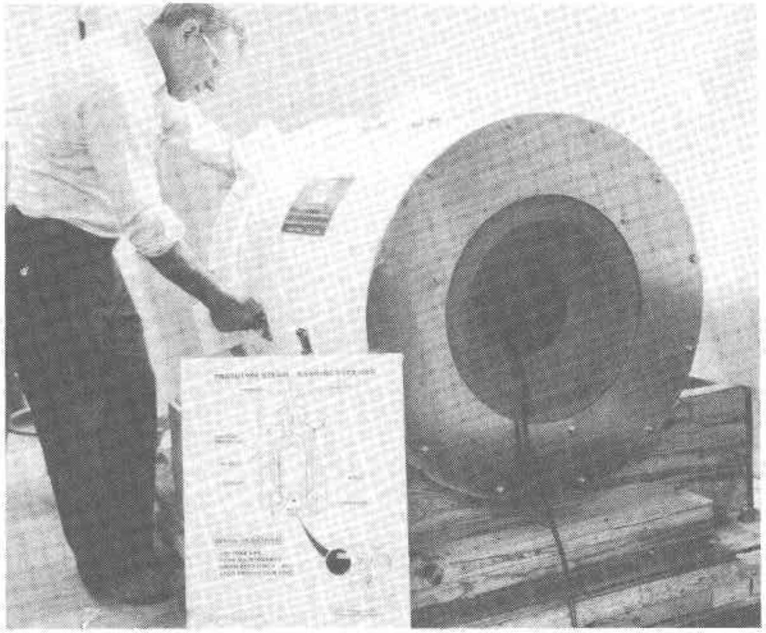


FIGURE 3

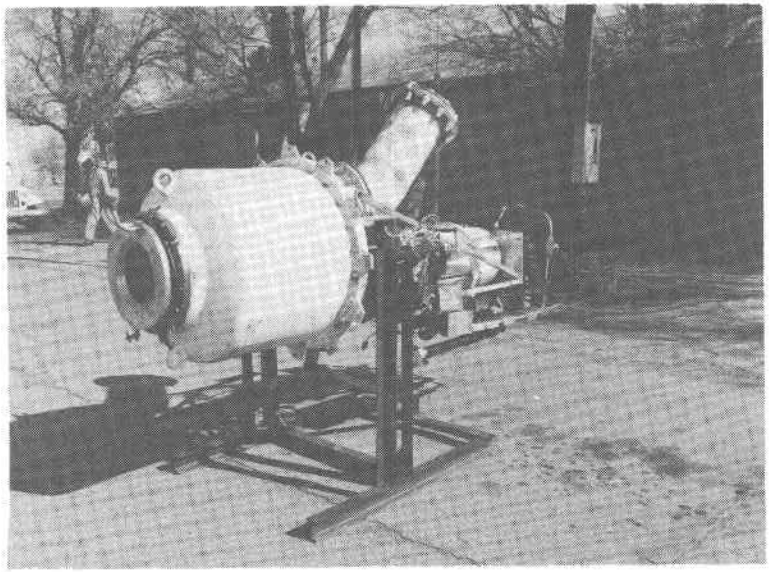
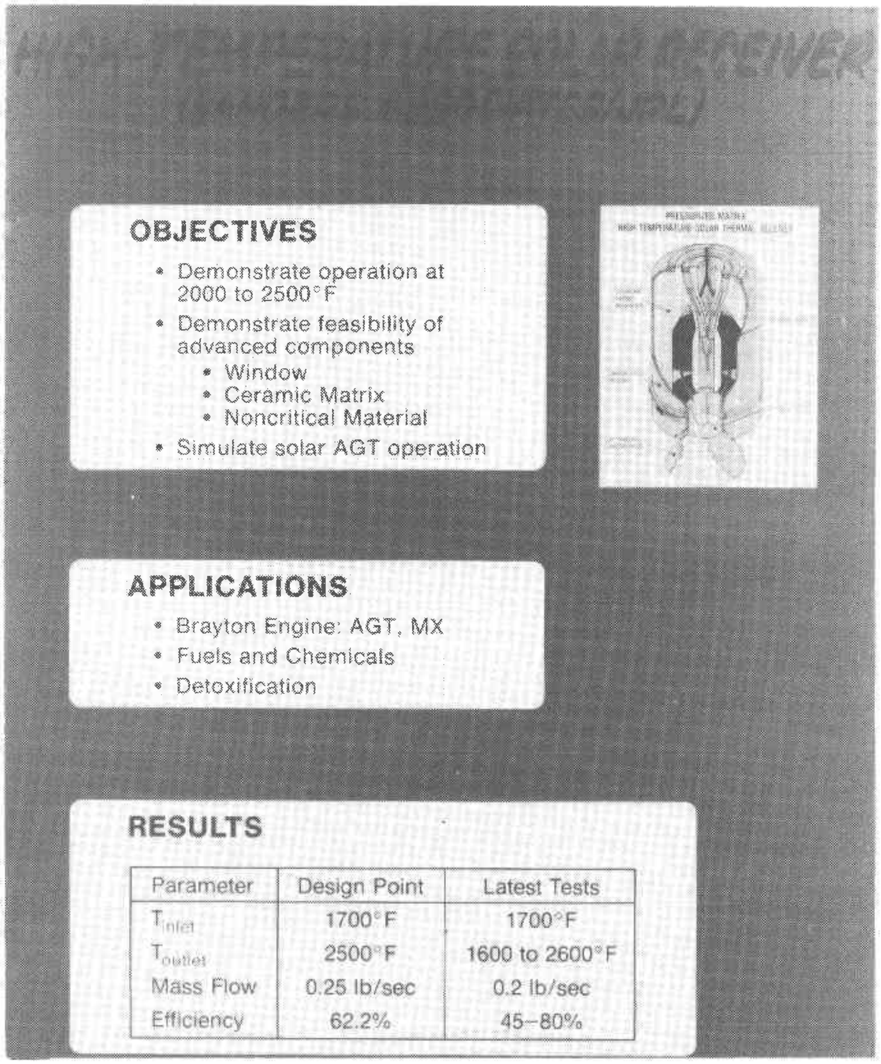


FIGURE 4



HIGH-TEMPERATURE SOLAR RECEIVER
([illegible])

OBJECTIVES

- Demonstrate operation at 2000 to 2500°F
- Demonstrate feasibility of advanced components
    - Window
    - Ceramic Matrix
    - Noncritical Material
- Simulate solar AGT operation

APPLICATIONS

- Brayton Engine: AGT, MX
- Fuels and Chemicals
- Detoxification

RESULTS

Parameter	Design Point	Latest Tests
T_{inlet}	1700°F	1700°F
T_{outlet}	2500°F	1600 to 2600°F
Mass Flow	0.25 lb/sec	0.2 lb/sec
Efficiency	62.2%	45–80%

FIGURE 5

ADVANCED COMPONENTS TEST FACILITY

C. Thomas Brown

Georgia Institute of Technology

This paper was unavailable for publication. For further information, please contact the author.

Non-Solar Power Tests At
The Central Receiver Test Facility (CRTF)

John T. Holmes
Division 4713
Sandia National Laboratories
Albuquerque, New Mexico 87185
April 22, 1981

The CRTF has been described in detail in earlier STTF-UA workshops.[1,2] A recent publication documents the operation and maintenance of our 222 working heliostats over the period 1978 through 1980.[3]

We have tested and characterized three major solar receivers during 1978 through 1980. A 1MW air cooled receiver sponsored by EPRI and built and operated by the Boeing Company was operated in 1978 and 1979. A prototype of one of the 24 panels used for the DOE 10MWe pilot plant now under construction near Barstow, California was tested by a Rockwell International, McDonnell Douglas team, in 1979 and early 1980. Most recently, in 1980 and 1981, we completed the characterization of a DOE 5MWt capacity molten nitrate salt cooled receiver designed and operated by Martin Marietta. We are currently preparing the CRTF for a test of a sodium cooled solar receiver in a cooperative program between DOE and Rockwell International.

During 1979, 80 and 81 we have also been characterizing the performance of a variety of heliostat designs for power plant applications.

The first prototype heliostat evaluated at the CRTF was developed and fabricated by Westinghouse. Experience gained during our evaluation was used by Westinghouse in later heliostat design refinements.

From June through September, 1979, we conducted a test program to determine if the Martin Marietta (MMC) and the McDonnell Douglas (MDAC) prototype heliostats met the performance requirements established for the

10MWe central receiver pilot plant now under construction near Barstow, California. This test program assisted DOE in selecting Martin Marietta for production of the 1818 pilot plant heliostats.

DOE is now sponsoring a second generation heliostat development effort to produce four different heliostat designs that should have improved performance and lower cost. We are currently evaluating two prototypes from each of four contractors. Boeing Engineering Company, Martin Marietta, McDonnell Douglas, and Northrup, Inc.

Evolution of the prototype heliostats in the last three years has resulted in improved performance, increased size (37 to 58 m^2), reduced weight (2950 to 1900 Kg) and reduced cost (800 to 150 $\$/m^2$). We will continue to perform long term component and heliostat tests at the CRTF.

In addition to these programs to develop central receiver technology components, we have performed a number of other tests that use some of the unique capabilities of the CRTF. The three major non-central receiver component tests have been a Navy/Applied Physics Laboratory simulation of aerodynamic heating of a missile nose-cone, a Sandia/Rockwell International gallium arsenide photovoltaic array, and a DNA/Science Applications development of a secondary beam concentrator.

NAVY/APL AERODYNAMIC HEATING

The CRTF has been used for simulating aerodynamic heating of a missile radome for the Navy and the Applied Physics Laboratory (APL) of Johns Hopkins University. This Navy missile seeks its target by use of a radar set in the glass-ceramic nose-cone. This nose-cone has a prescription ground wall to minimize its effects on the radar signal passing through it. New missiles designed for higher flight speeds will subject these nose-cones to high temperatures from the aerodynamic heating by the atmosphere.

The nose-cone we tested is about 25 inches long and about 14 inches in diameter. It is supported by a fixture to orient it toward the center portion of the heliostat field. The fixture is mounted on a work platform which we located on the northeast corner of the top of the CRTF tower. Figure 1 shows the nose-cone undergoing a solar test.

In October 1979, APL ran a series of calibration tests using a number of thermocouples attached to the inside of the nose-cone to measure wall temperatures. At the same time, optical pyrometers were focused at the thermocouple locations but on the outside of the nose-cone. In this way the thermocouples were used to calibrate the optical pyrometer readings by adjusting the emissivity setting. This calibration is important because thermocouple wires cannot be used in the tests with the radar antenna in place. These tests were also used to select the heliostats needed to achieve preselected temperature profiles in about 2 minutes (Figure 2).

In December 1979, APL returned to CRTF with a refined test fixture which allowed them to mount the radar antenna inside the nose-cone and it also provided independent rotation and sweeping of the antenna and nose-cone. During that time, engineers from General Dynamics Company installed a radar null seeker on one of the heliostat foundations in the heliostat field. This allowed the radar boresight error to be measured over a ±30° look angle through the nose-cone.

Nose-cones of three different designs were brought to CRTF in January 1980. The boresight error measurements were first made at ambient temperature. Then a number of heliostats were focused on the nose-cone to bring it to an intermediate (800°F) or a high (1200°F) temperature, and the radar boresight error was measured again. The highest temperature occurs at the front of the nose-cone.

After testing the MMC receiver in 1981 we completed the final phase of this program. The final test of that series was a fast, high-heat flux exposure of a darkened nose-cone to measure the thermal and mechanical stresses expected in an advanced application. We provided a gravity-operated shutter made of ceramic insulating materials (Figure 3). It survived only long enough to gather important data in this single test using the full CRTF heliostat field.

GaAs PHOTOVOLTAIC ARRAY

An array of 256 densely packed gallium arsenide (GaAs) solar cells was designed and fabricated by Rockwell International for Sandia's Solid State Device Physics Division to explore the feasibility of operating photovoltaic receivers with central receiver solar input (Figure 4). For this type of application it is essential to maximize the utilization of incident solar flux by reducing the amount of inactive area exposed to the collected solar radiation. This was accomplished by overlapping a series of solar cell modules so that current buss strips, interconnects, coolant lines, and other nonactive elements are shaded from the beam. The array presents a frontal area of .040 m^2 and consists of 16 modules of 16 GaAs cells each, connected in series.

During illumination at flux densities of about 100 W/cm^2, this array was designed to generate an electrical output voltage of 230 volts and 20-25 amperes of current. Theoretical analyses indicate that an overall photovoltaic conversion efficiency greater than 16% might be achieved.

Testing of a densely packed array of GaAs photovoltaic cells was completed May of 1980. The initial solar tests covered the range from 10 to 65 W/cm^2 insolation. The electrical performance data at 65 W/cm^2 (Figure 5) shows a fill factor of about 0.32 which is below the 0.7 to 0.8 value that was expected.

Increasing the insolation to about 90 W/cm^2 caused a failure in an aluminum base plate on the array. The array wiring was burned by direct exposure to the beam. The cleaning process used to remove the combustion products damaged some of the metalization and antireflective coating and the capacity of the array was reduced to about one-half that of the original. After refurbishing the wiring and base plate, the array was exposed to intensities of up to 120 W/cm^2. Testing was terminated by a failure in some passive insulating materials which again allowed solar beams directly onto the wiring and this time caused failure beyond repair. Tentative observations included:

1. The poor electrical performance (0.32 fill factor at 65 W/cm^2) has been attributed tentatively to improper current matching of the individual cells.
2. Cell cooling performed as designed, suggesting that a combined photovoltaic/thermal cycle is promissing.
3. Careful attention must be given to the thermal protection provided for relatively small experiment packages which are exposed in the large solar beam to high solar conditions.

EVALUATION OF SAI FLAT MIRROR BEAM RECONCENTRATOR

Science Applications, Inc. designed and constructed a secondary beam concentrator for testing at the CRTF. The concentrator is made of four, first surface silvered, water cooled, flat mirrors. The concentrator is constructed of thin copper plates, soft-soldered at the joints. The soldered construction and wall thickness of the panels restricted their use to 10 psi inlet pressure and an atmospheric outlet pressure. This limited the amount of coolant available to the mirrors. A sketch of the mirror arrangement is shown in Figure 6. Five flux gages were located at the working aperture of the concentrator.

The concentrator was evaluated using groups of 6, 11, 19, 29 and 40 heliostats. The concentration achieved was determined by comparing the average of the flux gage readings to the average flux density determined using the HELIOS code, for the unconcentrated beam. During the test with 40 heliostats the mirror coolant containment failed as a result of stagnant flow areas within the concentrator mirrors. This led to localized boiling and the high temperatures melted the soft solder joints. The concentration we achieved in these low power test was about 1.6 to 1.8.

This relatively simple, flat plate geometry can be used to provide significant reconcentration of the CRTF beam. Any future reconcentrator designs will have to provide improved structural and heat transfer features to assure longer survivability and use with higher power inputs.

SUMMARY

The CRTF has proven its utility for the development of solar power plant components and its unique capabilities are also being used for a variety of non-solar power research and development programs.

Summary

The RTAF has proven to be an important system for measuring receiver efficiencies during test operations. We are continuing to improve the mechanical designs, develop fast response flux sensors and improving our ability to translate data accurately from measurements taken at one location to what the conditions are at the aperture of an experiment.

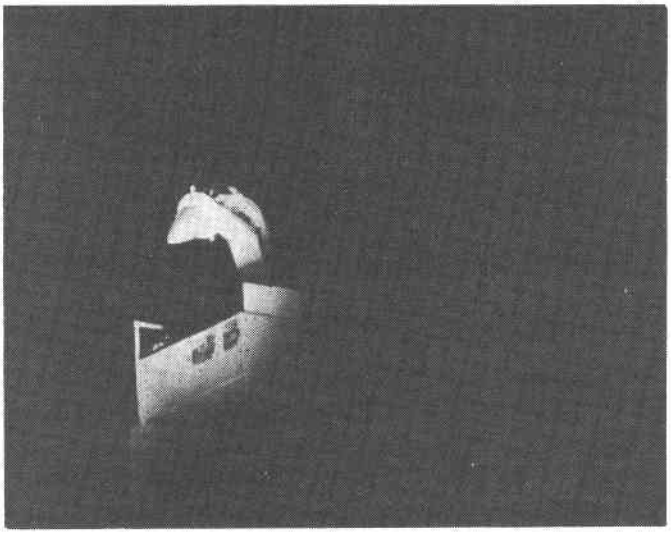


FIGURE 1 Navy/APL Nose-Cone Experiment under Test at the CRTF

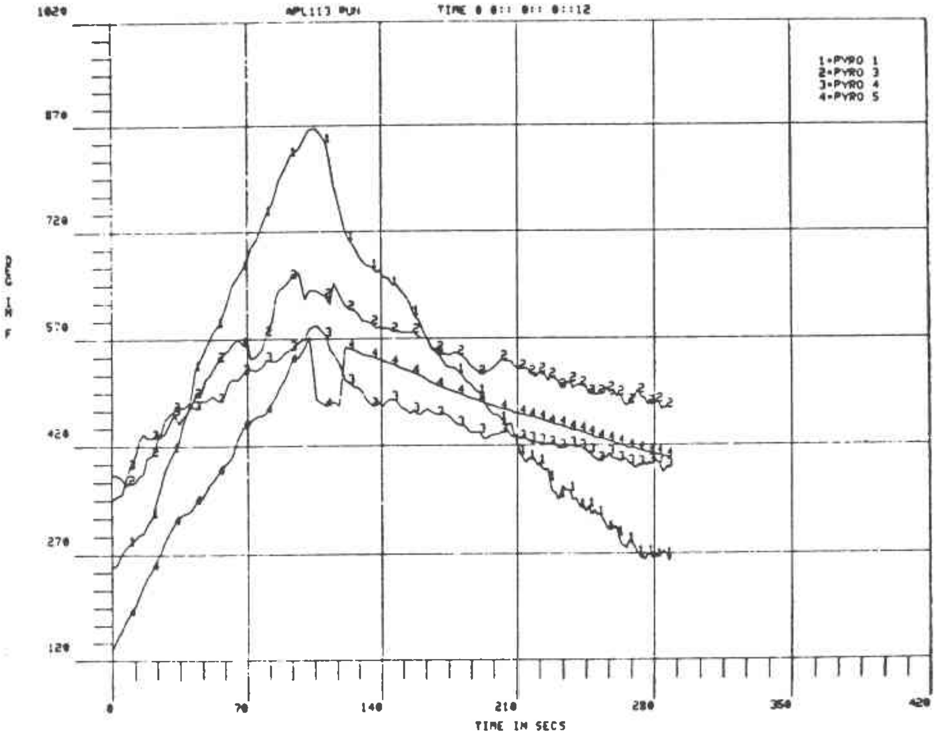


FIGURE 2 Navy/APL Nose-Cone Test Temperature Data

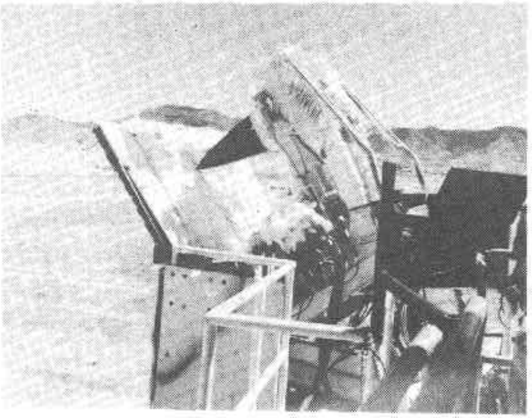
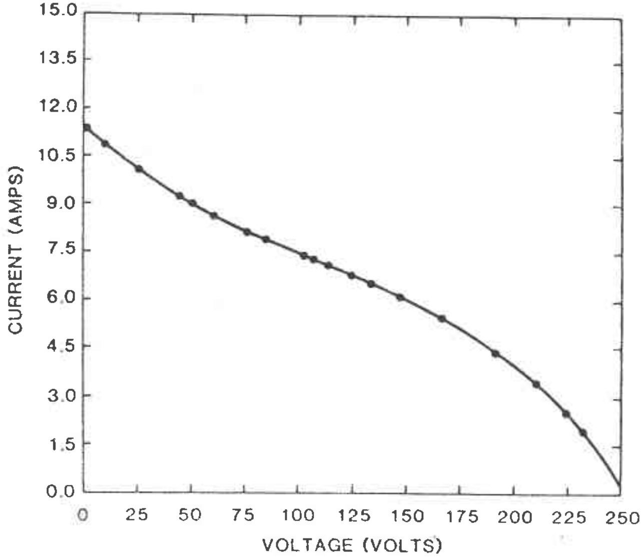


FIGURE 3 Setup for Fast, High-Heat Flux, Aerodynamic Heating of Navy Nose-Cone



MAXIMUM POWER	=	916 WATTS
VOLTAGE AT MAX. POWER	=	162 VOLTS
CURRENT AT MAX. POWER	=	5.6 AMPS
CONCENTRATOR EFFICIENCY	=	3.5%
FILL FACTOR	=	.32
OPEN CMT. VOLTAGE	=	250 VOLTS
SHORT CMT. CURRENT	=	11.3 AMPS
ARRAY TEMPERATURE	=	27 DEGREES C.
DATE & TIME OF TEST		5-12-80 12:45:4

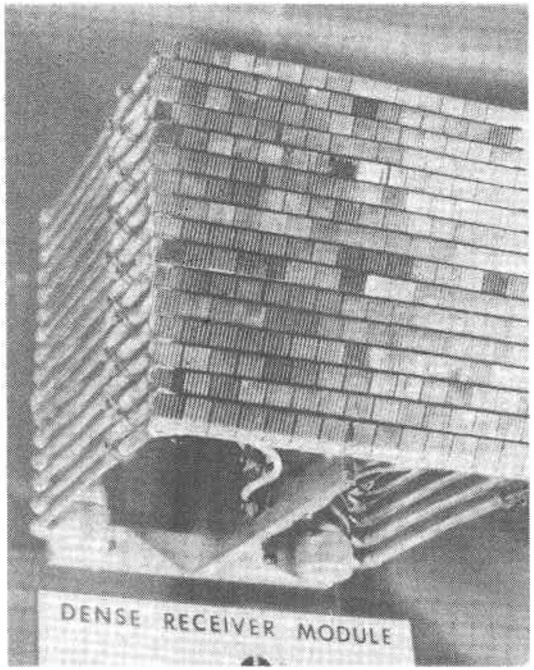
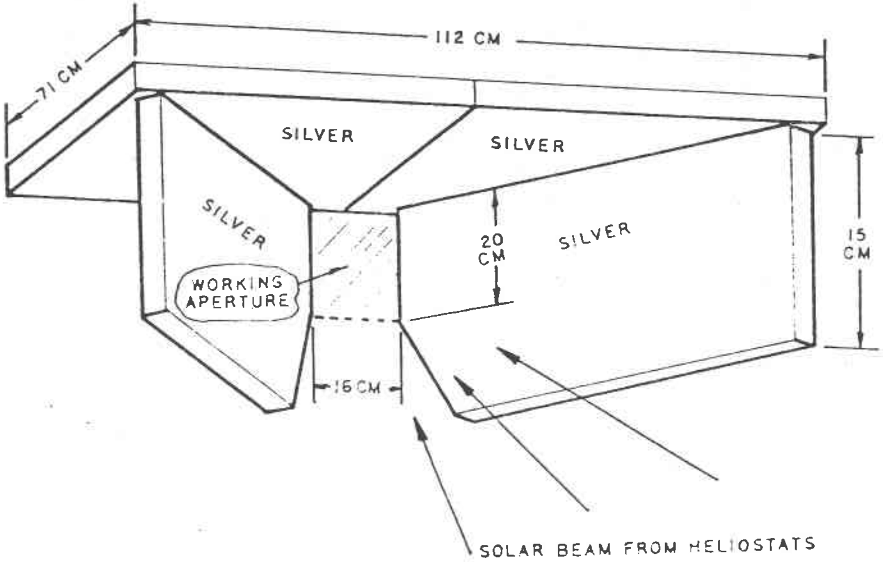


FIGURE 4 5-kW Photovoltaic Array



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1. J. T. Holmes, "Heliostat Operation at the CRTF (1978-1980)", Proceedings of Workshop on Long Term Performance, Solar Thermal Test Facilities Users Association, Albuquerque, New Mexico, January 7-9, 1981
2. J. T. Holmes, "Operation of Central Receiver Test Facility", Proceeding of Facility Operators and Experimenters Workshop, Solar Thermal Test Facilities Users Association, Albuquerque, New Mexico, May 3-4, 1979
3. J. T. Holmes, "Heliostat Operation at the CRTF (1978-1980)", SAND 81-0275 (Albuquerque: Sandia National Laboratories, May 1981)

Walton - We have time for a couple of questions.

Hays - What was your response time to that shutter?

Holmes - The shutter was gravity-operated with a rope and just allowed to fall away; and although it dropped in less than a second, it was already being consumed by the beam. It was a hairy experiment.

The more we test the ceramic materials, the more we don't know about them. There are serious problems in getting ceramics to stand up in large scale with high fluxes. I am sure John Gintz would agree, because they had some problems with materials in their receiver at flux densities which were not very high. This was our total beam. The shutter lasted only a few minutes, and the zirconium oxide front surface was the best material we knew.

Hays - A lot of interesting work is to be done with materials.

Walton - Almost ten years ago, we did our first work at Odeillo with something more than 16,000 concentration. That facility is not quite so high now, but with a high-purity centrifuge we could take 30 seconds at about 18,000 concentration with no melting. It begins to melt after about 30 seconds, and after a minute we had melted maybe half an inch through that material. Refractoriness is not the total answer; absorptivity is the principal factor. For example, plasma-sprayed aluminum oxide has a very low absorptivity, and with a reasonable heatsink behind it--you can take a total of 5,000 powers per square centimeter at thes flux levels of 250 powers per square centimeter a second. Rather than refractors, I would have opted for higher reflectivity for your setup, but that's part of what this game's all about. It's a combination of refractoriness, thermal conductivity, reflectivity, etc.

Holmes - We need materials that last more like 30 years than 30 seconds.

Walton - Yes, that's what you are talking about. I'm talking about 10 times that flux. I would take this flux indefinitely. It just won't be effective at that flux level, assuming you have some depacity behind it.

Hildebrandt - Could you comment on your earlier statement that the flux level was not desirable to the agency with whom you were working?

Holmes - Our peak flux density on the order of slightly more than 2,000 suns. For the work they want to do, Science Applications would like flux levels on the order of 5,000 to 10,000 suns with a lot of power. Those flux densities can be achieved in smaller facilities, but not on the scale they would like for their experimentation. We hope to develop secondary concentrators to do that, and the flat plate gadget I showed you is the first attempt to learn something about secondary concentrators.

Laboratoire des Ultra Refractaires

Jean-Pierre Coutures

CNRS

Odeillo, France

This paper was unavailable for publication. For further information, please contact the author

THE WHITE SANDS SOLAR FACILITY

Richard A. Hays
White Sands Missile Range, NM 88002

INTRODUCTION

The White Sands Solar Facility (WSSF) is operated by the Nuclear Weapon Effects Branch of the Applied Sciences Division, Army Material Test and Evaluation Directorate. The primary mission of the Nuclear Weapon Effects Branch is to provide the capability for the testing of systems and components to the environments which would be encountered in the event such systems or components were exposed to a nuclear weapon detonation.

The WSSF provides the capability for: (1) simulating the thermal environment associated with a nuclear weapon detonation and (2) carrying out efforts associated with the development of solar energy as a source of power. The WSSF is available for use by the Department of Defense and its contractors, other Government agencies and their contractors, private industry, and universities.

DESCRIPTION OF THE FACILITY

The WSSF is a focusing-type thermal facility. It consists of four main components: (1) heliostat, (2) attenuator, (3) concentrator, and (4) a test and control chamber.

The heliostat consists of 356 flat plate mirrors, each two feet by two feet, mounted on a steel frame 40 feet wide and 36 feet high. Each mirror is front surfaced with an aluminized acrylic material in order to provide as much ultra violet radiation as possible in the concentrated solar beam. In operation, the heliostat reflects the thermal energy received from the sun along the optical axis of the WSSF to the concentrator. The heliostat automatically tracks the sun during the day, or moon at night, thus keeping the concentrated thermal energy located at the focal plane in a fixed position during the course of an experiment.

The concentrator consists of 180 spherical mirrors, each approximately 2 feet by 2 feet and mounted on a steel frame 30 feet by 30 feet located 96 feet south of the heliostat (See Figure 1). Each mirror comprising the concentrator is individually positioned to concentrate the thermal energy at the focal plane, 36 feet to the north, located inside the test and control chamber.

The attenuator, which is located between the test and control chamber and the concentrator, consists of a louvered structure whose blades can be positioned in such a manner as to regulate the amount of thermal energy reaching the concentrator. The attenuator can continuously vary the power level of the WSSF to suit test requirements.

The test and control chamber is eight feet by eight feet in cross section presented to the reflected thermal energy from the heliostat and is sixteen feet in length. It contains the experimental test area, the controls for operation of the facility, and shutter systems for modulating the thermal energy.

OPERATIONAL CHARACTERISTICS

Since the WSSF is dependent upon atmospheric conditions for its operation, the following information is provided in order to help plan experiments to be conducted at the WSSF.

Cloud cover can reduce the operational capability of the WSSF. Cirrus-type clouds cause flux level variations at the focal plane while stratus-type clouds can cause erratic solar tracking by the heliostat, causing the termination of an operation. To detect changes in solar insolation (cloud cover, atmospheric aerosols, ect.) a direct incident pyroheliometer is used.

Wind and cloud cover data taken for a period of 30 years by the Atmospheric Sciences Laboratory, indicates the White Sands Missile Range as a good location for the WSSF. Information on wind and cloud cover by month and hour indicates an average of 1200 hours of operation time per year is available at the WSSF based on a 2080 hour work year, 5-day work week, and a 0800 to 1600 hour workday. The weather data has been summarized in Table I into four categories of cloud cover and wind velocities.

Table II lists months of the year indicating the percentage operational time available for each month in Category IV of Table I.

EXPOSURE CHARACTERISTICS

The maximum flux is obtained at the center of the focal plane of the WSSF. Figure 2 shows normalized isoflux contours of the beam cross section at the focal plane taken in February 1981. The maximum measured flux level at the focal plane to date is 90 cal/cm^2 sec. A flux level of 85 cal/cm^2 sec is easily obtainable with a total power of 30,000 watts thermal available on a normal day with a direct solar insolation of 920 w/cm^2. Flux levels with a uniformity of $\pm$5% of maximum are obtained over an exposure diameter of approximately two inches. Table III gives some of the important exposure characteristics pertaining to a typical day at the WSSF.

The equilibrium temperature corresponding to the maximum flux is 2541.0 degrees centigrade.

Thermal energy modulation can be provided at the WSSF. The two basic modes are shaped (nuclear) and rectangular. For the rectangular mode, rectangular pulse shapes with nominal use and full times of 30 milliseconds, pulse widths as short as 100 milliseconds and as long as required can be produced.

Using the attenuator very slow increases or decreases in power level can be achieved in order not to thermally shock a test item.

Also a subsonic wind tunnel can be installed at the focal plane of the WSSF to provide air flow up to velocities of 37,000 feet per minute over a sample size of 4 inches by 4.5 inches.

INSTRUMENTATION

Instrumentation presently available in support of the WSSF consists of the following:

A. Assorted power supplies, oscilloscopes, oscillographs, digitizing storage oscilloscope, voltage and current meters, temperature, and emissivity measurement instrumentation.

B. Circular foil heat flux gauges include the following:

0.25 - 30 Microns Range Watts/cm^2	Accuracy ± 5% Response Time (milliseconds)
17	200
34	200
68	150
134	150
340	120
567	100

C. Four inch integrating calorimeter

0.25 - 35 microns accuracy ± 5%
Total power 50 watts

D. Optical pyrometers

Range	Spectrum	Accuracy
1000°C - 3000°C	0.7 - 1.0 microns	± 2%
200°C - 2450°C	4.2 - 4.3 microns (solar blind)	± 2%

E. Spectroradiometer .38 - 1.1 microns

F. Three axis positioning table

Maximum Load - 100 lbs

Accuracy ± 0.25cm

GENERAL SUPPORT

An on-site professional staff is readily available to the experimenter for consultation and assistance. Facility personnel will operate the solar furnace and provide full operational support.

Services of a machine shop and machinist are available for services which might arise during the course of the experiment. Additional laboratory and office space is available upon request.

A 25 foot by 8 foot airconditioned and heated instrumentation van is available with instrumentation racks and a patch panel with 40 signal channels from the test and control chamber to the van.

Communication via intercom between the heliostat, test and control chamber, mechanical equipment room, instrumentation van, and the concentrator is provided for experimenter use.

Electrical power is available consisting of 440, 208, 120 volts ac, 3-phase 100 amp per phase. High pressure air and cooling water is also available in the test and control chamber.

TABLE I

CATEGORY	CLOUD COVER	WIND	AVAILABLE HOURS PER YEAR
I	Clear	<5 Knots	395
II	Clear	<14 Knots	666
III	<50 %	<5 Knots	666
IV	<50%	<14 Knots	1200

TABLE II

MONTH	% OPERATIONAL TIME
September	71
October	70
June	70
May	61
November	60
August	59
July	57
December	53
April	51
January	50
February	50
March	48

TABLE III

FOCAL PLANE CHARACTERISTICS
FOR
TYPICAL EXPOSURE OF 335 w/cm^2

DIAMETER (cm)	2.54	5.08	7.62	10.16	12.7	15.24	17.78
% TOTAL POWER	4.8	25.4	54.6	76.3	87.7	96.4	100
POWER (kilowatts)	1.3	7.2	15.4	21.4	24.7	27.1	28.1
MIN. FLUX (w/cm^2)	328.8	298.7	209.2	119.7	59.8	12.1	0
MEAN FLUX (w/cm^2)	331.4	313.8	224.1	134.6	75.0	20.9	6.0

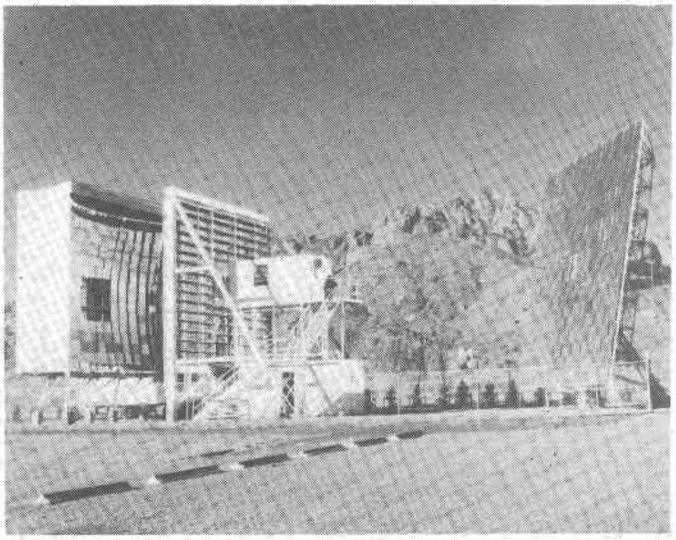

FIGURE 1

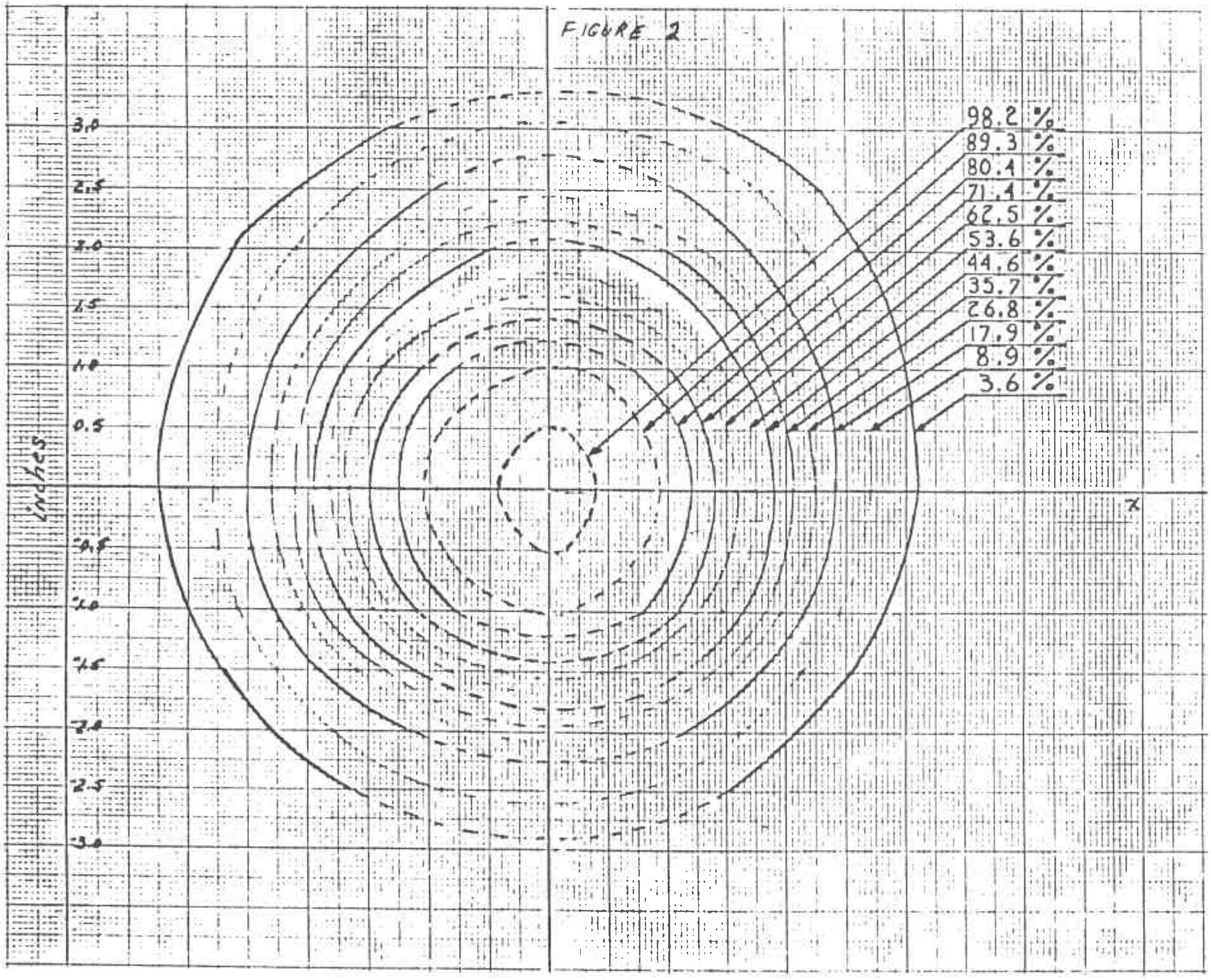

FIGURE 2

NEW MEXICO STATE UNIVERSITY/PHYSICAL SCIENCE LABORATORY SOLAR FURNACE FACILITY

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Department of Mechanical Engineering

and

W. C. Stevens
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INTRODUCTION

The NMSU/PSL solar furnace facility is located on the campus of New Mexico State University within the Physical Science Laboratory service compound. The campus is located on the southern edge of Las Cruces, near the confluence of Interstate 10 and Interstate 25, approximately 50 miles north of El Paso, Texas and within 35 road miles of the White Sands Solar Facility.

The facility, which has been operational since May 1980, was designed for long duration, high flux density material testing and flux-gage calibration and evaluation. It consists of a 3.66 m by 4.27 m heliostat covered with 0.6 m-square mirrors mounted on an Army surplus 584 radar pedestal, a 3 m-square concentrator with small flat mirrors designed to focus on a test area 2.6 m from the center of the concentrator and an attenuator designed to vary the flux-density at the test area, Figures 1 and 2.

The heliostat reflecting surface is FEK-244 aluminized acrylic placed on the front surface of 0.6 cm plate glass and the concentrator facets are back-surfaced iron glass 6.3 cm-square and 0.3 cm thick. Heliostat tracking is accomplished by balancing photoconductive cells which trigger a drive pulse generator to the heliostat motor armatures.

The attenuator, located between the concentrator and the test area, is capable of limiting the flux-density at the test area to any level between zero and full power. It is a venetian-blind type of structure with five rows of blades which can be set at any position between full open and completely closed. An electric motor, gear box and crank mechanism actuate the attenuator through an electric clutch. It takes approximately eight seconds to go from full-open to full-closed and can be released to close from full-open in 0.5 seconds during an emergency.

A second facility to be located just west of the present facility is being planned. This facility will consist of two small vertical beam solar furnaces, Fig. 3. The concentrator mirrors will be 1.52 m diameter electro-formed copper parabolic mirrors surfaced with Rhodium.

SOLAR FLUX-DENSITY MEASUREMENTS

Flux-density measurements on the NMSU/PSL furnace have been made by R. Edgar and L. K. Matthews of Sandia National Laboratories and by S. R. Skaggs of Los Alamos Scientific Laboratory [1]. The measurements made by Edgar and Matthews are shown in Fig. 4. These measurements were obtained by mounting nine circular foil heat flux gages in a water cooled copper plate and then placing the plate at the focal plane.

The flux-density measurements by Skaggs were made on August 29, 1980 with a single circular foil flux gage mounted in a water cooled copper plate. An x-y-z motion device was fabricated by using a lab jack in conjunction with the cross motion movement of the experimental table. The jack was moved in 1 inch increments in each direction and the grid shown in Fig. 5 is 1-inch squares. A complete description of the measurement technique is presented in Ref. [1] and can be obtained from the author.

The contours shown in Fig. 5 were measured at the approximate location of the focal plane. Subsequent measurements demonstrated that the furnace is capable of providing a peak concentration (measured flux-density divided by solar insolation) of 850 under ideal conditions, i.e., after carefully cleaning the heliostat and concentrator glass. This measurement was made during October, 1980 and used the same circular-foil flux gage as Skaggs.

Improvements planned for implementation in 1981 are projected to increase the concentration ratio to about 1000. One improvement will consist of refitting the heliostat with Corning Chemcor back-surface silvered glass mirrors. These mirrors will provide higher surface reflectivity than the present mirrors. Another refinement step will be to improve the concentrator mirror facet alignment.

EXPERIMENTS

The first use of the NMSU/PSL facility was to calibrate circular foil flux gages in a solar environment. L.K. Matthews and R. Edgar of Sandia National Laboratories conducted the calibrations during the summer of 1980. Their procedure consisted of evaluating each gage against a standard for various flux-density levels. The gages were placed in the focal plane of the furnace and various attentator settings were used to obtain the desired flux-densities.

The first experiment on the furnace was performed by S. R. Skaggs of Los Alamos Scientific Laboratory and consisted of roasting molybdenite ore in air. Skaggs' first experiments were conducted during August, 1980 and another series of experiments were done on October 10, 1980 after several improvements in concentrator mirror alignment were made.

A Solar coal gasification experiment was conducted by W.H. Beattie of Los Alamos Scientific Laboratory. His first tests were conducted during November, 1980 and a second series was made during March, 1981. A third series of tests is scheduled in the near future to verify his experimental technique before scheduling tests in larger furnaces such as White Sands.

VERTICAL BEAM FACILITY

The vertical beam facility will consist of two flat mirror surface heliostats mounted on azimuth/elevation tracking pedestals located directly below a parabolic mirror with its optical axis oriented vertically and coincident with azimuth rotation axis of the heliostat, Fig. 3. The facility is designed for attachment to the south wall of Anderson Hall, the PSL building on the NMSU campus. A sheltered experiment work area, facility control center and a test operation area which will overhang the building south wall are being planned, Fig. 6.

The heliostats will be similar to the one used for the horizontal beam facility, Fig. 7. Two 1.52 m diameter electro-formed copper parabolic mirrors surfaced with Rhodium will be used for the concentrator. These mirrors have a focal length of 0.65 m, a rim angle of 120 deg., and a focal ratio of 0.4. Both heliostats and mirrors are available at PSL as surplus radar pedestals and surplus military searchlights.

The hearth, or platform mounting the experiment, will be trolley-mounted to enable experimenters to control the exposure time for their samples. An adjustable attenuator mounted on the underside of the hearth trolley beam is also being planned. This design is basically a parasol, with opening or closing accomplished by a screw actuator, Fig. 8.

ACKNOWLEDGMENTS

The funds needed to complete the horizontal solar furnace project were provided by Sandia National Laboratories, Albuquerque, New Mexico, a prime contractor for the Department of Energy and by the Mechanical Engineering Department at New Mexico State University. The Physical Science Laboratory at New Mexico State University donated the land upon which it is located and provides the facility with water, air and electricity. Mr. Richard Hays of White Sands Missile Range, Mr. Robert Sabin, and Mr. Tom McConnell of the Physical Science Laboratory and Dr. Kenneth White of the Civil Engineering Department at New Mexico State University all provided valuable assistance during this project.

REFERENCES

[1] Skaggs, S.R., Mulholland, G.P., Clark, R., and Bryant, J., "Solar Flux Measurements on the New Mexico State University Solar Furnace," submitted to Solar Energy.

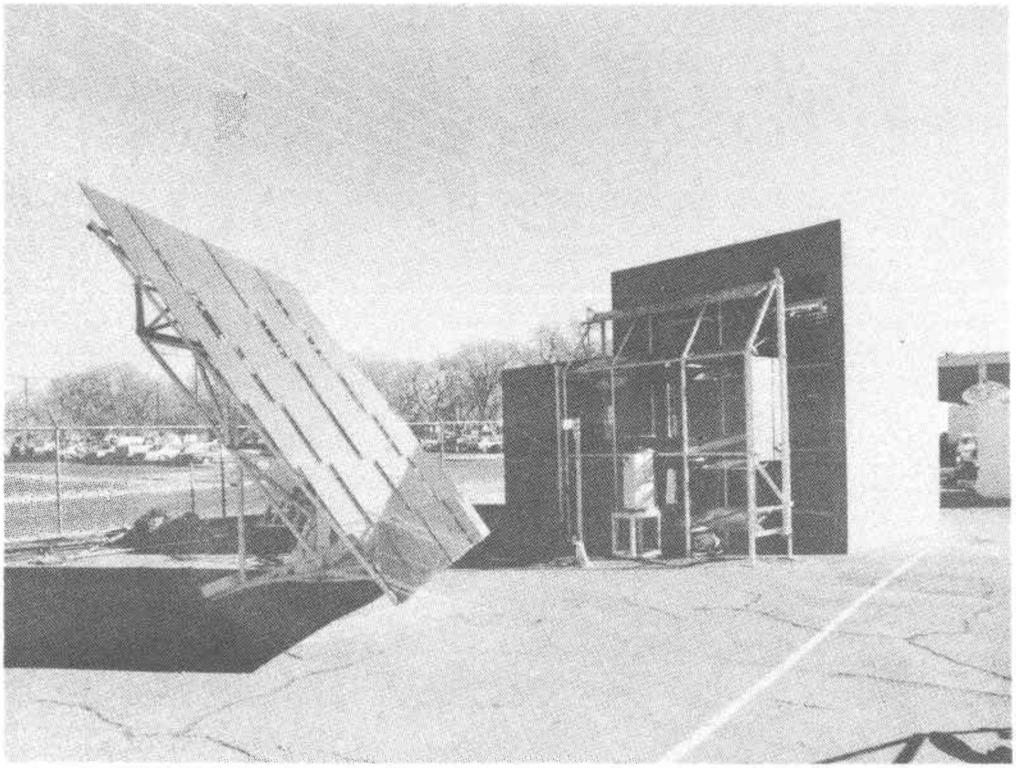


Figure 1. NMSU/PSL Horizontal Solar Furnace

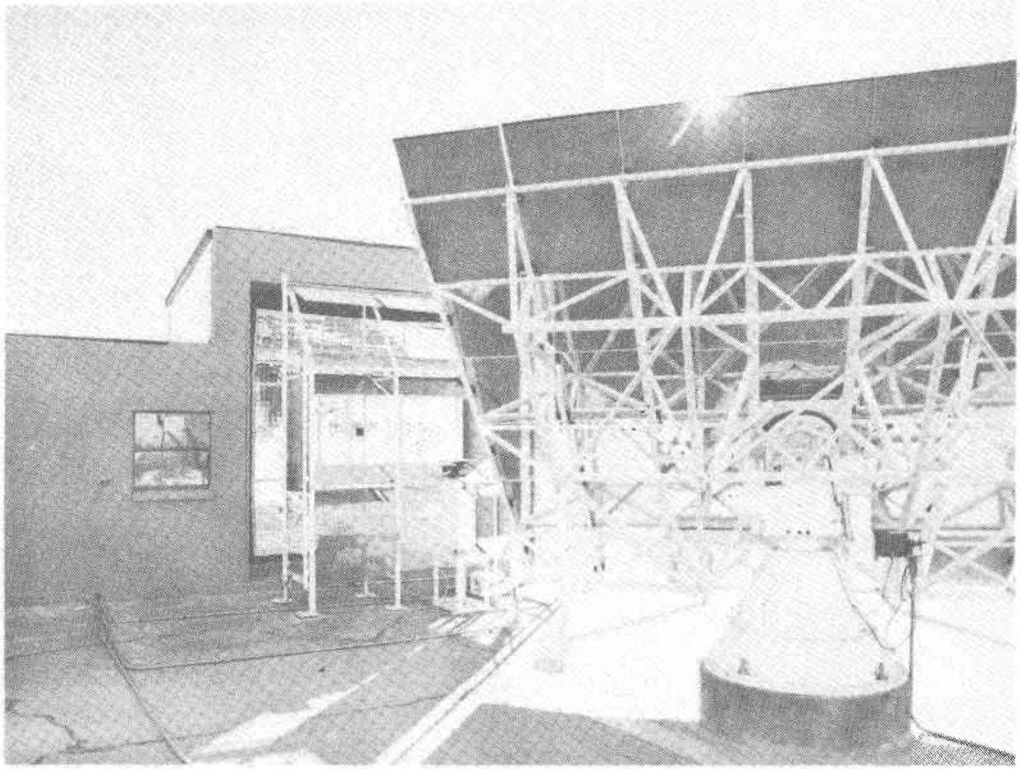


Figure 2. NMSU/PSL Horizontal Solar Furnace

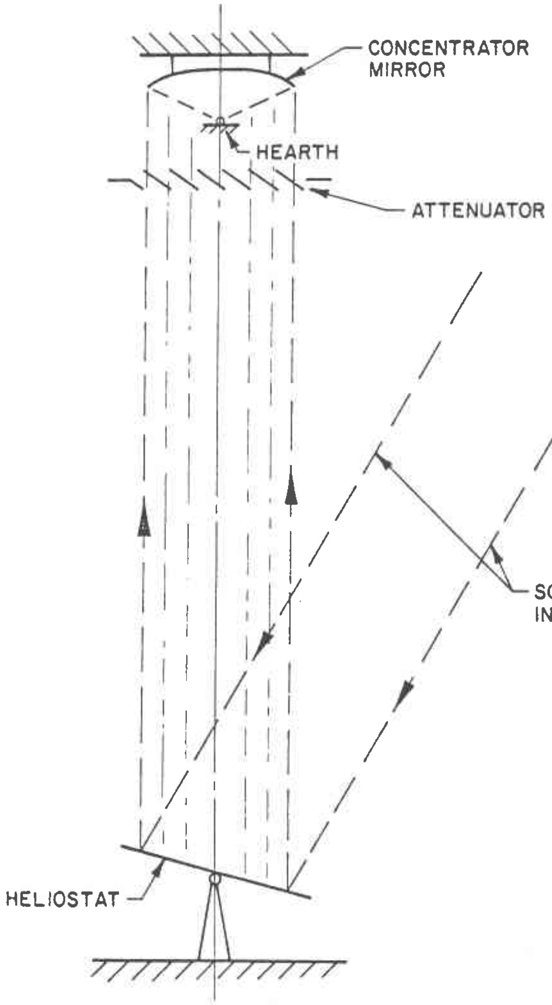


Figure 3. Basic Solar Furnace Optical Geometry

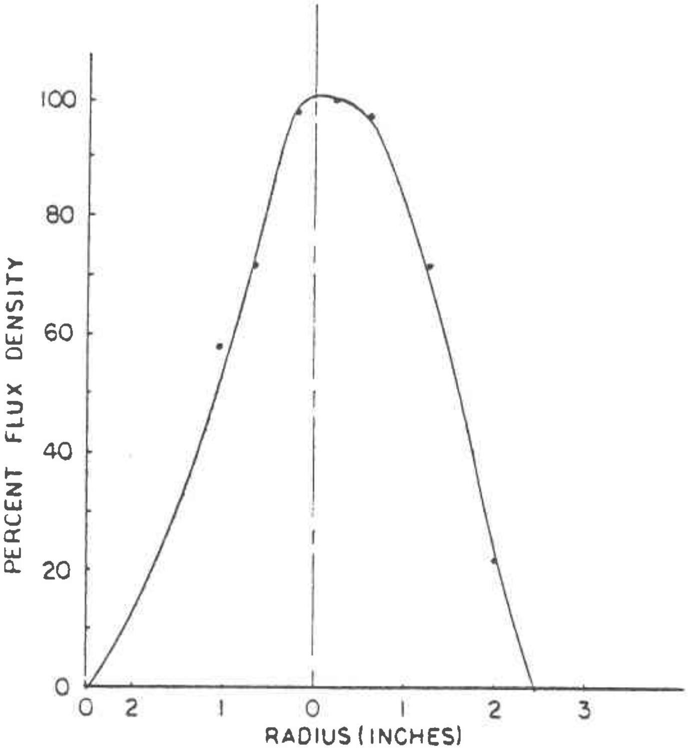


Figure 4. Flux Density Profile at Focal Plane

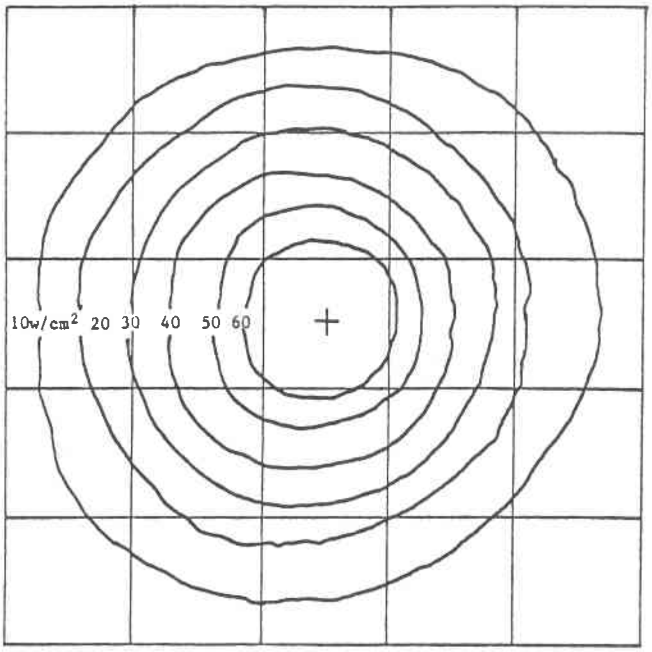
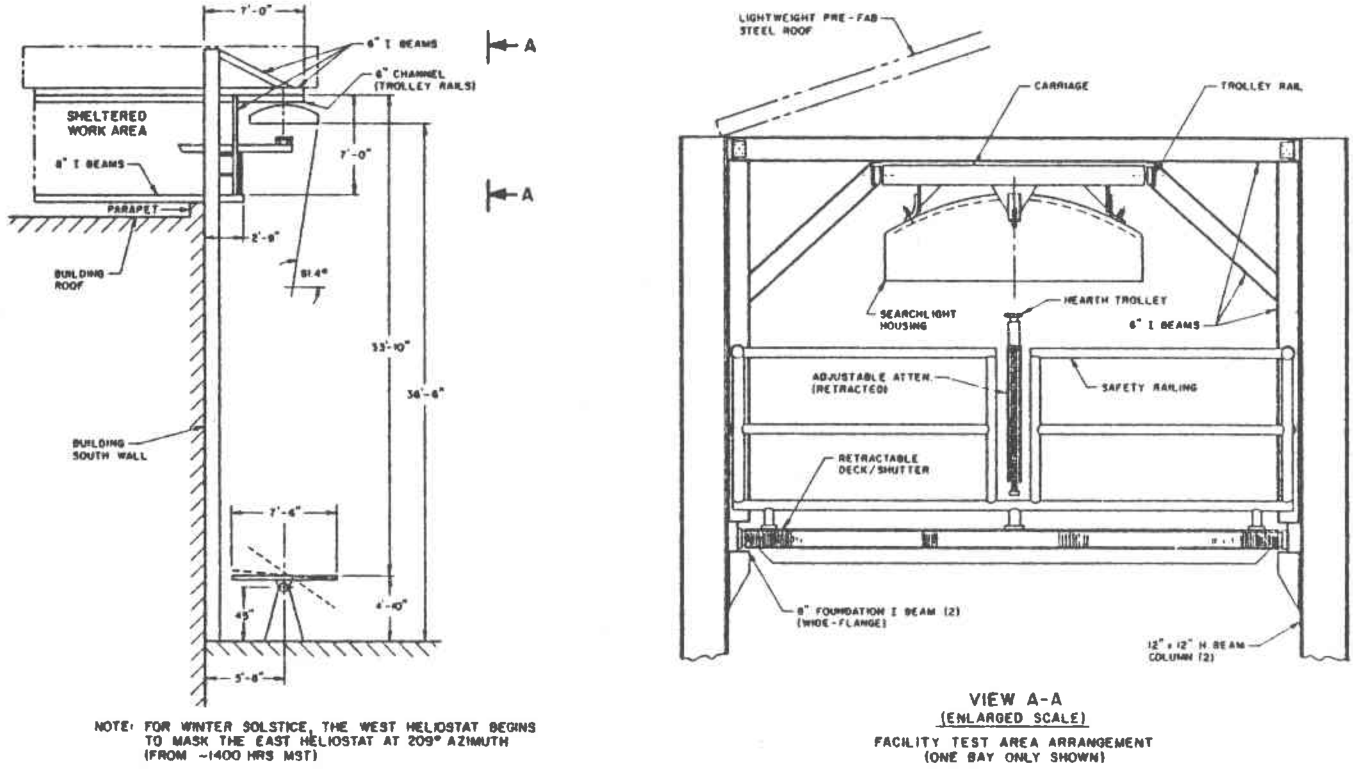


Figure 5. Flux-density Contours at the Approximate Location of the Focal Plane. Solar Insolation was 966 W/cm^2.



NOTE: FOR WINTER SOLSTICE, THE WEST HELIOSTAT BEGINS
TO MASK THE EAST HELIOSTAT AT 209° AZIMUTH
(FROM ~1400 HRS MST)

VIEW A-A
(ENLARGED SCALE)
FACILITY TEST AREA ARRANGEMENT
(ONE BAY ONLY SHOWN)

Figure 6. Configuration of Proposed Facility

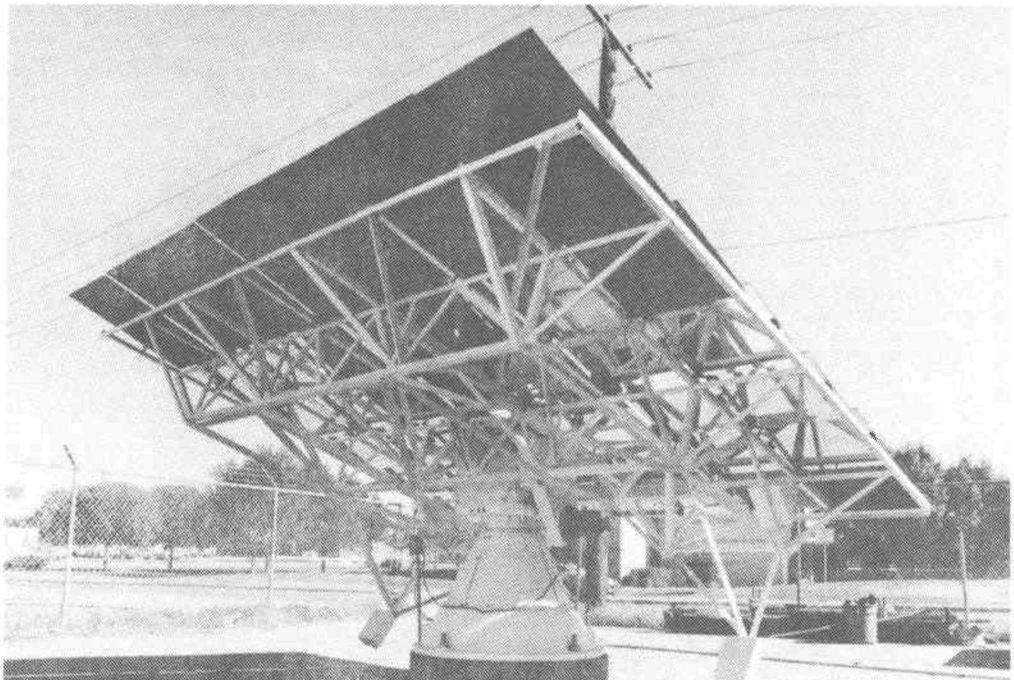


Figure 7. Back Structure of Existing Horizontal Furnace Heliostat

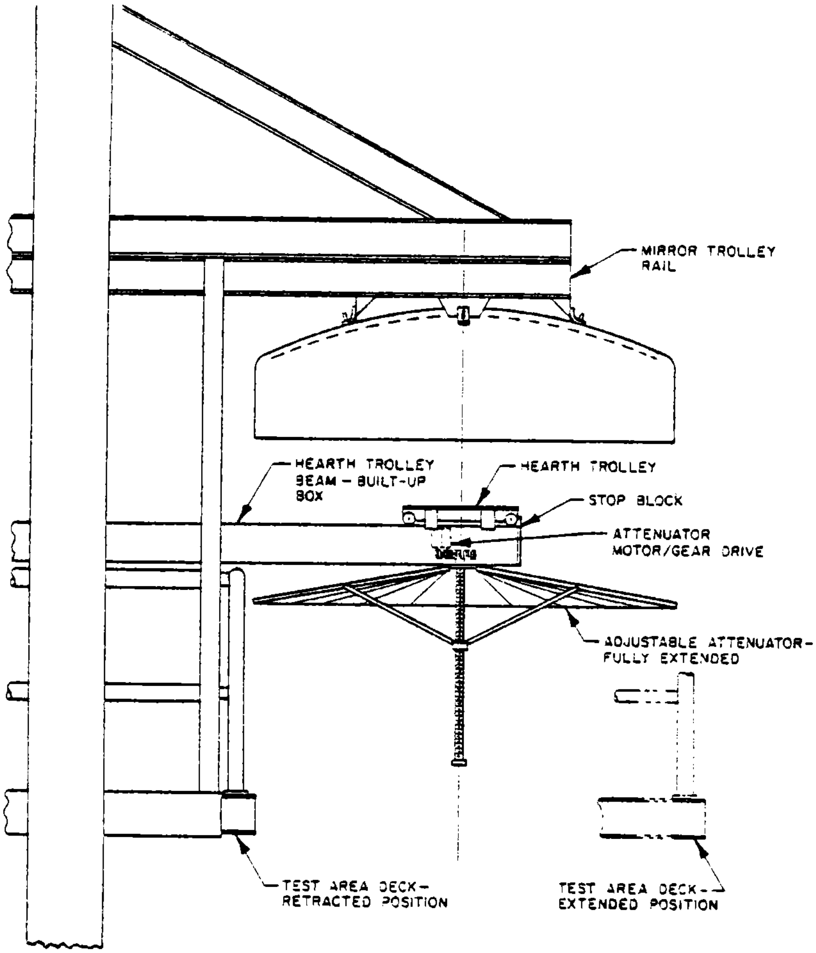


Figure 8. Test Area Deck, Adjustable Attenuator and Hearth Trolley Details

Facility Flux Mapping Capabilities and Problems

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This paper was unavailable for publication. For further information, please contact the author

FLUX Mapping at the CRTF

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April 22, 1981

The CRTF uses an array of flux density sensors to measure the power and flux density distributions for major receiver test programs.

A mechanical device, called the Real Time Aperture Flux system was used to move a row of individual sensors across the aperture of the EPRI/Boeing air cooled receiver and the DOE/Martin Marietta molten salt cooled receiver. We used a fixed array of sensors mounted between the tubes and at the perimeter of the DOE/McDonnell Douglas water-steam cooled receiver.

In all cases we have used commercialy available sensors of the circular-foil type. These consist of a thin disk of constantan foil supported by a water cooled copper tube. A copper wire connection is made at the center of the disk thus forming a differential thermocouple. The output is proportional to the heat input to the foil. The foil is blackened to provide a known and constant emmissivity. These sensors have a relatively slow time constant of about 0.3 to 0.5 seconds but do have a flat spectral response over the solar spectrum.

We, at Sandia, have also been developing photon sensors that have much faster response times; on the order of a few microseconds. The advantage of a fast response time is that an aperture scanning system can move faster, and thus provide less blocking of the receiver and also have to withstand a lower total fluence. To date, our success with the photon sensors has been marginal. Survivability at high flux densities and resolving their spectral resonses are still uncertainties that need to be refined.

RTAF Moving Bar System

The instrumented moving bar or bars used to take data is supported by a water-cooled frame that also provides protection for the bar drive components and the power/data umbilical connections (Figure 1). The bar is moved across the aperture by a modified Geneva drive or stepping motor coupled with a ball screw arrangement. These drives give periodic zero velocity points during the traverse of the bar across the aperture. The flux density data are taken at the zero velocity locations so the sensors can adequately respond.

The moving bar is populated with water-cooled heat flux sensors along its length. Data are collected from the sensors by an on-board microprocessor-controlled data acquisition system and are sent to the RTAF computer in the central control room located over 400 m away. This on-board data system allows information to be gathered from many flux sensors on the bar with a minimum of encumbrances to inhibit the bar movement.

RTAF CONTROL AND DATA COMPUTER SYSTEM

The RTAF computer system is located in the central control room and provides data handling and reduction, flux density-related experimenter display generation, bar drive control, and data archiving.

Some of the parameters calculated from the flux gage data are:

1. Flux density distributions in the RTAF aperture plane.
2. Total power in the RTAF aperture plane.
3. Estimated power on the experiment if the experiment is smaller than the RTAF aperture.

4. Estimated power on the equipment if the RTAF and the experiment planes are not the same.
5. Total energy delivered to the experiment over specified time periods.

The data we receive from the moving bar is obtained in a plane parallel to but not at the experiment surface or aperture. The actual flux distribution and magnitude at the experiment can be significantly different from that at the plane of the sensors. This difference is primarily a function of the distance between the measuring plane and the experiment. As the distance increases, our ability to ascertain power input to an experiment and flux density distributions from the RTAF measurements becomes less certain.

The method we use to determine the power at the experiment aperture, given the power in the measuring plane, involves a set of calculations using heliostat transfer functions. These transfer functions are derived utilizing computer simulations obtained with a Sandia developed computer program, HELIOS, and actual flux density measurements in both the measuring plane and the experiment plane. When the solar power tests are actually run, the experiment power input is calculated using the power measured by the RTAF and the previously derived heliostat transfer functions. Data determined in this way have an expected accuracy of about ±8%.

This information is presented to the experimenter in real time on a color graphics system. The computer graphics reconstructs the sensor outputs versus location (Figure 2), provides 2-dimensional iso-flux displays and 3-dimensional flux density distributions in the measuring plane are also available.

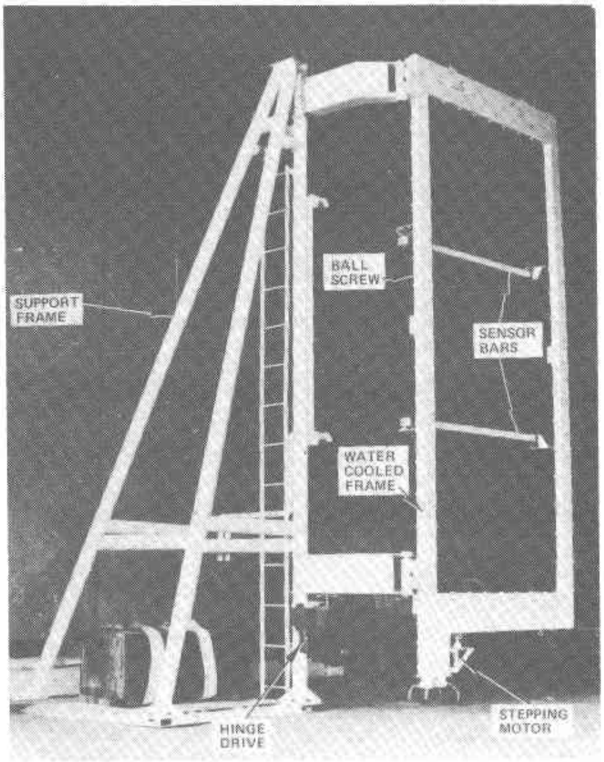


FIGURE 1 Real Time Aperture Flux System for Use with the ESG Sodium Cooled Receiver

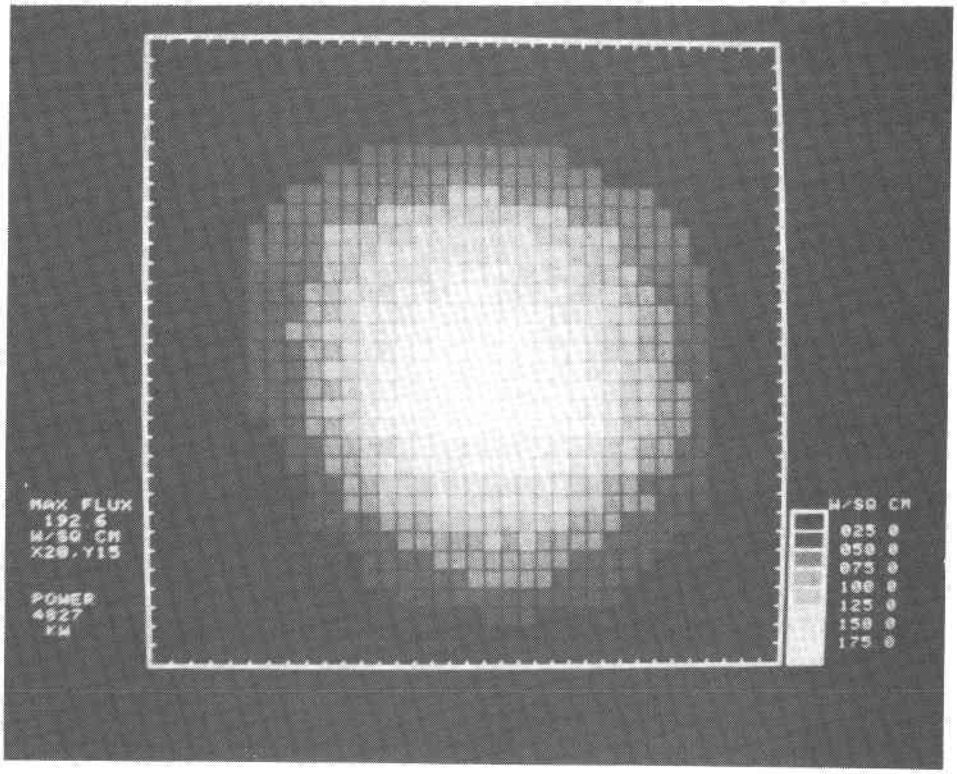


FIGURE 2 Typical RTAF Display

Gintz - Thank you, John. We have time for questions.

Walton - It's interesting that when the 1,000 kW furnace in Odeillo was first calibrated, they used magnesium oxide on a water-cooled aluminum plate to do exactly what you are talking about, and they scanned it with an optical pyrometer working at .65 microns. They were measuring apparent temperature, which is really reflective of that magnesium oxide, and the magnesium oxide was at .99 reflectivity. It's a beautiful material, and I think that's a good way to accomplish what you were talking about.

Antal - We have a well-calibrated Hy-Cal calorimeter which holds up well. That gives a sense of the quality of calibration received on these devices and how long they last.

Brown - John, the data you gave is consistent with the time constant data that I gave-- 50 milliseconds.

Holmes - Measured by you, or the manufacturer?

Brown - We have done both on some of the gages we have purchased. We requested a time constant of better than 50 milliseconds, and have verified that we are actually getting into 30- to 40-millisecond time constants.

Comment - If you take five or six, your number is achieved.

FACILITY FLUX MAPPING CAPABILITIES AND PROBLEMS AT THE PARABOLIC DISH TEST SITE

Darrell Ross
Jet Propulsion Laboratory
Pasadena, CA

My talk concerns the flux mapping which has been done at the Parabolic Dish Test Site during the past year. The flux mapper was developed for four primary reasons: 1) to assist in receiver design; 2) to help characterize concentrators; 3) to verify analytical techniques; and 4) to evaluate system performance.

Figure 1 shows the flux mapper in sketch form. Designed and developed by the instrumentation section at JPL, it is comprised of four main parts: the scanning mechanism, the radiometer probe, the control and data acquisition/display electronics, and data management and reduction. Note that the equipment mounted on the concentrator is shown on the left and the equipment in the control room is shown on the right. Each of these four main parts will be discussed briefly.

The scanning mechanism moves the probe to a predetermined point on the Z axis and then scans in the X and Y direction in a 16 x 16" plane. When this plane is fully mapped, the probe is moved to a new position on the Z axis and the same process is repeated, providing a three dimensional plot of the flux pattern and intensity at the focal plane. The scanning mechanism is driven by stepping motors, with all components or surfaces that come in contact with the solar flux being water cooled for survival. The scanning time for a given plane on the Z axis is approximately 30 to 40 minutes, and the typical number of points taken during that scan is 1,056.

The second of the four main parts is the radiometer probe. We have actually used two different probes in our flux mapping--a PIN Diode and an Absolute Cavity Radiometer. Today I will discuss the Kendall Absolute Cavity Radiometer, because we have used it primarily, and also because it's the one we have used almost exclusively in the past 6 to 8 months. With this radiometer we have been able to make measurements up to about 16,000 suns. It has a time constant of 4 to 6 seconds with an overall accuracy of about 2 percent. The acceptance angle is on the order of 60 degrees on each side of the axis for a total of 120 degrees.

The third of the four main parts is the control and data acquisition/display electronics. This part of the flux mapper allows us to obtain a quick look data review as we are going through a scan sequence on the concentrator under test, and an X-Y plotter gives us an intensity plot as we are scanning through the X-Y plane. We also have a calibration printout which gives us calibration data for that particular plane.

Finally, there is data management and reduction. The data control processor formulates the data and transmits it to magnetic tape for permanent storage and later nonreal-time data reduction. A computerized program for plotting flux mapper data is available and has been extensively used.

To date, the flux mapping we have done varies from a partial to a full concentrator system, ranging from 5 to 82 kW_t. The overall accuracy of the flux-mapping system is ± 5 percent.

As mentioned previously, we record 1,056 data points for each X-Y scan. The procedure used is to step to one particular point in the Z axis and begin scanning in the X-Y direction. The probe stops at each of the 1,056 points and takes a reading when the data has reached steady state. Then it moves, stops, and takes another reading, until all 1,056 points have been measured. Typical distances between data points are one-half inch in the X axis and one-half inch in the Y axis. When we know where the focal plane is, we usually take three scans--one at the focal plane and one on either side of the focal plane. If we don't know where the focal plane is, we do have an 18-inch travel of the radiometer probe along the Z axis, and we can take scans along that entire 18 inches, usually at one-half to one inch intervals.

Figure 2 is a sketch of the Radiometer probe we are using, which was developed by Jim Kendall of the instrumentation section at JPL.

The probe is basically a ruggedized version of a laboratory instrument, the world standard radiometer that Jim Kendall developed some years ago. The key parts are the aperture and the radiometer itself. We also have a water-cooled thermal shield, a radiation guard, and a mounting probe for mounting it to the scanning mechanism.

Figure 3 is a photograph of the flux mapper mounted at the focal point of one of the concentrators at the PDTS. The radiometer and the scanning mechanism to which it attaches can be seen clearly. The electronics for the flux mapper are hidden behind the shield to protect them from the solar flux. Figure 4 is the same configuration as Figure 3, but with the photograph taken from a slightly different angle. This photograph provides a better view of the scanning mechanism and the electronics package which contains the signal preamplifiers that amplify the signal before it is sent back to the control room.

At the PDTS we have had to overcome the problem of working with the very high flux intensities at the focal plane, which have approached 1,500 W/cm^2 or 15,000 suns. We attempted to reduce that peak intensity while at the same time maintaining

98 percent of the energy within an 8-inch diameter aperture. This is shown in Figure 5.

Gintz - What's the measurement on that?

Ross - The vertical scale is in W/cm^2, and the horizontal scale is as shown in the lower right portion of the photograph.

Figure 6 is a three dimensional flux plot of actual test data taken from the second Test Bed Concentrator at the PDTS. Note that a peak flux of 861 W/cm^2 was achieved. This data was taken with only 50 percent of the mirrors exposed, so with all of the mirrors exposed we would achieve a peak flux of 17,000 suns. This high peak flux was required for a different test application.

The software program that produced Figure 6 also enables us to view this flux plot from different angles and/or different locations. It is also possible to look directly down on the flux plot and produce a contour map.

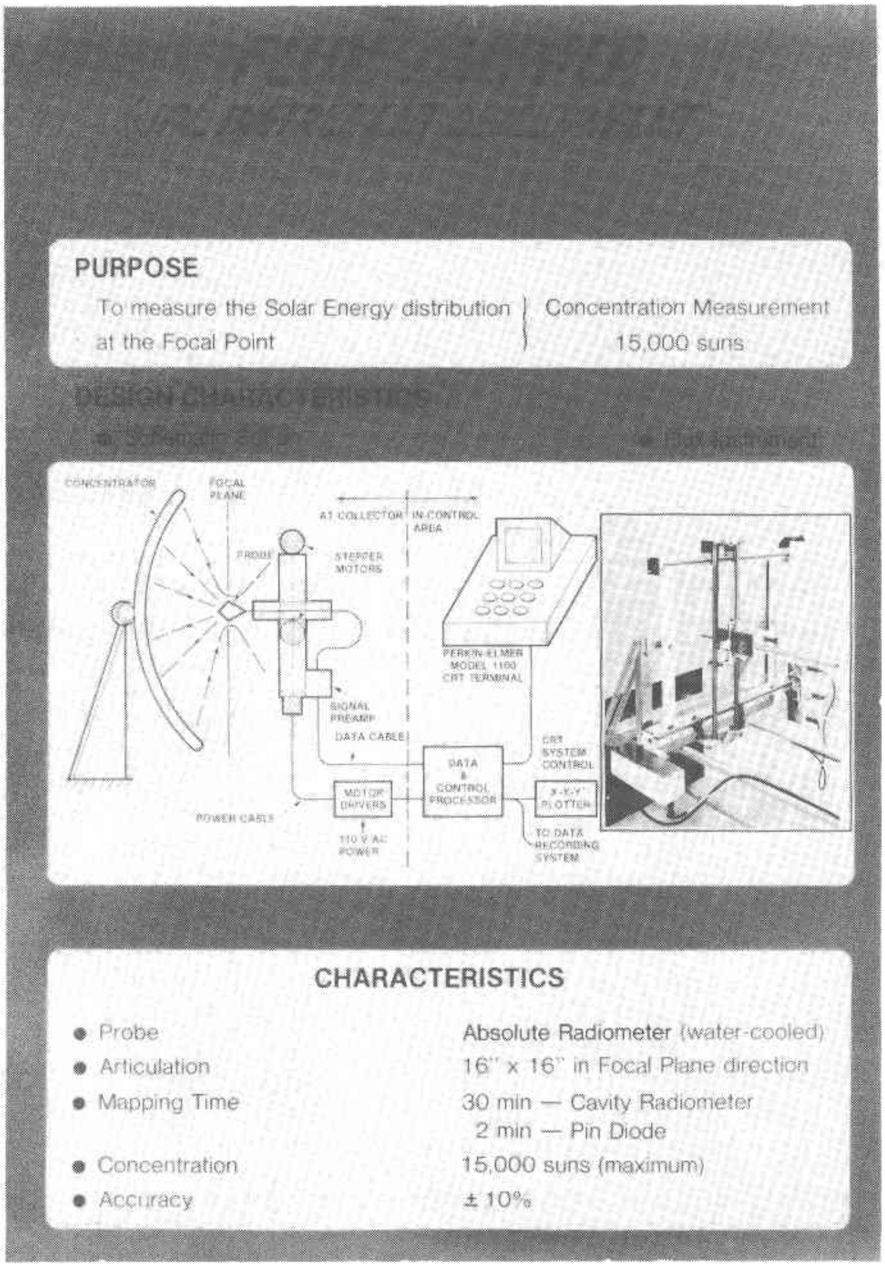
The only major problem we have encountered with flux mapping is survival at the focal plane, because we are working with temperatures in excess of 5000°F and peak fluxes of 17,000 suns. It's a challenge to have anything survive at the focal plane under those conditions. However, the solution was fairly straightforward: We simply water-cooled all the components and surfaces that were exposed to the solar flux. Once that was accomplished, the operation of the flux mapper became pretty routine.

Gintz - Thank you Darrell. Are there any questions?

Question - Do you have the length of time it takes to do an X-Y scan referenced against a standard radiometer?

Ross - We use two modes--a relative mode and an absolute mode. In the relative mode a Pyrheliometer mounted on the back of the flux mapper gives us a reading of the direct component of radiation at all times during the flux mapping process. However, one has to believe something, so it is a choice between the Kendall Radiometer or the Pyrheliometer on the back of the flux mapper. Since we have a high level of confidence in the Kendall Radiometer, we have typically used the reading of the Kendall Radiometer. While it's true that the insolation level can change during that 40-minute period of time, we have eliminated this factor as a potential source of error by simply flux mapping only on clear days. If clouds pass over during a flux mapper scan, we discard that scan and begin again.

Kendall - We have calculated the accuracy of the Absolute Cavity Radiometer to be one percent or better. This one percent does not depend on anyone else's standard. We have built into the radiometer an electric heater which provides heating of the cavity that is accurately equivalent to radiation heating. We have tested this concept extensively, and we have made various kinds of radiometers on that principle. We have found it to be very good. Our other radiometers achieve accuracies of better than 0.5 percent--typically about 0.25 percent. So, we think we are going to have absolute calibrations here and that we are in pretty good order.



PURPOSE

To measure the Solar Energy distribution at the Focal Point | Concentration Measurement 15,000 suns

DESIGN CHARACTERISTICS

- Schematic Design
- Flux Instrument

CHARACTERISTICS

● Probe	Absolute Radiometer (water-cooled)
● Articulation	16" x 16" in Focal Plane direction
● Mapping Time	30 min — Cavity Radiometer 2 min — Pin Diode
● Concentration	15,000 suns (maximum)
● Accuracy	± 10%

FIGURE 1

10,000 S.C. RADIOMETER ASSEMBLY MOUNT

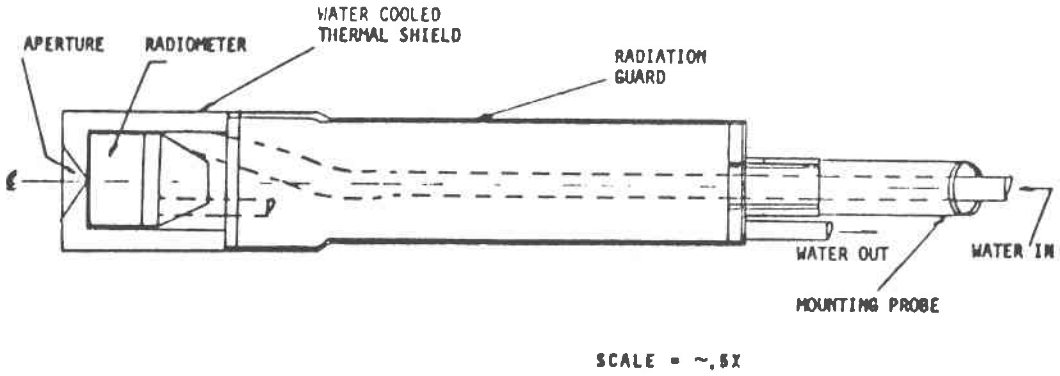


FIGURE 2

FIGURE 3

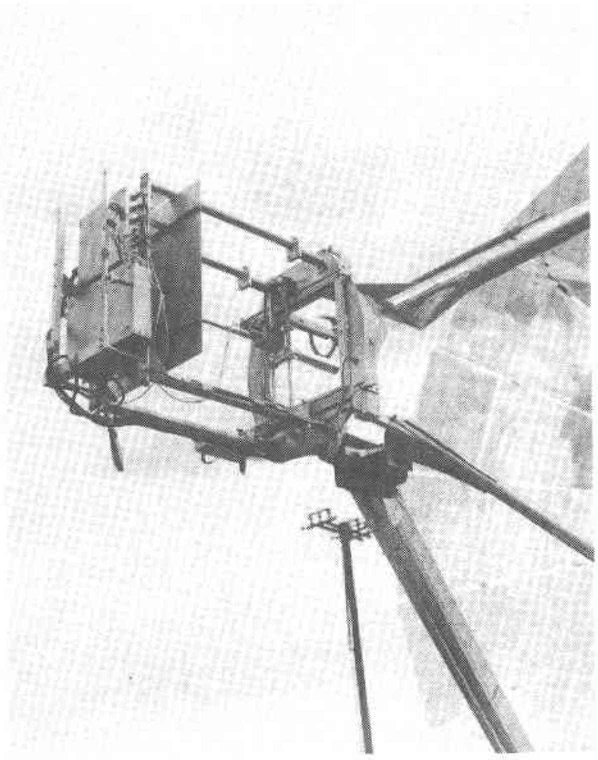


FIGURE 4

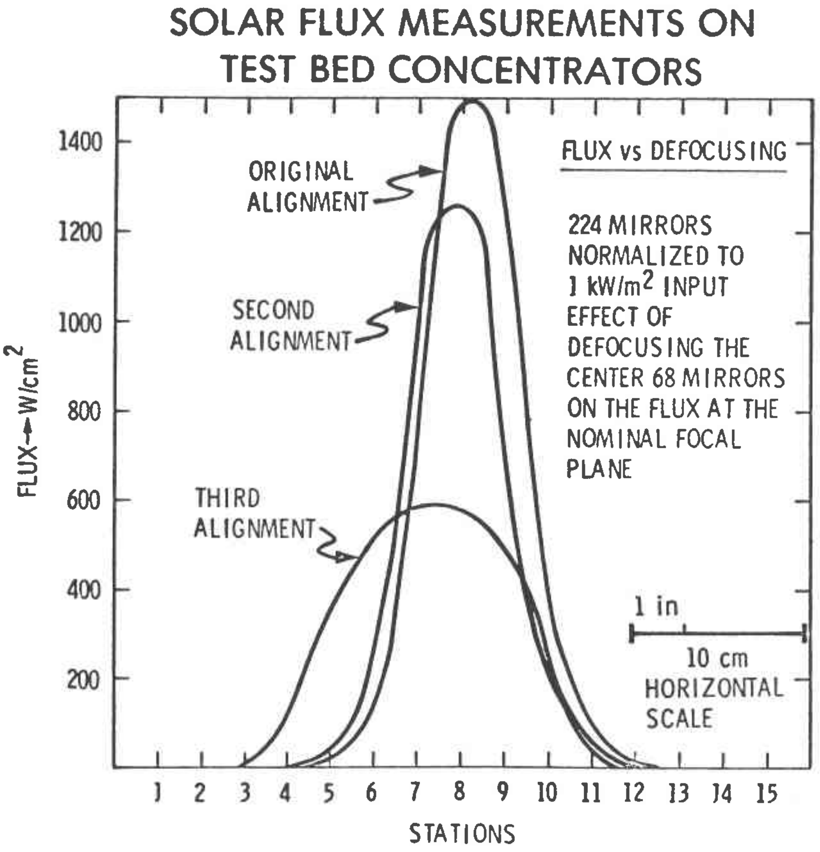


FIGURE 5

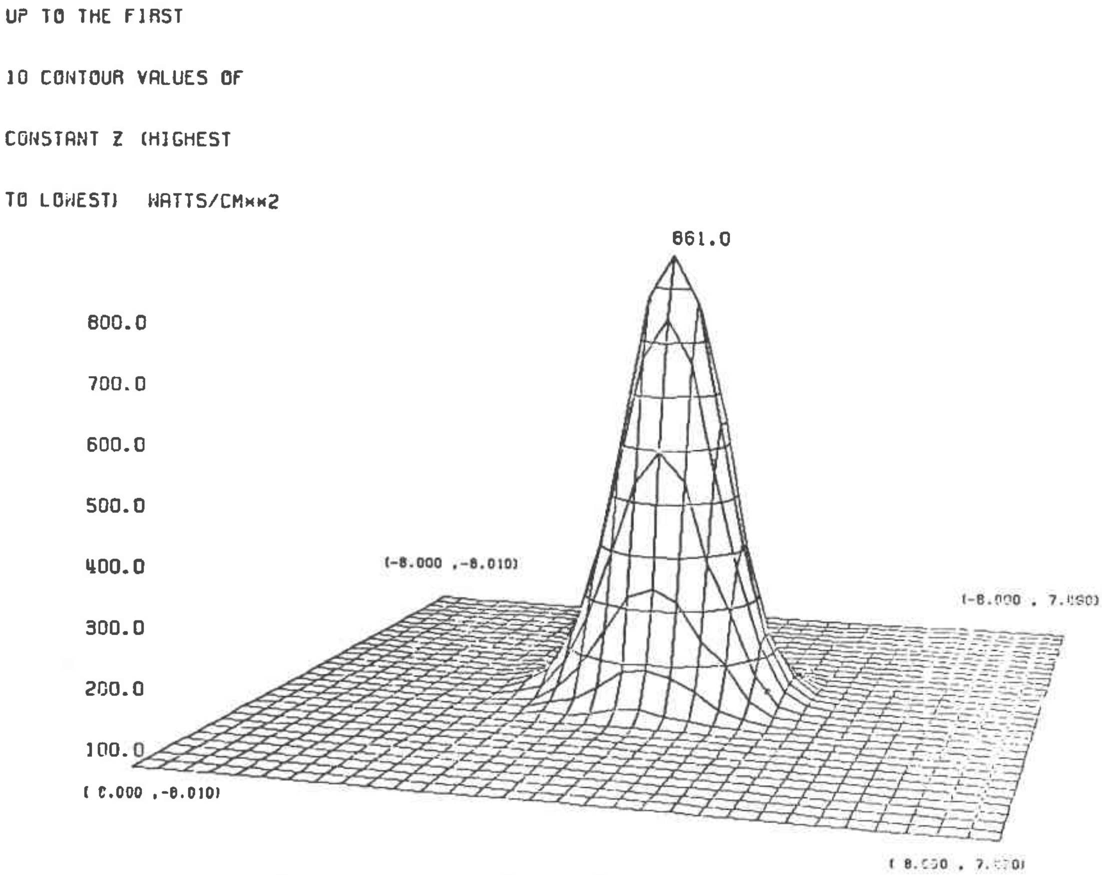


FIGURE 6

FLUX MAPPING AT THE WHITE SANDS SOLAR FACILITY

Juan A. Briones
and
Richard A. Hays
White Sands Solar Facility
White Sands Missile Range, New Mexico 88002

INTRODUCTION

The White Sands Solar Facility (WSSF) has been operational at the White Sands Missile Range since 1973. Previously, from 1959 to 1972 it was located in Natick, Massachusetts. The WSSF was designed to produce a thermal flux in excess of 377 watts/cm^2 with an exposure area of 10 centimeters in diameter. This is accomplished by super-imposing 180 concentrated solar images at the focal plane located in the test and control chamber of the WSSF. This paper will address the procedures utilized in obtaining a flux map of the WSSF exposure area.

Procedures Obtaining Flux Map Data

Figure 1 illustrates the physical configuration of the instrumentation required in obtaining a flux map at the WSSF. The procedure is for the calorimeter to horizontally traverse the focal volume at the focal plane from a point four inches either side of the optical axis. The calorimeter is then raised one half inch above the optical axis and again traversed in the horizontal direction. This procedure is repeated in one half inch increments up to four inches above the optical axis. Figure 2 shows the calorimeter on the three axis table and illustrates the horizontal and vertical reference lines to denote the movement of the calorimeter at the focal plane with variation above and below the optical axis.

The horizontal position of the calorimeter is referenced by the three axis table X drive potentiometer output. It produces a voltage proportional to the table or calorimeter position. The gain on the X axis input of the XY recorder is set so that for every one inch displacement of the three axis table in the X direction the XY recorder X axis indicates one inch displacement. Figures 3 and 4 illustrate typical plots of the flux level as a function of position of the calorimeter. Typically 50 percent of maximum flux is used to generate such flux profiles. The flux profiles generated by this method are then reduced to produce isoflux contours at the focal plane or within the WSSF exposure volume as required.

Reduction of Flux Profiles

Figure 3 illustrates the upper mode (above the optical axis) with seven profiles labeled as to their individual positions from the optical axis. It is noted that the heliostat experienced wind gusts at the time when the calorimeter was traversing across at 1.5 inches above the optical axis. This shifted the flux pattern and an off-center profile resulted. Figure 4 illustrates the downward mode (below the optical axis) with eight flux profiles plotted. It is again noted that the heliostat experienced a severe wind gust for one of the traverses, but it was repeated.

First Order Reduction

In a first order reduction, coordinate points from the flux profiles are reduced to coordinates of points making up isoflux levels. Each point along the profile curve indentifies coordinates describing the calorimeter's position and the incident flux at that particular point. At constant millivolt values selected from each flux profile, coordinates are taken where the profile interacts the millivolts value (contstant flux). These coordinates (X and Y) are then plotted on a reference grid. This graphical representation becomes one isoflux contour referenced to the optical axis (o,o).

All measured coordinate points are connected with straight-line segments and dashed lines are used to connect missing coordinates where data was not obtained. As can be seen from Figure 5 the points along the 1.5 inch Y coordinates are abnormal in location. This is due to the gust of wind indicated in the original flux profile.

Second Order Reduction

In a second order reduction, the line segments making up the isoflux contours are further reduced by french curving a smoother more representative plot. This effort could be avoided by plotting a finer resolution of the isoflux XY coordinate points. From Figure 3 it was noted that the flux profile peak was shifted by approximately 0.3 inch to the right due to the wind gust. In the second order reduction the 1.5 inch Y axis flux profile was shifted back to the left 0.3 inches thus eliminating the error generated by the wind gust. Each isoflux contour was then normalized to the maximum flux level obtained at the optical axis (o,o). Also if the flux profiles were not obtained during a constant solar insolation then each flux profile would be scaled accordingly.

Instrumentation

The instrumentation used to measure the flux at any given position within the WSSF focal volume is a circular foil type heat flux gauge. Details on the operation of such heat flux gauges can be found in the technical literature and will not be discussed here.

The WSSF presently utilizes two sets of five such gauges. Each set consists of five different heat flux ranges. Each set is returned to the manufacturer every six months for calibration which is traceable to the National Bureau of Standards. Thus, one set is being calibrated while one set is being utilized at the WSSF. The manufacturer specifies gauge accuracy to within ± 3 percent upon calibration. The manufacturer's calibration is for the absorbed flux, not the incident flux environment. Therefore, in order to determine the incident flux environment the manufacturer specifies an absorptivity of 0.89 over the spectral range of 250 nanometers to 30,000 nanometers. It has been determined by different users of these gauges in the solar spectrum that the actual absorptivity is 0.94. Therefore, the WSSF corrects the calibration for an absorptivity of 0.94 instead of 0.89 to determine the incident flux.

Closing Remarks

Undertaking a flux mapping operation at the WSSF requires several operational conditions such as clear skies and minimal to non-existent wind. If windy conditions do occur during a flux profile measurement, it becomes very evident from the data and in some cases it can be corrected or additional data can be taken. Presently, instruments exist at the WSSF to digitize the flux mapping data and soon the software will be written to reduce the data to a flux map.

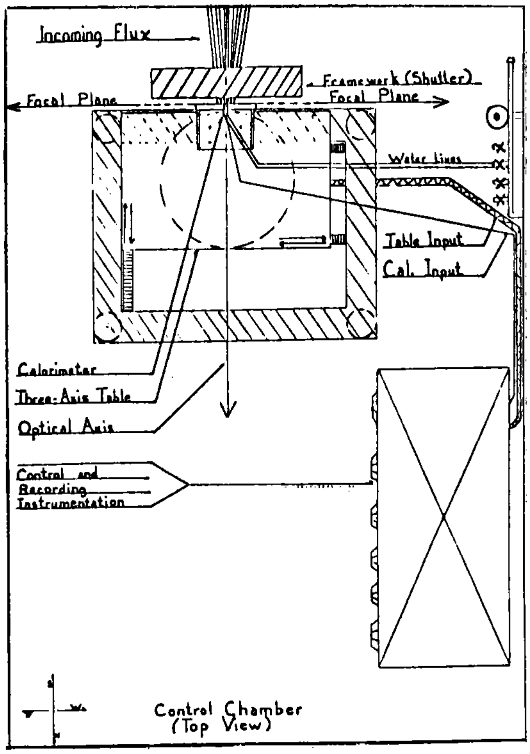


FIGURE 1

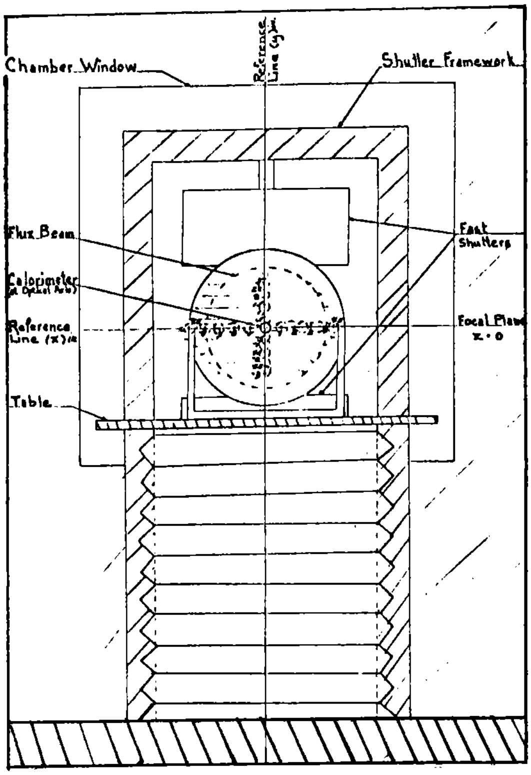


FIGURE 2

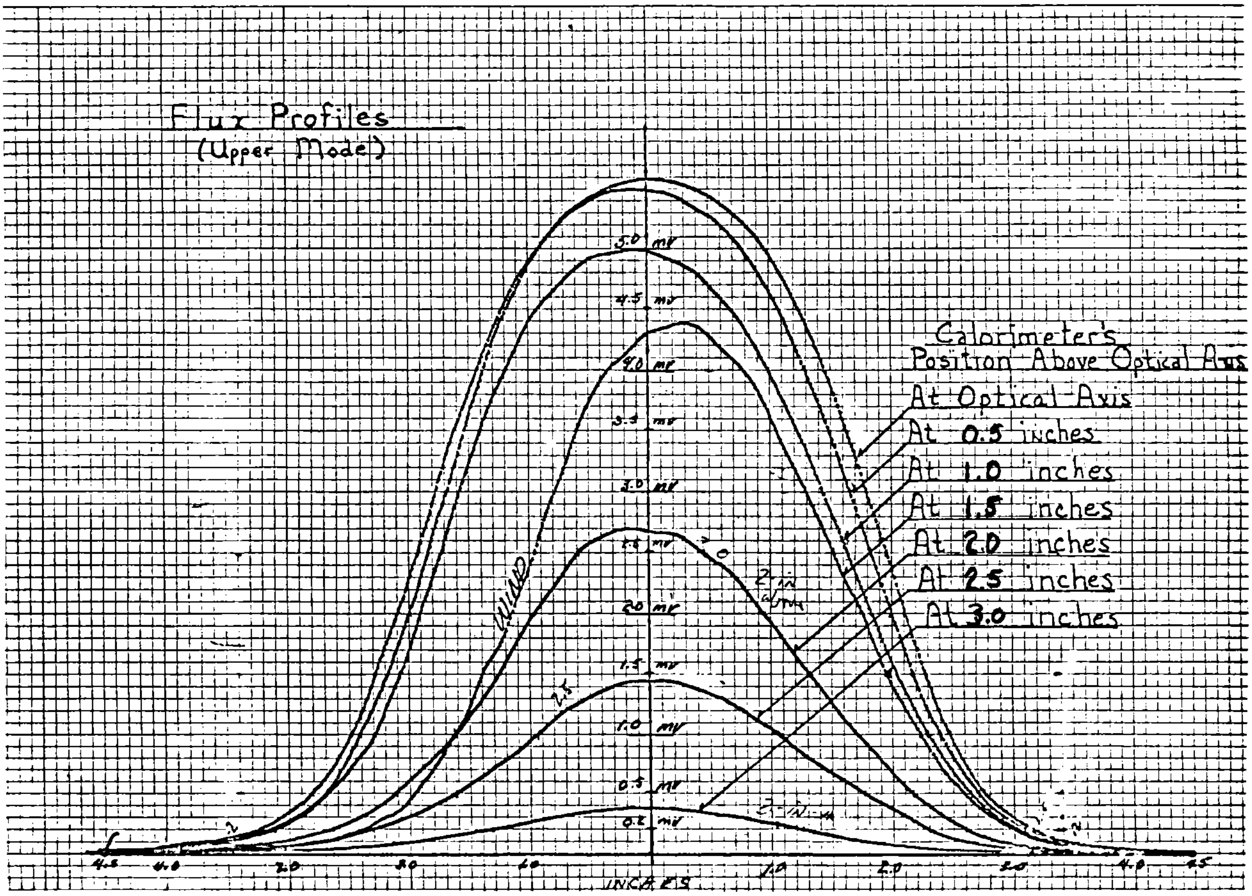


FIGURE 3

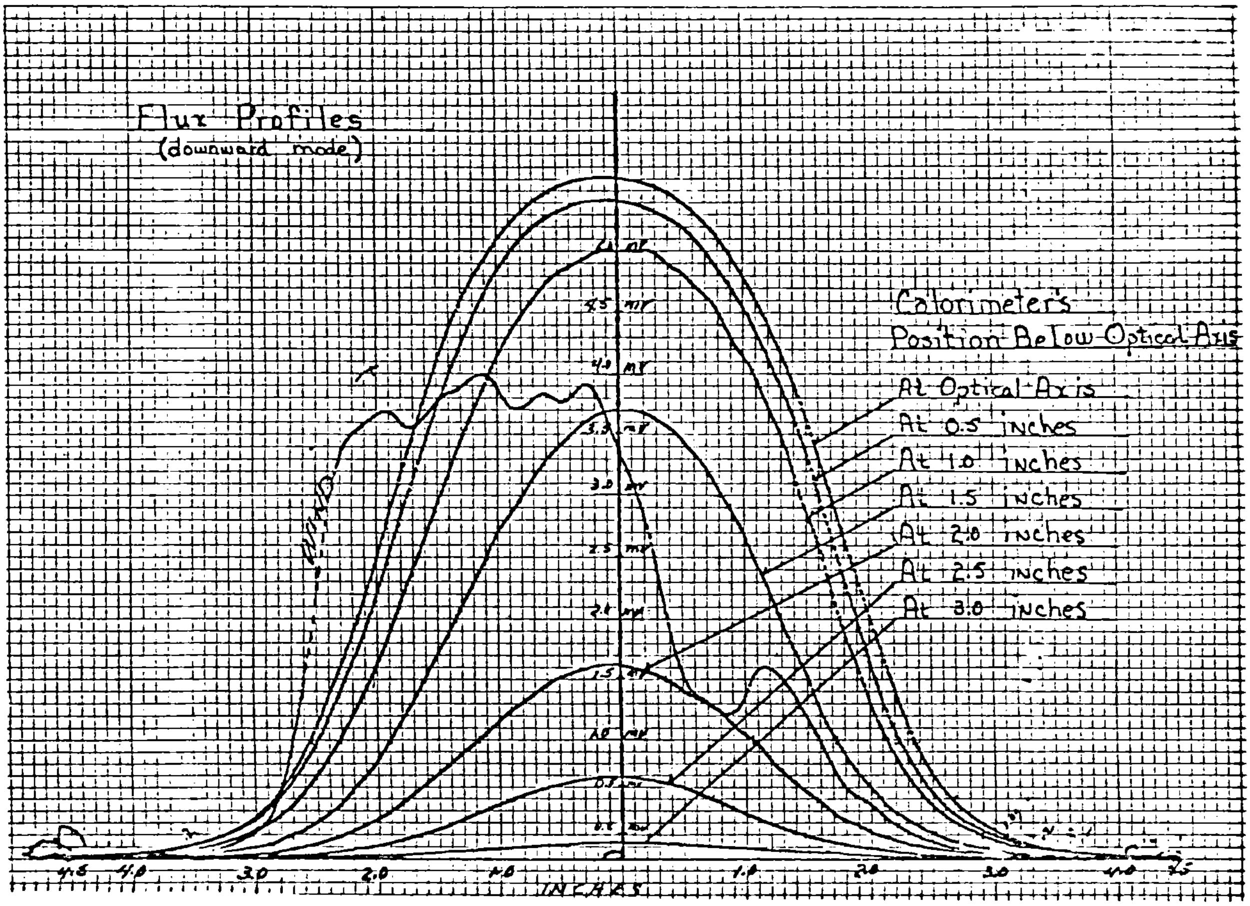


FIGURE 4

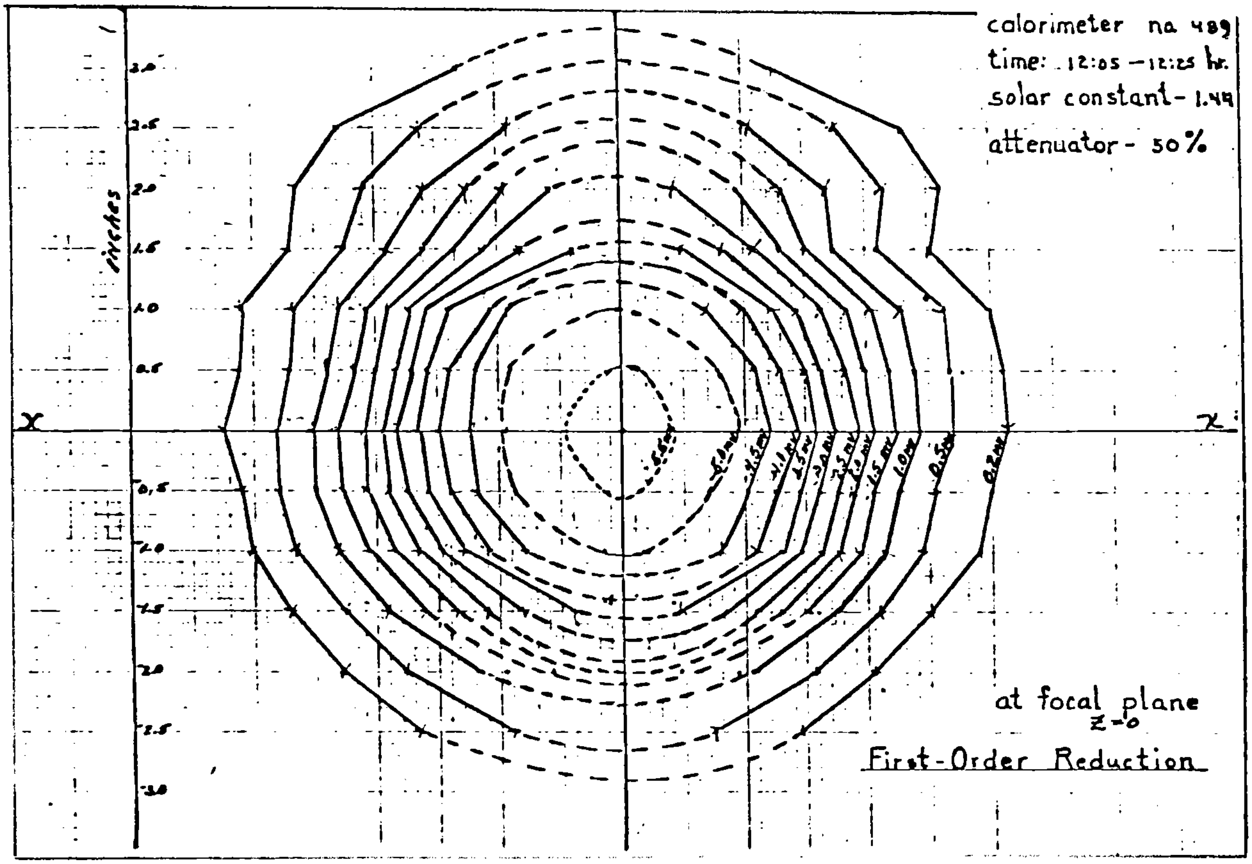
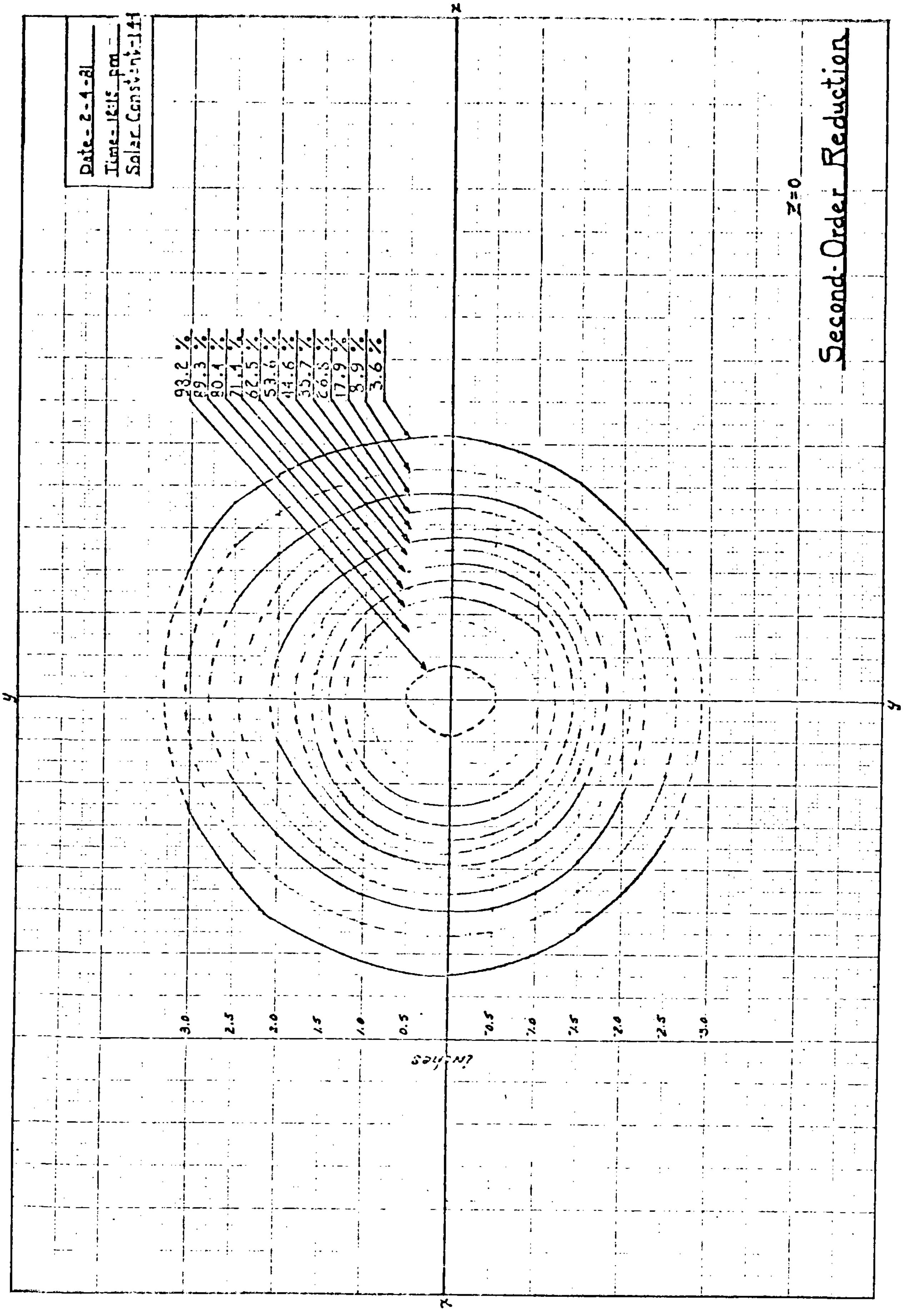


FIGURE 5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Time - 12:15 pm
Solar Constant - 1.4
Second-Order Reduction
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89.3 %
80.4 %
71.4 %
62.5 %
53.6 %
44.6 %
35.7 %
26.8 %
17.9 %
8.9 %
3.6 %
x
y
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x
3.0
2.5
2.0
1.5
1.0
0.5
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
inches

FIGURE 6

CNRS, Laboratoire des Ultra-Refractaires

Jean-Pierre Coutures

CNRS

Odeillo, France

This paper was unavailable for publication. For further information, please contact the author

SESSION II DISCUSSION

Gintz - When Tom Brown talked about his accuracy in repeatability, it seemed phenomenal to me. It would be good to have Kendall, Antal, and the facility operators address that question.

We might also discuss the transfer function problem that occurs particularly with central receiver facilities. John Holmes pointed out that you are trying to do real-time scanning of the flux at the aperture, and I know that we, as designers of test hardware, have done a poor job of working with the facility. Boeing presented a difficult problem in that its receiver design prevented positioning the flux scanning device closer than within about 30 inches of the receiver aperture in a field that is converging rapidly. An error of a few percent in the transfer function can kill you in calculating the flux. Boeing is redesigning its receiver and will try to schedule work with the CRTF in the next test period we're starting with the EPRI system. We are trying to design the receiver so the aperture plane can be positioned flush with the structure of the receiver. Having a flux measuring device that can actually go right into the aperture plane will rid us of an uncertainty which has gone unresolved in the past program.

Brown - Let me clarify a point on the data concerning accuracy and reliability. We have manufacturer's data from Hy-Cal, but we ourselves do not have the capability to make that kind of measurement. We purchased one set of calorimeters from Hy-Cal and placed them on 2" centers on the scanning bar. About 18 months later we purchased another set of calorimeters and placed them between the existing ones, so that in the middle of the bar they were on 1" centers. The second set had a different sensitivity from the original ones. We find very good correlations between adjacent calorimeters, and that's a good sign. I can't put anything quantitative on that.

Gintz - Have you ever pulled a calorimeter after some period of operation and sent it back to the manufacturer for recalibration?

Brown - Yes, I have a horror story on that. After operating the units for close to a year, we returned them to Hy-Cal, asking for recalibration and return. They recoated and recalibrated them, so we lost the data point. They maintained the calibration was not off that much, but I don't know. We lost extremely valuable information. It might be advantageous to test to determine whether it is possible to stabilize the instrument after having used it for some period of time.

In a somewhat unrelated experience, we have operated some Gardon gauge units at the large furnace in France, and they were compared against a Kendall radiometer. This is a primarily standard device, and the agreement was within one percent of the measurements we had made.

We are continually aware of the potential problems of transfer function that you mentioned. It was necessary for our standard bar to be as thin as possible and still do the job. As I mentioned earlier, we can accommodate about a 5.25" gap between the aperture and where the scan is being done; and with special calorimeters, the backs of which could be wetted with cooling water, we have been able to get a calorimeter bar down to about 1.5". We feel we are scanning a surface about 1.75" out in front of the experiment aperture.

Gintz - Thank you, Tom. John (Holmes), can you add anything about your calibration calorimeters to the discussion?

Holmes - We returned some calorimeters to the manufacturer for recalibration after having used them for quite some time. As I recall, the new calibration was not far from the old, even though the black coating appeared to have become severely degraded. I don't have hard numbers with me, but I would say on the order of a few to a 5 percent change over the life.

Because of some confusion about the coating itself, we are developing our own in-house calibration ability. Hy-Cal uses a proprietary coating, which we don't want to continue using, so we began recoating with Nextel products. Now, they are off the market and unavailable, putting us in a quandary. Carbon black is not as stable as some of the high-temperature paints, so we are not sure what coating material we will use. Once we have the in-house ability to calibrate, we will calibrate before and after use on all of our calorimeters in order to follow these changes.

Skaggs - John, we used one of your flux gauges to measure the flux at New Mexico State University. The first measurements were taken in August and the second in October. Do you know anything about the aging characteristics of those gauges, whether the values we measured two months apart are going to be the same?

Holmes - I have no idea. That's why we need the ability to do this rapidly. I do know that we have used gauges, factory calibrated, then recalibrated without the coating, and they were not all that far apart. I suspect they are clearly stable.

Skaggs - There were some chips on it the second time, but for all practical purposes it appeared that it was giving the same kind of data the second time around.

Question - How would you feel about that calibration with a facility having the ability to position the gauge in a well-defined beam? The beam will be defined by a Kendall calorimeter as a primary state.

Antal - How much would JPL charge for a Kendall radiometer? Can we buy them?

Kendall - They are available for sale, but I would have to get a price quotation for you. I'd like to talk a bit about the radiometer. The aperture is very small, on the order of .01 cm^2 in area. We get 10 watts, that's all we have to deal with. This does not come onto a flat surface but into a pattern where the black paint has an absorptivity of approximately 96 (we were using the paint that was leftover). The quality gives it an enhancement of about 8 to 1, so we come up with an absorptivity of the cavity of .996. When the absorptivity of the paint changes, the degradation is cut down by a factor of 8, putting us in a better position than on a flat surface. As I mentioned earlier, we use an electrical heating which is accurately equivalent to radiation heating. It is therefore necessary to measure the current and voltages, multiply the two together, then multiply by a so-called correction factor which takes into account area, absorptivity, and nonequivalence. The nonequivalence is quite small, but it still is on the order of 0.2 of a percent. Taking all of this into account we come up with, say, one percent accuracy.

The people at Edwards have had as much experience with the radiometer as we have had, and apparently it is doing pretty much what it is supposed to do.

Alper - It might be worthwhile for the Users Association to consider having a workshop on radiation measurements, bringing people together who are specifically interested in the field and have enough time to focus on that issue.

Gintz - I agree. First of all, Tom says he is quoting the numbers, and I seriously question them. I think they are lucky if they are within five times the accuracy. They come from a catalog that states they are ± half a percent, and most of us know that this means under ideal laboratory conditions. The numbers are quite different in actual field tests.

Ross - Just a couple of comments, John. This is a cold-water cavity calorimeter that was developed by the instrumentation group. We used it at the focal point of the test concentrator to measure the thermal power, and it was calibrated using electrical heaters. We ran it at a mass flow rate of 50 gallons per minute with a maximum fluid temperature of 12°C, and we were able to determine the thermal power to an accuracy of about 2 percent. We integrated the flux from the flux mapper, then compared that with the thermal power measured here, and we were within 2 to 3 percent of these numbers. So, we feel pretty confident in saying the accuracy of the flux mappers is certainly below 5 percent.

Question - Darrell, what is the aperture on this? You said a 1" coil, but is that just a cylindrical wrap?

Ross - The coil is 1" in diameter, and the aperture is variable from 20 inches down to 6 inches.

Hays - We use two sets of Hy-Cal gauges, alternating every six months and sending the extra set back for recalibration. About three years ago we thought there was a problem with one of the apertures which provided increased flux concentration. We were recording fluxes 20 percent higher than those recorded the day before, so we realized the gauge had gone bad. We removed the calorimeter and replaced it with one of the calorimeters in a concentration. Basically, we decided the repeatability from the two different gauges OK after six months, which we figured to be very good. The absolute calibration (we took that at its face value, and at the same time we sent them back every six months) and the calibration curve looked almost identical to the calibration of a year ago.

That told us that we should either use another calibration curve or adjust that curve. We destroyed the coating on one gauge, sent it in, and it came back with a curve that was within a half percent or so from the previous calibration. Therefore, I think the repeatability is extremely good. So far as the absolute accuracy is concerned, it would be interesting to put a Kendall gauge right next to the Hy-Cal and compare.

Holmes - We had a similar testing setup on the tower about a week ago, just ready to put the beams up, and winds took it off the tower.

Hays - There is good calibration, also. We operate ours in a particular way in which we could use three different gauges, and they all agree quite well. I don't remember exactly, but they were within 4 to 5 percent from three different gauges covering three different ranges.

Gintz - I hadn't intended this question and answer period to become a premature workshop in calibration of flux gauges, but do any of you have other questions or subjects to discuss with the facility operators?

Walton - With regard to transfer function, it seems to me that in the types of experiments you ran there should be some calorimeters around the aperture as part of the experiment in order to cross-check the transfer function. If you have moved away, but at the same time when the experiment was not there, you have made a scan that there should be a transfer, and you had a reference somewhere in the neighborhood by putting a calorimeter near the aperture on your experiment, it seems to me that it is an obvious requirement.

Gintz - You say when the experiment isn't there, you probe the aperture plane, but you need an immense volume of data. There are so many variables: many heliostats--each having different characteristics; time-of-day; different test conditions, etc.--and any of these can change from day to day. It seems to me that with a big experiment field of heliostats, taking heliostats off and on, each one gives some separate function and energy. I think the only way to do it is with a real-time flux measuring device. We must design the aperture so we can, in fact, take the measurements in the aperture plane rather than 30 inches out in front of it.

Walton - I don't know whether you will ever arrive at what you are asking for in an experiment. Perhaps you can make a curlicue-kind of beam to go into the cavity and measure the energy coming in. As long as there is a finite separation, some finite error will be built into it, and there is also a cost limit. I feel that if one can obtain some data around the aperture it is better than not having any at all.

Mulholland - I would like to ask Darrell Ross a question about the big calorimeter. Do you take measurements of the water temperatures? Is that how you arrive at your flux measurements?

Ross - We use thermocouples to determine the temperature.

Gintz - One comment regarding J.D.'s suggestion about instrumentation of calorimetry in the experiment itself. We obviously didn't have any calorimetry in the aperture plane except during some very low-power levels when we were initially working with the facility development on this transfer function, and we did have water-cooled calorimeters actually spanning the aperture plane and very low-power levels from different parts of the field. We compared data measured on the real-time measuring device and then corrected the transfer function. We compared that with real data measurements in the aperture, and that allowed us to evaluate the accuracy of the transfer function. However, we kept running into the problem of making a scan for one time of day and one particular test condition, and then late in the afternoon or early the next morning with a different mix of heliostats in the field, it wouldn't work again. So, we didn't try any universal transfer function that applied to that field and that configuration receiver. We had several calorimeters in the receiver itself. I think the next time we will have quite a few more; we had only a few on the back wall. We were able to make some comparisons of first incidence flux inside the receiver and make judgmental values concerning what data to believe and what not to believe. Essentially, I agree with John Holmes that we were ± 10 percent. We felt that knowing the measurement of the actual flux entering the aperture was about as good as we could do.

Bill Kaspar
Department of Energy, San Francisco Operations Office

First, I should mention that I am not here to espouse the Administration's new solar policy as it is still under negotiation between the Administration and Congress. But nothing prevents me from giving my own personal perceptions of the accomplishments of this program and where they fit into the overall DOE research and development program.

It's easy to get involved in all the budget cuts and become very concerned about the level of effort that will result. However, I have an analogy about problem-solving in general and how it relates to the energy field in particular. Then I would like to discuss the Users Association program and how its activities fit into that program.

In most problem-solving there are five basic steps. The first step is to ignore the problem and say there is no sense in worrying about it. If you think back to the late '50's and early '60's, there were those who were discussing the probability of a real energy problem emerging, but most of the American people chose to ignore the problem.

When ignoring the problem doesn't work any more, we move on to the second step, which is actively denying that the problem exists. That step was seen in the early '70's. Even when we had the first oil embargo there was a tendency to deny the problem existed and say, "As soon as this embargo is over, it'll be back to the good old days".

The third step in problem-solving is to blame others. That is, "I don't own the problem; 'they' own the problem." Americans went through an era where they blamed either the Federal Government--they caused the problem and they ought to resolve it--or they blamed the oil companies--they are the ones reaping all the benefits. We felt "they" were the problem and as soon as those people got straightened out the problem would go away. There was an underlying feeling that people considered the cheap energy an inalienable right.

The fourth step in the problem-solving scenario is partial acceptance of the problem. Maybe the problem is still basically "their" fault, but maybe I can try to do a little bit to alleviate it. That is an important crack in the argument. People begin to realize that maybe they don't need the big cars and maybe they should have their houses insulated. The important thing is the internal realization of the problem that, "Maybe I could get along without using all this energy." I think we have reached the point where people are beginning to buy solar equipment, as an example; it's not just one of those new-fangled ideas for the elite to put on their houses.

We are now at the point where we can really do some active problem-solving, which is the fifth and final step.

If we stand back a little and look at the amount of progress we've made over the last ten years, not only in technology, but in terms of the attitude of the people, I think we have made tremendous progress. We have set up the framework; the Federal Government is backing away from regulations, from commercialization activities, from involvement in the marketplace, and realizing the people are ready to buy solar equipment, and industry is moving to a position to provide what they want.

With the kind of framework we have today, I would like to address the Sunfuels Program in particular.

The Sunfuels Program is an attempt to apply power tower-type technology to the production of either transportable fuels or chemicals. There are people who claim, with some validity, that we don't have an energy problem in this country; we have a gasoline problem, an oil problem. So it addresses a critical need for the program for DOE.

In addition, R&D is an appropriate role for the Federal Government. It has the potential for being an exciting new program, one in which this group will be in the forefront and to which it will be a real contributor.

There remains, however, a challenge, and that is to bring some focus to the program. There has been some excellent work done in identifying some good particular applications and studying them at the research level. However, it has been spotty and there has been no real focus. Technical feasibility of several processes has been established and we will continue to support those exploratory experiments because they are the life blood of larger applications. But we can't rest on our laurels. Some of the exploratory experiments have been successful and others will continue to be. Now we need to give the program some focus and a little broader scale in terms of coming up with larger applications that have credibility with industry. They don't have to go all the way to major demonstration projects, but must have a large enough scale to make them credible to industry. That means the commitment of rather large dollars compared to the amount of funding we've had in the past; however, we think we're in a position to get that funding provided we can show the right kind of focus.

Several activities are going on right now to attempt to provide that focus for the larger experiments. One of them is to develop criteria. How would I recognize a good project or a good process if I found it? Having been associated with this program for maybe 4-6 weeks, I have been impressed with a number of people who have said to me, "You can stop looking now; I have found the answer." They are all well-intentioned people and within their criteria, they are probably right. What I am most interested in is, how did they come to that conclusion; what was the selection process they went through and how does it differ from group to group? If I can understand all these different selection processes and can find one that makes sense, then we can aim a large-scale test, probably at the CRTF, in the 1985 time frame. Black & Veatch is involved in trying to assist us in developing those criteria, providing input from an architect/engineer perspective, and trying to maintain the different perspectives so we can intelligently decide what the processes should be.

We intend to select a group of 3-6 processes, do some conceptual designs and make the selection during the next fiscal year. We would like to have as many processes as possible, but the number may have to be limited due to our budget allocation.

There will be a one-year conceptual design study for each process chosen, which will put some meat on the bones of each process, and eventually one will be chosen to put on the CRTF. There will be follow-up tests after 1985 and, again, we will continue to require these exploratory experiments.

The processes which were selected for conceptual designs but were not selected for the CRTF experiment would be eligible for further consideration. However, we need to give some focus to the program now so we have something that's exciting and aimed at real results.

I don't mean to belittle the exploratory experiment phase; it's a necessary step, but now we need to continue on to the next step.

In summary, the message I would like to bring you about the Sunfuels Program is that it is a survivor. After all the budget cutting has been accomplished, it survived. It is, I believe, in a very good position to attract funding and support. We are in a position to demonstrate that we have the technical feasibility, that it's an exciting program, and that we are ready to move. My encouragement to you is to continue to support the Users Association and Frank Smith, move ahead, and try to understand what the rest of the program will include as we move toward inclusion of more architect- and engineer-oriented activities.

Thank you.

Smith - You mentioned completing 5 or 6 processes; do you mean 5 or 6 entirely different processes, or 5 or 6 hydrogen processes?

Kaspar - We have not developed those criteria, but are trying to do so right now--how we would select the processes, how we would recognize a good process if we saw it. My recollection is that we would like to have several different processes. At the same time, there are some advantages to narrowing the potential applicants as it will be very difficult to compare proposed processes such as hydrogen and furfural and decide which is better to the extent that we can define what can be done in the 1985 time frame with really limited probablity of failure on a high-confidence level that it will work. If the the first one doesn't work, it will be difficult to attract further funding. It's a relatively low-risk but still a challenging R&D activity and that's the fine line. Within that framework, you lay on the different processes. It will be a very difficult selection processes and I would like to narrow it down that that it is manageable without being overly restricting because I'm not sure I want the government to impose those restrictions beyond the obvious technology.

Springer - Without the second D in R&D, my concern is that if we follow a certain path, doing a certain experiment, there is no certainty it will be picked up by the private sector. I'm worried we will go down a certain path because it is popular right now, but when we got to the end of the road, we will still be short of the point picked up by the private sector and then say that it doesn't fit R&D any longer. Someone will say, "Let's go on to something else," and that big gap will still exist.

Kaspar - I understand that concern and I can point to an instance where R&D activities really went ahead and got involved in the industry structure and took it all the way through to demonstrations and then had a positive effect on industry. I can play that back to you, though a different way, particularly in larger-sized projects where industry very well may have funded the building of the demonstration project but wanted to wait and see whether they could attract some of the Federal dollars before they spent any of their own precious internal dollars and that the Government wound up being their own worst enemy by holding out a carrot. It kept people from making those private investments with the expectation of being able to get a hold of that carrot.

You can play it both ways. All I'm saying is that I think we'll be in a position, at least in 1985, to take on a good, sound R&D program, and that industry will then pick it up. Also, it is our intent to include industry as closely as possible in conducting the program. We're hiring people to establish the criteria so they aren't necessarily Federally-mandated criteria, and will have some basis the industrial world will accept. The selectees will be industrial companies that can compete for Federal contracts and it will be taken outside the national lab family, unless they are in a supporting role to an industry.

Holmes - You spoke about requesting conceptual designs during the next fiscal year. Would these be development or experiment designs, or both?

Kaspar - We will not be asking for conceptual designs as such. Those will be developed during the one-year study. We will be looking for proposed processes, some initial analysis of what the market would be,how the process should work, and some laboratory or bench-scale testing that would substantiate the fact the process will work. With that we will make some comparisons, do the conceptual design, and from the better candidates we'll select a winner.

Besenbruch - You are looking at transportable fuel?

Kaspar - We are looking at production of fuels and chemicals.

Erhardt - Your method of selecting several processes concerns me. How do you hedge against the possibility of people who develop processes that may have risk as opposed to those who may have a highly innovative process they will drop because they know they will not be ready at the same time as the others which could have a bigger payoff? Some good processes may get dropped to the side.

Kaspar - Again, we are developing those criteria now, but my reaction to that issue is that the first project to be selected will be the one for the CRTF. If there is a process that has a higher risk then, in my judgment, the developer is not ready to be in the running just yet. This is not the last shot. There will be follow-up tests after the one at the CRTF in 1985. However, the first is a rather critical selection because the system won't tolerate a big failure the first time. However, it still has to be technically challenging in order to warrant Federal involvement.

Antal - Will the parabolic dish technology, such as JPL's, be a source of fuels and chemicals?

Kaspar - No. I don't mean to say that. I think the CRTF is a larger thermal output facility, one that has some credibility with the industrial sector, and beyond that, if you wish to model flux or temperature, the method you choose to do it would be up to you.

Antal - Let me rephrase my question. Is it known that all the potential fuel and chemical processes will be so large as to need 5 or 6 megawatts of thermal energy input?

Kaspar - No, it's not known.

Antal - Therefore, it's not known if the CRTF is the right power source for all the fuel and chemical processes?

Kaspar - No, not at this point.

Antal - If we understand what you said, from now until 1985 we have to look for a low-risk process adaptable to tower power. Is that the bounds of the program at the moment?

Kaspar - That is the bounds of this new thrust which we will be undertaking in subsystem development. There will continue to be exploratory experiment activities.

UA-RECOMMENDED EXPERIMENTS

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Significant progress has been made during the past 1.5 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 modeling characterize the primary activity. In technical readiness, having demonstrated proof of concept, greater consideration is given to performance improvements, component optimization and subscale production. Beyond technical readiness the activity progresses through additional stages of system feasibility, system readiness, and finally, commercial readiness.

A number of high temperature solar thermal experiments were successfully completed during FY80. Some of the experiments that were sponsored through the Solar Thermal Test Facilities Users Association (STTFUA) are briefly described in this paper. These experiments were technically managed by SERI during FY80.

Table 1 summarizes those experiments funded during FY79 and FY80. Although the experiments summarized in the table were conducted at three facilities, the ACTF, WSSF, and CNRS, four other facilities are also available to independent experimenters through coordination effort of the STTFUA. The other locations are the 5 MW_t Central Receiver Test Facility, Sandia National Laboratories, Albuquerque, New Mexico; the Parabolic Dish Test Site, Jet Propulsion Laboratory; Edwards Air Force Base, California; the CNRS 1000 kW_t Solar Furnace, Odeillo, France; and the Advanced Component Research (ACRES) facility at SERI.

The FY80 request-for-proposals solicitation by the STTFUA resulted in the conduct of four user test programs at the ACTF in the calendar 1980 time frame. A detailed technical discussion of each test program is beyond the scope of this paper. A summary of program objectives and major results will, however, be presented. The reader is directed to other references for detailed accounts of each test program (1-8).

High-Temperature Solar Steam Generator: A Solar Turbines International 25 kW_{th} high-temperature, high-pressure solar steam generator tested during March and April 1980 demonstrated that steam could be produced at 771°C (1420°F) and 10.7 MPa (1550 psia under steady state conditions). The receiver was a downward-facing cavity design and the design concept involved only the indirect solar heating of the fluid-containing heat exchanger. The receiver utilized a Hastelloy heat exchanger tubing in the once-through steam generator design. Numerous thermocouples were used to monitor the location of the water/steam interface and to ascertain the circumferential temperature gradient of the boiler tubing. Total experiment run time was 31.5 hours. Experimental details of this test program can be found in references 1 and 2.

Fluidized Bed Solar Receiver: The proof-of-concept demonstration for the application of fluidized bed technology to solar thermal receivers was carried out during May and June 1980. The basic receiver design was of Westinghouse origin and consisted of a 30.5 cm (12 inch) diameter by 1.22 m (4 ft.) long transparent quartz tube filled with bed materials. Compressed air, fed from below through a plenum, was used to fluidize the bed. The bed, placed at the facility focus, was directly heated by concentrated solar radiation. The test matrix conditions consisted of exit air stream temperature, fluidizing gas flow rate, output power, insolation, and type of bed material. Bed materials tested during more than 60 hoursof operation included copper shot, various sizes of sand, silicon carbide, alumina, and mixtures of these materials. Exit gas stream temperatures of 538°C (1000°F) were reached within the program. Widely varying optical, thermal, and mechanical results were obtained with the different bed materials. Additional details may be found in references 3 and 4.

Flash Pyrolysis of Biomass: The objective of this Princeton University experiment was to gather data on the flash pyrolysis of biomass using concentrated solar energy as the energy source. Of particular importance was the gaseous and liquid product yield as a function of type of biomass, type of carrier gas, solar flux concentration and biomass feed rate. Biomass material was heated directly by allowing it to fall under gravity through the facility focus. The biomass material and an upward-moving carrier/reaction gas were contained in a 2.5 cm (1 inch) diameter quartz tube. Gaseous, liquid, and solid samples were collected, analyzed, and used to generate a system mass balance. Four feedstocks were used: wood sawdust, ground corncobs, cellulose, and lignin. Technical details associated with this work can be found in references 5 and 6.

Heat Pipe Technology: The testing of a representative model of a heat pipe solar receiver under actual concentrated solar flux conditions occurred at the ACTF in October 1980. An array of seven liquid sodium heat pipes was exposed for a total of 25 hours of operation, during which 45 steady state data points were collected. Operating temperatures up to 970°C (1778°F) and output power levels up to 11.5 kW_{th} were realized. The thermal load for the heat pipes consisted of water-cooled gas gap calorimeters. During commercial use, these Dynatherm Corporation heat pipes would be finned on the condenser end and used to heat a compressed gas stream. Applications include Brayton cycle electric power generation concepts and high-temperature process heat. Several articles and reports are available describing the details of this program (7-8).

Thermochemical Transport: 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 a mass flow of 3 gm/sec at 15 kW_{th} input. Conversion efficiency (solar to thermal energy) was approximately 33%. The January 1981 tests, utilizing a larger six-coil reactor and similar feedstock composition ratios, resulted in a doubling of the efficiency to 67% with a power level input of 27 kW_{th}. 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 use 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.

Concepts and technologies, which after evaluation at the various test facilities appears ready for further development, are recommended to DOE for continued support. Larger scale testing of these technologies may occur at the 5 MW Central Receiver Test Facility. At this stage, technical feasibility is established through prototype fabrication and testing.

Through experiments of these types, an important interface is addressed between research and development and technology development in which innovative, conceptual designs advance to a state of technical readiness.

ACKNOWLEDGEMENT

Appreciation is gratefully expressed to Dr. C. T. Brown of the Georgia Institute of Technology for providing the descriptions of the GIT experiments.

TABLE 1. FY 79-80 EXPERIMENTS

Experiment	Test Location*	Contractor	Performance Period	Budget-$	Objective/Scope
Calcium Carbide Production	CNRS	Institute of Gas Technology	9/79-2/80	37,000	Demonstrate and measure calcium carbide production in a solar facility.
CO_2-CH_4 Reforming	WSSF	New Mexico State University	9/27-12/80	80,000	Quantify solar thermochemical energy capture using CO_2-CH_4 gas reforming.
High Temperature Solar Receiver	ACTF	Solar Turbines International	11/79-7/80	62,000	Design, fabricate, and test a high temperature (816°C) (1500°F) solar receiver/steam generation system for solar central receiver applications.
Heat Pipe Technology	ACTF	Dynatherm	9/79-11/80	66,600	Design, fabricate, test a small representative heat pipe solar receiver.
Fluidized Bed Technology	ACTF	Westinghouse	9/79-9/80	87,300	Investigate application of fluidized bed technology to solar central receivers.
Cadmium Oxide Decomposition-H_2 Production	WSSF	Institute of Gas Technology	9/79-9/80	103,800	Quantify thermochemical conditions in cadmium oxide decomposition as a step in producing hydrogen.
Flash Pyrolysis of Biomass	ACTF	Princeton University	10/79-12/80	109,000	Design and test a vortex flow reactor to process kinetic information in biomass pyrolysis.
Sulfuric Acid Decomposition-H_2 Production	ACTF	General Atomic Co.	5/80-2/81	98,000	Demonstrate use of solar energy in decomposing H_2SO_4 to produce H_2 based on a water splitting cycle.
Coal Gasification	WSSF	Lawrence Livermore Laboratory	6/79-7/79	23,000	Demonstrate production of hydrocarbon rich synthesis gas from coal and biomass exposed to solar energy.
Solar Processing of Ores	WSSF	Los Alamos Scientific Laboratory	2/80-1/81	98,000	Demonstrate feasibility of continuous processing of molybdenum ores in a solar receiver.

* WSSF - White Sands Solar Furnace, White Sands, New Mexico
CNRS - Centre National de la Recherche Scientifique, Odeillo, France
GIT/ACTF - Advanced Components Test Facility, Georgia Institute of Technology, Atlanta, Georgia

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FLASH PYROLYSIS OF BIOMASS USING CONCENTRATED SOLAR RADIATION*

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This is now the third time that you have heard about this work, and I am complimented that so many of you are sticking around.

We went to Odeillo during the summer of 1979 and did some experiments that seemed rather simple at the time. The results are summarized here.

We flash pyrolyzed cellulose at a solar flux of 200 W/cm^2. We knew the char yield would be rather low because the cellulose pyrolysis mechanism is competitive, and when it is heated rapidly, one of those reactions is deprived.

The other thing we knew was that the carbon efficiency--which we define to be the carbon in the gas divided by the carbon in the feedstock--would be affected by the gas phase conditions. The one on the left was relatively high, 50% of the carbon, whereas the other case was relatively low; and one poses the query, "Why should this be the case?" For the one case we have a treatment temperature of 900°C and the other case 400°C, and we knew from our earlier chemical work that the latter temperature isn't enough to effect gas phase pyrolysis. So we said, "Here's a real curiosity. Here's a way of flash pyrolyzing biomass materials and ending up with a high quantity of liquids." We neither collected nor analyzed them because this was somewhat unexpected. On returning from Odeillo we decided first to try to duplicate these results to see if they were real, and second, to try to exploit the unheard-of ability to obtain large yields of liquids from biomass feedstock. This was a bit of a contrast with the proposal which I submitted and which was funded before I went to Odeillo. Some of you may recall that the proposal was to design a gasifier. Returning, that no longer made as much sense to me, and in addition, the work that we originally proposed was development work which we had anticipated doing at Princeton before going to the big facility. When we were told we would go to a big facility we decided to go to Georgia Tech, where the flux levels were somewhat less than the original proposal had anticipated.

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* A complete discussion of this work including illustrations appears in Design and Operation of a Solar-Fired Biomass Flash Pyrolysis Reactor, July 1980, by M. J. Antal, Linda Hofmann, and J. R. Moreira of Princeton University, and R. Steenblik and C. T. Brown of the Georgia Institute of Technology. This paper is available from James Lefferdo at SERI, 1617 Cole Boulevard, Golden, Colorado 80401.

We set out to try to duplicate the Odeillo results to see if they were true and to gain greater familiarity with chemical reactor design. We had no money to do any bench-scale work; consequently, what we did had to be cost-effective. We bought two deep ellipses. We used a tungsten bulb, a 5-kW variety, an overgrown bulb such as that which is in our slide projector, and we built a system that looked like this. We were able to put the whole thing together for less than $1,000 in capital equipment, which was a good deal. It took a couple of months to get it all working. The problem is, you don't get something for nothing. One couldn't get much above 80 W/cm^2. Details of this design and other "cost-effective apparatus" have been published, and I am pleased to make them available to you. I understand that Arlon Hunt has used some of our ideas to design his own sources of energy.

The device looked something like this in the lab. If one looked up in the reactor, little shooting stars could be seen. The little flashes are shooting stars, and what one sees is the vapors that are coming off rapidly pyrolyzing biomass.

The outcome of these experiments was, in fact, that we were more or less able to corroborate the results of Odeillo, and we were able to obtain a yield of something like 70 percent sirup or liquid material by the flash pyrolysis process. And at least at that time, that yield was unheard of in the literature. It was higher than had been reported, and this seemed to be a good thing.

This sort of reactor seemed to be the one on which we did a lot of calculations, and based on those calculations we felt some confidence that it would work. One is aware that one must take a reactor that works to a facility because failure at the facility would be embarrassing for everyone. I am sure that you can appreciate that one becomes very conservative in one's design.

This was a counterflow reactor with steam flowing upwards. The biomass is flowing downwards. The counterflow originally was intended to extend the residence time of the falling biomass material in the concentrated flux as reflected down the cavity also to extend the residence time. The concept was a bit similar to the one we took at Odeillo, but we felt relatively comfortable, based on our calculations, that this would do well. However, it didn't do as well as we expected.

At Georgia Tech we had a great deal of assistance putting the device together when we arrived. The device involved two different groups of receivers, a lot of measurements and planning, etc., and in spite of all our effort, we still had to modify a few things that didn't fit.

One thing that complicates a chemical experiment is that protection from the elements is necessary, such as covering the entire thing with a plastic cover in the event of rain. The experiment goes to the top of the tower by way of a large crane. Here's a picture of the water-cooled cavity that we took to

Georgia Tech. This is a photo of the assembly of this system. It took perhaps a week to ten days of rather hard work and long days to assemble the experiment--an enormous feat. One understands the cost involved since the entire facility is shut down while such an experiment is assembled. One seeks to minimize the expenses associated with assembly.

This slide (the water cooling that went into the experiment) elicits the comment: "Why does one take a tiny experiment to a big solar furnace?" The answer is that, unlike Odeillo, there are no tiny solar furnaces around to use. I view it to be an unfortunate circumstance in this country, and we at the University certainly didn't feel comfortable in taking a large experiment with the risks it would involve, and we didn't have the budget to do that. In fact, the University is poorly-suited to field large experiments. From several points of view, it didn't make a lot of sense to attempt that.

From the top, the experiment looks something like this. The reactor was going through the silver-coated cavity.

A great effort was made to collect the sirups and other things we were producing because we were anxious to study them. During an experiment it looks something like this. It was rather bright. One sees a little light coming through the shield. Most ran for about 30 minutes. This is the only correction I would make to Jim's otherwise fine presentation. Ours was not a batch experiment; it was a continuous-flow experiment. We just stopped when the clouds appeared and when it was time to shut down. If one looked in the bottom, it looked something like this. You can see the reactor. It seemed to retain its integrity pretty well. It involved CO_2 instead of steam, but, in fact, with CO_2 as a carrier, the entire reactor turned black. We found that by passing steam through it, the water and gas reaction cleaned it right up. It's a curiosity to me because the thermochemical equilibria are about the same, but I wouldn't have anticipated it to make such a large difference with steam as a carrier. The reactor stayed very clean. Toward the end we did see some devitrification, but I think this was due to the rather nasty thermal beating the reactor took.

One encounters some difficulties. Our screw feeder plugged up. At many places this would be a disaster, but at Georgia Tech they simply straightened it, taking only an hour. It took us longer to get the screw out than it took them to straighten it.

After an experiment is completed, it takes about half a day to clean up. In order to get a good mass balance, one must collect every bit of sirup. This illustration shows Rick Steenblik of Georgia Tech doing a washdown, first with water, next with methanol, and then with acetone, keeping each one separate for analysis. The person on the accordion lift came up from the bottom to catch it all. It's a rather elaborate procedure to do a good experiment.

The results for the hardwood test came out something like this, and this was the best test we had.

Another problem was that there was moisture in the SCR control of the screw feeder. The SCR had to be taken apart, and we placed silica gel in it. This doesn't occur in a lab, and one's horizons must be expanded to consider new problems in a new environment.

For this particular test the screw feeder performed well, and we had a rather good mass balance, 0.94, and carbon balance, 0.94. Most people are proud of that, especially when it comes on top of a tower. We had about 90 grams of materials and collected 40 grams of solid. We collected 4 grams of sirup, and we had pretty good gas production.

Forty grams of the solid was unpyrolyzed wood. The wood did not enjoy a long enough residence time. All of our calculations indicated that it would be all right. The trouble with the calculations is that the material properties are largely unknown, and apparently we were too optimistic. This sort of reactor is not a good reactor. The first reason is that you can't control the residence time. Secondly, you don't get the result you want. I expected to have 40 grams of sirup and ended up with 10 percent.

We have a reactor into which a large quantity of finely-divided solids are falling, and one has an upward-flowing stream of sirups. The solids enter the reactor cold, and the sirups coming up are hot. What do they do? Sirups condense and go back into the reactor. This is the second reason this reactor is bad news. It's too bad one learns these things in retrospect. There is, in fact, a good gas yield, and the gas looks something like that. It contains CO and hydrogen and ethylene. Most people would be happy to burn it. You might look at getting the ethylene out, although that concentration is not particularly large. We were a little disappointed, but the other comment I can make is in the paper we prepared on this. We compared this data with the data obtained earlier, and that was a pretty darn good yield. So the thing did work as a good gasifier, but making gas was not our goal.

We have developed a computer program for simulating heat transfer within the reactor. You may wonder why these yields of sirups one would anticipate to be large, and the reason is shown here. We have a particle temperature, which is a line going upwards to 1,000 K, and we have a fluid temperature which peaks at 700 K. So one sees a temperature decoupling of 300 K. That temperature decoupling is a unique thing about visible radiation. One can use visible light to heat opaque solids in a nonabsorbing gas and keep the gas relatively cold.

What happens to the biomass? Small particles hit this intense radiant flux and vaporize, and the vapors quench rapidly in the cold surrounding gas. Complex polymers like wood are transformed into their monomeric units in a reactor like this. Under these intense radiant heating conditions, they hit the cold gas and freeze, and one ends up with a gaseous mixture of monomeric constituents of the woody material, and those are very interesting chemicals. This type of reactor is a rather interesting device, at least in part, because the only way such a reactor can be made to work is using visible light. So far as I know, the most economical light we have is the sun.

Are the sirups really valuable? I will address that question in a moment. We are back to reactor development, but we are not anxious to be developing reactors so expensively. We have finally succeeded in beginning to articulate a capability similar to that in Odeillo. It has taken us two years and a lot of pain. We still aren't there, but we have designed things similar to what my friends in Odeillo have. We try to learn from them. At the moment it has some problems. We are using this arc image furnace to begin studying new reactor concepts for this kind of work, and our first interest is in a spouted bed reactor, which is an unusual reactor. We can talk about it if you like, but it seems to be quite well suited for this kind of work.

I want to go over very briefly in chronological order the advantages of the kinds of reactors we are attempting to develop. I think it at least reveals a certain education process that we have undergone, and it points to some of the clever things one can do with solar energy.

Back in 1975 we recognized, "Well, gee whiz, if you take solar heat and make chemicals you store the heat as a fuel and you overcome the intermittency of solar energy." Trivial observation. You can use an endothermic reaction to store solar energy, and that way you magnify the energy of the feedstock. Another trivial observation, but interesting nonetheless.

In 1976 we began to realize that solar furnaces lack economies of scale, and it could be sized to the modest scale of a biomass source. More interesting.

Our system does not require an expensive oxygen plant. That's a good deal because you are using an external source of energy. You have a high-quality fuel output.

Along about 1978 we began to get a little more clever. We said "Ah-ha! the endothermic reaction is really not very endothermic." In fact, you get a leverage factor and a magnification factor, and if you put in one million Btus of heat, you can process ten million Btus of biomass. A lot of people are interested in strong endothermic reactions. Well, I'm not so sure solar heat is so inexpensive. I would rather use a little bit and get a magnification factor if possible.

In 1978 we began focusing on chemicals, and one can easily show that a 6 percent yield of ethylene can drive the economics of the process. So the ethylene is a valuable chemical and can be an important contributor even though it is a by-product.

In 1979 we began to see that by using a flash pyrolysis there is a large throughput. We also identified the fact that if radiant energy is used just to heat the biomass, there is a negligible thermal mass. The characteristic time of these tests is on the order of a second or so. So there is no problem with cloudy-day situations. When the sun goes under a cloud, you turn off the feeder. When it comes out, you turn on the feeder.

Finally, these liquid sirups can be obtained, and they are rather interesting. They are easily stored, and that is a key point because you can use a small solar furnace to produce them and put them in 55-gallon drums. They serve as an interface between the intermittent operation of the solar furnace and the continuous operation of a refinery.

The liquid sirup also serves as an interface between the inherently small-scale operations of the solar furnace and the big scale of a refinery. It is inexpensive to transport the 55-gallon drums, a dense form of energy, and one can imagine accumulating sirups at local refineries.

Finally, the sirups are rather exciting, new chemicals. The chemistry of sugar-related materials is much richer than the chemistry of hydrocarbon.

You are wondering what we can do with sirups. An interesting surfactant can be made from levoglucosan. The levoglucosan can be fermented to make ethanol. Levulinic acid has long been an interesting industrial chemical if only it can be made cheaply. You can make glucose; that's a food; maybe that's interesting. Levoglucosan can be put through a gas phase cracker to get ethylene.

I would like to leave you with the thought that the sirups are a rather exciting source of fuels, and they are also a source of new research.

<u>Hildebrandt</u> - Are there questions?

<u>Coutures</u> - Have you any idea what the main components of your sirups are?

<u>Antal</u> - Excellent question. With the cellulose we put through the reactor there were only two components: levoglucosan and 5-hydroxy methyl furfural. This specificity is unheard of in the literature. For the wood there are about seven major components. Levoglucosan appears to be a major peak with some other simple sugars, and one has the general idea that in this day and age you stick a sirup in a gas chromatograph and it tells you what things are. We are just beginning to get an idea of what these things are. I have a Ph.D. physical organic chemist who has been working full time along with the best organic chemists at Princeton. The area is a tough one to move in.

Voice - Did you have polymerization of your liquid polymers or gels?

Antal - Excellent question. Our liquid is washed down in a solvent. As long as you keep it relatively dilute, there is certainly no tendency to polymerize; it seemsto be relatively stable. However, one is aware over the long run that these sirups, as a maple sirup, will do that kind of thing. This is a subject of concern and study.

Voice - Can you see it thickening up?

Antal - No, we have not been aware of anything like that.

Silverstein - You demeaned the fact that there were no small solar test facilities in which to carry out your tests. How sensitive are the test results to the actual spectrum of the energy source? For example, could you have run those tests with radiant heat lamps and gotten similar results?

Antal - The subject of photolytic chemistry is an open question. The furnace we built has a spectrum which is essentially that of the sun. We do not anticipate major problems with that. The thing we are seeking to contrive to date is thermal effects of which we can feel confident.

Voice - Do you think your experiments would have been different if you had not used the actual solar insolation, but had used some type of simulated insolation in the laboratory.

Antal - I don't expect the results to be different using our furnace, but flux levels of the sort we are taking cannot be achieved if one goes to a light source such as a tungsten halogen bulb. You couldn't get more than 50 W/cm^2 out of that quartz bulb, and the trouble with lasers is they have a very small spot size, leading to reactors which are almost microscopic in size. In reactors smaller than one inch in diameter, the fluid flow is dominated by the wall, and I can't imagine what the cost of a CO_2 laser would be. That would give me 100 W/cm^2 over a two-inch tube.

Voice - About $100 K?

Antal - Yes, I built my furnace for $1,000.

Besenbruch - Mike, I have seen some studies in which people looked at biomass from wood, and it was concluded if your facility sits more than 40 miles around, the economies of transporting the biomass will kill everything.

Antal - That's more or less right. People might argue about 40 versus 50, but the idea is right.

Besenbruch - But where there is a lot of wood, there is generally not as much sun.

Antal - In 1978 we published some calculations we did for the Council on Environmental Quality. We used the center in Newark, New Jersey, which was $30,000 an acre in our calculation, and my belief--which may be hard to accept--is that if you are clever enough to take advantage of the very peculiar problems of solar energy, you will be able to pay for the cost. So, I agree with you. What I have done indicates to me that we can bear that price of solar energy if we are clever.

Hildebrandt - Thank you very much.

RESULTS OF WHITE SANDS SOLAR FURNACE TREATMENT OF MOLYBDENITE*

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Review

I would like to review briefly for the benefit of those who have not heard the details of this experiment before, just how we approached the treatment of molybdenite ore in preference to other minerals. In 1976 when I visited Dr. Jean-Pierre Coutures in France, two scientists from Brazil were there who had attempted to treat some molybdenite. They considered it a good choice for solar treatment from two aspects:

1) It does not melt but sublimes when converted to the oxide, thus facilitating removal from the carrier rock.

2) The conversion is exothermic so that once the reaction is started it should continue to completion.

I returned to Odeillo in 1977 with several grams of molybdenite ore of about 5-6 percent concentration. Coutures and I processed this in the 2 kW vertical axis solar furnace and got what we considered to be rather spectacular results: molybdic oxide with 99.9+ percent purity and silicon dioxide containing only trace amounts of molybdenum. The crystals grew on the edge of the pile of powder; they were of excellent purity, and the yield was high. At this time the Users Association began to support these experiments, and in 1978 I returned to Odeillo to conduct some rate experiments. On a 1-5g batch basis it takes only about two seconds to complete the oxidation of the MoS_2 when it is finely divided; the data were presented at a previous Users Association meeting. Based on these results, the Users Association saw fit to support a continuous flow experiment using a rotating kiln to treat molybdenite ore, shown schematically in Figure 1. I would like to describe the experiments that were conducted over the last year using a rotating kiln.

Apparatus

After an analysis of the various methods of treating ore on a continuous basis, we decided to use the rotating kiln (see Figure 2), an uninstrumented version. This style of kiln was thoroughly characterized in the late 19th and early 20th century in the brick and clay industries, and a good description can be found in Perry's Chemical Engineers Handbook. The system used here is a heavily instrumented type 304 SS tube which rotates at

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* This work supported by the US Department of Energy and the Solar Thermal Test Facilities Users Association.

fourteen revolutions per minute and can be elevated to about 20° to increase the mass flow rate through the tube. Figure 3 shows the kiln in position at the WSSF. All the reacted gas was collected at the upper end (by means of a slip joint manifold) and passed through an infrared analyzer to measure the amount of sulfur dioxide produced. The temperature distribution along the tube was measured with chromel-alumel thermocouples and with two infrared pyrometers. The thermocouple signals were taken off the rotating tube with a commutator ring; thence to a recorder.

Two parameters were adjusted to achieve a flow rate through the tube of approximately 300 g/min--a flow rate which was calculated to give the optimum residence time of 0.3-0.5 sec. for a particle of ore in the focal zone of the kiln. These were the angle of the kiln with respect to the horizontal; we ultimately chose 5-6° as the best angle to achieve this mass flow rate. And the rotational velocity was varied by adjusting the voltage on the self-excited DC drive motor. The optimum rotational velocity was chosen as 14 RPM (110 VDC). Gas collection was done by fabricating a slip ring manifold which fit into the back end of the tube and was sealed with teflon O-rings. Powder in the funnel provided a gas seal for the feed leg at the upper end.

In this series of experiments several preliminary runs were made at the New Mexico State University--partly by design and partly by the caprice of nature. I scheduled some time at White Sands during the second week of August in order to do some system checkout and debugging, but as you may remember, the largest hurricane of the century (named Allen) marched across the Caribbean and onto the continent during the first week in August. It and I arrived simultaneously at the White Sands Solar Facility and I am sure you can guess the rest. In order to salvage the preliminary runs I went to the Physical Sciences Lab at NMSU in Las Cruces and became the first experimenter to use the New Mexico State University Solar Furnace. It was a good compromise because the NMSU furnace had enough energy to partially drive the reaction, but this was more than enough for me to discover weak spots in the experiment; e.g., phenolic gears in the drive motor which failed three times in the solar environment and were ultimately replaced with brass gears. A possible solution is to paint everything white. Figure 4 shows the kiln in the operating position at NMSU.

Ore passed through the kiln and went from room temperature up to a measured value of about 875-1100°C depending upon the incident energy which was typically about 23-30 cal/cm^2-sec at WSSF and $\sim$15-18 cal/cm^2-sec for NMSU. Figure 5 shows a typical temperature profile for the kiln at 27.5 cal/cm^2-sec with a graded sample of --60 + 120 mesh ore passing through the kiln.

The major objective of this experiment was to treat the ore on a continuous basis and determine if the molybdenum sulfide could be oxidized and removed efficiently and successfully without forming a molten silicate rock which would gum up everything.

For comparison, even the conventional hydrometallurgical processing technique employed by AMAX is only a partial separation. From an ore containing an average of 0.27-0.30 percent Mo they manage to extract about two-thirds of the useful material and leave it with 0.09-0.12 percent Mo. With that as a basis for comparison, let us look at how successful the solar treatment was in this process. Starting with raw ore of 0.28 percent Mo content:

ORE	FLUX, CAL/CM^{2}SEC	% Mo, RESIDUAL		SEPARATION, %
Run-of-the-mill	25 WSSF	0.16		43
Run-of-the-mill	25 WSSF	0.15		46
--60 + 120 mesh	25 WSSF	0.13		54
--60 + 120 mesh	23 WSSF	0.13		54
--60 + 120 mesh	16 NMSU	0.24	1st pass	14
		0.21	2nd pass	25
		0.18	Final pass	36
Run-of-the-mill	30 WSSF	0.16		43
Pelletized - 5% initially (--60 + 120)	23 WSSF	2.84		57

Conclusions

From the above data we note the following things: At NMSU where we did not have sufficient flux to drive the reaction rapidly, we made several successive passes through the kiln, and you can see that each pass through the kiln achieved better and better separation. We conclude that a longer residence time would aid greatly in the efficiency of conversion, but economically it may not be tolerated at this flux level. At the higher flux levels available at WSSF, you will note that the process seems to be about 50% efficient for either graded ore or run-of-the-mill ore. A series of trade-off studies is called for here to determine at what point it is no longer economical to remove ore from the carrier rock--perhaps it is about the same level which AMAX achieves now.

The Los Alamos National Laboratory has completed the work it intends to do on molybdenite ore. The results of these experiments will be made available to anyone who desires to use this technique for production of molybdic oxide. I would like to take this opportunity to thank Frank Smith and the Users Association for supporting this work as one of their first experiments beginning in November 1977.

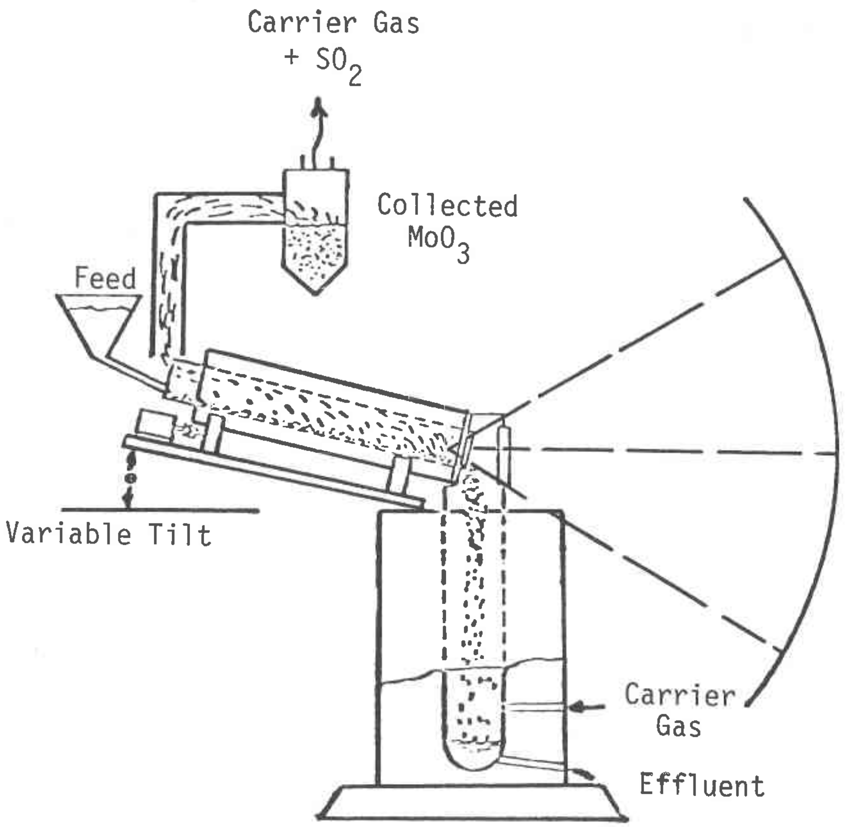

FIGURE 1. Schematic of Solar Kiln for Ore Treatment

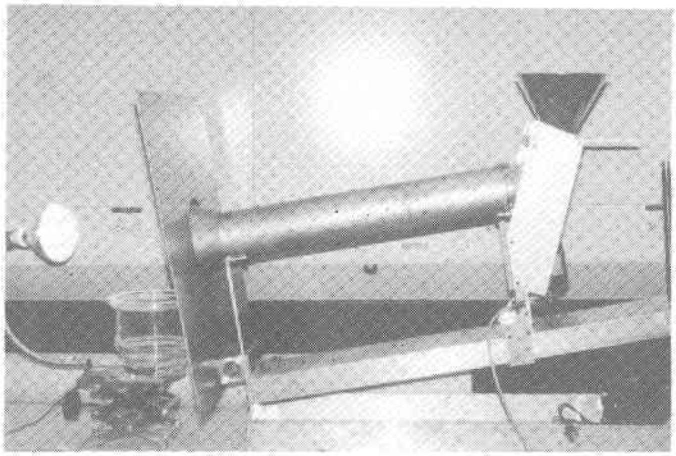

FIGURE 2

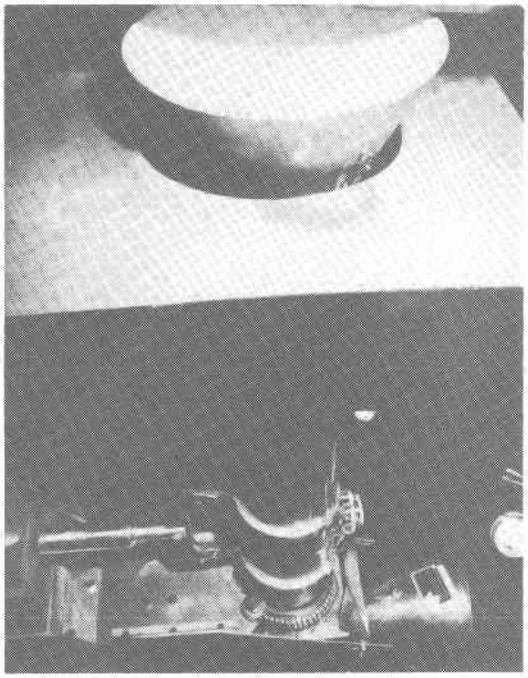

FIGURE 3

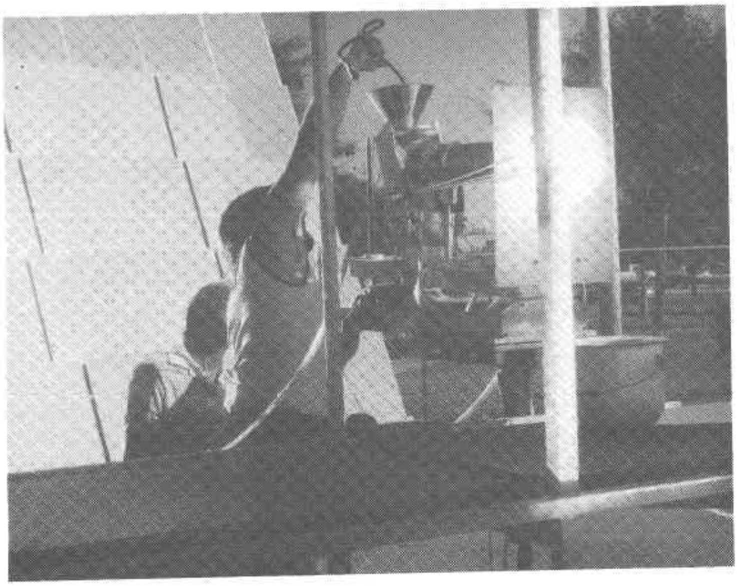

FIGURE 4

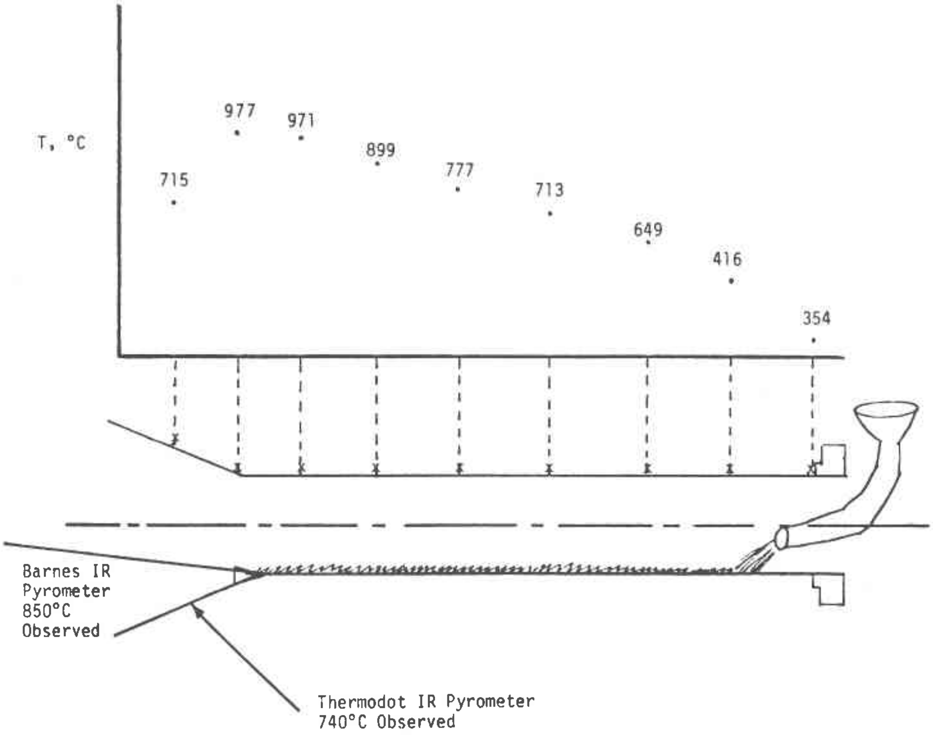

FIGURE 5

DECOMPOSITION OF CADMIUM OXIDE IN A SOLAR FURNACE

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Thermochemical hydrogen cycles are often referred to as water-splitting cycles because the <u>net</u> reaction is a dissociation of water into hydrogen and oxygen — as indicated by the following (hypothetical) reaction sequence involving the reaction of element M with water:

$$M + 2H_2O \rightarrow M(OH)_2 + H_2$$

$$M(OH)_2 \xrightarrow{T_1} MO + H_2O$$

$$MO \xrightarrow{T_2} M + 1/2\ O_2$$

NET REACTION: $H_2O \rightarrow H_2 + 1/2\ O_2$

For most thermochemical hydrogen cycles, temperature T_1 is relatively modest and T_2 is generally quite high.

The IGT cadmium cycle is an example of such a 3-reaction cycle. Cadmium metal reacts electrolytically with water to form hydrogen and cadmium hydroxide, the hydroxide then being dehydrated at modest temperatures (about 600°F) to cadmium oxide, which is then decomposed at about 2500°F to oxygen and cadmium metal, as shown by the following reaction sequence:

$$Cd + 2H_2O \xrightarrow{E} Cd(OH)_2 + H_2$$

$$Cd(OH)_2 \xrightarrow{600°F} CdO + H_2O$$

$$CdO \xrightarrow{2500°F} Cd + 1/2\ O_2$$

The reaction sequence has been carried out many times in the laboratory, using the solid product from each reaction as the starting material for the next, so as to simulate the recycle aspects of a continuous process. To carry out the same scheme for the solar furnace tests, cadmium hydroxide was dehydrated to cadmium oxide in the laboratory, after having been formed first by the reaction of reagent-grade cadmium chloride with aqueous sodium hydroxide. The analysis of the cadmium oxide thus prepared was: 94.7% CdO, 0.7% $Cd(OH)_2$, and 1.53% Cl^-. A more detailed description of the laboratory program on the cadmium cycle was presented at the STTFUA Workship, November 28-29, 1979.

Proposed Solar Test Program

The proposed solar test program involved the thermal decomposition of cadmium oxide in the horizontal beam of the WSSF facility and an attempt to determine the rate of decomposition by following the rate of oxygen evolution by measuring the thermal conductivity of the gaseous effluent. A major problem to be resolved was how to prevent the recombination of cadmium metal and oxygen once they were formed by the dissociation of CdO. One way to prevent, or at least minimize, this recombination was to use an inert gas (argon) to sweep away and dilute the gaseous products until the cadmium vapors could be removed by a cold-finger condenser. This meant that the thermal conductivity of the oxygen had to be determined from a mixture (oxygen and argon) in which oxygen was a minor constituent. This procedure worked out well in laboratory experiments, but as will be described later, the problems associated with the solar furnace runs greatly complicated the procedure.

Reactor Design

The problems that had to be addressed in designing the reactor were as follows:

- The reactor shell had to be water-cooled to prevent damage at the high temperatures in the solar flux.
- The reactant container had to withstand 2500°F temperatures, attack by CdO, and present maximum quantity of CdO to the incoming horizontal solar beam.
- As just described, a water-cooled condenser was required to condense the cadmium metal vapor from the gaseous reaction products and the argon sweep used to help prevent recombination of the cadmium metal and oxygen.

As shown in Figures 1 and 2, these requirements were met by using a water-cooled stainless steel shell equipped for an argon purge, two concentric ceramic heat shields to contain the heat within the reaction zone, a series of four zirconia troughs stacked vertically on top of each other to contain the cadmium oxide, and a water-cooled condenser to condense out the cadmium metal vapors. The inner heat shield of alumina and the outer heat shield of mullite (aluminum silicate) served the dual purpose of retaining the heat for the reaction and also protecting the outer stainless steel shell from the intense solar heat.

The reactor was equipped with fittings to permit a thermocouple in the cadmium oxide contained in each of the zirconia troughs. A 0.5-in.-thick quartz window, designed to withstand 30-psi pressure, was held in place with a gas-tight flange and was continually cooled (and cleaned) by the argon flow that swept across its inner surface.

Solar Furnace Tests

Two weeks of tests were planned at the White Sands solar furnace, but several cloudy/rainy days restricted the available time for experimental runs to only about half the amount that had been planned. After some exploratory tests to check out the reactor, the rate of attenuator opening to avoid undue thermal shock, and the preferred argon flow rate, several successful runs were completed and cadmium metal was produced as a coating on the water-cooled condenser at temperatures ranging from 1350°C to 1610°C, as determined by the four thermocouples embedded in the cadmium oxide samples. However, as indicated by the tracings shown in Figure 3, the temperatures in the four different zirconia channels varied considerably from 1 through 4, with a temperature difference of up to 300°C between Channel 1 and Channel 3. Within a given channel, the temperature remained fairly consistent but not consistent enough to be considered constant, as shown in Figure 3, which also shows the lack of good definition of oxygen evolution (the line designated "Effluent Gas"). It is obvious that variations in the solar flux density were too great to permit the constant temperatures needed for rate data. Furthermore, the baseline for the thermal conductivity detector (TCD) drifted quite badly during the experiments, which made measuring the oxygen content in the very dilute oxygen-in-argon mixtures very difficult and gave only rough approximations of the oxygen evolution.

In the laboratory work, constant TCD baselines on argon samples containing known oxygen contents were achieved quite readily and a nearly linear calibration curve was established:

$$\text{oxygen mole fraction, } X_{O_2} = 0.04924\ (\text{emf})^{1.0123}$$

where emf is the instrument reading in millivolts. During the calibration runs in the laboratory, oxygen concentrations as low as 0.0001 mole fraction (in argon) could be detected, even though the thermal conductivity of argon is only slightly less than that of oxygen. However, the severe baseline drift of the

TCD during solar furnace runs precluded the possibility of accurate oxygen determinations and, coupled with the variable temperatures across the reactant bed in the flux area, indicated that quantitative rate measurements should be carried out in the laboratory rather than during solar furnace runs.

Because analytical facilities for quantitative cadmium measurements were not available, a simple qualitative "fizz" test was used to detect the presence of cadmium metal. This consisted of adding the material to be tested, i.e., a piece of the product on the water-cooled condenser, to some dilute nitric acid and noting if gas evolved. Only cadmium metal would react with dilute nitric acid to generate hydrogen; cadmium oxide would simply dissolve without any gas evolution.

$$Cd + 2HNO_3 \rightarrow Cd(NO_3)_2 + H_2\uparrow$$

$$CdO + 2HNO_3 \rightarrow Cd(NO_3)_2 + H_2O$$

Results and Discussion

Although good rate data could not be obtained in the limited number of runs permitted by the weather, the solar receiver/reactor performed according to design and permitted good verification of the cadmium oxide decomposition. Samples taken back to the IGT Analytical Lab were analyzed and found to have the following analyses:

Experiment	Cd Metal, %	CdO	Cl^-
2	83.8	13.5	1.2
3	66.8	30.2	1.0
4	81.8	15.2	0.8

The chloride content was due to the chloride impurities present in the starting material, which had been made by reacting cadmium chloride with sodium hydroxide. The cadmium oxide content is undoubtedly due to partial recombination of cadmium and oxygen, and further experimentation would be needed to determine what operating conditions might minimize the CdO content. Nevertheless, the cadmium metal content is really quite high, considering that these were the first runs in the solar furnace, and certainly established the feasibility of the cycle as a potential solar thermochemical hydrogen cycle.

The zirconia channels were not affected by either the thermal shock or chemical attack by CdO. However, the ceramic heat shields and support rings cracked as a result of the thermal shock and have to be replaced for each run.

In general, the experiments were quite successful and gave valuable information that can be used for future work.

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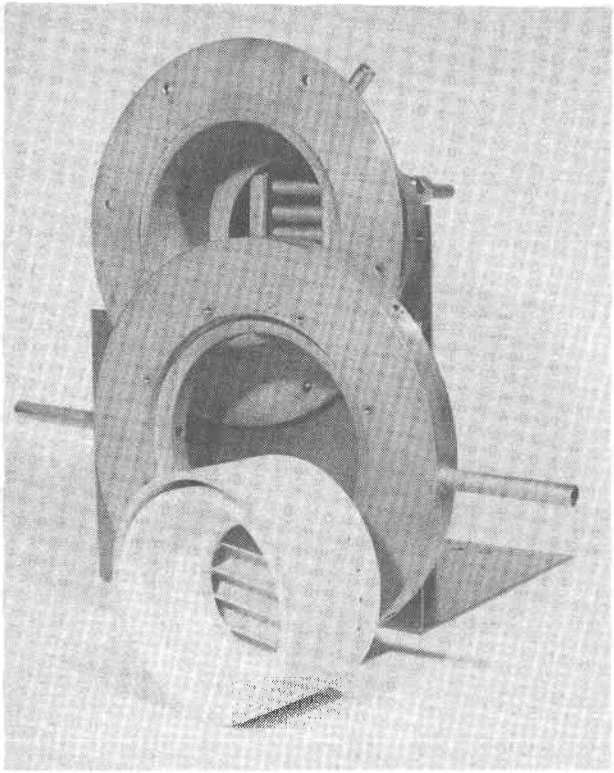


FIGURE 1. SOLAR RECEIVER/REACTOR, DISASSEMBLED

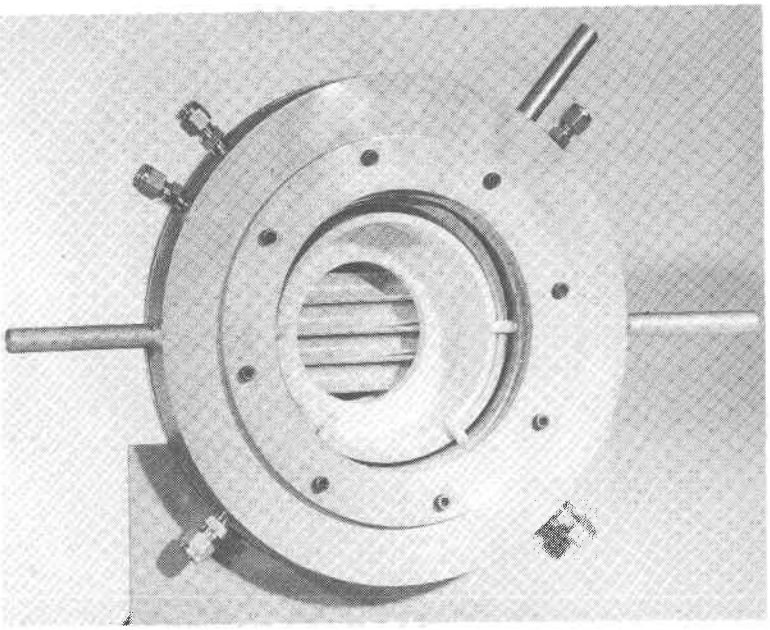
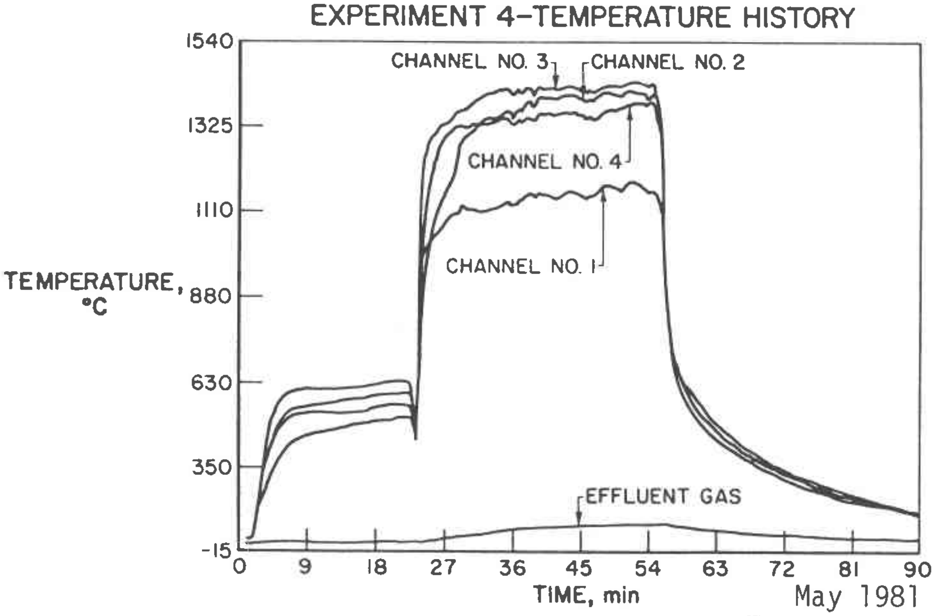


FIGURE 2. SOLAR RECEIVER/REACTOR, ASSEMBLED



May 1981
T.W 1 to 10
T.W- x 9

FIGURE 3. EXPERIMENT 4 - TEMPERATURE HISTORY

TESTING OF A HEAT PIPE CENTRAL RECEIVER MODULE AT THE ADVANCED COMPONENTS TEST FACILITY

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ABSTRACT

Two feasibility studies have established baseline designs and performance requirements for heat pipe central solar receivers for Brayton cycle power generation systems. In a program sponsored by the Solar Energy Research Institute, an experimental heat pipe module was fabricated and tested at the Department of Energy's Advanced Component Test Facility (ACTF) on the Georgia Tech campus in Atlanta, Georgia.

The experimental module replicates the illuminated surface of the baseline receiver. It consists of seven full-scale sodium heat pipes (diameter = 6 cm, length = 90 cm). The pipes are cooled by water-cooled gas-gap calorimeters which enable accurate measurement of heat pipe power throughput and wide ranges in temperature control.

The module was tested in the solar beam for a total of 21 hours. Tests were conducted under steady state insolation conditions, under simulated diurnal start-up conditions, and with natural and induced cloud cover transients. Incident flux levels at the receiver surface reached 90 W/cm^2. Successful start-up was achieved at rates equivalent to cold receiver start-up to full power in 10 minutes. The module was also successfully operated with one heat pipe purposely failed.

The test results demonstrate that heat pipes are capable of meeting the steady state and transient performance requirements of Brayton cycle receivers.

1. INTRODUCTION

Heat pipes have been considered for use in several solar receivers designed to heat gases. One of the design studies, undertaken jointly by Dynatherm and Foster Wheeler Development Corporation for the Department of Energy (1), was directed toward a central solar receiver used to heat air for a Brayton cycle power generation system. The basic receiver design which evolved from this study was also incorporated in a preliminary design of a central receiver hybrid power plant. This latter study was conducted by Bechtel Incorporated for DOE (2).

Heat pipes have several features which make their application to solar gas heaters attractive. Heat pipes operate essentially isothermally which enable them to perform as very efficient "thermal diffusers" between concentrated solar fluxes and lower heat fluxes compatible with heat transfer to gases. This feature, coupled with the inherent flux capabilities of the heat pipe, enable the "solar-gas heat exchanger" to be tailored to minimize illuminated receiver surface while maximizing heat exchanger efficiency. In addition, the use of heat pipes provides ample design flexibility to allow for gas stream pressure loss minimization which is crucial for Brayton cycle energy conversion systems. By virtue of their high heat transport characteristics, the heat pipes are also capable of reducing receiver temperature gradients and hence material stresses. The heat pipes also provide for receiver redundancy. Each heat pipe represents an independent heat transfer device. The failure of one pipe is not likely to affect the performance of the receiver, provided the receiver is designed such that heat pipe failure does not impact its pressure containment capabilities.

During the aforementioned programs, a baseline receiver design was selected and the heat pipe operating requirements associated with this design were defined. The baseline heat pipe receiver, shown schematically in Figure 1, is a north-facing cavity which is tilted 5^{o} from horizontal in a downfacing direction. The illuminated surface of the receiver consists of nine modular panels which form the semi-cylindrical backwall of the cavity. Heat pipes penetrate the wall of each panel at right angles. The sections of the heat pipes which extend into the solar cavity intercept the solar flux and act as evaporators. Not all of the flux entering the cavity impinges on the evaporators. Some of the incident energy strikes the receiver wall, which is protected by a layer of refractory insulation. Essentially, all of the energy absorbed by this insulation is reradiated thermally, and most of it is absorbed by the heat pipe evaporators. The energy absorbed by the heat pipe evaporators is transported through the receiver wall to finned heat pipe condensers which traverse the gas stream.

The illuminated portion of the heat pipe receiver is considerably more complex than more conventional receiver surfaces such as tube sheets. With the heat pipes protruding at right angles to the receiver wall, the illuminated surface takes on an added dimension (depth). As a result, the surface is very difficult to analyze properly under actual solar input. It is expected that the flux distribution throughout the receiver will be highly nonuniform, particularly due to shadows created by the heat pipe evaporators. Reflection and reradiation from the evaporators and the receiver wall only add to the analytical difficulties.

In order to investigate the performance of a heat pipe receiver surface with actual solar input, a program sponsored by SERI was undertaken in September of 1979. During this program, an experimental module was designed and fabricated which replicated the exposed surface of a heat pipe receiver. This module was tested at the Georgia Tech ACTF in October 1980 under a range of conditions typifying the operating conditions of a full-scale receiver. This paper discusses the design of the experiment and the results of the testing conducted at the ACTF.

2. DESCRIPTION OF EXPERIMENTAL MODULE

The heat pipe receiver experimental module is shown in Figures 2 and 3. Every effort was made to keep the illuminated portion of the experimental module identical to the illuminated portion in the full-scale receiver. The module consists of seven full-scale heat pipes (diameter = 6 cm) arranged in the same triangular pattern (pitch = 11 cm) used in the full-scale receiver. The pipes are made from Inconel 601 and are charged with sodium. The pipes protrude through the receiver wall exposing 40 cm of their length to the solar flux. This evaporator section includes a conical end cap which is 8 cm high. The receiver wall is a 31 cm diameter Inconel disc which has the same projected area as that section of the receiver wall in a full-scale receiver associated with seven heat pipes. The receiver wall is shielded from the solar flux by a 6 mm layer of ceramic insulation.

On the opposite side of the receiver wall, each heat pipe is enclosed by a water-cooled gas-gap calorimeter. That section of the pipes between the receiver wall and the calorimeters is insulated. The calorimeters are 30 cm long and are made from copper. These calorimeters provide a convenient means of cooling the pipes as well as measuring heat pipe power throughputs. In addition, the calorimeters allow for considerable flexibility in heat pipe temperature control, as the thermal resistance between the heat pipe and the water coolant can be varied by nearly an order of magnitude by varying gas mixture in the gas-gap from pure Argon to pure Helium. The calorimeters are connected in series to a common water supply and to a gas manifold.

The experimental module is surrounded by several shields shown in Figure 3. Two upper shields enclose that portion of the experiment above the receiver wall. They provide weather protection and protection from stray fluxes for the receiver instrumentation. The lower shield is a truncated right circular cone which begins at the extremities of the receiver wall and widens to its base which is described by a circular plane containing the tips of the heat pipe evaporators. This shield serves three purposes. It is designed to intercept the bulk of the reflected energy emanating from the heliostat field which does not strike the receiver surface. It is also intended to suppress convection losses from the experiment. But most importantly, its size and shape enables it to run at an average temperature which is equal to the heat pipe temperature. Consequently, the shield provides a radiation background similar to the radiation background seen by heat pipes in a full-scale receiver.

The heat pipes, calorimeters, and shields are supported by a baseplate at the upper end of the experiment. This baseplate is clamped to the receiver support structure at the top of the tower through a yoke assembly. The support structure, which was supplied by Georgia Tech, consists of a water-cooled box beam and a pair of trusses. The receiver is tilted 20 degrees from vertical with the heat pipe evaporators pointing north. This tilt directs the centroid of the incident flux on the underside of the heat pipe evaporators at approximately the same angle as in the full-scale receiver. The receiver is also oriented to place the focal zone of the heliostat field at the base of the conical end cap of the central heat pipe in the experiment.

The receiver was instrumented with approximately 50 high temperature thermocouples. Most of these thermocouples were placed on the heat pipes to monitor their performance and to determine the distribution of the absorbed fluxes. Thermocouples were also placed on the receiver wall and the lower shield to characterize the radiation background seen by the heat pipes. In addition to these absolute temperature measurements, differential water temperatures across each gas-gap calorimeter, water flow rate, and flow rates of each gas component in the calorimeters were also measured. The ACTF scanning flux calorimeter was mounted at the experiment's aperture to measure incident heat flux levels.

3. RECEIVER TESTING

3.1 Test Objectives

The overall objective of the test program was to characterize the performance of a representative portion of a heat pipe receiver with actual solar input under conditions which typify the conceivable operating conditions for a full-scale receiver. Specific test objectives included:

- Evaluate steady state performance of the receiver over the full range of heat pipe temperatures and heat loads.
- Evaluate transient receiver performance associated with diurnal insolation patterns and intermittent cloud cover.
- Characterize receiver performance following the failure of a single heat pipe.

3.2 Test Summary

The heat pipe receiver experimental module was tested at the ACTF during October 1980. The receiver was tested in the solar beam for a total of 21 hours. During this time, the incident insolation ranged from a peak of about 950 W/m^2 down to zero during cloud induced transients. Peak fluxes measured at the experiment's aperture with the ACTF scanning flux calorimeter were between 85 and 90 W/cm^2.

The bulk of the test period, approximately 17 hours, was spent characterizing the steady state performance of the receiver. During these tests, the power absorbed by individual heat pipes ranged from 3 to 11 kW. Heat pipe temperatures were varied by gas mixture changes in the calorimeters and ranged from 430 to 940°C. Table 1 provides a summary of some typical test data taken on a day when the insolation was reasonably good. The table shows the average temperature of the convection shield and the average heat pipe temperature in the cavity at several times during the test. The shield shows much smaller temperature variations as it is not actively cooled. The difference between the pipe and shield temperatures averaged 60°C during the test. Hence the shield does a reasonable job simulating the appropriate radiation background for the pipes in the experiment.

The table also shows the total power entering the experiment's aperture, the power which enters a hypothetical disc encompassing all of the heat pipe end caps, and the total power absorbed by the pipes. The input powers were obtained by integration of the flux measurements at the aperture plane, while the absorbed powers were calculated using the flow rate and the temperature rise of the water in the gas-gap calorimeters. There is a considerable difference between the input power and the power absorbed by the pipes. The bulk of this difference (~85%) is lost by the shield through radiation and convection to ambient. The remainder is lost through reflection and radiation and convection losses from other portions of the experiment. Note also that the power absorbed by the pipes always exceeds that which enters the hypothetical disc containing their end caps. Some of this difference is due to solar input which impinges on the pipes but does not pass through the end cap plane. But the influence of temperature difference between the shield and the pipes on the magnitude of power difference indicates that a considerable portion of the difference is due to radiation heat transfer between the convection shield and the pipes.

Figure 4 shows some typical test data for two of the heat pipes in the experiment during the same test. One pipe is the highest powered pipe in the experiment and the other is an average powered pipe. The figure also shows the peak load requirements for the heat pipes in the baseline receiver and the theoretical heat rejection capabilities of the gas-gap calorimeters when filled with pure Helium and pure

Argon. During the test period spanned by the data points, the input power to the experiment varied by approximately 10%. However, the power absorbed by the pipes decreased substantially with heat pipe temperature due to increased thermal losses. As a result of the increased losses and the power limitations of the facility, it was not possible to test the pipes to power levels consistent with the peak load requirement curve above 650°C.

A considerable amount of testing was also conducted to evaluate the transient performance characteristics of the heat pipes. One series of tests simulated the transient conditions associated with the diurnal start-up of a hybrid power plant. During such a start-up, the receiver would be preheated to the compressor outlet temperature, with the compressor-turbine set running at design speed. Then once a specified insolation threshold is reached, the input power to the receiver would be ramped linearly to full power during a five minute period as the heliostats are focused. Figure 5 shows a power-temperature path which would be followed during start-up by a heat pipe operating at 820°C under steady state conditions. During the five minute heliostat focusing period, the heat pipe would traverse the lower portion of the curve up to a power of 4.4 kW. Further movement along the curve would occur at a rate consistent with diurnal increases in insolation.

Two tests were conducted at the ACTF to simulate this diurnal start-up scenario. In each test, the heliostat focusing period was simulated by opening and closing the shutters at the ACTF on a predetermined schedule. The power-temperature path shown in Figure 5 was followed by appropriate calorimeter gas mixture manipulations. In two respects, the transient conditions to which the pipes were subjected during these tests were more severe than those associated with a normal start-up. First, the experiment was not preheated. Pipe temperatures at the initiation of the test were considerably colder (ambient versus 360°C). Second, the insolation during the tests was higher than the threshold value at which heliostat focusing begins. As a result, instead of ramping the pipes to 4.4 kW, the heat pipes powers stabilized between 6 and 7 kW. Despite the more severe start-up conditions, the heat pipes started successfully during both tests.

Another series of transient tests were conducted to evaluate receiver performance during simulated and actual cloud transients. In a series of simulated transients, the heat pipes were allowed to cool to 360°C, which corresponds to the compressor outlet temperature in the hybrid power plant study. Then the receiver was repowered to full power with two minute ramps and instantaneously. The tests were conducted with two different gas mixtures in the calorimeters. At all conditions, receiver restart was successful. In one test, heat pipe power and temperature stabilized after repowering at 8.6 kW and 780°C respectively; while, in another test, stabilization occurred at 6.8 kW and 840°C. The receiver also withstood several natural cloud transients of approximately four minutes duration. During cloud passage, heat pipe temperatures decreased to about 400°C. Afterwards, the receiver restarted successfully with no precautionary measures.

The last test conducted at the ACTF was a heat pipe failure mode test. Prior to experiment start-up, the central heat pipe in the experiment was purposely failed by drilling a hole into its envelope at its lower end, thereby venting the vapor space to the atmosphere. The module was then ramped to full power in five minutes. Once the sodium in the pipe was oxidized, the pipe developed large axial temperature gradients (1000°C). Evaporator temperatures stabilized at approximately 1200°C. The other pipes in the experiment continued to operate normally at power levels slightly higher than with the central pipe functional.

4. CONCLUSIONS

The tests of the heat pipe receiver module accomplished all of the program objectives with the exception of testing the pipes over their full steady state performance range. Incident flux limitations of the test facility were responsible for this shortcoming. The tests which were conducted have demonstrated that:

- The heat pipes are capable of meeting the steady state performance requirements of a baseline central solar gas heater for a Brayton cycle. At the upper end of their performance range (650-870°C), the heat pipes could not be tested to the full power requirements due to test facility limitations.
- The transient performance capabilities of the heat pipes exceed the requirements placed on them by transient receiver operation during

hybrid power plant start-up and cloud induced transients. Test results also indicate that start-up without receiver preheat periods are possible.

- The loss of a single heat pipe in the receiver does not severely degrade the receiver's performance. The heat pipes adjacent to the failed pipe tend to assume the heat load of the failed pipe. Admittedly, these conclusions may change at higher incident fluxes, when melting of the failed heat pipe's envelope could occur. However, at the flux levels present during the test, no detrimental effects on receiver performance were observed.

5. REFERENCES

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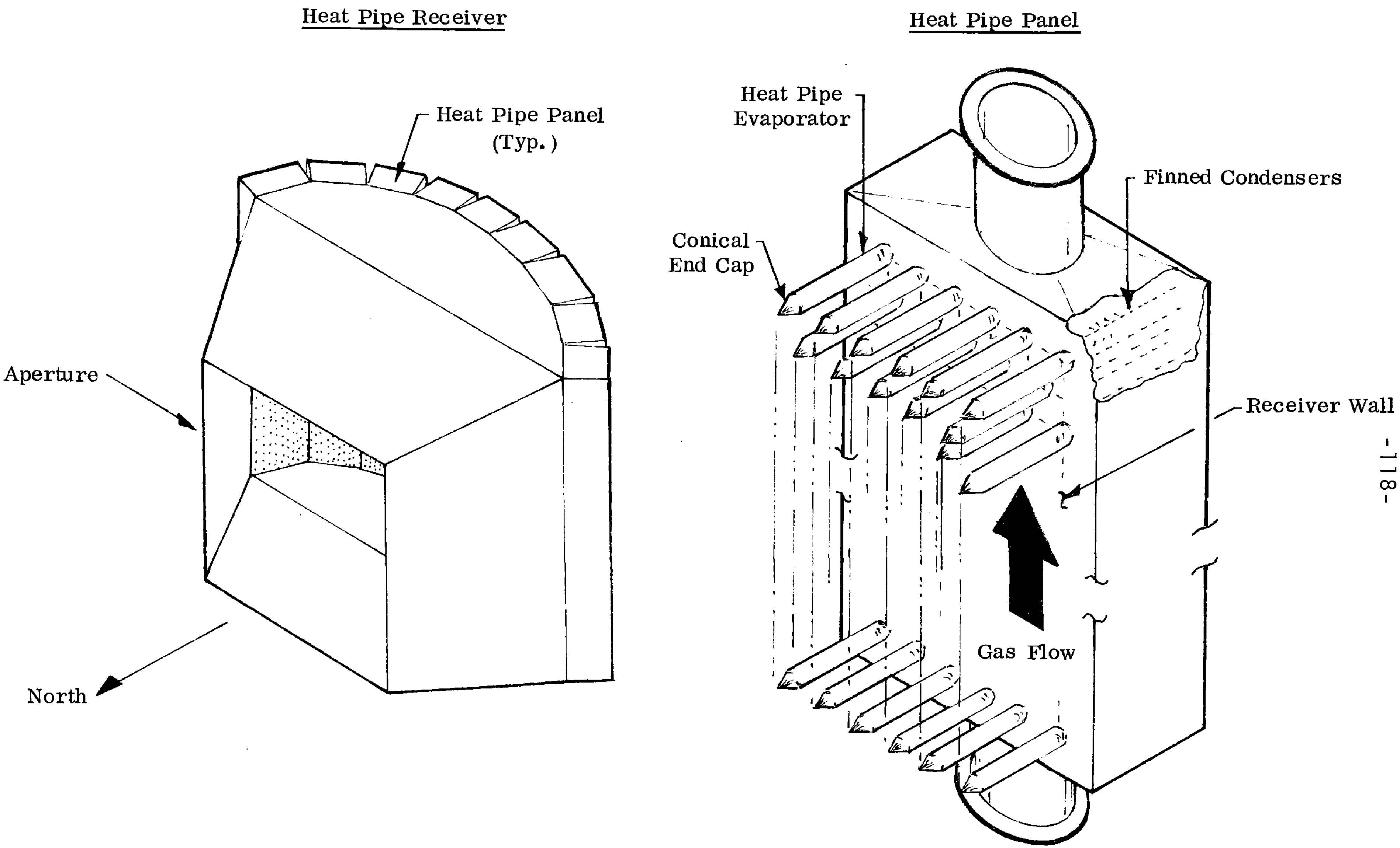
(2) Final Report for Heat Pipe Testing Program, Dynatherm Report DTM-81-2, 2/81

TABLE 1

TEST DATA SUMMARY FOR HEAT PIPE RECEIVER EXPERIMENT

Time	Insolation	Calorimeter Gas Mixture		Average Heat Pipe Temperature	Average Shield Temperature	Heat Input		Heat Absorbed
						Experiment*	End Cap Disc	Heat Pipes
		Ar (%)	He (%)	°C (°F)	°C (°F)	kW (10^5 Btu/hr)	kW (10^5 Btu/hr)	kW (10^5 Btu/hr)
1201	930	0	100	616 (1141)	775 (1427)	222 (7.58)	41.0 (1.40)	53.8 (1.84)
1300	936	20	80	694 (1281)	806 (1483)	242 (8.26)	44.6 (1.52)	59.2 (2.02)
1328	950	40	60	758 (1396)	820 (1508)	252 (8.60)	43.8 (1.49)	53.9 (1.84)
1400	950	60	40	790 (1454)	810 (1490)	245 (8.36)	47.4 (1.62)	48.3 (1.65)
1429	944	100	0	869 (1596)	816 (1501)	234 (7.99)	40.4 (1.39)	41.2 (1.41)

*Sum of input through aperture and assumed 22 kW to outside surface of convection shield



Heat Pipe Receiver

Heat Pipe Panel

FIGURE 1

BASELINE BRAYTON CYCLE HEAT PIPE RECEIVER SCHEMATIC

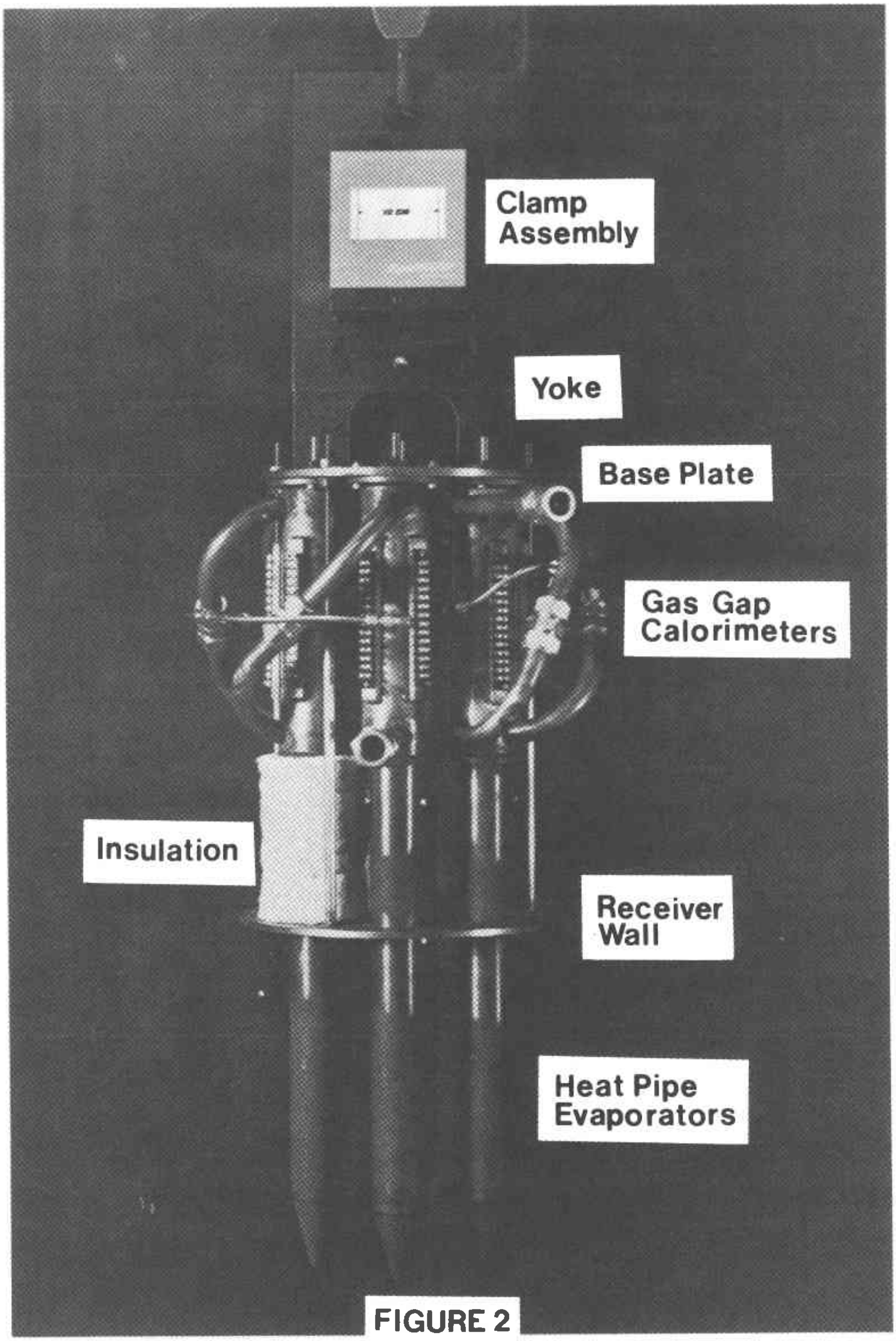

Clamp Assembly
Yoke
Base Plate
Gas Gap Calorimeters
Insulation
Receiver Wall
Heat Pipe Evaporators

FIGURE 2

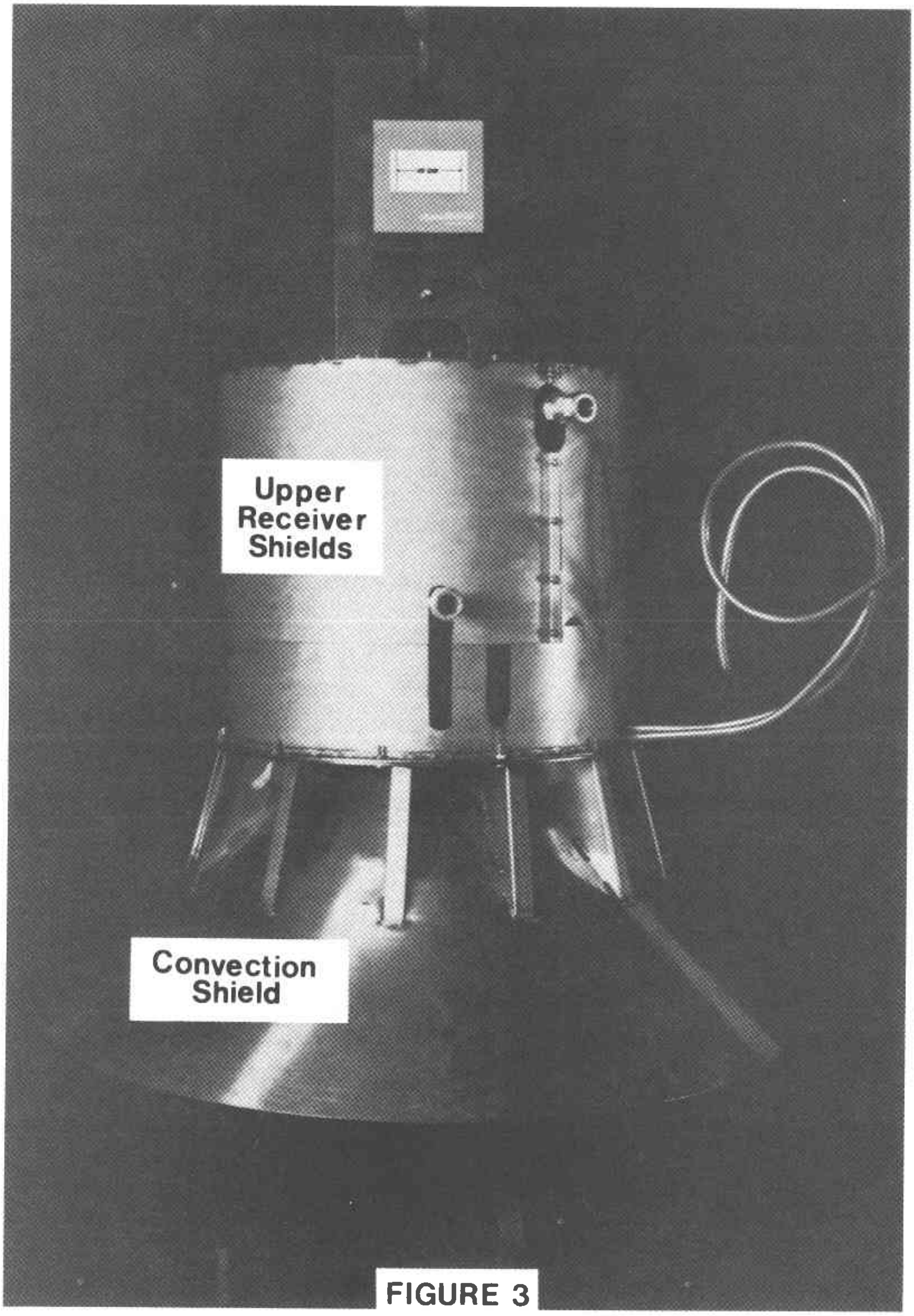


FIGURE 3

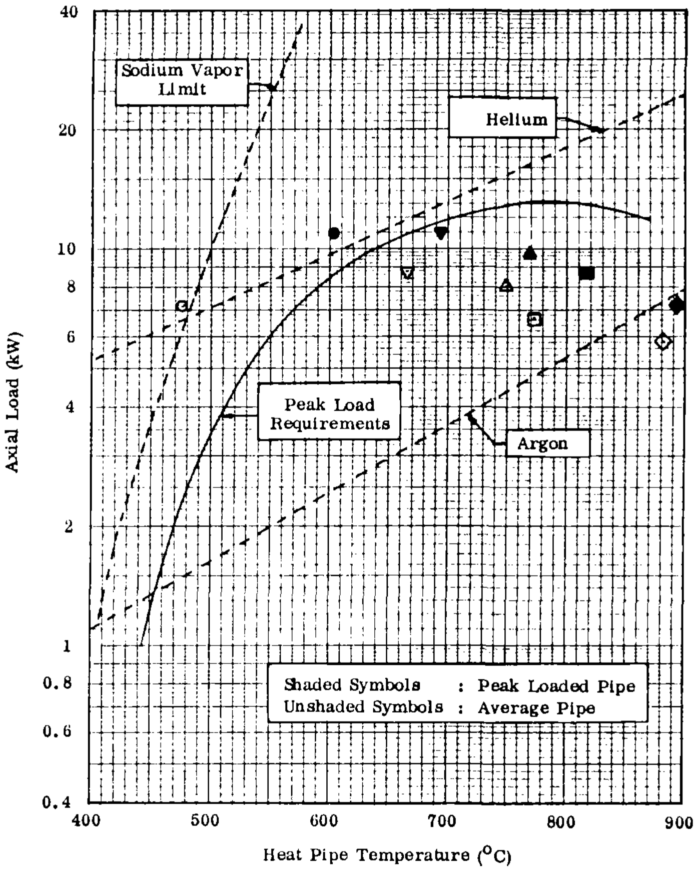


FIGURE 4

INDIVIDUAL HEAT PIPE PERFORMANCE

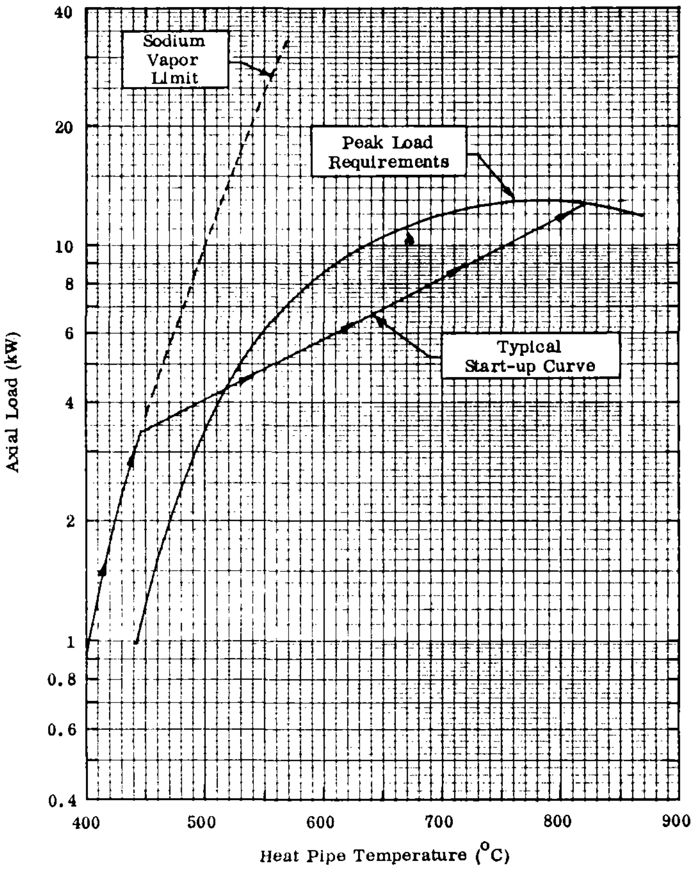


FIGURE 5

TYPICAL HEAT PIPE POWER-TEMPERATURE HISTORY DURING DIURNAL START-UP

A PROPOSED SOLAR FURNACE STUDY OF ZINC SULFATE DECOMPOSITION*

April 16, 1981

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Hydrogen production from water through the use of thermochemical cycles has now been successfully carried out in closed loop laboratory-scale experiments for several cycles that use the thermal decomposition of sulfuric acid as one of the critical steps.[1-3] However, there remain several problems in these H_2SO_4-based cycles that must be addressed as these cycles are further developed.[4] Some of the more important problems are:

1. The concentration and subsequent boiling of sulfuric acid solutions involves high heat requirements and difficult equipment problems, resulting in lower cycle efficiencies and higher capital costs.
2. Azeotropic H_2SO_4 is extremely corrosive to containment and heat exchanger materials during the boiling process.
3. The decomposition of gaseous H_2SO_4 ($SO_3 + H_2O$) and many metal sulfates is kinetically hindered and requires the development of suitable catalysts, which is often a difficult and expensive problem.
4. Gaseous H_2SO_4 is not completely converted to SO_2 during decomposition, resulting in the need to separate and recycle the gaseous reaction products.

One approach to overcoming these H_2SO_4-related problems is to replace the concentration and decomposition processes for H_2SO_4 with the precipitation and decomposition of solid sulfates. For instance, Mel Bowman and his associates[5-7] have suggested $Bi_2O_3 \cdot SO_3$ be added to the dilute H_2SO_4 solutions to precipitate $Bi_2O_3 \cdot 2SO_3$. The precipitate is then separated from the liquid, dried, and thermally decomposed to release SO_3 and regenerate $Bi_2O_3 \cdot SO_3$. The SO_3 is subsequently decomposed to SO_2 and O_2. Such a scheme bypasses many of the problems associated with the high temperature decomposition of H_2SO_4 solutions.

A similar approach based on $ZnSO_4$ can be used according to the following subcycle:[8]

1. $H_2SO_4(\text{aq. } 50\text{ wt\%}) + 5.44\ H_2O(\text{in soln. with } H_2SO_4) + ZnO(s)$

   $\xrightarrow{350\text{-}525K} ZnSO_4 \cdot H_2O(s) + 5.44\ H_2O(l)$

2. $ZnSO_4 \cdot H_2O(s) \xrightarrow{600K} ZnSO_4(s) + H_2O(g)$

3. $ZnSO_4(s) \xrightarrow{1000\text{-}1200K} ZnO(s) + SO_2(g) + 1/2\ O_2(g)$

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*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

Reaction (1) occurs in two steps; sulfuric acid is first neutralized to form zinc sulfate in solution and then the zinc sulfate is precipitated by increasing the temperature. The neutralization involved in reaction (1) is exothermic by 83 kJ/mol, which is sufficient to heat the solution to about 450 K. Reaction (1) would need to be conducted in an autoclave due to the high water pressures at the temperatures required to precipitate the monohydrate. Although the dehydration process in reaction (2) is endothermic by 80 kJ/mol, it would still produce high temperature process steam which could be used elsewhere in the various parts of the cycles. Reaction (3), which is endothermic by 338 kJ/mol, produces some SO_3 in addition to SO_2 and O_2, and the SO_3 requires recycling in a separate stream. The sum of these three reactions is equivalent to separating H_2O from H_2SO_4 (without boiling) and then decomposing the H_2SO_4 to form SO_2 and O_2.

The $ZnSO_4$ Subcycle presents a number of operational advantages over the direct decomposition of H_2SO_4. For instance, the cycle efficiency should increase due to reducing the heat requirements for evaporating water in the sulfuric acid concentration step. Also, a number of severe materials problems will be avoided for heat exchangers required to concentrate, boil, and decompose sulfuric acid. Furthermore, zinc sulfate lends itself well to coupling with solar central receivers, an alternative energy source which may introduce several additional advantages to sulfate-based thermochemical cycles.

Although the current thermochemical cycles were originally developed to use energy supplied by a high temperature-gas cooled nuclear reactor (HTGR), the high process temperatures ($\sim$1500 K) and power density levels (in excess of 2 $MJ/s{\cdot}m^2$) available from solar central receivers should substantially improve the kinetics and equilibrium constants for sulfate decomposition. This should reduce cycle times, amount of recycle, and equipment needs. Another advantage is that a solid sulfate decomposer can be directly coupled to solar radiation, and therefore should cost less and be more reliable than a heat exchanger from a HTGR for decomposing gaseous sulfuric acid.

There are particular advantages to coupling solar central receivers to the $ZnSO_4$ Subcycle. Our laboratory experiments using tungsten image lamps[8] as a radiant heat source indicate that rapid heating of the zinc sulfate particles through their 1015 K alpha to beta phase transition improves the subsequent decomposition kinetics. We feel that the 28% volume increase[9] in going from the alpha to beta phase causes extensive fracturing of the zinc sulfate particles during rapid heating. This produces a material of high surface area which increases the subsequent decomposition rate. The rapid heating available from solar furnaces should produce a similar phenomenon.

Our tungsten lamp experiments also indicate that zinc oxide acts as a catalyst in zinc sulfate decomposition, both accelerating the decomposition rate and leading to attainment of an equilibrium mixture of sulfur trioxide, sulfur dioxide, and oxygen in the decomposition products. This behavior eliminates the need for expensive platinum catalysts which might otherwise be required for sulfur trioxide decomposition. In addition, zinc sulfate can be decomposed at lower pressures than sulfuric acid, favoring the more complete decomposition of sulfur trioxide to sulfur dioxide and oxygen.

An important problem of using solar energy in a thermal process for thermochemical cycles is that the chemicals involved are frequently clear or colorless with low absorptivities. Although zinc sulfate is colorless, the zinc oxide formed during decomposition becomes orange-red when it is heated.[8] This increases the absorptivity of the overall reaction mixture and makes the zinc sulfate decomposition process more efficient to solar energy.

With the appropriate experimental design the problem of low sample absorbtivity can be reduced. In a well insulated solar reactor, the energy losses are primarily due to radiant energy lost by the reactor back through the window. (We are assuming to a first approximation that the receiver wall losses due to conduction are negligible.) If the receiver configuration is such that its behavior approaches that of a black body (large internal volume with a small opening), the receiver emissivity (ϵ_r) will approach 1. This means that the incoming radiation not directly absorbed by the sample will be converted into thermal energy rather than being directly reradiated out. Assuming the sample area is much larger than the area of the receiver wall, the radiant energy absorbed by the reactor will be a function of the sample emissivity (ϵ_s) and its area (A_s). Since the temperature (T) is the same for both the energy lost and the energy absorbed, the ratio of radiant energy lost to radiant energy absorbed becomes a ratio of window area (A_w) to the product of sample emissivity and sample area. This may be shown by these equations:

$$\frac{\text{radiant energy lost}}{\text{radiant energy absorbed}} = \frac{\sigma T^4\ (\epsilon_r)(A_w)}{\sigma T^4\ (\epsilon_s)(A_s)} = \frac{A_w}{(\epsilon_s)(A_s)}$$

where σ is the Stephan-Boltzman constant. Thus the energy lost can be reduced by using a relatively small window area, while the energy absorbed can be improved by increasing the area of the sample.

Our proposal to the Solar Thermal Test Facilities User's Association is to use a rotating kiln to study the advantages of the high temperatures and rapid heating rates provided by solar collectors for the decomposition of zinc sulfate. Radiant energy from the collectors will enter the kiln through a small window in an effort to reduce radiant energy losses. The rotating kiln will disperse the sample, increasing the sample surface area and hence the energy absorbed. The $ZnSO_4$ will begin to decompose as it is preheated by gaseous heat transport and direct contact with the receiver walls. The subsequent formation of colored ZnO will increase the absorptivity of the reaction mixture, improving the direct heating of the sample. With this special receiver and the higher absorptivity of ZnO, we expect to overcome the problem of working with the colorless zinc sulfate.

Figure 1 shows a schematic reflecting our initial ideas on kiln design. The goal of our final design will be to keep the kiln as simple as possible, with complex operating parts as removed from the beam as possible. A screw feeder will supply the zinc sulfate, which has been previously dried and characterized, into a feed tube which empties into the kiln chamber through a hole in the back. Thermocouples for monitoring ing the experimental operating temperatures at various points within the kiln will also enter through this back opening. The inside of the kiln will be lined with either of two types of Al_2O_3 liners; a smooth-surfaced liner or a liner with a fluted surface. This should allow some degree of control over sample dispersion and surface area. We will try to determine the effects of heating rate by comparing experiments using a preheated kiln with experiments where the kiln is slowly heated via the solar attenuators available at the White Sands Facility. The sample retention time will be controlled by varying the angle of tilt and rotation rate of the kiln. A quartz collector tube will collect the solid products as they leave the kiln. Graduation marks on the collector tube will allow us to monitor the rate of solid feed through the kiln during an experiment. The solid products will be characterized as necessary (mass balance, particle size distribution, phase identification, particle topography) at a later date.

The radiant energy from the collectors will enter the kiln through a quartz window, around which a series of gas jets (argon or nitrogen) will be installed in case the particles tend to adhere to the inner surface. Flow meters will determine the rate of window cleaning gas input as well as the total gas output from the cell, allowing calculation of the rate of gas evolution as the $ZnSO_4$ decomposes. (The principle method of analyzing decomposition rate will be by measurement of the gas evolution rate.) The exit gases will be sampled for later analysis using gas chromatography and other analytical techniques as necessary. Waste gases will be scrubbed prior to their release to the atmosphere.

In our proposed experiment we hope to study the advantages of the high temperatures and rapid heating rates provided by solar collectors for the decomposition of zinc sulfate. We also plan to demonstrate the use of a rotary kiln designed to improve the efficiency in working with solids that have low absorbtivities, such as solid sulfates. Our overall goal in this experiment is to establish the applicability of solar central receivers to thermochemical cycles that can utilize solid sulfate decomposition as the high temperature step.

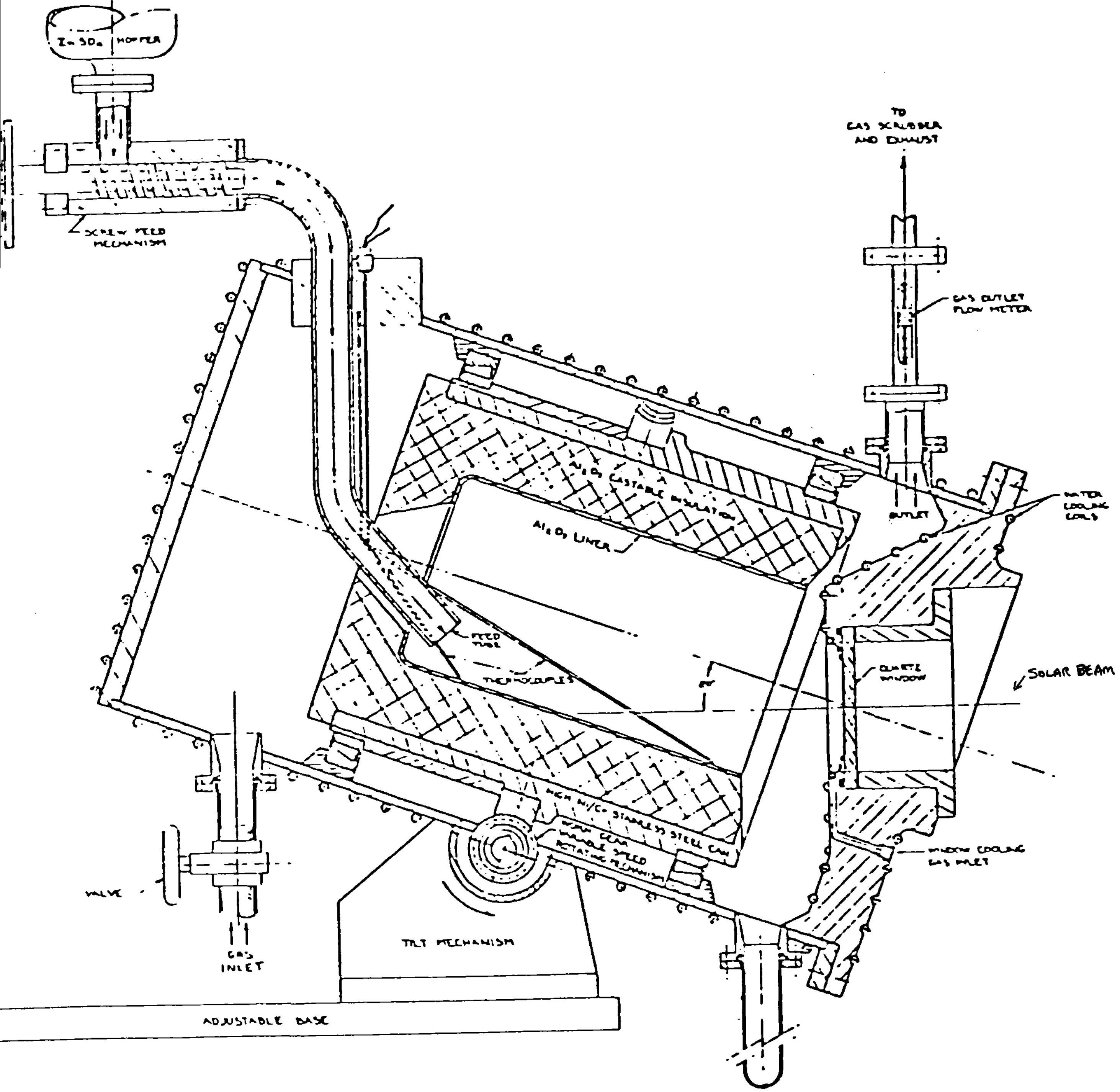

Figure 1. Schematic of a rotating kiln designed to increase the solar efficiency of $ZnSO_4$ decomposition.

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PRODUCTION OF ELEMENTAL PHOSPHORUS IN A SOLAR FURNACE

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One of the goals of the solar thermal energy program is to use high-temperature solar heat for producing fuels or energy-intensive chemicals. A good example of the latter is elemental phosphorus, which is produced commercially by heating a mixture of phosphate rock, silica, and coke at 1500°C in an electric furnace.[1,2] Because this is within the temperature capabilities of central receiver and solar furnace facilities, elemental phosphorus should be a good candidate for an energy-intensive chemical that can be produced by solar thermal energy.

Background

Annual production of elemental phosphorus was about 460,000 tons in 1979.[3] At 6.5 kWhr of electricity per pound of phosphorus produced[4] and an electricity generation efficiency of 30%, if solar energy could displace the entire use of electricity for elemental phosphorus production, the reduction in energy use would be about 12 million bbl/yr crude oil equivalent. Current phosphorus prices are 55¢ to 65¢/lb.[3] With electricity at 4.0¢/kWhr, electricity costs represent from 40% to 47% of the cost of phosphorus.

Two areas of the United States have extensive deposits of phosphate ores: the Northwest (Idaho, Montana, and Nevada) and the Southeast (North Carolina and central Florida). Because of the availability of low-cost hydroelectric power, the energy-intensive elemental phosphorus industry has been located in the Northwest. However, the region's population is growing and the demand for electric power has begun to outstrip the supply because the hydroelectric potential of the region is now exhausted and the development of nuclear power has been all but halted. As a consequence, the cheap electrical energy once available to produce phosphorus from phosphate ore in electric furnaces has become more expensive, if not unavailable. The solar insolation availability in the Northwest States where phosphate ore is found generally exceeds the national average. Because central receiver plants may be located close to the raw material, it is quite conceivable that economic utilization of solar energy for elemental phosphorus production may be possible in this region.

In Florida, however, a different situation exists. Elemental phosphorus is not produced in the Southeastern United States because, except for the region served by TVA (deposits of phosphate rock also occur in Tennessee), cheap hydroelectric power is unavailable. Thus, phosphate ore is generally processed by the "wet acid" process to produce different products than those derived from elemental phosphorus. Florida has good insolation characteristics and, as a consequence, the use of solar energy for elemental phosphorus production may allow the development of an industry for this important industrial chemical. However, the makeup of ore deposits in Florida is different than in the Northwest in that Florida ores are generally higher grade and less contaminated with silica and, thus, are more suitable for fertilizer production. The phosphate ores in the Northwest are less suitable to fertilizer, but ideal for elemental phosphorus because of the higher silica content. Furthermore, the overburden in Florida contains iron and aluminum phosphates that are currently not used, but that might be processed in a similar way to the apatite phosphate ore (that is, electric furnace or solar reduction) to produce elemental phosphorus.

Phosphorus Reduction[1,4]

Elemental phosphorus [chemical symbol "P," atomic weight 30.98, solid density 1.82 g/cm^3 (white phosphorus), melting point 44.1°C, liquid density 1.74 g/cm^3, boiling point 280.5°C] is made commercially by the reduction of phosphate rock (fluorapatite) with carbon and sand at 1500°C in an electric furnace, according to the following equation:

$$\underset{\text{(fluorapatite)}}{4\ Ca_5F(PO_4)_3} + \underset{\text{(silica)}}{18\ SIO_2} + \underset{\text{(coke)}}{30\ C} \xrightarrow{\text{(heat)}} \underset{\text{(slag)}}{18\ (CaO\cdot SiO_2\cdot 1/9\ CaF_2)} + \underset{\text{(carbon monoxide)}}{30\ CO} + \underset{\text{(phosphorus)}}{3\ P_4}$$

In the commercial manufacture of phosphorus, a charge is made up for the electric furnace consisting of phosphate rock and silica material sized by reduction or agglomeration, as necessary, to particles 0.25 to 2 inches in diameter. Coke is added to the mix as particles 1 to 1.5 inches in diameter. The furnace feed is in this size range because it must have adequate porosity so that the gases evolved in the reaction (carbon monoxide and phosphorus) can escape from the reaction zone near the bottom of the furnace.[4] Table 1 gives typical operating data for a commercial electric furnace operation. Of the 6.5 kWhr/lb of phosphorus, 50% of the energy used (11,100 Btu/lb) is used to supply the heat of reaction. The remaining 50% supplies sensible heat to raise reactants to reaction temperature and to make up thermal losses through the reactor insulation.

Table 1. OPERATING DATA FOR A COMMERCIAL ELECTRIC FURNACE[4]

Average Potential Between Electrodes, V	300
Raw Materials Consumed per lb of Elemental Phosphorus Produced	
Power, kWhr	6.5
Phosphatic Material, lb	10.0
Silica Material, lb	1.5
Coke Material, lb	1.5
Products Formed per lb of Elemental Phosphorus Produced	
Slag, lb	8.9
Ferrophosphorus, lb	0.30
Carbon Monoxide, lb	2.8
Recovery, as the Element, of the Phosphorus Charged, %	87

The reaction temperature at which phosphorus is produced is in the range of 1450° to 1550°C (2642° to 2822°F). The reaction temperature corresponds closely to the temperature of the slag and represents the temperature at the baked carbon electrodes at which the reaction takes place. No electrolysis occurs in the production of elemental phosphorus.

A typical electric furnace for phosphorus production consists of a refractory inner shell and an outer shell made of steel sheet, welded together to prevent leakage of gas. The shell is often cooled by sprays of water. The floor of the furnace is monolithic carbon that extends several feet up the side of the furnace, above the surface of the molten slag within. The carbon floor is made of carbon blocks that blend together with the carbon paste used to fill the cracks when the furnace is first brought to temperature. The upper walls are made of firebrick or cast refractory cement and most furnace roofs are cast monolithic structures.[4]

In commercial systems, the gases evolved in the reaction come off at about 700°F (371°C). The bulk of the gas (>90%) is carbon monoxide, and the remainder is primarily phosphorus with some silicon tetrafluoride and dust. The phosphorus is usually condensed in towers equipped with water sprays held at 45°C. Carbon monoxide is burned in the agglomerizing kiln or burned to the atmosphere. The condensed phosphorus goes to a holding tank where it settles out of the water. For safety, phosphorus is always kept stored under a layer of water.

The cost of electricity represents about 40% of the cost of phosphorus. With the annual production in 1979 of some 460,000 tons, the elemental phosphorus industry realizes an annual gross income of over $500 million. The United States exported about 25,000 tons of phosphorus in the year 1980.[3] (The United States imports negligible amounts of phosphorus.) The major derivatives of phosphorus are primarily phosphoric acid and its derivatives. Approximately 45% of elemental phosphorus is used to produce industrial phosphates for use in detergents, about 15% in foods and beverages, and about 10% in metal treating. Other uses are for flame-retardant additives for polymers, liquid fertilizers, wear-extending additives for lubricating oil, and pesticides.

Proposed Solar Phosphorus Program

The program scheduled to be carried out on preparing elemental phosphorus in the solar furnace at White Sands Missile Range consists of three parts:

1) A laboratory program to prepare elemental phosphorus, using an electric tube furnace to determine reaction temperatures, reaction times, materials for a reactant holder, and a method of collecting phosphorus for subsequent use in carrying out the solar furnace program

2) A 1-week program at the White Sands Solar Furnace, using the reaction conditions defined in the first task, to prepare elemental phosphorus and define parameters for any future extension of this work

3) Analysis of both the product and the slag, and issuance of a final report.

The same reactor designed and used for the thermal decomposition of cadmium oxide at White Sands will be used for the preparation of elemental phosphorus. This reactor, shown in Figures 1 and 2, is designed specifically for the horizontal beam of the White Sands solar furnace and involves a water-cooled stainless steel shell with two concentric ceramic heat shields to contain the heat in the reaction zone defined by the focal area of the solar beam. The heat shields, the inner one of alumina and the outer one of mullite (aluminum silicate), retain the heat for the reaction and also protect the outer stainless steel shell from the intense solar heat. The window is a 0.5-in.-thick quartz plate and the reaction "vessel" is a series of zirconia troughs stacked vertically on top of each other to provide a maximum reactant surface perpendicular to the horizontal beam. Because the phosphate rock-silica-carbon reaction produces a liquid slag at 1500°C, the troughs will have the ends closed to prevent the slag from running out onto the alumina heat shield. Graphite might be used in place of zirconia, and will be tested in the lab program.

The reactor is equipped with fittings to permit an inert gas (argon) sweep and still other fittings to permit a thermocouple in each of the zirconia troughs. A water-cooled tube condenser is located just behind the reaction zone for condensing out products such as cadmium metal or elemental phosphorus. Whether or not this condenser will be used will depend on the laboratory program. Phosphorus is collected under water and this may obviate the need for a water-cooled condenser.

The solar furnace tests are scheduled to take place during the week of August 24-28, 1981, weather permitting. Based on our experiences with the cadmium oxide runs in the solar furnace, we do not plan any quantitative experiments that depend on a reasonably constant, uniform temperature (such as reaction rate studies), but will try to verify some time/temperature/yield relationships to help in the design of future experiments. Our major objectives are to establish that elemental phosphorus can be produced in a solar furnace in acceptable yields and to identify factors that can help guide future work.

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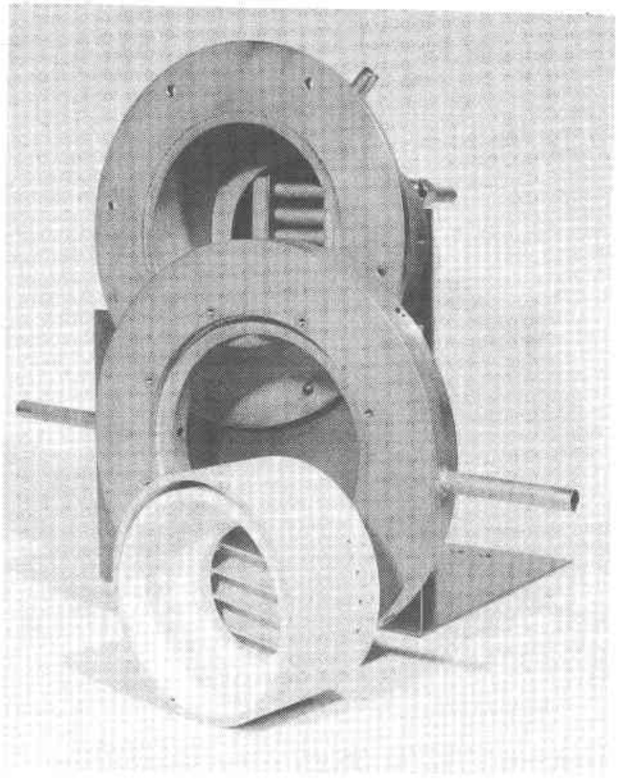

FIGURE 1. SOLAR RECEIVER/REACTOR, DISASSEMBLED

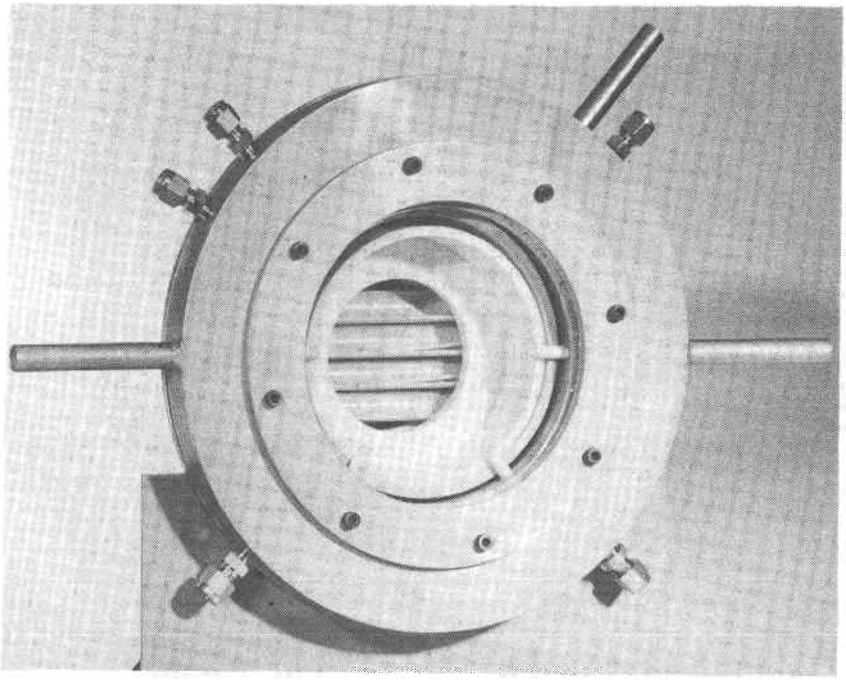

FIGURE 2. SOLAR RECEIVER/REACTOR, ASSEMBLED

Window Curvature Measurement

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ABSTRACT

Sanders Associates has developed and tested compact high temperature solar receivers which are configured with ceramic honeycomb panels arrayed within a windowed cavity. Design of the windows and associated mounting hardware is a complex task than can be materially assisted by use of valid computer models.

Sanders has proposed to build a laser based instrument to measure window curvature on an operating receiver to validate the computer window simulation model. The instrument and potential applications are discussed.

REPORT

Sanders Associates, Inc of Nashua, NH has proposed to build and subsequently employ special instrumentation to monitor the curvature of pressurized high temperature solar receiver aperture windows.

Solar thermal receivers operate by absorbing solar radiant energy on a collecting surface. That energy is usually carried off by a convective fluid for use in space or water heating, in industrial processes, in fuels and chemical reactions, or in heat engines.

Low temperature applications, generally within 70 F of ambient temperatures require little or no light concentration for efficient operation. At higher temperatures, to 700 F above ambient, convection to the surrounding environment predominates as the loss mechanism. These convective losses are adequately overcome by use of trough or mosaic concentrators. Radiant energy can be focused onto the external surface of (typically) cylindrical or spherical receivers.

At temperatures above 700 F, reradiation of thermal energy becomes an important loss mechanism. The effect can be offset to some extent by increasing the concentration ratio of the concentrator; but the effective harvesting of the too concentrated heat flux from the receiver surfaces is limited by convective film coefficients and tube wall conductivities.

The reradiant losses can be reduced by use of a cavity receiver. In cavity receivers highly concentrated light passes through a relatively small entrance aperture onto the interior surfaces of a radiation cavity. Relatively copious area can be provided within the receiver to absorb and subsequently convect the heat into the transport fluid, while reradiation losses are limited by the comparatively diminutive aperture.

Three loss machanisms act to limit the efficiency of cavity receivers: conductive losses through the wall, reradiation through the aperture, and convection exchanges at the aperture.

Wall conduction losses are minimized by using effective insulation and by reducing external wall area. This reduction of wall area, in turn, provides an upper flux limit for receivers (particularly tube and slip cast receivers) wherein the initially absorbed radiation must first be conducted through a finite duct wall thickness before it can be convected into the heat transport loop. This limitation is avoided in matrix receivers where the absorbing surface is the convective surface; intervening conduction temperature gradients are eliminated. Furthermore, use of an absorbing matrix allows the packing of large surface areas within small cavity volumes. This compact packing facilitates the reduction of receiver size and reduces associated wall conduction losses.

Convection losses at the aperture of an open high temperature cavity can account for a 5% energy loss at unfavorable cavity tilt angles. Convective loss suppression measures are clearly warranted. A window is the obvious means to the elimination of mass transport losses across the aperture. A sealed window of adequate thickness can withstand significant pressure loads to permit receiver operation in pressurized process or engine loops. The pressure capability of the windowed receiver eliminates (for many applications) the need for sealed tubing within the receiver.

Sanders Associates has been involved in the research, development, and testing of windowed solar receivers since 1976. The 10 KW receiver, tested at White Sands, NM in 1976, operated at 1750 F and 45 psig. The 80 KW receiver recently (Nov 80-Jan 81) tested at the Parabolic Dish Test Site on Edwards AFB, CA operated at 2500 F and 30 psig. Test results have confirmed the potential efficiency, durability, and cost advantages offered by the windowed cavity matrix receivers.

Window performance and integrity is obviously critically important to the success of the design. As such, it received rigorous attention during the prototype receiver design effort.

Stochastic modeling computer methods were used to define the solar flux distribution at the window. Prediction of volumetric heat absorption throughout the window (axial and radial distributions were considered) was performed using spectral transmissivity characteristics of candidate materials, spectral distribution of the (terrestrial) solar irradiance, geometry of the window, distribution of the concentrated solar flux, and cavity radiation temperatures as input parameters.

Heat transfer analyses were performed using calculated values of volumetric thermal absorption and relevant convection and radiation boundary conditions at the external and internal surfaces of the window.

Calculated three dimensional temperature profiles, selected pressure loadings, and alternate boundary conditions were used in the calculation of window stresses and deflections. The calculations and design iterations yielded a prediction that the window--though stressed to 1000-3000 psi at critical locations--would survive. Material tensile strength is given as 9000 psi, but a working stress of 1000 psi is the maximum recommended design limit.

A key element in the success of engineering projects is the efficacy of the methodology. Even refined methods of detailed design analysis are not sufficient. The results of such analyses--even of parametric analyses--must be carefully evaluated to be of value in the intelligent revision and improvement of designs.

Iteration of the design and analysis tasks are necessary to assure definitization of a viable design.

A necessary part of this process is the development of valid computer models. In retrospect, the models developed and used in the course of the Prototype High Temperature Solar Receiver program were generally valid, though the structural model of the window was oversimplified. Boundary conditions were substituted for the window support and retaining flanges. The selected boundary conditions would have sufficed for a pressure loading analysis, but they could not properly account for thermal distortion of the flanges.

During early testing of the 80 KW receiver the window failed three times. Field modification of the window clamping hardware corrected the failure problem, and subsequent testing was successful. The field fix consisted of providing sufficient clearance to allow the flange to distort without physically pinching the window. The field fix, while successful, represented different boundary conditions for the window than had been anticipated during design.

Failure analysis of the receiver and fractured windows revealed the following:

1. The first window failed when the concentrator was misaimed. The concentrated solar flux impinged on the window flange, rather than on the window. The misdirected flux landed at the two o'clock location of the aperture and locally warped the flange. The resulting stress concentration broke the first window.

2. Subsequent failures occured when heating from the spillage (fringe illumination) from the properly aimed solar flux caused the window retaining flange to cone inward and fracture the window.

The proposed instrument is important for three reasons:

1. It will provide means to measure actual deflections and thus validate computer models. Identified discrepancies between the computer simulated model and the actual hardware can be resolved--often by the modification of the model elements or of boundary conditions. Once reliable correlations are achieved the model becomes a useful design aid which can be used with confidence to reduce technical and cost risk on subsequent programs.

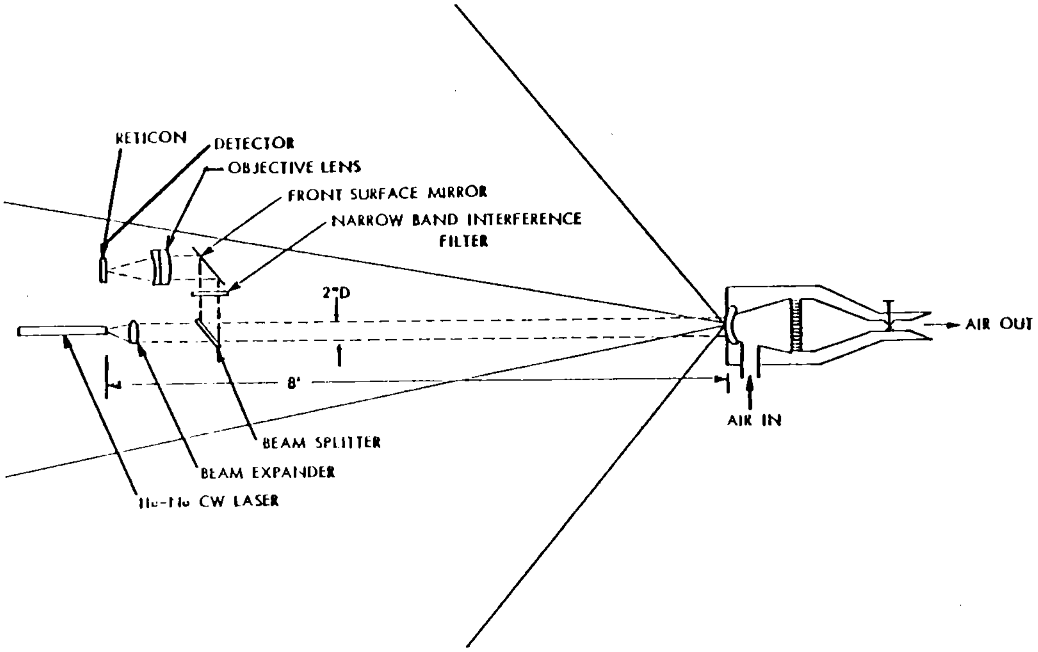
2. Suitable as an experiment monitoring instrument window deflections can be observed. Window failures such as those experienced during the early test sequences of the high temperature solar receiver can be anticipated--even avoided.

   Failure analysis activities would be streamlined; local flange warpages or uniform distortions like the inward conical deflections could be detected and recorded.

3. Maintenance activities, such as the monitoring of long term window creep in an energy farm could be facilitated without pulling systems off sun. Even internal air flow anomalies resulting in non-uniform window cooling could be detected prior to catastrophic failure events.

The Proposed Instrument

Sanders has proposed to build and test an instrument for the Users Association to remotely measure the window surface deflections, both in the laboratory and in the field under operating conditions.



Remote Spherometer Schematic

The attached figure shows the schematic approach to the instrument. In principle a cw laser projects a beam forward though a beam expander. A (2") beam is projected forward to the window surface. A flat and perpendicular window, by virtue of its dielectric refraction constant bounces a portion of the beam energy back toward the instrument. The return beam is diverted by a beam splitter through an objective lens set onto the detector. Background solar irradiance is eliminated by use of narrow band interference filters. A convex (concave) window surface will reflect a convergent (divergent) beam back to the instrument. Spot size on the detector will be a function of window curvature.

Instrument misalignment from the window normal will be evidenced by displacement of the return image from the detector center. The instrument is sensitive to these angular misalignments, having a full scale sensitivity of 5-10 m-rads, depending on return optics diameter. The instrument is relatively insensitive to range errors, with the error sensitivity being described by the ratio "diameter error:diameter::range error:range."

Alternate techniques employing an optically scanned laser pencil beam are under consideration to improve the ease of installation and use as a field maintenance test unit. Specifics of implementation will constitute the body of the proposed program. In the interim, Sanders is conducting basic optical bench experiments to determine error sensitivities and relative merit of alternate configurations.

CONSTRUCTION AND DEMONSTRATION OF A SOLAR COOKER USING THE GEORGIA TECH SPIRAL CONCENTRATOR

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Georgia Institute of Technology

INTRODUCTION

The purpose of this talk is to introduce a new type of point-focusing concentrator that I believe is uniquely suited for Third World applications and to describe its use for solar cooking. But before that I want to give a little background on the development of this particular concentrator. I will be referring to it as Georgia Tech spiral concentrator. Figure 1 shows an example of one of the spiral concentrators with its inventor, Mr. Rick Steenblik. He was a student at Georgia Tech at the time he came up with the idea of this type of concentrator.

One of the most attractive features is that it provides a means of making a point-focusing concentrator out of a flat sheet of material without the need to be formed into a compound curve. Thus, because of its simplicity, it can be fabricated from a wide range of materials.

The basic component of the concentrator is a computer-generated spiral pattern. The parameters established by this pattern are the concentration ratio and focal length. The concentration ratio is determined by the width of the spiral segments. The focal length is determined by how tightly the spiral is coiled. This is established by a series of mounting points. These mounting points are located so that when they are aligned in a straight line and attached to a planar surface, each spiral segment assumes the proper angle (twist) to make the reflector act as a point-focusing concentrator. During construction, each set of mounting points is attached to a frame so they are held in a straight line. The size of the pattern determines the power that can be obtained, as is the case of any concentrator. The construction materials are (1) any flat sheet of material that's homogeneous; either a reflecting material or a non-reflecting material plus a reflecting surface, (2) the frame members themselves, and (3) the support structure.

Referring to Figure 1, the concentration ratio is about 500 which is evidenced by the narrow width of the spiral elements. As mentioned, the focal length is determined by how tight this spiral is twisted, which in this figure is equal to the diameter of the concentrator. For this concentrator there are six support members. The spiral is made of electropolished aluminum which is attached to the support members at the mounting points located on the computer-generated pattern. This concentrator can provide a temperature of about 2000^{0} F which ignites wood in a matter of two or three seconds as shown in the figure.

The concentrator that I am going to describe represents a concept that can be used to make a very inexpensive solar cooker. For this application a concentration ratio of 50 was selected. This will provide a temperature of about 600 degrees Fahrenheit, and that's why this particular cooker has a fairly wide element.

Solar Cooking

Figure 2 shows a solar cooker used in a demonstration program in Upper Volta in West Africa. For this program the typical parabolic dish type of cooker is being used. These concentrators, made of aluminum, were provided by a Danish organization called Danchurchaid. These cookers are fairly expensive; the dish itself is about $30, and the support mechanism because of the weight of the dish and strength required is another $30, for a total of $60. Now, that's completely unaffordable in a village, and practically unaffordable even in the city, where a family of six must spend $15 a month for firewood. However, the wood problem is so serious that they are trying all means possible to reduce the consumption of wood. In a small country like Upper Volta, I was told that they are losing about 10,000 acres a year of wood, at least half of which is going for cooking. About 90 percent of the thermal energy that is consumed in the Third World is from wood and 50 percent of the wood is used for cooking. The problem is that many people in the Third World live on marginal land bordering deserts and as wood is cut the desert spreads causing a movement of the people to areas already populated so that wood use becomes accelerated on the remaining land. Although solar cooking has the potential for reducing wood consumption, it faces the serious problem of high cost and social and cultural acceptance.

The purpose of this talk is to describe a cooker which has the potential of being very inexpensive and thus overcoming one of the problems which has worked against the widespread use of solar cookers in developing countries.

The talk will describe a recent effort to demonstrate the construction of the Georgia Tech spiral cooker in Bamako, Mali, in West Africa.

Construction and Demonstration of the Spiral Cooker in Mali

Mali is west of Upper Volta, and is one of the poorest countries in Africa. Much of Mali is on the border of the Sahara Desert and deforestation and scarcity of wood are serious ecological and human problems. So my job was to take the first step in an effort to see if the spiral cooker might help to relieve these problems.

Although we probably could find the materials for the cooker locally, I shipped all the materials I needed to make the first two concentrators. This included pressed hardboard, aluminum foil, water-soluble glue and spiral patterns.

From the beginning, the local engineers carried out the actual construction with a minimum of assistance. Figure 3 shows Mr. Sidibé, the engineer with whom I worked, applying glue to the hardboard. One of the reasons we picked a water-soluble glue is the fact that it can be made from milk. Powdered milk is widely used in West Africa as evidenced by the can in the background. In addition to milk, the ingredients of milk glue are water, vinegar and sodium bicarbonate. Therefore, they can readily make that kind of glue from materials on hand.

In this figure the commercial glue has been diluted about 50-50 with water, and he's just squirting it on a piece of hardboard and then spreading it with a paint brush. In Figure 4, Mr. Sidibé is applying the aluminum foil and rubbing it down with a paper towel. The hardboard (4 x 4 feet) is covered by applying three strips of 18-inch wide foil. After the third strip is down, the same glue is used to coat the aluminum foil so that the spiral pattern can be applied (Figure 5). After the pattern has dried the holes for mounting the spiral are drilled. Figure 6 shows these holes being made using a simple hand-powered drill. Naturally we want to do everything without power since ultimately it should be possible to make these cookers completely in the village setting. In this figure he's using a Yankee drill with an eighth-inch bit to drill the mounting holes, which can be seen to form a curve as previously described.

After the holes are drilled, the spiral pattern is cut out using a keyhole saw as shown in Figure 7. It's interesting to note that in Mali, although much of their lumber is sawn by hand they don't saw in the same way we do; they always saw away from themselves. Therefore, in Figure 7 Mr. Sidibé is learning to saw in a way that is not familiar to him. But he was very quick to pick up on this and did a very nice job of it. After the spiral is cut, the pattern is removed by wetting it with water and peeling it off. After the pattern is removed the surface of the aluminum foil is cleaned with water and then the cut spiral is placed on the cross members as shown in Figure 8. The next step is to begin coiling and tying the spiral to the cross frame as shown in Figure 9. In this case Mr. Sidibé is using plastic-coated steel wire. In this figure you can see the twist in the surface beginning to take shape. This is a natural twist that results from the coiling. Every element of the reflective surface assumes the right angle naturally when placed on a flat surface.

As pointed out previously, the focal length depends on how tight the coil is twisted. For the cooker the focal length was selected to be equal to the radius. For a short focal length some blockage is to be expected. For this case it was about 13 percent. For a focal length equal to the diameter, it drops to about 5 percent. Figure 10 shows the completed spiral concentrator.

The next step is to make a frame to support the concentrator. For the cooker application I went back to the design in Upper Volta. This design is significant because it illustrates what we can learn from the people who are going to use a cooker. It should be remembered that solar cookers have been studied and attempts have been made to introduce them in developing countries for over a hundred years, essentially without success. I believe this is at least in part due to the fact that solar cookers are designed by engineers or technical people with little or no interaction with the user.

Typically, a point-focusing solar cooker sits on a frame that looks like the one in Figure 11. The support arms for the concentrator are equal to the focal length, so that the concentrator can rotate up and down around the focal point which, of course, is what you want. The support arms are usually attached to the upper ends of a "U" frame that pivots around an axis at the center of the bottom of the "U" to follow the sun's East-West motion. To support the food, a platform is connected across the top ends of the "U" frame. Unfortunately, in this design the food is located in a very unstable position and is easily upset if the concentrator or frame is suddenly shaken. However, if the cooker is to be able to follow the east-west motion of the sun, some method of rotation must be provided and the pivoting "U" frame has been a typical design.

In the Upper Volta case, the technicion working with the women didn't know that the cooker had to be rotated, so they made a rigid frame. Referring to Figure 2, it can be seen that the support arms for the concentrator are equal to the focal length. However, the vertical supports continue beyond the focal length and are connected by a bar at the top. By designing the support frame this way, they could support the food by hanging it on the crossbar. Hanging the food provides much more stability than placing it on top of a rotating frame. But the other advantage is in tracking the sun. The vertical motion is followed by the tilt of the concentrator on the two support arms. However, as the sun moves east-west, the food is moved on the crossbar to follow the reflected image of the sun rather than turning the entire cooker. Thus, by involving the local women in the design of the solar cooker, a much more practical, simple, and easy-to-use system was developed.

Because of the stability provided by this design, it is capable of cooking dishes that require vigorous stirring. In Figure 12 a stiff bread-type food is being prepared that requies a good bit of energy to stir it. Also, if she wishes, she can easily move it over to the side to do the stirring. Although Danchurchaid intended for the aluminum concentrator to be used as it was, it was necessary to use an aluminized plastic over the aluminum surface to provide adequate power. This was done by the women, illustrating their capability in handling materials and how easily they can become involved in the construction of simple devices. The Danchurchaid program also illustrates the ability of the village women to adapt the solar cooker to the preparation of their local dishes. Figure 2 shows a woman broiling a chicken, which was as good as I've eaten anywhere.

With this background the decision was made to build a support for the spiral concentrator in Mali based on the one developed in Upper Volta. Only in this case we used locally available material, which turned out to be mahogany. We felt that wood would be sturdy enough, since the spiral concentrator is much lighter than the aluminum dish. Again, the support arms for the concentrator were cut equal to the focal length. Figure 13 shows two of the spiral concentrator solar cookers being demonstrated on the wooden model of the Danchurchaid support frame.

Two different reflective surfaces were used on this program and are shown in Figure 13. The one on the right is an acrylic coated aluminized polyester film. It was supplied with a water-activated adhesive which was used to bond it to the hardboard. The reflectivity of the film is 85 percent and the specularity is over 90 percent. The other one is covered with aluminum foil.

The performance of these cookers was determined by using the concentrated solar energy to heat water in the locally available cast aluminum pots. To improve solar absorptivity the pots were placed over an open fire for about 30 minutes. Although better than the freshly cast aluminum surface, it was not as black as would be desired. However, with a little experimentation it should be possible to develop a good black coating using locally available materials.

Figure 13 shows Mr. Sidibé with the spiral concentrator being used to heat the aluminum pots filled with water. He used a stick to support the back of the concentrator at the proper position. The concentrator is refocused and/or the pot moved along the support rod at about 15 minute intervals.

To give an idea of the temperature that can be provided by this concentrator, Figure 14 shows a piece of wood being set on fire. The man on the right is the SERI engineer in charge of the AID solar program.

Summary

To summarize: the Georgia Tech spiral concentrator can be designed with a concentration ratio from about 50 to as much as 2000. The one shown in Figure 1 had a ratio of 500. The focal length can be selected from equal to the radius to about five times the diameter.

A wide range of power levels is possible, depending on size. Low-cost materials can be used and the fabrication method is simple. The resulting structure is light weight and because of the open structure, wind loads are likewise low. For high-power applications the question remains as to whether to build one large concentrator or several small ones. One possible idea is to borrow a solar cooker design developed by Professor Tabor in Israel. His design used several parabolic concentrators on a single frame, all aimed at a common focal point. Figure 15 shows how 18 of the 1.2-m (4 ft) diameter spiral concentrators might be used to provide the power available from a 5 meter parabolic dish. Such a system might be used to generate steam and drive a steam engine to give about 2-kW mechanical power for much needed water pumping in a developing country. The system could be supported on an equatorial mount and sun-tracked with a simple clock mechanism.

Are there any questions?

Silverstein - The concept is an intriguing one. My question relates to the safety of the device. What happens if some kid comes along and sticks his hand in the focal point, etc.

Walton - That's interesting. Getting burned is a problem of everyday life in those countries. They have fires, hot pots, etc., and the children just learn to live with them. However, the women often gave this potential problem as a reason for not using the cookers.

As you probably know, there's a long list of reasons why cookers won't work in developing countries, and most of them are our concept of why they wouldn't work--things we wouldn't want to do. Fear of being burned is high on the list.

When I first went to Upper Volta, I was a bit shocked to see the women tilt the concentrator back and forth and put their hands in the focal zone to find the hottest spot, then put the pot there. This doesn't seem too odd when you learn that these women handle pots right off the fire with their bare hands; they don't use potholders as we do. The psychology is entirely different.

In addition to the problem of getting burned, another problem often mentioned is that cooking is not done in the middle of the day. That is true in some places, although in most of the cities and larger towns they do cook in the middle of the day because they are following Western habits. Also, those people have to pay for wood, and it may be that solar cookers should be introduced in the towns and cities rather than in the villages. If the people start using them in the towns, it will get to the village.

Cherne - J. D., it seems to me that the materials of construction would add up to more than the $5 limit you set.

Walton - I paid retail prices for the hardboard, the aluminum foil, the glue, and the sticks. These came to just about $5. I located 3 mm plywood in Mali at a cost of about $10 for a 4 x 8' sheet, so there went my $5 for one 4 x 4' sheet. But again, that was buying through a merchant in Bamako. There, aluminum foil would be a little more expensive than what I paid. I bought the 100-ft^2 roll for about 2.5¢ per ft^2. So that's not expensive. They can make the glue, so the cost is not really far from $5.

If a person is spending $15 a month for wood and he realizes that he can save at least half of that the first month, he might be willing to put up $5. If not, I think the government would. I heard it said that if the government were convinced that people would use the cookers, it would buy them. There would be no need to worry about the people having to purchase them.

Holmes - How long will the cooker last under the weather conditions?

Walton - While I was there, the wind blew quite a lot, but I did not get the feeling that dust or sand was a problem. Concerning water or rain, at Tech we accidentally left one of the cookers out over the weekend when we had a 3-inch rain. This was aluminum foil glued on untempered pressed hardboard, and on Monday morning it looked like a disaster. It was just sort of hanging, but by the time it dried out we couldn't tell any difference. The milk glue didn't come loose. I'm not suggesting that getting it wet is the thing to do. The concentrator is so light that I think people would pick it up and put it under a tree or take it inside the house. At this time I'm not sure if lifetime is a problem. Also, I don't know whether aluminum foil would be used in the final design.

These questions are not even beginning to be resolved yet. This was simply a demonstration to show that a point-focusing solar cooker could be constructed in a very primitive situation by the local villager, and I am satisfied that they can do a lot better job than I can.

Silverstein - What was the construction time?

Walton - Maybe four hours for the concentrator; the stand was another two hours. With practice and experience, I would think a good craftsman could build two a day.

Cherne - How did they develop the spiral?

Walton - They didn't; I did. I took the spiral pattern with me. I think if someone were to make a hundred or so cookers we would provide them a dowel and string and let them draw their own patterns. We would then give them the template to locate these mounting points. They'd just take that and locate them on the spiral. They could make as many as they want. I don't think we'd go through the trouble of printing patterns and sending them over there.

1. High Concentration Ratio Georgia Tech Spiral Concentrator
2. Solar Cooker Used in Danchurchaid Program in Upper Volta
3. Applying Glue Used to Bond Reflective Film to Hardboard
4. Bonding Aluminum Foil to Hardboard
5. Applying Pattern to Aluminum Foil Surface
6. Drilling Mounting Holes
7. Sawing Spiral Pattern
8. Placing Cut Spiral on Support Cross Members
9. Tying Spiral onto Cross Members
10. Completed Spiral Concentrator
11. Typical Point Focusing Solar Cooker
12. Danchurchaid Cooker Used to Cook Food in Hanging Pot
13. Two Models of the Spiral Solar Cooker Being Used to Heat Water in Cast Aluminum Pots
14. The Spiral Concentrator Igniting Wood at the Focal Point
15. Conceptual Arrangement of Multiple Spiral Concentrators to Act as a Single Large Concentrator

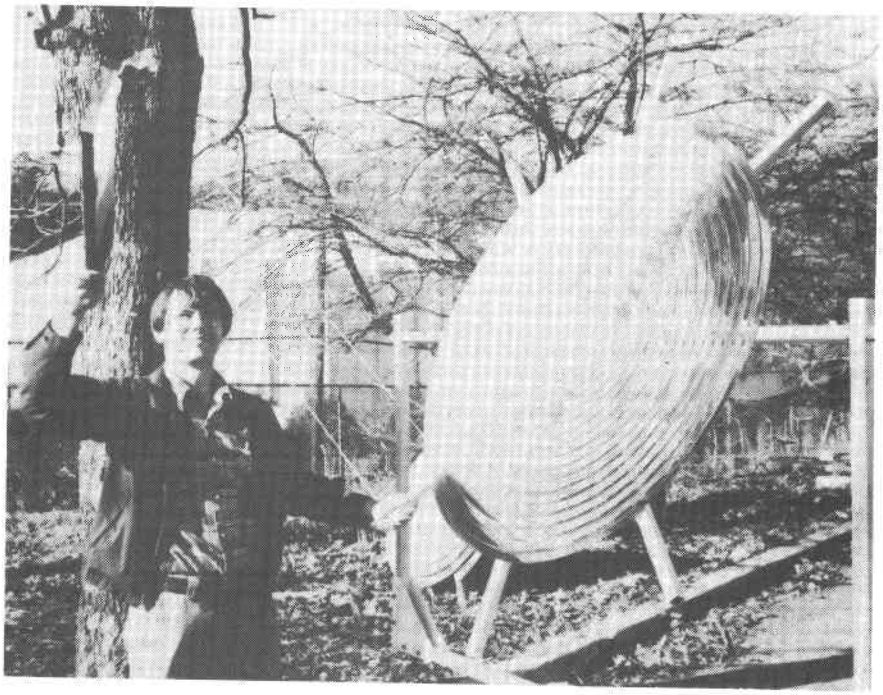

Figure 1. High Concentration Ratio Georgia Tech Spiral Concentrator

Figure 2. Solar Cooker Used in Danchurchaid Program in Upper Volta

Figure 3. Applying Glue Used to Bond Reflective Film to Hardboard

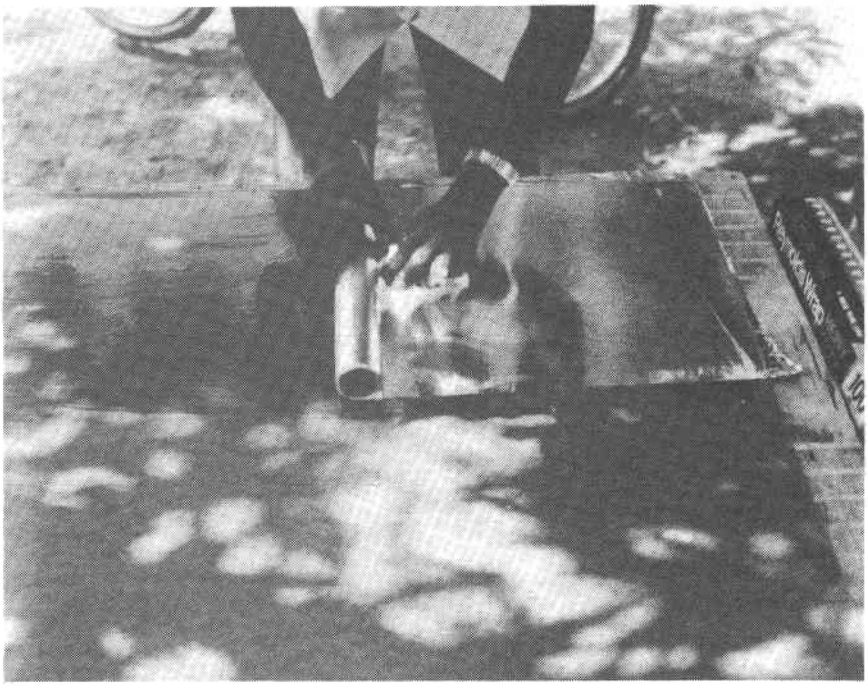

Figure 4. Bonding Aluminum Foil to Hardboard

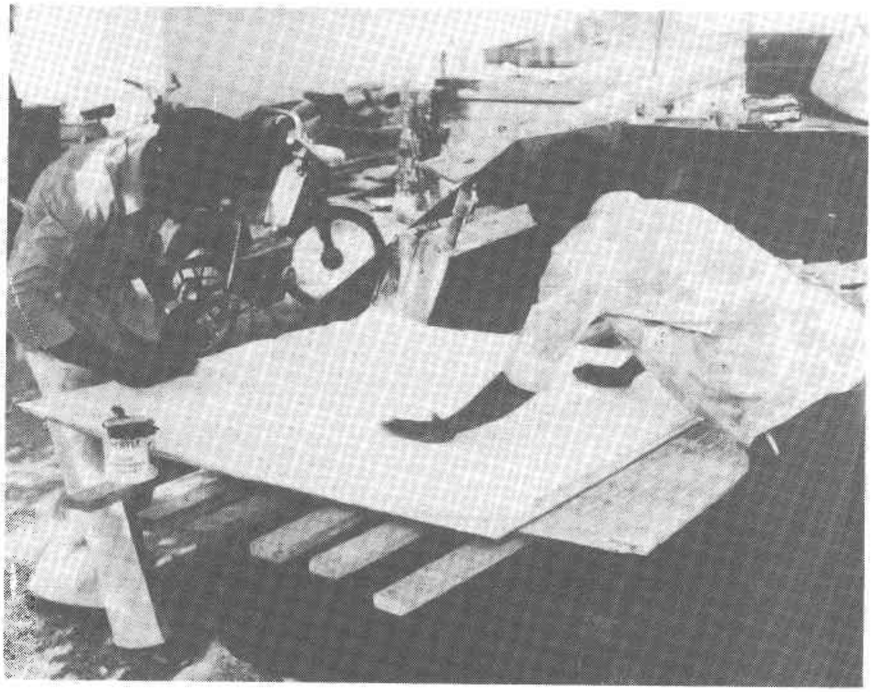

Figure 5. Applying Pattern to Aluminum Foil Surface

Figure 6. Drilling Mounting Holes

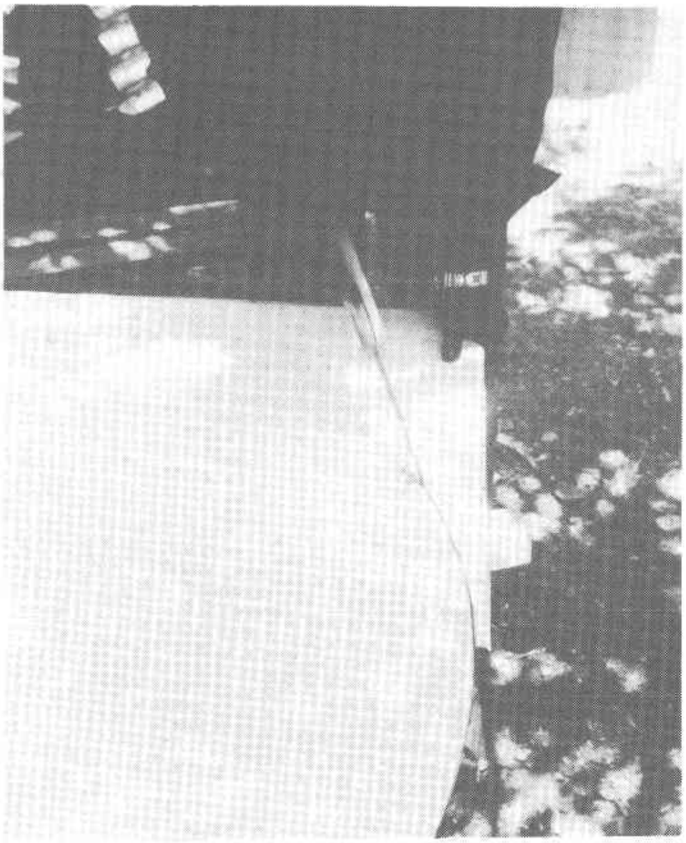

Figure 7. Sawing Spiral Pattern

Figure 8. Placing Cut Spiral on Support Cross Members

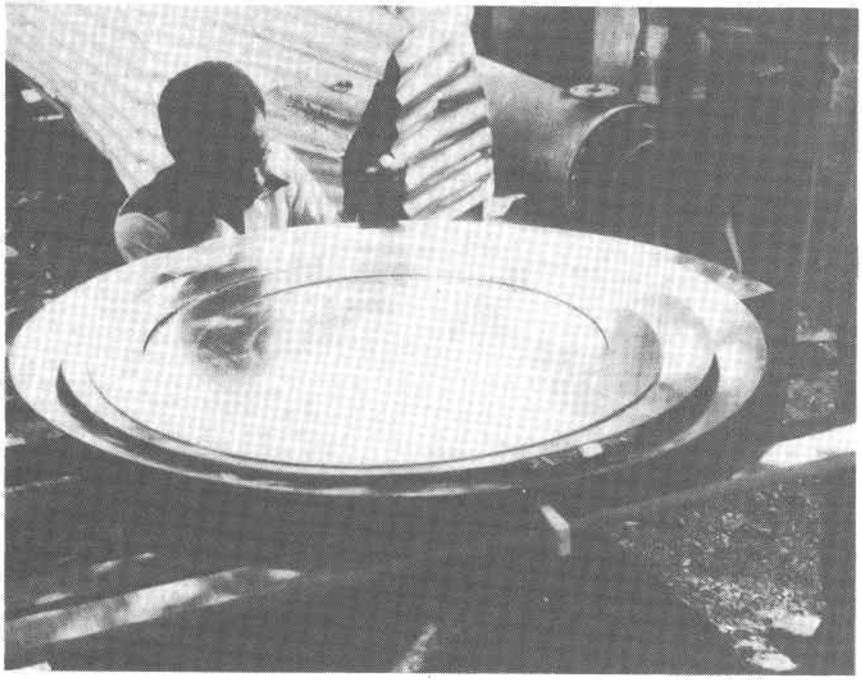

Figure 9. Tying Spiral onto Cross Members

Figure 10. Completed Spiral Concentrator

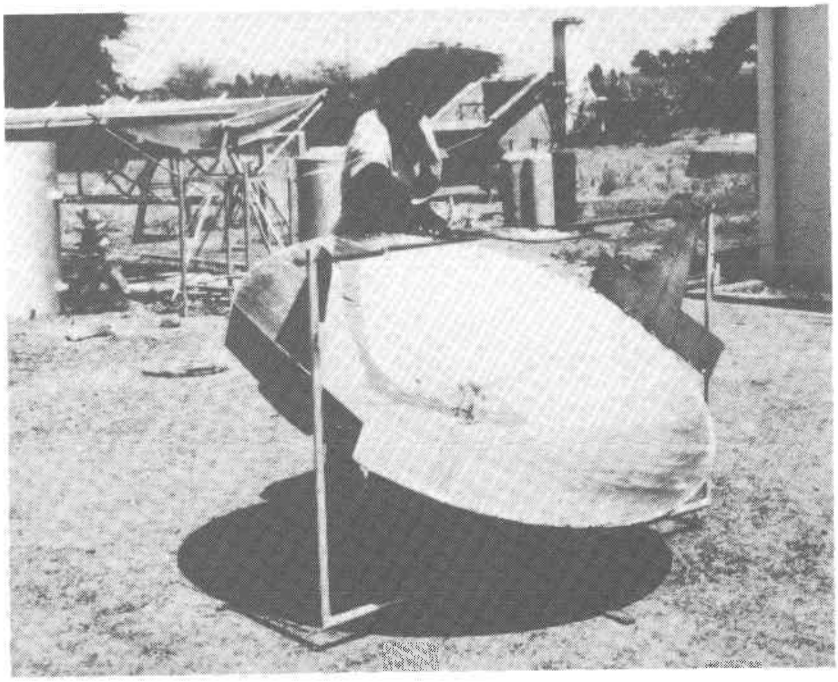

Figure 11. Typical Point Focusing Solar Cooker

Figure 12. Danchurchaid Cooker Used to Cook Food in Hanging Pot

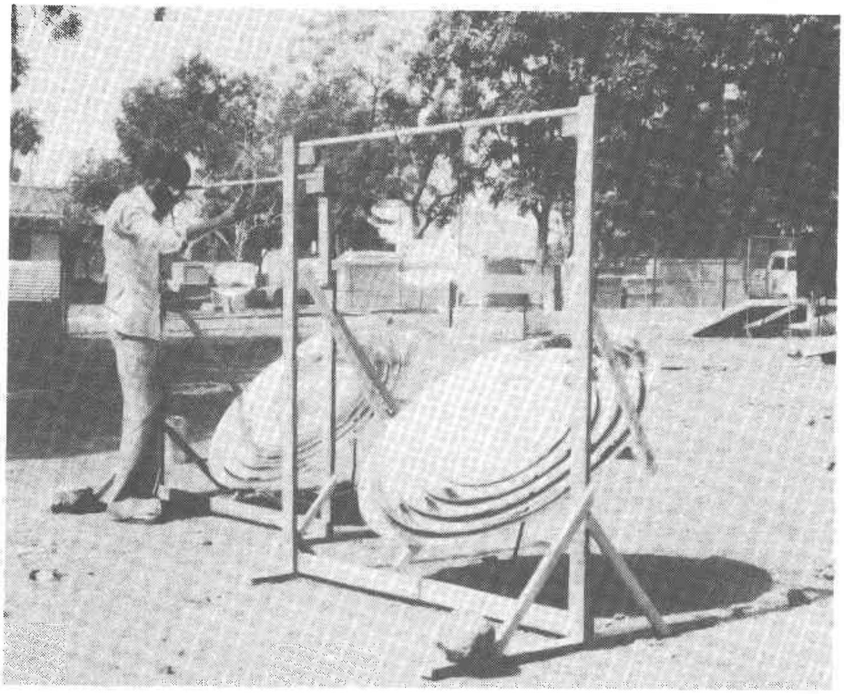

Figure 13. Two Models of the Spiral Solar Cooker Being Used to Heat Water in Cast Aluminum Pots

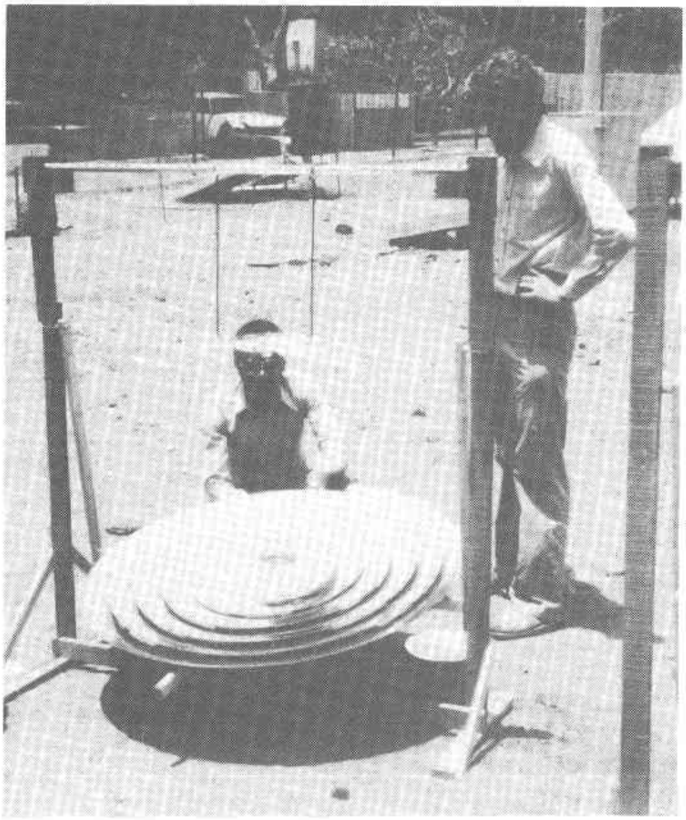

Figure 14. The Spiral Concentrator Igniting Wood at the Focal Point

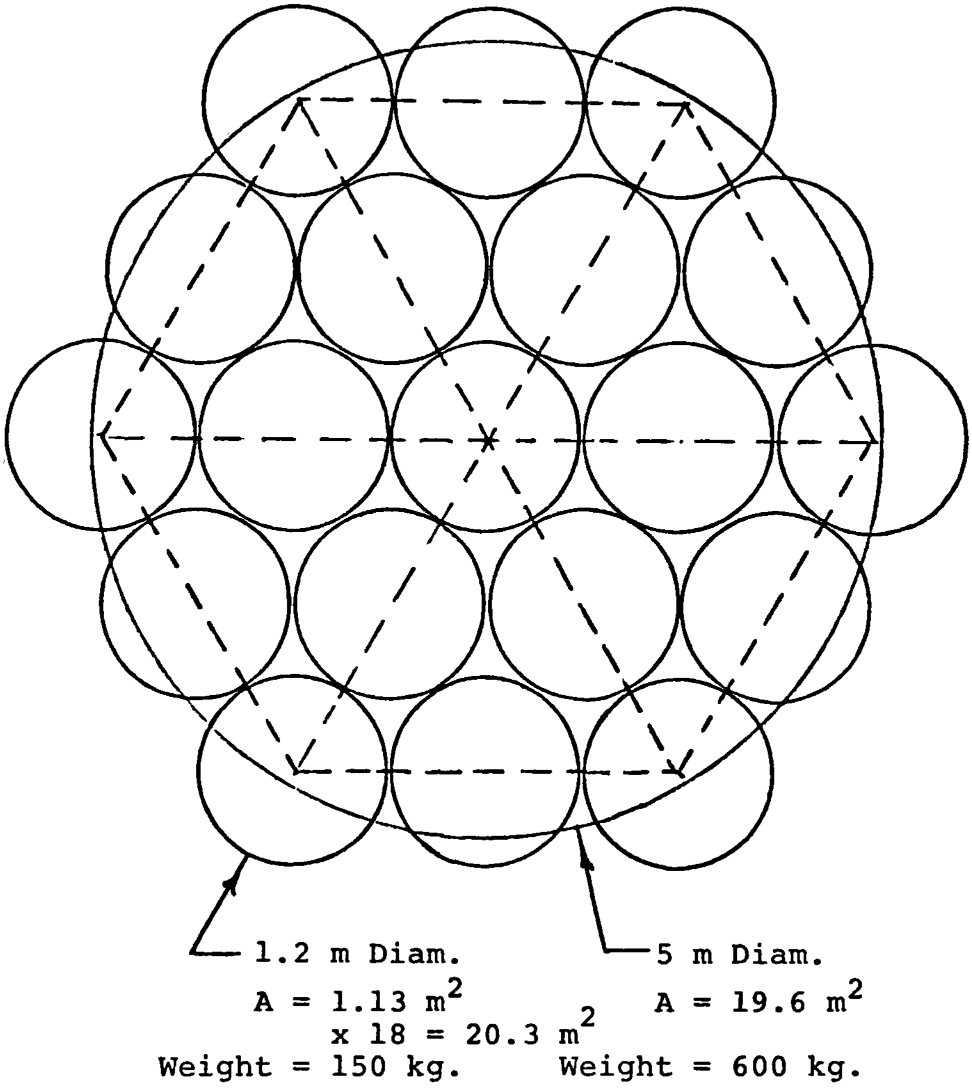

Figure 15. Conceptual Arrangement of Multiple Spiral Concentrators to Act as a Single Large Concentrator.

SOLAR THERMAL FUELS AND CHEMICALS: WHERE DO WE STAND?

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ABSTRACT

The United States has pursued one of the most comprehensive solar energy development programs in the world. Yet, until about four years ago, the concept of solar thermal fuels and chemicals, let alone any significant development effort in this area, was virtually unknown. In the relatively brief span of time which has elapsed since then, solar thermal fuels and chemicals has moved from a "nonentity" in Department of Energy solar thermal planning to a position of major research emphasis in the proposed Solar Thermal Energy Systems Multiyear Program Plan for 1981.

This paper traces the historical factors which have led to the current position of prominence held by solar thermal fuels and chemicals. It explores the rationale for concluding that solar thermal fuels and chemicals production may prove to be one of the most significant applications for solar thermal energy. The current status of solar thermal fuels and chemicals is reviewed, and suggestions are offered for future program needs and priorities. The central role of hydrogen is emphasized, along with the continuing need to devise new hydrogen production concepts.

INTRODUCTION

The drastic reductions which have been proposed for the solar thermal budget are consistent with the plans of the new administration to achieve major "across the board" cuts in the rate of government spending. The opportunity now exists to fashion a leaner, more productive solar thermal program which is more responsible to the current reality and future needs of our energy situation.

The current reality is that there is no way to significantly impact our dependence on imported oil over the next decade other than through the increased production of domestic energy resources for which commercial utilization technologies are already available. At the same time, the introduction of more efficient energy utilization devices will help to lower the energy consumption rate below what would otherwise have been the case.

In the decades beyond the 1980s, we must look to our renewable energy sources, such as solar thermal energy, to help mitigate, and hopefully eliminate, our dependence on imported oil. Before technologies based on renewable energy sources can be widely deployed, they must first be developed and shown to be a practical and preferable alternative to other energy technology options.

Until about four years ago, the only "officially" recognized applications for solar thermal energy were electricity generation, process heat, or combinations thereof in total energy or cogeneration systems. The concept that elevated-temperature heat from solar thermal concentrating systems could facilitate endothermic chemical reactions was simply not recognized as a legitimate application of solar thermal energy.

This situation was a consequence of the recommendations of the Solar Energy Panel, jointly convened by the National Science Foundation and NASA in 1972 to assess solar energy as a national resource. The panel concluded that viable solar energy systems could be devised for the following applications: heating and cooling of buildings; biomass production and conversion to fuels; and electricity generation via solar thermal, photovoltaics, wind, and ocean thermal energy conversion. The panel's recommendations set the pattern for a national solar energy program which was to be initiated by NSF, transferred to ERDA upon its formation, and then to ERDA's successor, DOE.

The absence of a solar thermal fuels and chemicals application in the panel's recommendations was an oversight which was not corrected until 1977, when DOE Solar initiated support for process development of the Sulfur Cycle hybrid thermochemical process for the production of hydrogen. This milestone was the culmination of a growing realization over the prior three years by officials of both industry and government that fuels and chemicals production could be one of the most significant applications of solar thermal energy.

THE CASE FOR SOLAR THERMAL FUELS AND CHEMICALS

The dependence of the nation's transportation network on imported oil had become painfully apparent during the 1973-74 OPEC oil embargo. Similarly, the natural gas crunch of 1976-77 brought home the realization that our domestic natural gas was no longer the highly reliable, limitless energy source it had once seemed.

Solar thermal was then seen increasingly as having the potential not only to supplement our nonrenewable fuels for electricity and process heat, but also to address the nation's most critical problem--the need to reduce our dependence on imported oil--by the production of fuels and chemicals. At the same time, it was recognized that conversion of solar energy to chemical form represented a convenient solution to one of the principal deterrents to the widespread use of solar energy--the difficulty of fully matching solar energy availability to user demand.

By converting solar energy to readily storable and transportable chemical form, the utility and attractiveness of solar energy as an energy resource is increased tremendously. Unlike thermal storage, which is of limited duration and is generally utilized at or near the solar plant site, the storage of solar energy in chemical form transforms solar energy into an article of commerce. Solar energy then becomes a commodity which can be bought and sold, readily transported, and used at a time and place quite remote from the time and place of initial collection.

The ultimate consumer of solar energy is then no longer restricted to regions of optimum solar insolation, does not have to lay out large front-end costs for a solar thermal energy system, is not required to have space available to accommodate the solar collector field, does not have to be concerned with the impact of clouds and the diurnal cycle on availability of his energy supply, is not required to maintain a backup energy supply capability, and can continue to use his existing fuel utilization system. These quite legitimate concerns associated with use of the solar energy resource would then lie in the exclusive province of the producer of solar thermal fuels and chemicals.

Since 1977, reflecting the growing realization of its significance, interest in solar thermal fuels and chemicals has mushrooomed. Additional studies and evaluations have been carried out by JPL, IGT, ORNL, and the Aerospace Corporation. DOE support has been given to Westinghouse and General Atomic for the development of competitive thermochemical hydrogen production processes. Experimental studies verifying the feasibility of gasifying coal with direct solar thermal energy have been carried out by Lawrence Livermore Laboratory and Los Alamos Scientific Laboratory. A recent workshop of the STTF Users Association was devoted exclusively to solar fuels. For the first time, solar fuels and chemicals appeared as a distinct element in the 1979 DOE Solar Thermal Program Multiyear Plan. In the proposed 1981 version of the Plan, solar thermal fuels and chemicals is given major research emphasis.

SOLAR THERMAL ENERGY AND SYNFUELS

While solar thermal energy may in theory be substituted for any other thermal energy source in chemical processes, those processes should be emphasized with the potential for significantly reducing the nation's dependence on imported oil, and for alleviating the effects of domestic oil and natural gas supply interruptions. Other processes for which the introduction of solar thermal energy results in unique advantages such as increased yields, higher purity, or reduced environmental contamination also warrant support and development.

Solar thermal energy has the potential to contribute in a major way to the national goal of energy independence by being employed in processes for the production of liquid or gaseous synthetic fuels. The solar thermal energy would be used to supply the sensible heat and heat of reaction for the conversion of coal-water mixtures to liquid or gaseous hydrocarbons, hydrogen for direct hydrogenation of coal to synfuels, or both. Solar thermal energy could also be used to supply the needed carbon via thermochemical carbon dioxide decomposition reactions. Solar-produced hydrogen is also a viable candidate to provide the fuel requirements ments of fuel cell electricity generators, as well as other applications for hydrogen fuel, as they reach commercial feasibility.

The benefits of using solar thermal energy in synfuels production in terms of product yield and carbon dioxide emissions can be substantial. For the case of synthetic natural gas production from char (the carbon constituent of coal), the use of solar thermal energy for both thermal energy and hydrogen requirements can triple the yield and reduce carbon dioxide emissions from 5.5 lb per lb of product to zero.

The key to optimizing the effectiveness of solar thermal energy for synfuels production, as well as for the production of important chemicals such as ammonia, is the availability of a hydrogen production process which does not require a fossil fuel feedstock. Possibilities which have been identified include the direct thermal decomposition of water, thermochemical water decomposition processes, hybrid processes utilizing both electrochemical and thermochemical steps, and ion exchange techniques. At the present time, maximum interest is being shown in the Sulfur-Iodine thermochemical process under development by the General Atomic Company, and in the Sulfur Cycle hybrid process under development by Westinghouse Electric Corporation.

The technical feasibility of providing the heat of reaction needed to gasify coal-water mixtures with solar thermal energy has been demonstrated by Lawrence Livermore Laboratory. The low or medium Btu gas thus produced has utility both as a fuel and as a feedstock for liquid or gaseous synthetic fuel. The Livermore work has also laid the groundwork for tests to demonstrate the feasibility of using solar thermal energy for the direct hydrogenation of coal to produce liquid or gaseous synfuels.

AUGMENTING DOMESTIC OIL PRODUCTION WITH SOLAR THERMAL ENERGY

Solar thermal energy can also be used to augment the production of domestic oil, thereby reducing the need to import oil, by supplying the steam needed for the recovery of viscous heavy oil and for the retorting of shale oil. Since as much as one barrel of oil out of three barrels recovered may be consumed to generate the steam used for recovery, the alternate use of solar-generated steam can increase yields by as much as 50 percent. These applications are attractive because the recovery processes are already in the advanced demonstration or commercial stages, and because the energy in the recovered oil is several times greater than the solar thermal energy expended for recovery.

PROCESS EVALUATION CRITERIA

In pursuing the development of solar thermal fuels and chemicals processes, criteria for judging the merit of a particular process are urgently needed. Process efficiency is the criterion most frequently cited as a measure of process attractiveness. While high process efficiency is certainly beneficial from the standpoint of reducing total energy needs and hence solar plant costs, these benefits can be offset by higher process plant costs if the high efficiency is the result of recovering a very high percentage of process waste heat. (The heat transfer surface area required for recovery of 95 percent of the theoretical maximum waste heat recovery is almost five times that required for 80 percent recovery.) Thus, the percentage of possible waste heat recovery and the associated heat transfer surface area should also be considered as important process evaluation criteria.

In the design and development stage of a project, the accurate estimation of capital and product costs is extremely difficult and may easily be uncertain by a factor of several. Yet, there is a need to characterize the relative cost of a particular process compared to other competing processes before a major commitment of development funds is incurred. One suggested measure for providing some light on expected process plant cost is the ratio of the process plant heat transfer area to the solar collector surface area. By applying suitable cost factors per unit area for the solar and process plants, an indication of the cost of the process plant relative to the solar plant may be obtained. By parametrically varying the percentage of waste heat recovery, this approach may also be useful in identifying an optimum recovery percentage for minimum total plant cost.

When calculating values of the above criteria for use in process evaluation, the influence of basic process parameters must always be considered. It cannot be sufficient to calculate process efficiency solely on the basis of projected values of process parameters. The process efficiency must also be determined for values of the process parameters which have actually been measured in the laboratory. Only then can a reasonable determination be made of process development status in relation to projected goals. It must also be emphasized that process parameter goals must be theoretically achievable, and not adopted simply on the basis of commercial feasibility requirements.

PLANT INTEGRATION CONSIDERATIONS

Overall process plant economics will be influenced by the manner in which the process in question is integrated with the solar heat source, as well as by process characteristics. Considerations relevant to process plant integration will now be presented.

Decoupling from Solar Energy Cycle

Process plant costs will be reduced to the extent that individual process steps can be carried out continuously on a 24-hour/day basis, rather than in accordance with the solar diurnal cycle. By operating on a 24-hour basis for a given daily output, process equipment need only have a capacity between 1/3 and 1/4 what would be required for operation on the solar diurnal cycle, with a corresponding reduction in cost. While extended operation can be accomplished with thermal storage, substantially greater economics should be possible by provision for storage of the intermediate chemicals involved in the process.

Isothermal Reactions

The efficiency and economics of chemical reactions will generally be favored if the reactions proceed isothermally at the maximum allowable reaction temperature. Isothermal reaction conditions will usually be difficult to achieve when sensible heat is transferred to the reactants in conventional heat exchangers. These conditions may be approached more readily through matching of the heat addition rate to the heat absorption rate by direct absorption of incident solar radiation, or by the use of heat transfer techniques which are inherently isothermal. These include latent heat transport systems, such as heat pipes, and systems which achieve near isothermality through internal circulation, such as fluidized beds.

Segmented Solar Thermal Sources

If process temperature requirements cover a wide range, there may be economic advantages to segmenting the total solar thermal energy requirement into several distinct sources, each with a temperature capability tailored to the need of specific process steps. For example, if only a small fraction of total process heat is to be delivered at the maximum process temperature, a separate solar collector field and high temperature receiver may prove to be an advantageous solution. Similarly, if a large fraction of the total heat requirement is needed to concentrate a reactant at low temperature, a separate field of flat-plate or single-axis parabolic collectors could represent the most cost-effective approach.

Hybrid Operation

Processes which operate in a hybrid mode utilize solar energy during the day and fossil fuel at night. In such an operational mode, plant components are sized on the basis of continuous, 24 hr/day production. The solar plant is then 1/3 to 1/4 the size and cost of a plant where solar energy is the only energy source. While the fossil fuel savings with a hybrid plant are much less than for a solar-only plant, the cost benefits should be substantial. There may also be situations where fossil needs of specific process steps, or to provide the electric and pumping power requirements of the process.

FUTURE PROGRAM NEEDS AND PRIORITIES

The most important immediate need of the solar thermal fuels and chemicals program is the development of useful criteria for the evaluation, selection, and support of competitive processes. These criteria should be applied to the re-evaluation of processes currently under development. The development of alternative processes with good prospects for lower cost and greater process simplicity should also be encouraged.

In any process selected for development, early emphasis should be placed on identifying key problem areas and achievable process potential. Criteria should be available for measuring developmental progress in these key problem areas. The validity of experimental data should be confirmed through repeated testing. Measures of process performance such as efficiency should be calculated on the basis of measured data as well as achievable process parameter goals. Such calculations should be updated continuously to reflect the latest available data.

The development of nonfossil hydrogen production processes should be an important element of any solar thermal fuels and chemicals program because hydrogen is an essential constituent of modern fuels and chemicals technology. In particular, solar-produced hydrogen along with solar thermal heat can be integrated with synfuels production from coal to achieve substantial increases in product yields simultaneously with major reductions in carbon dioxide emissions. The role of hydrogen as a chemical feedstock rather than an end product should be recognized and emphasized in program development plans.

Program emphasis at all times should be on minimizing end product cost. However, it should also be recognized that the rationale for the solar thermal fuels and chemicals program is not its capability to compete economically with other methods for the production of fuels and chemicals. Rather, the rationale is to insure the continued availability of essential products whose production would otherwise be curtailed by foreign or domestic disruptions in the supply of petroleum and natural gas.

The commercialization of solar thermal fuels and chemicals may well be more dependent on the national perception of its contribution to the goal of energy independence than on product cost. If the production of solar fuels and chemicals is determined to be in the national interest, then government subsidies, tax credits, etc., can be anticipated to reduce or eliminate noncompetitive price differentials to the consumer.

Lab-Scale Solar Furnaces for Future Development of High-Temperature Solar Energy Chemical Processes

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This paper was unavailable for publication. For further information, please contact the author

PLANT DESIGN AND ECONOMIC ANALYSIS FOR SOLAR COAL GASIFICATION

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ABSTRACT

The advantage of the solar coal gasification (SCG) method, compared to a similar Lurgi plant, is conservation of coal; 40% more product can be produced from a given amount of coal. The primary detriment of SCG is an 8 hr/day operation; which leads to a higher plant investment for a given annual production. This higher plant investment is twice as important as the cost of the heliostat field. Providing excess heliostat capacity to maximize the output of the processing units probably is economically justified.

Operating costs are lower for SCG, but capital costs are higher. In the future, as coal costs increase relative to investment costs, the SCG plant will become more economical than the Lurgi plant.

INTRODUCTION

Production of fuels using solar thermal energy can conserve our resources of fossil fuels in a number of ways. For example, fuel energy can simply be replaced by solar energy to produce process heat. In steam-flooding an oil field about one quarter of the oil is burned to raise the steam. Solar energy can substitute for this oil. In some other processes, use of solar energy can be even more advantageous because of its unique properties. Very high heating rates can be attained and the energy is delivered without adding anything else to the process stream. These properties can result in higher process efficiency.

We are currently engaged in developing two concepts that use focused solar energy to produce fuels from fossil energy resources: Solar Coal Gasification (SCG) and Solar Oil Shale Retorting (SOSR). A preliminary analysis of SCG was made,[1] a field experiment was performed,[2] and a simple model for the gasification process was discussed.[3] Our Solar Oil Shale Retorting investigations have also been reported.[4,5]

The purpose of the present paper is to present a possible plant design for SCG and an economic analysis of that design. The plant has a straightforward, simple design: solar energy is focused directly on reacting coal char with no intervening heat transfer stages and the plant operates only when the solar energy is available with no storage schemes considered.

Analysis of a simple configuration is a good starting point because the concept's strengths and weaknesses are revealed. Alternative configurations

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may alleviate weaknesses in SCG without compromising its strengths. Various other concepts are being considered: (1) Indirect gasification using a heat transfer fluid. This allows the gasification reactor to be on the ground separate from the solar reheat furnace. (2) Hybrid gasification using solar energy when available and coal combustion energy at other times. (3) Syn gas storage so that the down-stream processing units can continue to operate through the night. (4) Solar energy storage so that the entire processing plant can continue to operate through the night.

The intended use of this process simulation and economic analysis is to illuminate the differences between solar thermal processing and conventional techniques. The results are sensitive to the assumptions made in the analysis and should be used only for internal comparison purposes. The process flows are reasonably good estimates, but the economic results are not as well founded. Several of the assumed values could be in error by 50% or more. The tables can be used for recalculations with other assumed values, if the reader wishes.

COAL GASIFICATION

Coal gasification involves two basic chemical steps: pyrolysis and char gasification. Coal decomposes when heated in the absence of air:

$$\text{Coal} \longrightarrow \text{Char} + CO + CO_2 + H_2 + CH_4 + \text{tars} \qquad (1)$$

This pyrolysis is essentially complete at temperatures well below char gasification temperatures. Compared to the char gasification reaction relatively little energy is required for the pyrolysis reaction because the decomposition reactions are only slightly endothermic; the energy required for pyrolysis is primarily that which is needed to heat the coal to the pyrolysis temperature.

Gasification of char occurs by endothermic reactions with H_2O or CO_2 that are similar to the following:

$$C + H_2O \longrightarrow H_2 + CO \qquad \Delta H_{1000K} = 135.85 \text{ kJ/mol} \qquad (2)$$

$$C + 2H_2O \longrightarrow 2H_2 + CO_2 \qquad \Delta H_{1000K} = 100.95 \text{ kJ/mol} \qquad (3)$$

$$C + CO_2 \longrightarrow 2CO \qquad \Delta H_{1000K} = 170.75 \text{ kJ/mol} \qquad (4)$$

These reactions proceed at reasonable rates only above about 1000K. In steam gasification, reaction (2) dominates at high temperatures. Reaction (4) is unimportant if H_2O is present. Reaction (3) is the sum of reaction (2) and the slightly exothermic water-gas shift reaction:

$$CO + H_2O \longrightarrow CO_2 + H_2 \qquad \Delta H_{1000K} = -34.90 \text{ kJ/mol} \qquad (5)$$

Graphitic carbon has been used to represent char in these reactions. Char is not a well defined material and its thermochemistry depends on its conditions of formation. Its chemical activity is higher than that of graphite by a moderate but not well known amount. The higher chemical activity reduces the endothermicity of the char reactions slightly.

Energy must be supplied to drive these gasification reactions. The "wet" coal must be heated, dried, and heated further to attain the gasification temperatures at which the heat of reaction must be supplied. The "bound" water, which is very loosely attached, is removed in the drying process. During the second heating phase, pyrolysis occurs by processes that are about neutral thermally. Char gasification with steam probably occurs via Reaction 2 or Reaction 3. There is more than enough available energy in the hot products from char gasification to heat, dry, and pyrolyze the coal if counter-current processing is used.[1,6] Thus, the energy requirement amounts to 101 to 136 kJ per mol of char gasified plus an allowance for high temperature heat loss.

In conventional gasifiers this energy requirement is supplied by burning part of the coal. Air is used to burn the coal in certain applications where all that is required is a combustible gas product. Most applications, however, require a nitrogen free product. This product is used as a chemical reactant to synthesize methane, methanol, gasoline, ammonia, or a wide range of other products including monomers for plastics. For the gasifier to supply a nitrogen-free product, oxygen must be used rather than air.

Solar coal gasification does not use coal combustion to supply the energy, so oxygen is not required and in addition less coal is needed for a given amount of useful product. These two advantages for solar coal gasification have a major impact on the fundamental economics of the process.

A SIMPLE MODEL OF SCG

A simple model of SCG has been used to match the product composition obtained in a field experiment in SCG.[3] Table 1 compares experimental data and the model's results for fixed-bed gasification and also shows the model's results for a moving-bed gasifier. The particular constants used were for subbituminous coal from the Roland seam in the Powder River Basin of Wyoming. The model parameter "x" reflects the relative importance of Reactions 2 & 3. Parameter "F" is the fraction of the char produced in the pyrolysis front that reacts in the char gasification front. For a moving bed gasifier at steady state, F = 1. This model has been built into a process analysis code that is used to analyze the plant design.

A PRELIMINARY PLANT DESIGN

A preliminary plant design study has been made for an SCG plant producing nitrogen-free synthesis gas that is converted into methane for substitute natural gas (SNG). This design study was patterned after a Lurgi gasifier SNG plant that was to have been located near Farmington, New Mexico in the Four Corners area. The Lurgi plant design was part of a legal submission that requested a Certificate of Public Convenience and Necessity from the Federal Power Commission, Docket No. CP73-131, filed October 9, 1973.[7] This plant was designed to produce 288.6 MM SCFD of pipeline gas at 954 Btu/scf.

A reasonably complete set of process flow sheets is available in this submission. The design was developed by Stearns Roger based on technology provided by Lurgi Mineralotechnik GmbH. Lurgi proprietary information was excluded from the submission.

The Stearns-Roger/Lurgi (SRL) design was adapted to incorporate solar coal gasification with several assumptions: The solar coal gasifier performs

Table 1. Solar Coal Gasification Model Results.

Basis: 1 mol of coal feed.	Expt Data	Model Results			
		Fixed Bed		Moving Bed	
Model Parameters:					
F		0.692		1.000	
x		0.518		0.518	
Product Gas:	Mol Frac	mol	Mol Frac	mol	Mol Frac
CO_2	0.205	0.292	0.19	0.406	0.20
CO	0.190	0.271	0.18	0.378	0.18
H_2	0.57	0.881	0.59	1.232	0.59
CH_4	0.0351	0.050	0.033	0.050	0.024
C_3H_7	------	0.013	0.0086	0.013	0.0063
Solids & Liquids:					
Tar ($CH_{1.4}$)		0.128		0.128	
Net Char ($CH_{0.14}$)		0.221		0	
Ash (g/mol)		(0.76)		(1.1)	
Net H_2O		-0.177		-0.504	
Gross H_2O		-0.755		-1.09	
Energetics:*		kJ		kJ	
Char Gasification		59.2		85.5	
Gross Steam		33.2		48.0	
Coal		485		485	
Total of Inputs		577		619	
Product Gas		401		531	
Tar		75.8		75.8	
Net Char		91.5		0	
Total of Products		568		607	
Total Products/Total Inputs		0.98		0.98	
Total Products/Coal		1.17		1.25	
Fraction of Stored Solar Energy in Product Gas		0.15		0.20	

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* Based on heats of combustion (HHV) except for the steam and char gasification entries where the energy required to raise steam or to gasify char was used.

Specie	CO_2	CO	H_2	CH_4	C_3H_7	Tar	Char	Ash	H_2O
HHV, kJ/mol	0	283	286	891	2100	592	414	0	(44)

Char Gasification Energy, kJ/mol of char $= x\ 101 + (1-x)\ 136$

as predicted by the previously discussed model.[3] All required steam is generated in the gasifier water jackets. The non-solar processing units perform as in the SRL design.

Changes in performance due to transient response are not considered in the analysis. Careful design will be necessary to allow for daily startup and shutdown and there would be energy "losses" in heating up the equipment during startup. A much more detailed analysis of the plant would be required to allow for these factors, but they should be kept in mind as debits against the SCG plant.

A code was written that calculates process flows. This code is modular in nature and can be applied to many different plant designs. An example of the output provided for each plant area is shown in Figure 1. A listing of this self-documented code is available on request.

The SCG plant described below was analysed using the code in order to obtain the process flows and economic parameters. An equivalent analysis was made of the SRL plant for comparison.

PLANT LAYOUT

A schematic of the solar coal gasification/SNG plant is shown in Figure 2. The functions of all of the areas of Figure 2 are quite conventional except for areas 33 and 35 which are the Heliostat Field and the Gas Generator.

Coal is crushed, screened, cleaned, and stored in Area 25. This coal is fed into the Gas Generator, exposed to the concentrated solar flux, and gasified in Area 35 which is adjacent to Area 33, the Heliostat Field. Part of the crude gas is fed into the shift converter to increase the hydrogen content. The other portion of the crude gas bypasses the shift converter. The bypass ratio is adjusted so that when the two streams are reblended, the composition will match the requirements of the methane synthesis reactor. Because of the high H_2 content of the SCG syn gas, 88% could be bypassed around the shift converter compared to 55% for the Lurgi.

Liquid organic compounds and NH_3 are removed from the gas in Areas 35, 45, 55, and 65. In addition to removing the last of the liquid organic compounds, Area 65 removes the acid gases, H_2S and CO_2, with a chilled methanol wash. This is the Lurgi Rectisol Process. The cleaned and shifted feed gas enters the methane synthesis reactor. The product of this reactor is compressed, dehydrated, and injected into the Product Pipeline.

By-products are separated from the main stream and processed in peripheral areas. These products have substantial value depending on the marketing circumstances, but in any case the plant must dispose of them. The by-products consist of coal tar, coal oil, naptha, phenols, ammonia, liquid sulfur, carbon dioxide, and the fines separated in the coal preparation areas.

Detailed flow sheets are available for all of these processing units in Reference 8. The performance of each unit, other than the gasifier, is assumed to be similar to those in the SRL design with no adjustments for size. This assumption is reasonable because these plants are composed of multiple units and size variations are accomplished by adding or subtracting units rather than by changing sizes. For example, in the SRL design there are 28 Lurgi gasifier units.

```
Plant Area:      91, Calc Box: SUMRY ,   FILE/ ^SIM,  SOLAR COAL GASIFICATION PLANT (78 COSTS)

Process Stream Name/Number        DRIED PRODUCT             SUMMARY OF                OFF GAS FROM
                                  TO PIPELINE        /25    SEPARATED BYPROD /48      SULFUR RECOVERY  /35     SOLID WASTE         /37
                Mol Wt   HHV      -------------------       --------------------      --------------------     --------------------
                g/mol    kJ/mol   kgmol/s      VOL X        kgmol/s      VOL X        kgmol/s      VOL X       kgmol/s      VOL X
                ------   ------   -------      -----        -------      -----        -------      -----       -------      -----

CO2             44.010      0.    .3049        2.366        0.000        0.000        9.772        36.72       0.000        0.000
CO              28.010    283.    1.784E-04    1.384E-03    0.000        0.000        0.000        0.000       0.000        0.000
H2               2.018    286.    .3862        2.997        0.000        0.000        0.000        0.000       0.000        0.000
CH4             16.042    891.    12.20        94.64        0.000        0.000        0.000        0.000       0.000        0.000
C2H4            28.052   1412.    0.000        0.000        0.000        0.000        0.000        0.000       0.000        0.000

C2H6            30.068   1561.    0.000        0.000        0.000        0.000        0.000        0.000       0.000        0.000
C3+             45.111   2100.    0.000        0.000        0.000        0.000        0.000        0.000       0.000        0.000
H2S             34.082    563.    0.000        0.000        0.000        0.000        0.000        0.000       0.000        0.000
NH3             17.032    383.    0.000        0.000        0.000        0.000        0.000        0.000       0.000        0.000
N2              28.016      0.    0.000        0.000        0.000        0.000        0.000        0.000       0.000        0.000

O2              32.000      0.    0.000        0.000        0.000        0.000        0.000        0.000       0.000        0.000
P12              0.000      0.    0.000        0.000        0.000        0.000        0.000        0.000       0.000        0.000
P13              0.000      0.    0.000        0.000        0.000        0.000        0.000        0.000       0.000        0.000
P14              0.000      0.    0.000        0.000        0.000        0.000        0.000        0.000       0.000        0.000
P15              0.000      0.    0.000        0.000        0.000        0.000        0.000        0.000       0.000        0.000

H20G            18.016      0.    0.000        0.000        0.000        0.000        16.84        63.28       0.000        0.000
Tot Wet Gas      0.000      0.    12.89        0.000        0.000        0.000        26.61        0.000       0.000        0.000
Tot Dry Gas      0.000      0.    12.89        0.000        0.000        0.000        9.772        0.000       0.000        0.000
------------------------------------------------------------------------------------------------------------------------------------
M.Wt.  WG-DG        g/mol         16.28        16.28        0.000        0.000        27.56        44.01       0.000        0.000
HHV    WG-DG        kJ/mol        851.8        851.8        0.000        0.000        0.000        0.000       0.000        0.000
------------------------------------------------------------------------------------------------------------------------------------

                                  kg/s         MJ/s         kg/s         MJ/s         kg/s         MJ/s        kg/s         MJ/s
                ------   ------   -------      -----        -------      -----        -------      -----       -------      -----

Tot Dry Gas      0.000      0.    209.9        1.098E+04    0.000        0.000        430.1        0.000       0.000        0.000
Coal            16.300    485.    0.000        0.000        36.17        1076.        0.000        0.000       0.000        0.000
Char            12.400    414.    0.000        0.000        0.000        0.000        0.000        0.000       0.000        0.000
Ash               .000      0.    0.000        0.000        2.459        0.000        0.000        0.000       50.88        0.000
Tar             13.400    692.    0.000        0.000        5.252        232.0        0.000        0.000       0.000        0.000

Oil             13.400    592.    0.000        0.000        18.82        831.4        0.000        0.000       0.000        0.000
Naphtha         13.400    592.    0.000        0.000        13.57        599.4        0.000        0.000       0.000        0.000
Phenols         94.111   2930.    0.000        0.000        6.127        190.8        0.000        0.000       0.000        0.000
Water-liq.      18.016      0.    0.000        0.000        0.000        0.000        0.000        0.000       0.000        0.000
NH3-Soln..      17.032    383.    0.000        0.000        5.664        127.4        0.000        0.000       0.000        0.000

CO2-Soln..      44.010      0.    0.000        0.000        0.000        0.000        0.000        0.000       0.000        0.000
H2S-Soln..      34.082    563.    0.000        0.000        0.000        0.000        0.000        0.000       0.000        0.000
Sulfur-Liq.     32.066    297.    0.000        0.000        3.171        29.37        0.000        0.000       0.000        0.000
P34               .000      0.    0.000        0.000        0.000        0.000        0.000        0.000       0.000        0.000
P35               .000      0.    0.000        0.000        0.000        0.000        0.000        0.000       0.000        0.000

P36               .000      0.    0.000        0.000        0.000        0.000        0.000        0.000       0.000        0.000
P37               .000      0.    0.000        0.000        0.000        0.000        0.000        0.000       0.000        0.000
Steam           18.016     44.    0.000        0.000        0.000        0.000        0.000        0.000       0.000        0.000
Elect Power      1.000      1.    0.000        0.000        0.000        0.000        0.000        0.000       0.000        0.000
Solar Energ      1.000      1.    0.000        0.000        0.000        0.000        0.000        0.000       0.000        0.000

PARAMS =         0.000  0.000  0.000  0.000  0.000  0.000  0.000          0.000  0.000  0.000
COSTS =        0.000     0.000     0.000     0.000     0.000
```

Figure 1. A Process Flow Sheet Example. A summary of inputs and outputs for the SCG plant is shown.

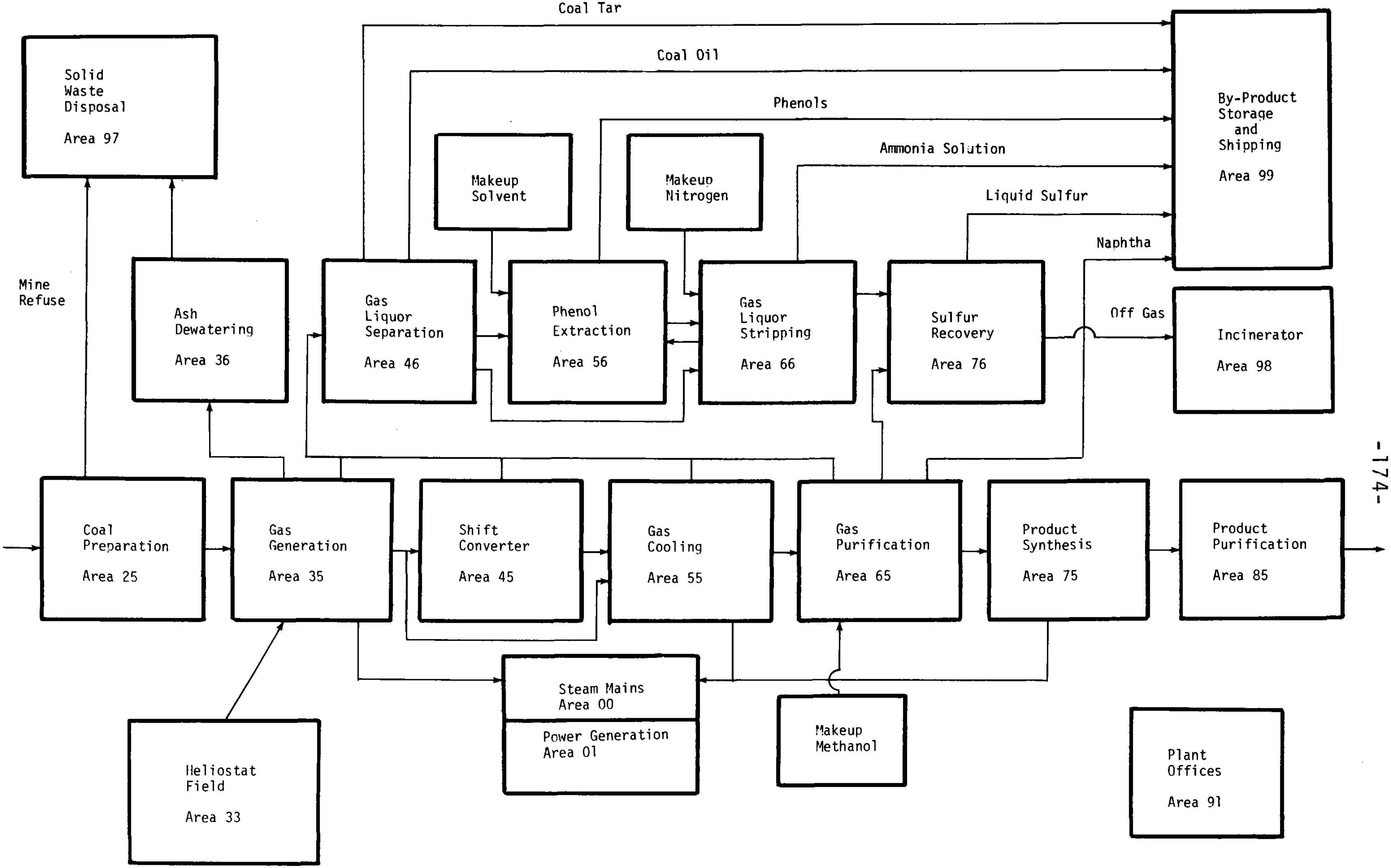

Figure 2. Schematic of a Solar Coal Gasification/Synthetic Natural Gas Plant.

PLANT PERFORMANCE SUMMARY

The overall performance of the solar coal gasification plant can be obtained by comparing the input and product streams as in Table 2. The flow of energy is shown for various important streams. This energy flow is the "cold gas" heat of combustion except for the solar energy and steam streams.

Table 2. Coal Gasification Plant Performance.

	Solar	Lurgi
(1) Coal Energy (excluding coal fines), MJ/s	12370	5271
(2) Steam (Heat of Vaporization), MJ/s	1335	548.7
(3) Solar Energy, MJ/s	6154	NA
(4) Clean Syn Gas Heating Value (excluding NH_3 & H_2S), MJ/s	13557	3853
(5) Organic Liquids Heating Value, MJ/s	1728	309.4
(6) Ammonia Heating Value, MJ/s	127.4	49.95
(7) Hydrogen Sulfide Heating Value, MJ/s	55.68	28.18
(8) Char Heating Value, MJ/s	nil	nil
(9) Total Gasifier Product Heating Value, MJ/s	15470	4240
(10) Stored Solar Energy (10 = 9 - 1), MJ/s	3094	NA
(11) Product Gas Storing Fraction (11 = (10/9)x100), %	20	NA
(12) Solar Energy Storing Efficiency (12 = (10/3)x100), %	50	NA
(13) Gasifier Thermal Efficiency (13 = (9/(1 + 2 + 3))x100), %	80	80
(14) Finished Product HHV, kJ/mol	851.8	855.7
(15) Finished Product Rate, kg/s	209.9	63.07
(16) " " " kgmol/s	12.89	3.921
(17) " " " MJ/s	10980	3355
(18) " " " 10^{15} J/yr*	104.3	104.3
(19) " " " 10^{12} Btu/yr	98.86	98.86
(20) Finished Product Energy/Coal Energy, %	88.76	63.65

* SCG - 8 hr/day, 330 day/yr
Lurgi-24 hr/day, 360 day/yr

Sized coal with a heat combustion of 12370 MJ/s is gasified with steam (heat of vaporization energy of 1335 MJ/s) by use of solar energy (at 6154 MJ/s). Heat loss from the gasifier of 20% of the total energy input is assumed. This heat loss matches the heat loss from the Lurgi gasifier. The gasifier product consists of clean syn gas -- 13557 MJ/s, organic liquids -- 1728 MJ/s, ammonia -- 127.4 MJ/s, and hydrogen sulfide -- 55.68 MJ/s. The total gasifier product heat of combustion is 15470 MJ/s.

The amount of stored solar energy (6154 MJ/s) is the total product energy (15470 MJ/s) minus the coal energy (12370 MJ/s). The steam requirements can be met by raising steam in water jackets around the gasification reactors using part of the 20% heat loss (3972 MJ/s).

The Product Gas Storing Fraction (fraction of the product energy which is stored solar energy) is 20%. (See Table 2.) Solar energy is treated here as if all of the heat loss is supplied by the solar energy and none by the coal energy. The energy efficiency (total product energy divided by total input energy) is 80%, which is a direct consequence of the 20% heat loss assumed in order to match the Lurgi units. The Solar Energy Storing Efficiency is the Stored Solar Energy divided by the Total Solar Energy. In this case it is 50%.

The ability to convert 50% of the incoming solar energy into chemical energy in the syn gas is remarkable. This efficiency compares to the efficiency of an electric plant which is below about 40%.

Because solar energy supplies all of the gasification energy and heat loss energy and eliminates the need for oxygen separation energy, the SCG plant produces more product per unit of coal. The SCG plant produces 89 kJ of product energy per 100 kJ of coal energy vs 64 kJ for the SRL plant. (The product rate is less than the coal energy rate because the product synthesis reaction is exothermic.) The SCG plant produces 40% more product than the SRL plant per unit of coal energy. This reduces the coal requirements and is the key economic advantage of SCG.

Energy is available in this plant at a relatively high temperature that can not be used in the process. The exothermic product synthesis reaction releases energy, the hot synthesis gas must be cooled in Area 55, and the gas generators have a heat-loss flow in excess of that needed for steam generation. These energy flows could be used in a cogeneration mode to produce substantial amounts of electric energy for sale on the grid. Allowance for this possibility would improve the performance and economics of this plant significantly.

AN ECONOMIC ANALYSIS

An economic analysis has been made of the solar coal gasification plant described in the previous section. This analysis was based on the cost data released in the same legal submission[7] that provided the data for the flow sheets. As in the calculations for the flow sheets, it is assumed that modest changes in the size of the plant will have little effect on the costs per unit of production rate. The cost data was updated from 1973 to 1978 to compare to 1978 heliostat cost data using the Nelson Refinery Cost Index and Chemical Index.[9] The cost ratios were 1.498 and 1.635 respectively.

CAPITAL COSTS

For each of the major processing areas (Figure 2) the cost was assumed to be proportional to the production rate of the area's product (Table 3a). In sizing the units to give the same annual production rate, 8 hr/day and 330 day/yr was used for SCG and 24 hr/day and 360 day/yr was used for Lurgi. The shorter year allows for bad weather.

The cost for the gasifier area itself can only be roughly estimated at this time since only general ideas of its design are known. The simplest of the current ideas[1] include a moving bed with coal surface exposed to solar energy at the top. This moving bed arrangement is somewhat like that of the Lurgi gasifier, so the costs may be similar. The Lurgi design requires drive shafts that penetrate the pressure shell into the high temperature zones. These drive shafts would not be required in the SCG gasifier, which would reduce the cost. However, a window to admit the solar energy will be required, which would increase the cost. For the purpose of the present analysis, the cost of the gasifier area per unit production rate will be assumed to equal that for the SRL plant.

Table 3a. Processing Plant Investment

	units	Solar	Lurgi
COAL HANDLING			
Crushing, Screening, Blending, and Storage	k$	47787	21977
Lock Gas Storage and Compression	k$	4033	1855
Total Direct Cost--Coal Handling	k$	51820	23832
PROCESSING UNITS			
Gas Production	k$	293921	97121
Shift Conversion	k$	8929	11064
Gas Cooling	k$	43636	11841
Gas Purification	k$	201493	45839
Refrigeration	k$	62480	14214
Product Synthesis	k$	106619	27228
Product Purification & Final Preparation	k$	50382	12867
Gas Liquor Separation	k$	11643	2153
Phenol Extraction	k$	45113	8468
Ammonia Stripping	k$	19115	7496
Sulfur Recovery	k$	19744	9993
Total Direct Cost of the Processing Units	k$	863075	248283
UTILITY PLANTS			
Fuel Gas Production & Treating	k$	0	40316
Air Compression	k$	0	30668
Oxygen Production & Compression	k$	0	43343
Steam & Power Generation	k$	25402	44591
Cooling Water System	k$	5289	8699
Raw Water System	k$	6130	10078
Miscellaneous Plant Utility Systems	k$	1842	7403
Total Direct Cost--Utility Systems	k$	38662	185148
ASH HANDLING AND RAW WATER SYSTEMS			
Ash Dewatering & Transfer	k$	4443	2043
Water Pumps, Pipeline, & Storage Ponds	k$	12960	21312
Total Direct Cost--Ash Handling & Raw Water Systems	k$	17403	23355
Total Direct Cost of the Processing Plant (Including Contractor Engineering & Fees, Licenses & State Tax with no Contingencies)	k$	931140	302873

The effect of errors in estimating the gasifier cost can be estimated as a fraction of the other costs. The gasifier cost is less than 20% of the total cost for the plant including the heliostat field, and the capital costs are less than 60% of the cost of the final product ($2/gJ coal cost); so less than 12% of the product cost is from the gasifier capital costs. A 50% error in estimating the gasifier cost becomes less than a 6% error in the product cost.

The cost of the heliostat field to supply the solar energy was estimated from information developed for the DOE Prototype Heliostat program (Table 3b). The energy collected and costs for a McDonnel Douglas heliostat were used.[10] These $49m^2$ heliostats will collect 368 gJ/yr under Barstow conditions and will cost $3136 (1978$) apiece installed.

Table 3b. Solar Facility Investment

Solar Energy Collection Rate	kW/Heliostat	35
Cost of Heliostats (installed & wired)	k$	3.136
Land Required	sq meters/heliostat	245
Solar Energy Required	MW	6154
Number of Heliostats Required		175835
Total Heliostat Cost	k$	551419
Land for Heliostat Field	sq mi	16.63
Price for Land	k$/sq mi	100
Cost of Land for Heliostat Field	k$	1663
Total Cost of the Solar Facility	k$	553083

The total capital required for the processing plant is 1439 M$ for SCG and 465 M$ for Lurgi (Table 3c). The solar facility for SCG would be an additional 553 M$. The additional processing plant investment for SCG is due to oversized equipment that compensates for the 8 hr/day operation. The additional processing plant investment is approximately twice the cost of the heliostat field.

An underlying assumption has been that we must obtain the maximum output from the heliostat field. However when SCG is used rather than Lurgi gasifiers, the increment in the processing plant cost is twice the cost of the heliostat field. This fact implies that when the detailed design of a solar coal gasification plant is done, it will be better to provide excess heliostat capacity in order to maximize the operating time of the processing equipment. If this were done, then at noon on a clear summer day part of the heliostats would be stowed and not collecting energy. The processing plant could then be at full production even on slightly overcast days and earlier or later in the day before the heliostat field comes up to full performance.

Other uses might be implemented for the solar energy not needed at noon on a clear day. These uses would have to tolerate long periods between operation and short operation times. Incineration of toxic wastes might be such a use. Like the cogeneration concept, such supplementary use of the heliostats would improve the economics of the process, but evaluation of the importance of such concepts will have to await a more detailed analysis.

Table 3c. Summary of Investment Requirements

	units	Solar	Lurgi
1. Total Direct Cost of the Processing Plant (including contractor engineering & fees, licenses & state tax with no contingencies)	k$	934140	302873
2. Initial Catalysts and Chemicals	k$	38948	9946
3. Cost of Land for Processing Plant	k$	457	151
(Land for processing plant)	sq mi	4.57	1.51
4. Site Improvements & General Facilities	k$	157204	51945
5. Funds for Use During Construction (20% of the cost of the processing plant)	k$	186828	60575
6. Startup Costs (8% of the cost of the processing plant)	k$	74731	24230
7. Working Capital	k$	46707	15144
8. Total Capital Required for the Processing Plant (8 = 1 + 2 + 3 + 4 + 5 + 6 + 7)	k$	1439014	464864
9. Total Cost of the Solar Facility	k$	553083	none
9a Total heliostat cost	k$	551419	none
9b Cost of land for heiostat field	k$	1663	none
10. Total Capital Investment (10 = 8 + 9)	k$	1992097	464864
11. Total Depreciating Investment (Subtracting: land costs, working capital, initial catalysts, and chemicals) (11 = 10 - (3 + 9b) - 7 - 2)	k$	1904322	439623
12. Total Plant Investment (Subtracting: working capital, startup costs, initial catalysts and chemicals) (12 = 10 - 2 - 6 - 7)	k$	1831711	415544

OPERATING COSTS

The annual operating costs consist of Raw Material Costs, Labor and Maintenance, Local Taxes and Insurance, Depreciation, and annualized costs for the capital investment minus the by-product credits. The Annual Operating Costs and Product Costs are shown in Table 3d. Allowing for by-product credits is difficult because marketing conditions vary with plant location. For example, in some locations the CO_2 will also have value for flooding oil fields in tertiary recovery operations or for other purposes. The values of the by-products were obtained from Chemical Marketing Reporter.[11]

Table 3d. Annual Operating Cost & Product Cost

RAW MATERIALS	units	Solar	Lurgi
Raw Coal Cost	k$/yr	255688	356390
Price of Raw Coal	$/gJ	2.00	2.00
Catalysts and Chemicals	k$/yr	11408	9532
Water Costs	k$/yr	938	1014
1. Total Cost of Raw Materials	k$/yr	268034	366937
LABOR			
A. Operating Labor	k$/yr	7812	7751
Operating Labor Force		313	310
Labor Pay Rate	k$/yr	25	25
B. Supervisory Labor--20% of (A)	k$/yr	1563	1550
C. Overhead--60% of (A)	k$/yr	5629	5580
D. Supplies--30% of (A)	k$/yr	2345	2325
2. Total Labor Costs	k$/yr	17355	17206
3. Maintenance (3% of the Direct Cost of the Processing Plant Plus 1.5% of the Total Cost of the Solar Facility)	k$/yr	36320	9086
4. Local Taxes and Insurance (1.5% of the Total Plant Investment)	k$/yr	27476	6233
5. Gross Operating Cost (5 = 1 + 2 + 3 + 4)	k$/yr	349185	399463
BY-PRODUCT CREDITS			
A. Liquid Sulfur	k$/yr	1507	2496
B. Ammonia	k$/yr	7001	8985
C. Coal Tar	k$/yr	9485	5446
D. Coal Oil	k$/yr	59015	36220
E. Phenols	k$/yr	47165	28970
F. Naphtha	k$/yr	39968	21864
G. Coal Fines	k$/yr	10228	15392
6. Total By-Product Credit	k$/yr	174367	119372
7. Net Operating Cost (7 = 5 - 6)	k$/yr	174818	280091
8. Depreciation (5%/yr of the Total Depreciating Investment)	k$/yr	95216	21981
9. Allowance for: Interest on Debt, Return on Investment, and Income Tax (8% of Total Capital Investment)	k$/yr	159368	37189
10. Total Operating Cost (10 = 7 + 8 + 9)	k$/yr	429402	339261
11. Total Product Energy	10^{15}J/yr	104.3	104.3
--Total Flow Rate of Product Gas	kgmol/s	12.89	3.92
--HHV of Product Gas	kJ/gmol	852	856
12. Product Cost (12 = 10/11)	$/gJ	4.12	3.26

For the coal cost of $2/gJ used in Table 3d, the Total Operating Cost is 429 M$/yr for the SCG plant and 339 M$/yr for the SRL plant.

PRODUCT COSTS

These plants produce 104.3 10^{15} J/yr of product energy, so the product cost is $4.12/gJ for the SCG plant and $3.26/gJ for the SRL plant with coal at $2/gJ.

The cost of the coal affects the product cost significantly (Figure 3). The Lurgi plant has lower product cost up to a coal cost of about $4.00/gJ. Above this cost-crossover point the lower coal requirement for the solar gasifier results in lower costs.

The advantages and disadvantages of SCG are well summarized in Figure 3. The initial disadvantage of higher investment requirement is reflected by the intercept on the vertical axis. The way in which this initial disadvantage can be overcome at high coal costs is shown by the way the cost lines cross. The different slopes reflect the different coal requirement.

Some uncertain factors in the gas cost are the annuallized cost of capital and allowance for by-product value. Annuallized capital cost covers interest on debt, income tax, and return on investment. The rate used for this cost was 8%. This rate is appropriate for an economy with mild inflation. The effects of higher rates with and without by-product credits are shown in Table 4.

Other estimates[12] have shown higher product costs than the estimates shown in Figure 3 for both solar and Lurgi coal gasification. The present results were intended to be used for internal comparison only. Resolution of differences between the sources of data is beyond the scope of the present paper. The internal consistency in the present results should be adequate for comparison of solar coal gasification with Lurgi coal gasification. This paper is not intended to be the final answer on SCG costs. The assumed values for a number of the parameters could be different from those the reader may prefer. The installed cost of the heliostats is an open question. The value of the byproducts depends on marketing factors. The required rate of return on the investment is extremely uncertain in these times. The format of the results allows recalculation using other assumed values for these parameters.

The only hard information on costs comes from actually building a plant and operating it for a period of many years.

Table 4. Gas Costs with and without By-Product Credits and with the Annuallized Capital Cost (ROC) at 8, 16, & 24% of the Total Capital Investment. (1978$)

	With By-Product Credits		Without By-Product Credits	
Coal Cost $/gJ	Gas Cost SCG $/gJ	Gas Cost Lurgi $/gJ	Gas Cost SCG $/gJ	Gas Cost Lurgi $/gJ
With ROC = 8%				
0	1.66	-.15	3.33	0.98
1	2.89	1.55	4.56	2.68
2	4.12	3.26	5.79	4.39
4	6.57	6.68	8.24	7.81
With ROC = 16%				
0	3.18	0.21	4.85	1.34
1	4.41	1.91	6.08	3.04
2	5.64	3.62	7.31	4.75
4	8.09	7.04	9.76	8.17
With ROC = 24%				
0	4.70	0.57	6.37	1.70
1	5.93	2.27	7.60	3.40
2	7.16	3.98	8.83	5.11
4	9.61	7.40	11.28	8.53

All efforts at economic analysis give results that are soft to some degree. The results of our analysis are based on an adaptation of a particular plant design to SCG. A rather modest level of effort was available to make this analysis. As development of the SCG concept proceeds, better plant designs and better economic analysis will be required.

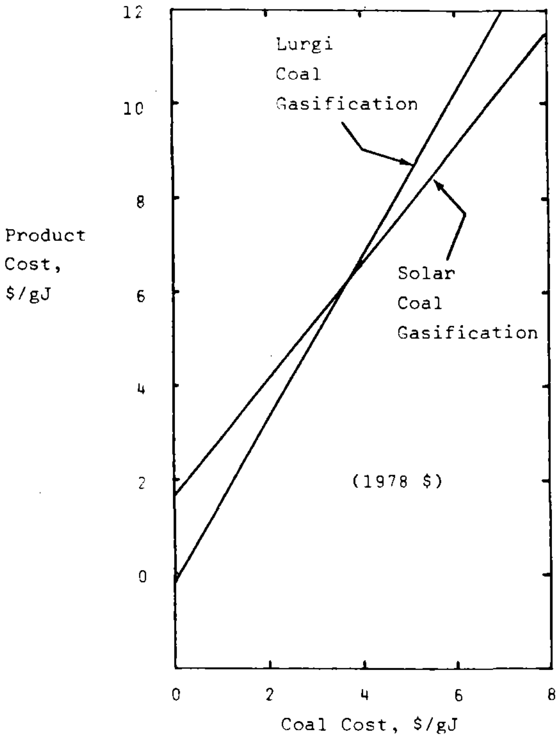

Figure 3. Product Cost for Solar Coal Gasification and for Lurgi Coal Gasification as a Function of Coal Cost.

Even the straightforward, simple plant layout analyzed here is not unreasonably expensive compared to a Lurgi plant; in addition, minor changes in the process performance or cost parameters can have a major effect on the location of the cost-crossover point. The location of this point is sensitive to small changes and modest improvements in the SCG process may move the crossover down into the range of current coal costs.

The largest detriment for SCG is the 8 hr/day operation. This detriment is the main cause of the high capital requirement for a given annual production. Alleviating this detriment should be the first goal of further work on SCG.

SUMMARY

The present paper is one further step in the process of developing the concept of Solar Coal Gasification. A number of problems were revealed and some advantages were quantified.

A plant was layed out and analyzed with the aid of a code that calculates process flows and plant economics. This plant is the simplest, most straightforward plant and thus it was the most appropriate for the initial analysis. Solar energy was focused directly on the reacting coal and no energy storage schemes were considered in this analysis. Various improvements on this simple scheme can be made.

The process analysis showed that 40% more product can be produced from a given amount of coal compared to the similar Lurgi plant. The fraction of the solar energy that can be converted into usable energy by these thermochemical means is greater than the fraction for any other method with the exception of conversion to simple thermal energy.

The economic analysis showed that for a plant that produces a given amount of product per year, the capital costs are much higher but the operating costs are much lower. These cost differences reflect the 8 hr per day operation for the SCG plant plus the cost of the heliostat field, and the lower coal consumption for the SCG plant.

The increased capital costs for SCG compared to Lurgi were not primarily due to the cost of the heliostat field. The increment in the processing plant cost due to the 8 hr/day vs 24 hr/day operation was twice the cost of the heliostat field.

Product costs were derived as a function of coal cost. The Lurgi plant was more economical when coal was less than about $4/gJ. The SCG plant was more economical when coal was more than $4/gJ. Currently Coal Week shows most coal costs between $1/gJ and $2/gJ. Mine-mouth coal is cheaper than the coal listed in Coal Week.

Eventually coal prices may rise to a level (relative to plant costs) where the simple, straight-forward SCG plant will be cheaper than a Lurgi plant. In the meantime we should look for better SCG concepts. Alternative concepts being considered for economic and practical reasons include:

(1) Indirect gasification using a heat transfer fluid.
(2) Hybrid gasification using solar energy when available and coal combustion energy at other times.
(3) Syn gas storage so that the downstream processing units can continue through the night.
(4) Solar energy storage so that gasification can continue through the night.

In the early stages of developing a new concept, each step is very likely to reveal more problems than the step has cleared up. We are certainly in this position now. Analysis of the straightforward plant design has revealed many problems. We will have to be more clever to get a design that can be considered practical.

CONCLUSIONS

Providing excess heliostat capacity to maximize the operating time of the processing equipment will probably be economically beneficial. This concept may require a shift in attitude towards solar energy. In chemical processing, the heliostat costs may not be dominant in the overall plant design. These costs may even be minor in some applications.

It seems clear that SCG will become competitive economically if the price of coal increases sufficiently compared to plant costs, because SCG conserves coal. In addition, since it is in the national interest to conserve coal; use of SCG might be subsidized.

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A NEW METHOD FOR HIGH TEMPERATURE SOLAR THERMAL ENERGY CONVERSION AND STORAGE

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I. INTRODUCTION

Current and proposed technologies involved in solar central power generation systems do not fully exploit the potential advantage of the high thermodynamic availability of solar energy. Thermal storage is rarely carried out at high enough temperatures to achieve the thermodynamic cycle efficiency available from solar energy systems. Furthermore, few near-term solar power systems directly integrate energy storage. Often, the waste heat from a primary cycle is stored for use at low temperatures in less efficient bottoming cycles. When the energy storage is provided for use in the primary cycle, such as in the sodium liquid metal energy storage system, heat is transmitted through a heat exchanger. Such systems tend to be expensive and heat exchanger materials severely limit the working temperatures.[1] Recently, Hertzberg identified a number of promising power generation cycles with efficiencies from 45% to 70%, involving peak temperatures of up to 2000°K.[2] High temperature heat storage facilities and heat transfer devices are essential for central solar energy stations based on these cycles if they are to be economically attractive.

Exploiting high temperatures presents unique problems to the designer, however. One is faced, in particular, with the problem of thermal shock, due not only to the diurnal nature of solar energy but also to the ever-present danger of briefly losing solar energy by isolated clouds or sudden storms. Power plants in general do not tolerate rapid thermal cycling and consequently potential performance must be degraded to allow for the severe practical problem of the rate at which they can be turned on and off.

In the search for methods of making solar central energy systems truly competitive with conventional energy sources such as coal or nuclear, we set out with a "clean sheet" approach to develop a potentially practical system which would be able to run at near constant load and constant temperature at the very high temperatures needed. Our approach dictated that a fully integrated system for generation and storage be designed. The solar collector, thermal storage system and heat exchanger at minimum are conceptually all part of the same system. The temperature required carries us beyond the capabilities of conventional solar receivers involving tube heat transfer and conventional heat exchangers.

Capacitive heat exchangers and storage systems circumvent tube wall temperature limitations by using high temperature materials and transporting them into direct contact with the heat source. Common examples are blast furnaces, packed bed regenerative heat exchangers, and fluidized bed heat exchangers. Solid phase capacitive elements, which must operate in a cyclic fashion, are subject to physical degradation due to thermal shock and represent a high fraction of the total system cost involved. The problems of these systems become increasingly acute as the maximum temperature and rate of temperature change are increased.

The approach described here is based on the premise that the classical inefficiencies associated with capacitive heat exchangers can be circumvented if the capacitive elements are mobile and are remanufactured during each temperature cycle, eliminating the degradation due to thermal shock. Thermal energy storage equipment is an integral part of the system. Storage temperature can be high enough to make use of the maximum thermodynamic potential of solar radiation, even allowing for reradiation losses.

The proposed approach involves a phase conversion of a refractory oxide, such as silica, which is very stable at high temperatures, to a liquid in a solar-heated furnace. The capacitive material, fortunately, is a relatively cheap substance, widely available and benign in its contact with the environment. A schematic of a proposed 100 MW solar power pilot plant which utilizes the novel heat exchanger and storage system appears in Fig. 1. The working material is delivered to the top of the solar receiver tower as a uniform aggregate of small beads, which are melted by a combination of direct solar radiation and reradiation from the cavity walls. The resulting liquid collects in a crucible at the bottom of the receiver. In this form the refractory is delivered to the storage vessel and thence to the heat exchanger. The molten material is injected into the heat exchanger under pressure as small diameter streams, which break up into drops. The drops fall through a counter-flowing high pressure working gas, giving up their heat by convection and changing phase into the solid bead state in the process. The solidified droplets are collected at the bottom of the heat exchanger as an aggregate and delivered directly back to the furnace. The heated gas is removed at the top of the heat exchanger and employed by a heat engine at a temperature range corresponding to the necessary operational parameters of the system desired.

A unique feature of this system is that thermal storage is accomplished at the same high thermodynamic potential at which the solar radiation is absorbed in the solar collector. The high efficiency at which the energy conversion and storage take place reflects favorably back through the cost of the entire solar energy system. More useful energy is obtained from a smaller heliostat field and other components. The system presented here has not been optimized; rather it is a point design which serves the purpose of an example and which will be the basis for further investigations.

II. THE HEAT TRANSFER AND STORAGE MATERIAL

The heat transfer and storage material must obviously have a melting point in the range desired for an operating and storage temperature. It must also be inert at high temperature with respect to air and the working gas and should have a low vapor pressure to avoid contamination of the gas in the heat exchanger. Refractory oxides come immediately to mind as being inert at the desired temperatures. Properties of the more common oxides are listed in Table I. Silica has a number of attractive properties. It has a relatively low melting point, is abundant, and therefore inexpensive, and is also environmentally benign. The principal objection to the use of silica is that it is relatively viscous in the molten state. Addition of metallic oxides such as Na_2O, K_2O, Li_2O, MgO and PbO tends to reduce the viscosity of a silica melt by breaking the continuity of silicate cross-linking.[3]

Lyon[4] has studied the viscosity reducing effect of the addition of a number of metallic oxides, and presents a procedure for predicting the viscosity of a mixture as a function of temperature, using the Fulcher equation.[5] The results of this procedure for three silica glasses are shown in Fig. 2. Note that at 1725°K, the viscosity of the pure silica is approximately 10^3 poise. The addition of 35% Na_2O reduces the viscosity to 22 poise. The addition of 26 % Li_2O to the pure silica reduces the viscosity even further to 4.8 poise. The effect of Li_2O addition to silica is a relatively recent result of our continuing effort to discover more suitable materials for high temperature applications. Although the reduction in viscosity possible by the addition of Li_2O is potentially of great benefit, much remains to be determined about the use of Li_2O in the heat storage material. For example, the effect on the vapor pressure and the possibility of chemical attack on the vessel lining are areas that will require further work. Therefore, although the use of Li_2O shows promise, we continue to use our earlier results based on silica doped with Na_2O for the purpose of an example.

It must be pointed out that the materials that have been discussed above as the capacitive and storage material by no means exhaust the possibilities available to us. Under the constraints that the material should be available, cheap and benign, there are numerous other possibilities that must be looked at from the point of view of ease of handling and other potential advantages. For example, glasses involving various mixtures of the alkaline oxides of sodium, lithium and potassium are known to be stable and may have favorable properties in this application.

The effects of contamination remain to be examined. However, to the authors' best knowledge, most common materials decrease the viscosity of silica. Alumina is one exception, so that the possibility of alumina contamination must be evaluated. Indeed, even common slag, containing oxides of the most complex nature, has viscosities which could be useful.

III. THE SOLAR CENTRAL RECEIVER

The radiation receiver is a critical component of the proposed solar power plant and energy storage system. It is here that the refractory beads are melted and heated to the desired temperature for storage and subsequent use in the direct contact droplet heat exchanger. The design considerations for an optimum receiver geometry are only exploratory at this stage and one of the basic problems that must be studied involves the mechanism of the absorption of solar energy and the transformation of the refractory beads into a high temperature molten stream.

One of several possible solar receiver designs is shown in Fig. 3. The solid glass beads are delivered to the top of the receiver and fall through the solar flux as a shower of particles, to be collected at the bottom in a refractory-lined crucible. On their downward passage the beads absorb the solar radiation and are heated in the process.

Preliminary considerations of the radiative coupling to the beads indicate that secondary radiative transfer from the receiver wall and/or doping the glass with an efficient absorber of solar radiation will be required to heat the beads to the desired operational temperature range (1700-2000°K). The flow of beads would be controlled to keep the melted glass in the refractory crucible at its proper maximum operating temperature.

The molten glass flows out of the crucible at a controlled rate through an orifice equipped with a slide or flapper valve. The passage from the outlet of the crucible to the storage vessel at the foot of the solar collector tower consists of a large, suitable insulated, ceramic pipe having a diameter ∿3-4 times that of the crucible's exit aperture. The molten material issues as a free viscous jet from the orifice and travels down through the pipe without contacting the wall. Preheating this passage would not be necessary since the molten material would heat it by radiation.

The radiation receiver is lined with a refractory in much the same way as the storage vessel, whose construction is described in Section IV. The pipe connecting the receiver to the storage vessel would also follow this design philosophy.

In the case of loss of insolation due to a sudden overcast or nightfall, the injection of beads at the top of the solar receiver would automatically stop and the molten material in the crucible would be emptied into the storage vessel. At restart the receiver crucible would be partially filled with glass beads, which would be melted by the reradiation from the upper section, or cap, of the receiver. Once the initial charge was melted, the injection of beads would be resumed and normal operation would proceed.

The above scenario is only illustrative at this time and is being used as a starting point to develop the necessary design parameters for an optimum configuration and operation scheme.

IV. THE ENERGY STORAGE SYSTEM

The capability of storing energy at the same high thermodynamic potential at which it is collected in the solar central receiver is a unique feature of the integrated system proposed here. Absorbing energy directly into the heat storage material in the solar central receiver leads to a storage method that is very easily integrated with the power cycle. Energy storage is accomplished by piping the molten refractory to a large storage vessel. The material fills the vessel and then proceeds to the heat exchanger tower. Thus, a reserve of high temperature molten refractory is available at all times, a feature of particular importance for solar central systems.

The energy storage vessel, which in the point design being considered is located at ground level directly beneath the solar collecting tower, is a relatively large, unpressurized container, insulated on the inside. It is sized to hold sufficient material to supply energy to the power plant for the period it is wished to accomodate. The power plant represented in Fig. 1 has a 100 MW net output and requires 180 MW circulating power with the argon Brayton cycle illustrated. Storage capacity E_s of 8640 MWH would supply the power generation cycle for 48 hours.* Silica glasses have a heat capacity, C_p, of 0.360 cal/g°C, and a specific gravity of 2.4. For a temperature drop of 825°K through the droplet heat exchanger (see Section V) this results in a storage mass M_s of

$$M_s = \frac{E_s}{C_p \Delta T} = 2.5 \times 10^7 \text{ kg} \tag{1}$$

and storage volume of $V_s = 1.04 \times 10^4 \text{m}^3$.

The storage container must be designed with due regard for the physical and chemical stability of the liquid and the container. Much information relevant to this problem is already available from the highly developed technology of the nuclear power and glass industry.[6] For example, the vessel walls might be constructed as shown in Fig. 4. The hot face, which is in contact with the molten storage material, consists of fused-cast alumina-zirconia blocks, in a layer 30 cm thick. This material has been developed for the sidewalls of glass-melting furnaces and is resistant both to the high temperature and the chemical attack by the molten storage material.[7] The blocks are very dense, and are manufactured to close dimensional tolerances, effectively eliminating the porosity in the surface and at the joints, which make common refractory materials subject to corrosion by the liquid glass. A lining constructed of assembled blocks is more easily repaired than a monolithic structure. The storage vessel thus promises to be relatively inexpensive to maintain.

Next are a 23 cm layer of lightweight, insulating silica-alumina refractory with a temperature rating of 1900°K and a 47 cm layer of similar material which will withstand 1500°K. Outside the refractory is a steel shell to contain the pressure head resulting from a full vessel of liquid glass. The roof could be constructed entirely of silica-alumina fiber refractory, since it will not be wet by the molten material. A 50 cm layer would provide a resistance to heat flow equal to the wall construction outlined above. Assuming an ambient temperature of 305°K, a common value in a solar resource area, the heat loss through this construction from a storage temperature of 1725°K would be 0.49 KW/m^2. A cylindrical vessel of equal height and diameter would have a high volume-to-surface area ratio to minimize heat loss, yet be relatively easy to fabricate. Such a vessel, for the example being considered, would have inside dimensions of 23.7 m. Considering the one meter wall, total heat loss through the 3100 m^2 outside area would be 1520 KW or 0.85% of capacity in 48 hours. A higher level of insulation on the storage vessel to reduce the storage heat loss could prove to be economical, depending on the cost of the additional insulation relative to the cost of providing the thermal energy.

A conduit of similar construction could be used to carry the material from the storage vessel to the heat exchanger. If the conduit were insulated similarly to the vessel, the temperature drop in the material as it traveled from the storage vessel to the heat exchanger, assuming a conduit 100 m long and 30 cm ID, would be less than 1.5°K.

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*Storage capacity sufficient for 48 hours operation was chosen for the purpose of an example. There is no fundamental reason to prevent it from being sized according to individual power plant requirements.

The heat lost by conduction through the walls of the vessel will be easily dissipated by convection to the surrounding air. Locating the tank below ground level, while allowing a somewhat simpler supporting structure, would, by virtue of the insulation value of the surrounding earth, accumulate heat in the vessel lining until the temperature limits of the lining materials would be exceeded. The vessel would thus require an active cooling system, a complication which would offset the simpler structure.

In Table II, the unit capital cost estimate for the proposed molten silica storage system is compared with costs of the Reference Thermal Storage concepts of the Thermal Storage Development Plan enumerated in Ref. 8. The low unit cost of the silica based storage system relative to the others listed is due primarily to the low cost of the storage material. In addition, its low vapor pressure and chemical stability enable it to be used at very high temperatures in a container of relatively simple construction.

Only energy related costs have been compared--the costs for equipment required to charge and discharge the system are not included. At present we do not have the power-related costs for the molten silica system well enough defined to make a comparison, but the energy cost comparison indicates a potential for great cost savings for the molten silica system.

V. THE HEAT EXCHANGER

The accessibility of the stored energy to the working fluid of the energy conversion system has proved to be a problem in many of the energy storage systems considered to date.[1,9] The system that is proposed here allows direct contact of the stored material with a working gas at high pressure.

Engineering simplicity is also a requirement of the heat exchanger in the temperature range we are considering. Normal heat exchangers tend to consist of long passages of tubing and at best represent a complicated plumbing system subject to the potential for catastrophic single point failure. The benign nature of the glass-like storage material allows a rather unique approach which fully integrates the heat exchanger and storage system into essentially one unit.

In the system discussed here we envision a single large pressure vessel, again insulated from the inside, as is the storage tank, to minimize the internal ducting of the system. A pressurized gas system would be used to force molten glass from the storage chamber through an insulated refractory pipe. Preheating of this conduit is expected to use a conventional gas flame system during the startup to prevent accidental plugging of this critical passage. The molten material is injected into the heat exchanger through a refractory nozzle plate pierced with small holes, as shown in Fig. 5. The resulting thin streams break up quickly into a series of uniform drops, which fall through the heat exchanger giving up their heat to a clean working gas capable of running a high temperature heat engine. (See Refs. 10 and 11 for details of the droplet formation process.)

Heat Transfer Process

For the purpose of this analysis, the heat exchanger has been modeled by a simple one-dimensional flow problem. It is assumed that the refractory droplets are uniformly distributed across the flow area and are of uniform radius, r_p. The droplets are all injected at the same speed, namely, the terminal velocity in the gas at the conditions existing at the top of the tower, and the bead velocity has no radial components. The tower is a cylindrical volume with perfectly insulated sides. The gas enters at the bottom and leaves at the top with a velocity profile that is uniform across the flow area. For present purposes, argon has been chosen as the working gas and it is assumed that the gas velocity at the top is 80% of the droplet terminal velocity.

Since the density, velocity and viscosity of the gas change as a function of height in the tower, the droplets do not retain their initial injection velocity with respect to the gas. The equation of motion of a spherical particle falling through a gas is

$$\frac{4}{3}\pi r_p^3 \rho \frac{dU_r}{dt} = \frac{4}{3}\pi r_p^3 \rho g - \frac{1}{2}\pi r_p^2 C_D \rho_g U_r \left| U_r \right| \qquad (2)$$

where r_p and ρ are the particle radius and density, respectively, U_r is the relative velocity between particle and gas, g is the acceleration of gravity, C_D is the drag coefficient, and ρ_g is the gas density. The buoyancy, "added mass" and "history" terms[12] are negligible and have not been included. In a cloud of particles it is known that C_D does not follow the usual behavior with Reynolds number R_e as for a single particle.[13] However, there is little agreement among published results. For the time being we have used the single particle correlation for C_D given by Kliachko, et al.[14] for Re < 1000:

$$C_D = \frac{24}{R_e} + \frac{4}{R_e^{1/3}} \qquad (3)$$

where the Reynolds number is based on the local relative velocity between particles and gas. For $1000 < R_e < 10^5$, we have assumed $C_D = 0.42$.

Bandrowski and Kaczmarzyk[15] have demonstrated that the heat transfer rate between a gas and a cloud of particles depends on the volumetric concentration of the particles as well as the particle Reynolds number. They offer the following correlation:

$$N_u = 0.00114 \beta_v^{-0.5984} R_e^{0.8159} \qquad (4)$$

where β_v is the volumetric concentration of the particles. This relationship is applicable in the range of $0.00025 < \beta_v < 0.05$ and $180 < R_e < 1800$, which falls within the regime of operation of the droplet heat exchanger.

The thermal conductivity of the refractory oxides of interest as a working material is relatively small, and as a result the internal resistance of the particle becomes significant in the calculation of the heat transfer rate from the drops to the gas for drop sizes $\gtrsim$ 2 mm. This effect has been included in our analysis.[11]

Data for the viscosity μ, and thermal conductivity k, as functions of temperature, were obtained from standard reference sources[16,17] and subjected to a first order least squares procedure to obtain analytical expressions for use in the computer program. The heat capacity of argon is constant at 0.124 cal/g°K over the temperature range of interest. The thermal conductivity and heat capacity of the glass droplets are 20 mW/cm°K and 0.36 cal/gm°K, respectively, and are also constant.

A computer code was generated to calculate the temperatures, heat transfer rate and gas properties stepwise through the heat exchanger for heating argon at 20 atm by molten glass beads (65% SiO_2, 35% Na_2O) injected into the heat exchanger at 1725°K. Gas inlet and exit temperatures of 675°K and 1500°K were respectively chosen to illustrate an example. The gas exit temperature is not limited by any essential part of the equipment. Higher temperatures could be achieved by choosing a particle material with a suitable melting point and designing a suitable refractory wall. Temperatures of 2000°K should be attainable with current refractory practice. Similarly, the working gas could be any mixture that has properties to match the power generation cycle.

For present purposes a Brayton cycle with an inlet temperature of 1500°K at 20 atm was chosen. The turbine expands the argon to 2.63 atm and 667°K. Heat is rejected at constant pressure in a conventional heat exchanger, cooling the argon to 300°K. (This low temperature heat exchanger could also be a direct contact type, similar to the high temperature droplet heat exchanger described above, but using a different droplet medium such as a low melting point metal eutectic or a silicone oil. The flow of heat in this case would be from the gas to the droplets.) The gas is then recompressed to 20 atm and 675°K prior to re-entering the high temperature heat exchanger. The cycle efficiency is 56% under these conditions. Assuming no electric generation losses, a pilot plant of 100 MW output would require 180 MW of thermal power to be delivered to the turbine inlet and would require an argon mass flow of 1.51×10^6 kg/hr and a mass flow of beads of 5.2×10^5 kg/hr.

Particle size is of great importance to the design of the heat exchanger. The height of the heat exchanger is strongly dependent on the particle size, scaling as shown in Fig. 6. However, smaller particles require more injector orifices to maintain the necessary mass flow of glass. Beads of 2 mm dia provide a reasonable compromise. To produce droplets of this size an injector nozzle diameter of 0.74 mm is required. The required mass flow of droplets is achieved through the use of 146,000 such nozzles spaced on a 1.1 cm grid. The injected streams of glass breakup in 0.34 m, which is a small portion of the heat exchanger height. The vertical droplet spacing is $\sim$1 cm.

Transfer of the required 180 MW is accomplished in a tower 11 m high x 4.6 m dia. The beads fall through this height in 8.6 sec. The velocity profiles of the beads and gas in the heat exchanger are shown in Fig. 7. Gas velocity is so low everywhere that its kinetic energy can be neglected. The relative velocity between beads and gas is close to but somewhat lower than the local terminal velocity at any point. The temperature history of the gas and the beads is shown in Fig. 8. The particle temperature T_p is averaged over the radial temperature profile in the beads. Although the droplets solidify during their transit, there is no release of heat of fusion due to the amorphous nature of the glass bead material.

End effects, the turbulence resulting from the presence of the cloud of beads and the interaction of the flow with the walls, will cause deviations from the simple one-dimensional flow assumed here. The magnitude of the deviations and their effect on the trajectories of the beads remain to be determined. Collisions between beads in the area of the heat exchanger where they are still molten will result in some degree of agglomeration which will affect both the heat transfer rate and the velocity relative to the gas of the individual particles. These effects will be the subject of future investigations.

Other effects which have received preliminary attention are injection and transport losses, vaporization of the refractory and working gas losses.[11] Briefly, the parasitic losses due to injection and transport of the molten refractory in the system presented here are estimated to be only ∿0.2% of the plant's net electrical output. The vaporization of the refractory in the heat exchanger has been calculated to be of the order of 10^{-3} kg/hr. When compared to the argon mass flow rate of 1.5×10^{6} kg/hr, it is evident that the contamination of the working gas is negligible. Similarly, the loss of working gas resulting from removal of the solid bead aggregate at the bottom of the heat exchanger is estimated to be only ∿0.05% of the mass flow of the gas.

The Energy Conversion System

Insofar as possible, the energy conversion system would be built around systems involving near-term technologies, with the exception of the heat exchanger. High efficiency Brayton cycles are possible, as indicated in our preliminary design study, or somewhat more sophisticated variations utilizing a simple Brayton cycle in a combined cycle system such as those currently being studied for combined coal power plants.[18] However, the technology here is expected to be simpler since the working gas is clean, enabling the maximum potential efficiency of such systems to be exploited. We again emphasize our desire to operate at high thermal efficiencies, provided the conversion technology does not prove too expensive. Preliminary studies indicate that this reflects favorably back through the entire system, including the heliostat field. For example, raising the thermal efficiency from 30% to 60% effectively cuts the size of the heliostat field in half or doubles the capability of existing systems. Even increasing the efficiency to only 50% is clearly significant. A conventional combined cycle utilizing the clean gas output of such a system contains the promise of efficiency in excess of 50%.

Acknowledgements

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TABLE I. PROPERTIES OF SOME REFRACTORY OXIDES

NAME	FORMULA	WEIGHT	FUSION PT.^{1,2} °C	BOILING PT.^{2} °C	HEAT OF FUSION^{2} (cal/g)	HEAT CAPACITY^{3,4,5} cal/g °C
alumina	Al_2O_3	101.96	2050	2980	256	.339
lime	CaO	56.08	2570	2580	218	.294
chromic oxide	Cr_2O_3	151.99	2435	4000	37.7	.220
magnesia	MgO	40.31	2830	3600	459	.360
silica	SiO_2	60.09	1713	2230	56.7	.360
zirconia	ZrO_2	123.22	2710	4910	168.8	.195

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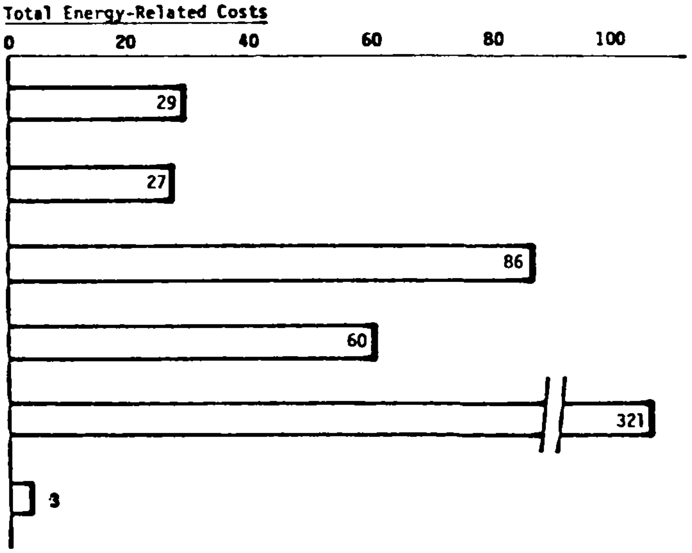
TABLE II. THERMAL STORAGE CONCEPT COST COMPARISON C_S (T/KWH)

Solar Thermal System	Storage Type	Total Energy-Related Costs
Water/Steam Receiver	Oil/Rock	29
Molten Salt Receiver	Dual Tanks, External Insulation	27
Liquid Metal Receiver	Dual Tanks, External Insulation	86
Hot Gas Receiver	Ceramic Brick, Welded Steel Tank	60
Organic Fluid Receiver	Oil/Rock	321
Proposed Integrated Molten Glass Receiver	Internally Insulated Steel Tank	3



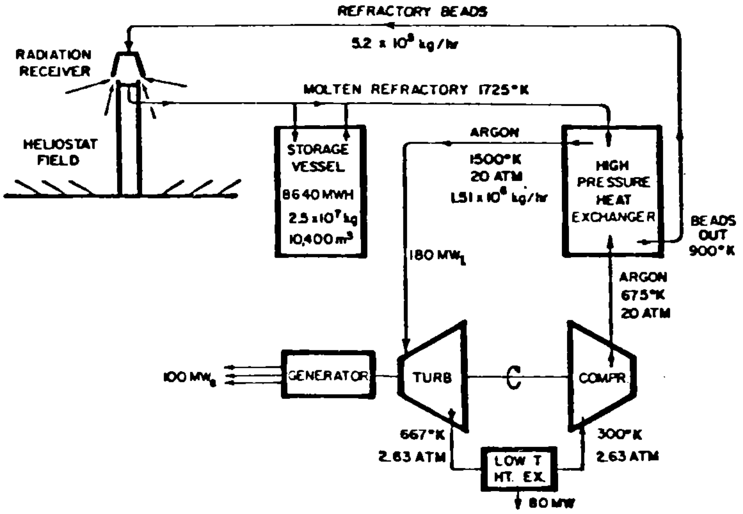


FIGURE 1. Schematic of Proposed High Temperature Solar Power Plant

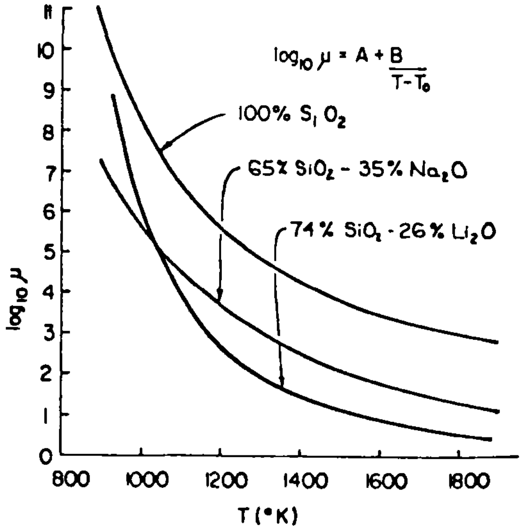


FIGURE 2. Effect of Alkali Oxides on the Viscosity of Silica

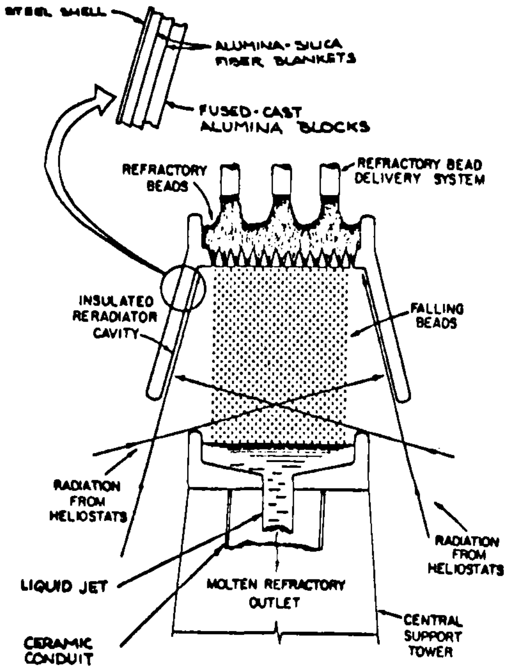


FIGURE 3. Schematic of Annular Flux Solar Receiver

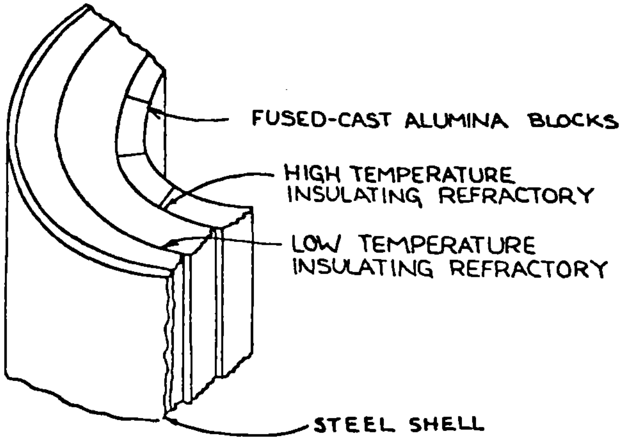


FIGURE 4. Storage Vessel Construction

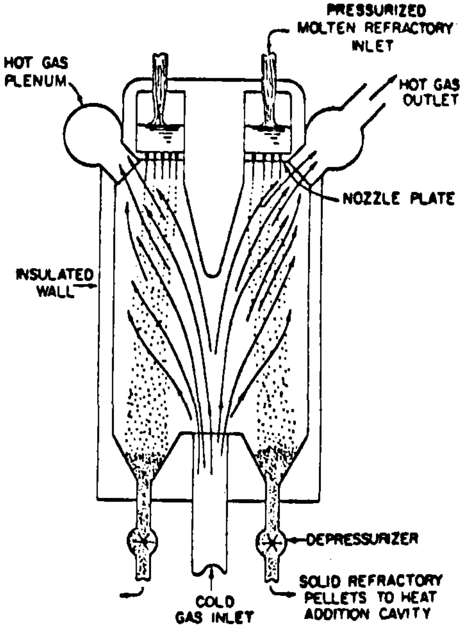


FIGURE 5. High Temperature Direct Contact Droplet Heat Exchanger

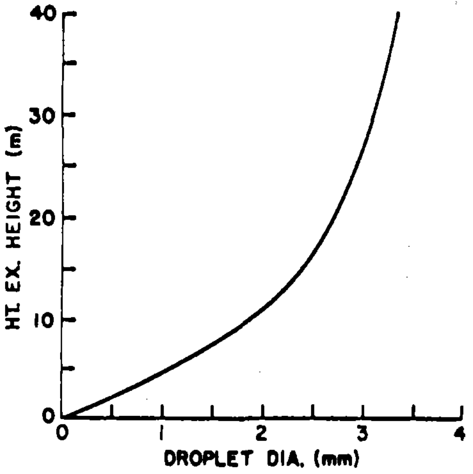


FIGURE 6. Dependance of Droplet Heat Exchanger Height on Droplet Diameter

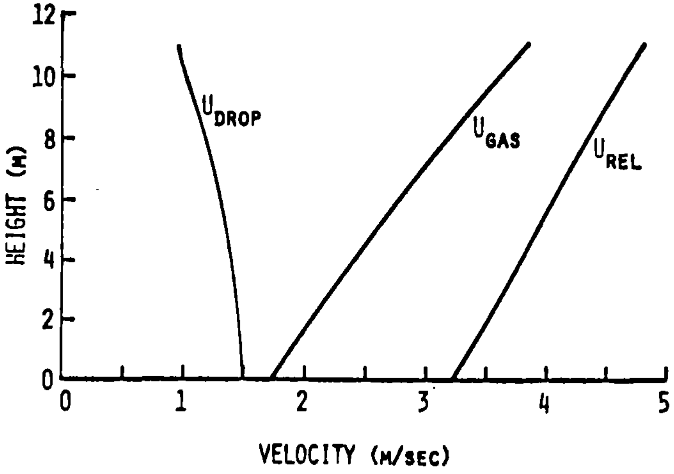


FIGURE 7. Droplet Heat Exchanger Velocity Profiles

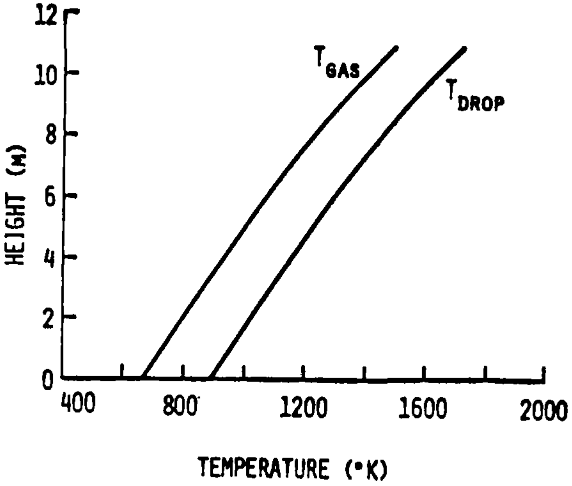


FIGURE 8. Droplet Heat Exchanger Temperature Profiles

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SOLAR POWER FOR INDUSTRIAL APPLICATIONS - 1500°F to 3600°F

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The work reported here was partially funded by the Department of Energy, San Francisco Operations Office. The purpose of the study was to investigate the potential of using heliostats to provide high-temperature solar energy for industrial applications. The primary emphasis in the current heliostat developent program has been on low cost designs which have been optimized for steam generation. These heliostats operate effectively in the temperature region of 600°F to 1200°F. However, many industrial processes require substantially higher temperatures. This study focused on the temperature range from 1500°F to 3600°F. Just from the speakers we have heard during the past two days, I think there is ample evidence that for fuels and chemicals processes it is this high-temperature region which is of interest.

The basic problem definition is: given an energy input, that input is consumed partially by the process and the rest of it is lost somewhere in the system. For this particular study, the energy input came from a heliostat collector field. The field itself has certain losses, but from the viewpoint of the receiver, the energy that is actually delivered to the aperture is utilized by the process or is lost. The losses are due to conduction, convection, and reradiation. These losses are primarily associated with the receiver and its operation environment.

A quick overview of candidate receivers shows that they fall into two classes, external and cavity. External receivers were primarily designed for steam generation so they're designed to employ fluids and usually do not permit any type of volumetric processing. By that, I mean processing some type of material that occupies a specific volume and requires the energy in that volume. In general, it has been shown in various studies that external receivers ar best suited for temperatures below 1200°F. However, current research indicates that some materials exist to allow operation upward to 1800°F.

On the other hand, cavity receivers can be used with both solids and liquids and provide a large processing volume. I think we have seen from virtually all of the papers presented during the past two days that some type of cavity receiver has been employed in the experimental work. The cavity receiver has been shown to be best suited for the high-temperature applications, particularly in the materials process field. Thus, constraining our discussion to cavity receivers, a solution to the problem of energy utilization is to minimize the receiver losses.

Conductive loss is best handled by some type of insulation technique and by minimizing the area through which the conductive losses occur. The convective losses present a more difficult problem. One solution is to shield the receiver or in some way reduce airflow around and through the receiver. This is particularly important for very large cavity receivers where conditions favorable to forced convection exist. Windows on the cavity aperture may also be used. Although, for many processes, the area that would have to be covered by a window and the internal cavity pressures are probably beyond our current window technology. As with conductive losses, an approach is to minimize the area through which the convective losses occur. Again, we're primarily concerned about convective losses through the entrance aperture.

Reradiation is a very serious problem at the higher temperatures. Windows again could be used, especially if they had selective coatings. However, no coatings have been developed as yet that are effective in the high temperature region. There has been some experimental work using gray gas to absorb the reradiation at the front of the receiver. However, its application to solid materials processing has not been demonstrated. Again, we can minimize the aperture through which the energy enters the cavity and through which it is also reradiated. At the very high temperatures, reradiation losses tend to predominate over conduction and convection. An example of how the reradiation losses go up with temperature is presented in Figure 1. At 2000°F the reradiation loss is less than 50 watts per square centimeter. However, at 3000°F and above, the losses, which are going up as approximately the fourth power of the temperature, become extremely severe. When the mid-3000°F region is reached, the receiver is reradiating energy faster than most surround fields can put it into the aperture.

Therefore, to achieve high-temperature operation, it is necessary to have a very high flux input. The input must be high enough to achieve the operational temperature, in spite of the losses, and still have energy left over to drive the process in question. This implies that the receiver aperture should be the smallest possible in order to minimize reradiation losses. In order to accommodate a small aperture, and at the same time introduce enough energy to the process to make the process economical, very high concentration ratios with a very small, well-focused image size must be achieved. More importantly, and this is something we don't hear discussed very often, image size has to remain relatively constant throughout the operational day and throughout the year.

The study presented in this paper was a computer simulation of a north field heliostat configuration. The study was conducted at the 1, 10, and 25 megawatt thermal level, but this paper only presents the results from the 10 MWt simulation. The design point was taken to be noon of the winter solstice, which is fairly common for north field configurations, and the 1976 Barstow insolation data base was used. The receiver was a north-facing cavity with an aperture centered approximately 8 meters above the ground. Heliostat reflectance was taken at 0.9 and atmospheric transmittance at 0.99, which is approximately right for this size of field. Included in the simulation was a ±3 millirad tracking error randomly distributed across the heliostat field.

The design point flux contours for this particular field are shown in Figure 2. The scale is in meters from the center of the receiver aperture. You can see that virtually all the energy was delivered within a 2-meter radius. The very high intensity part of the beam, 100 watts per square centimeter and above, was delivered within a 1-meter radius. This is a common flux contour plot but what is important here is the image size and the constancy in size throughout the day and year as demonstrated in the following series of figures. Figure 3 is a slice through the beam to illustrate flux amplitudes as a function of the hour of the day. It can be seen on the design day, the flux varied from 100 watts per square centimeter at 8:00 in the morning to 200 watts per square centimeter at noon. Figure 4 is the same type of plot for the opposite point of the year, which is the worst day for a north field. The peak flux was somewhat reduced, due to cosine factor, and only achieved about 165 watts per square centimeter. However, of significance here, is at 8:00 in the morning the flux was above 100 watts per square centimeter. I would draw your attention to the radial distribution again. The total beam has a radius of 1-1/2 to 2 meters which is comparable to the design day radius. Additionally, the radius which encompasses the 100 watt per square centimeter area is 1 meter, which is identical to design point. This demonstrates the constancy of the size of the image both throughout the day and throughout the year.

Figure 5 is a composite day, sort of an average of all the data throughout the year. It plots the hour, the watts per square centimeter, and the associated stagnation temperatures. It can be seen that it is possible to achieve 1500 degrees with a low flux input. To achieve 2500°F requires around 50 watts per square centimeter. This yields an average operational day which is in excess of eight hours. Even at 3000°F the composite operational day exceeds eight hours. However, as the temperatures approach the top range the operational day becomes more limited. At 3600°F the operational day is between five and six hours long and, in some of those hours, there is a very marginal amount of energy left over to be absorbed by or activate a process.

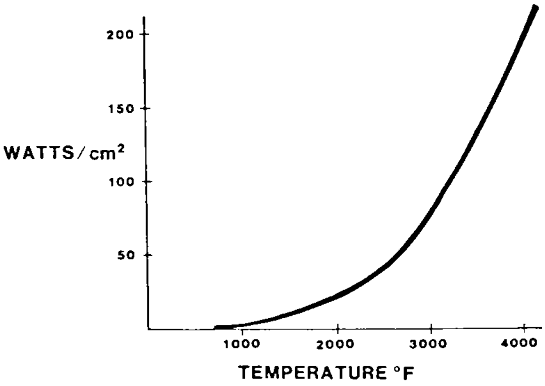
As pointed out in several discussions both here and elsewhere, before any of the solar technologies will ever be accepted by industry, we, as promoters of solar energy, are going to have to provide three things - or at least convince any industrial partner that it is possible to provide three things. First, we must provide a reliable energy input. Second, we must provide that input across a reasonable length working day. Third, we must provide that input throughout the working year.

The conclusion that may be drawn from this study is that it is possible to meet those criteria. Barring an occasional cloud, the sun is historically reliable. We can satisfy the criteria of a high flux density, with small image size, to make high-temperature processes operate. The length of our working day, while limited at very high temperatures, is at least 8 hours throughout the year up to 3000°F. The challenge now remains to discover and develop those processes which produce high value products and make solar energy an economically viable alternative.

Are there questions?

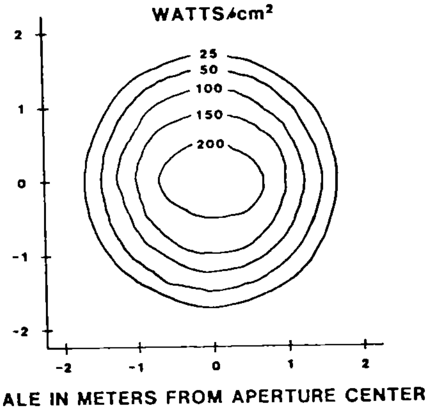
Holmes - What kind of heliostat did you assume would give you these flux densities?

Ehrhardt - It was a two meter by three meter heliostat on an equatorial mount with a toroidal mirror surface.



RERADIATION LOSSES

Figure 1



DESIGN POINT FLUX CONTOURS

Figure 2

DESIGN DAY FLUX VARIATIONS

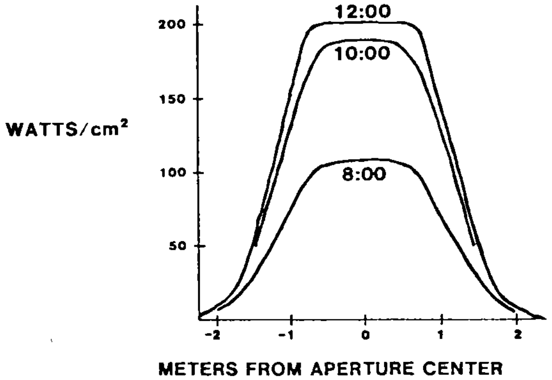


Figure 3

WORST DAY FLUX VARIATIONS

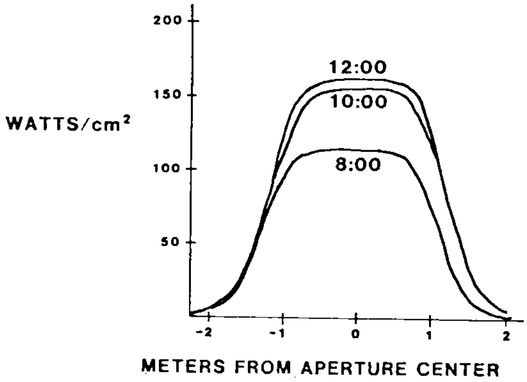


Figure 4

AVERAGE DAY TEMPERATURE CAPABILITIES

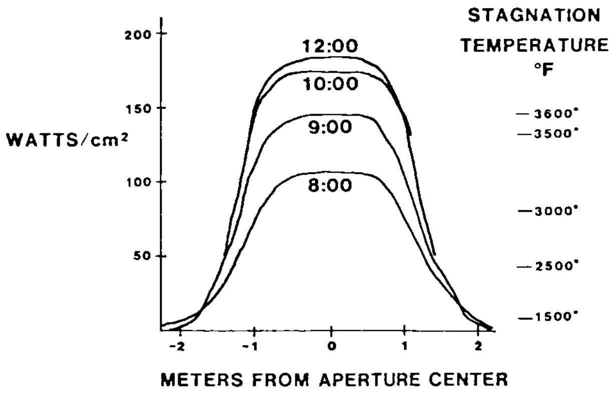


Figure 5

POINT FOCUSING SOLAR COLLECTOR SYSTEM

H. Hopmann, H. Zewen, J. Hofmann
Messerschmitt-Bolkow-Blohm GmbH

For solar thermal power plants the MBB Space Division has developed point focusing solar collector systems which differ significantly in their functional requirements. For instance, while the 100 kW_e KUWAIT plant follows the distributed absorber concept (Figure 1), the design of the 1 MW_e EURELIOS power plant in Sicily is based upon the central tower/receiver concept (Figure 2). In both cases the special design criteria had been selected in such a way that long-term trends in technology as well as in solar thermal systems development could be observed in addition to the general aspects of economy, transport to site, and maintenance.

Particular attention had been given to all design features which have immediate influence on the total plant efficiency and performance, either by the accuracy of the collector system itself or by the characteristics of the material employed.

The 100 kW_e power plant is installed in the desert of KUWAIT, 35 kilometers west of the capital (Figure 3). It forms the nucleus of a so-called solar-food-water-power-system just under construction at the Sulaibiyah agricultural test area of the Kuwait Institute for Scientific Research. The aim of the solar power plant is to provide thermal and electric energy to various facilities of the agricultural zone, such as pump stations, desalination plants, irrigation systems, greenhouses, and cold storage.

The development contract was awarded to MBB in May, 1978. In order to facilitate project control, the work plan was divided into three stages:

(1) development of critical components and prototype testing

(2) plant installation and acceptance testing

(3) application and test program

The project is funded primarily by the Kuwaitian Ministry for Electricity and Water, but it is also supported by the German Ministry for Research and Technology, particularly during the activities of stage 3.

The basic flow schematic is shown in Figure 4. A farm of parabolic dishes collect and convert the solar radiation into useful energy by heating up a recirculating thermo-oil to a temperature level above 400°C. For bridging over cloudy periods and to ensure steady-state conditions at the boiler inlet of the turbine loop, a thermocline storage system is installed. Because of its superior performance characteristics for small-scale prime mover systems, an organic Rankine cycle (ORC) has been chosen, using toluene as the working medium. In order to make full use of the advantageous properties of this cycle, a recuperator is assembled downstream of the turbine (see Figure 5). The collector field consists of 56 parabolic dishes, each 5-m in diameter (Figures 6 and 7). Thus, the entire collector area comes to about 1,000 m^2. It collects 740 kW thermal energy at specified insolation rates of 940 W/m^2. The mirror unit consists of a parabolic-shaped reflector surface subdivided into 6 systems (Figure 8). Thin glass facets of 0.9-mm thickness cover only the reinforced plastic support structure, guaranteeing high reflectivity values combined with good erosion and corrosion resistance.

The collected solar radiation is concentrated 200-fold and directed onto a spherical surface absorber (Figure 9). A reflective coating with protective glass jacket can be omitted in view of the relative small absorber surface and because of the chosen temperature level. The absorber is fixed directly to the collector steel structure, thereby avoiding flexible hoses and rotating seals. The absorber diameter amounts to 170 mm.

The applied absorber technology has been derived from the MBB technology for regeneratively-cooled rocket thrust chambers (Figures 10 and 11). The Sulaibiyah agricultural test area offers favorable climatic conditions so far as yearly average duration and intensity of insolation are concerned; rain and cloudy periods seldom occur during the day. The climate is hot, dry, desert type. Brackish water is found at the site in 70-m depth. As mentioned above, the conceptual design of the power station considered the final use of the plant for generating electric as well as thermal energy in the sense of a total energy system. Therefore, the condensation temperature of the ORC turbine loop was set at a level high enough to tap off useful thermal energy for the envisaged thermal users. Figure 12 shows the artist's concept of the final stage of the project.

In 1976, the European Economic Communities (EEC) placed a contract for a system definition study of a 1 MW_e solar thermal power plant. The study was performed by the industry of the participating countries--Great Britain, France, Germany, and Italy--and with the advice of Professor Francia of the University of Genoa. It was decided to base the ensuing project realization phase--the detailed design and components development phase--on the central tower-multiheliostat concept, using a cavity-type receiver.

The construction and installation work started in late 1978 and was finished at the end of 1980. Thus, EURELIOS represents the world's first solar power station connected to a utility grid. It is located near Adrano, Sicily, at the foot of the Etna volcano (Figure 13). The project was carried out by AMN/ANSALDO (Italy) responsible for receiver and steam cycle, CETHEL (France) providing the heat storage system, electric system and a part of the heliostat field, and MMB (FRG), which delivered the other part of the heliostat field. ENEL as utility company acts as host partner, being responsible for site infrastructure and later operation (Figure 14).

Two main aspects of the project topics should be mentioned:

(1) Operational requirements: The EURELIOS power plant serves as a demonstration facility to study the performance and functional behavior of the system itself and of critical components, e.g., receiver, energy storage and different types of heliostats. Moreover, it will produce electricity and will deliver this electric power into a public grid. Thus, the power plant will allow the study of electric power generation and grid interfaces of a solar power plant; therefore, it is a step beyond those facilities where strictly developmental work is done and where the thermal energy generated by the sun is not used further.

(2) The receiver design is based on previous small-scale experiments of Francia and ANSALDO (Figure 15). It operates at 512°C and produces 4.8 MW_t. The use of steam as cooling fluid allows the direct feeding of the turbine loop and the utilization of off-the-shelf materials and components (Figure 16). On the other hand, the cavity type receiver requires a more careful design of the heliostat field, its shape, dimensions, and capability for accurate focusing.

The heliostat field comprises about 6,200 m^2 reflecting surface and consists of two types of heliostats: one provided by MBB, one by CETHEL. Therefore, the entire field is subdivided into a west field (CETHEL) and an east field (MBB). Both portions are computer-controlled and linked to a master control system (Figure 17). For each heliostat the position of the sun and the required angles for azimuth and elevation are calculated by individual microprocessor units (Figure 18). DC motors bring the mirror surface into the predetermined position; deviations from the nominal positions will be detected by 13-bit encoders. Signals for plant operation and safety modes are given by the central unit, which represents the intelligent interface between the heliostat field and the plant control system with the master clock. Although MBB and CETHEL heliostats apply the same design principles and are subject to the same system requirements, they differ in many details, particularly with respect to dimensions and optical characteristics (Figure 19).

The reflecting surface of the MBB heliostat is 23 m^2. A tubular steel pedestal carries the drive unit on which the two steel structure wings are mounted (Figure 20). The mirror surface consists of 16 second-surface reflector elements, each of which is bent in two dimensions for a focal distance of 190 m. During plant acceptance testing, each heliostat element has been adjusted under actual conditions at the site (Figure 21). The maximum beam pointing error does not exceed 4 mrad at the nominal wind speed of 18 km/h (Figure 22).

The receiver is mounted on top of a 55-m high steel tower with an inclination of 110°. Its aperture diameter is 4.5 m. In the course of the ongoing acceptance test program the performance level of the receiver could be raised rather rapidly and without any major problems. The turbine-set was put in operation last month, and the grid surface has been checked. The plant delivered electricity into the grid for the first time on April 14, 1981. Therefore, we are confident that the plant will be ready for commissioning and test program performance under full capacity within a period of the next six weeks. The official inauguration is scheduled for May, 1981.

Fig 1 DISTRIBUTED ABSORBER CONCEPT

Fig. 2 CENTRAL TOWER/RECEIVER CONCEPT

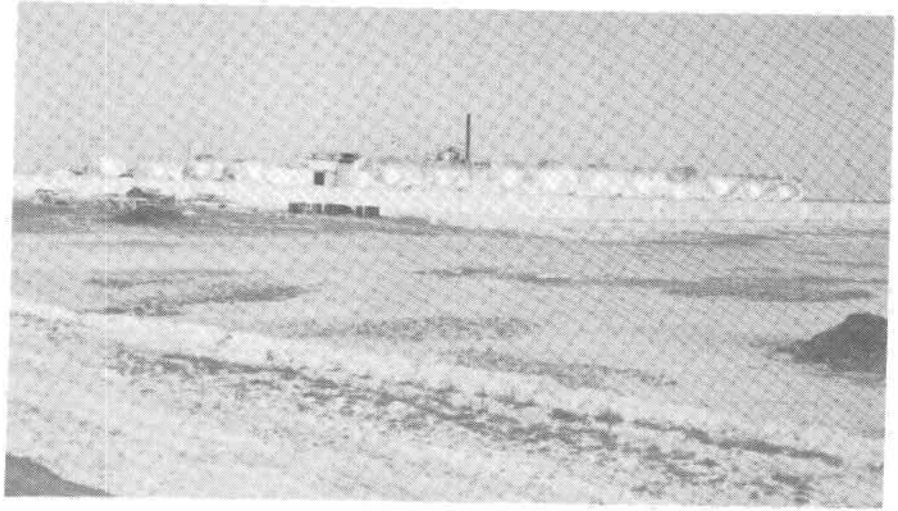


Fig. 3 100 kW_e SOLAR POWER PLANT IN KUWAIT

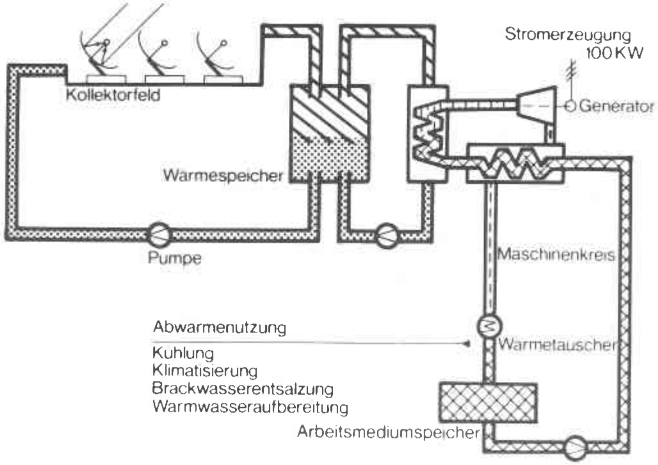
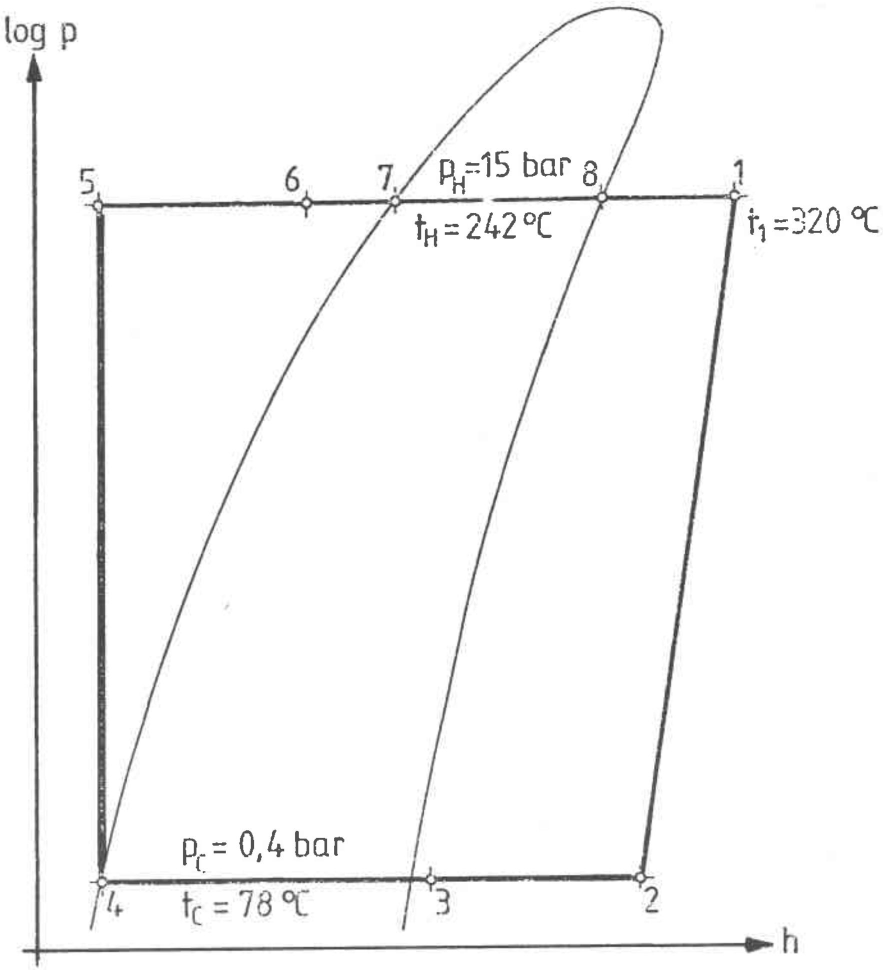


Fig 4 FLOW SCHEMATIC



1-2	Expansion Turbine
2-3	Regenerator
3-4	Condenser
4-5	Pressure Pump
5-6	Regenerator
6-7	Pre-Heater
7-8	Vaporizer

Fig. 5 TOLUENE RANKINE CYCLE

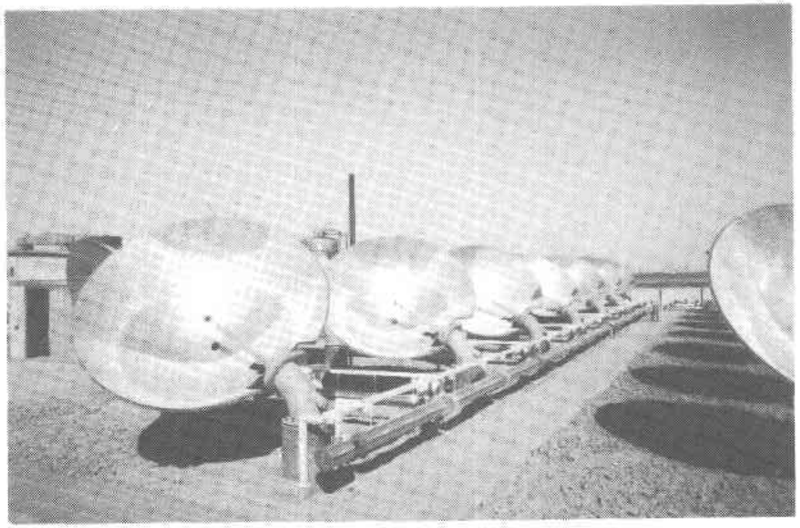


Fig. 6 COLLECTOR FIELD

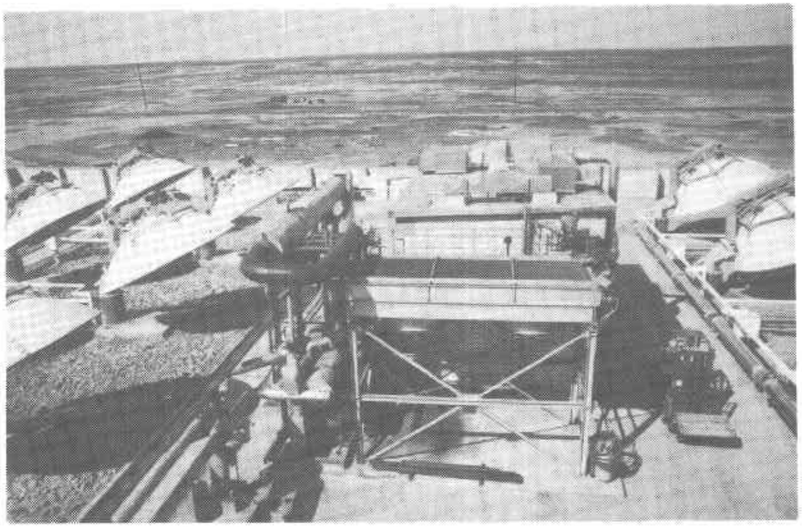


Fig. 7 AIR COOLED POWER CONVERSION SYSTEM

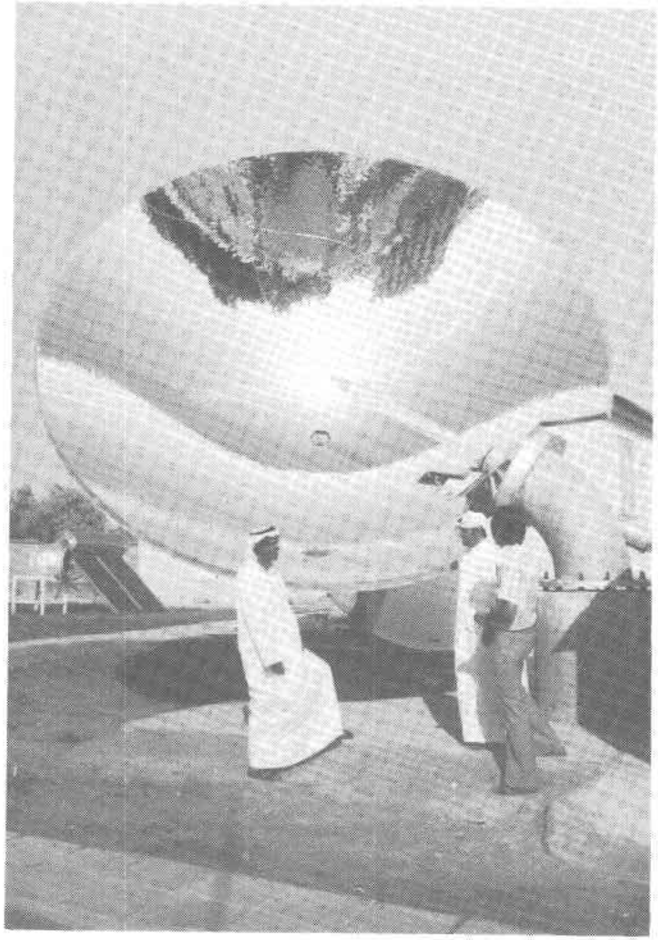


Fig. 8 POINT FOCUSSING SOLAR COLLECTOR

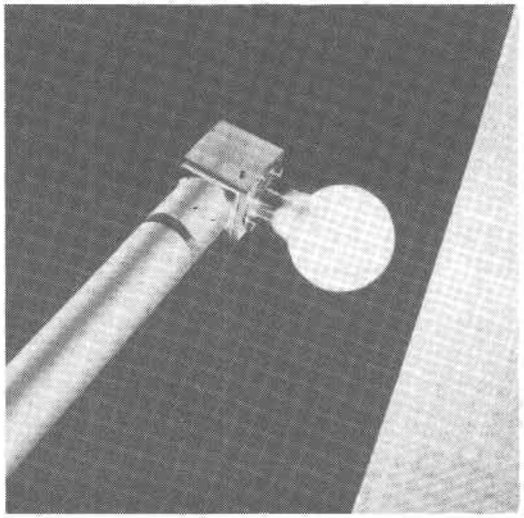


Fig. 9 ABSORBER IN OPERATION

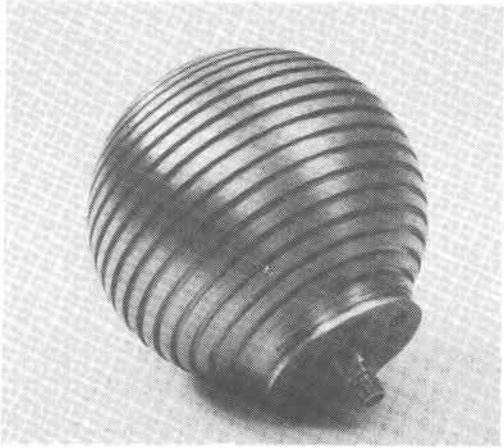


Fig. 10 ABSORBER BODY

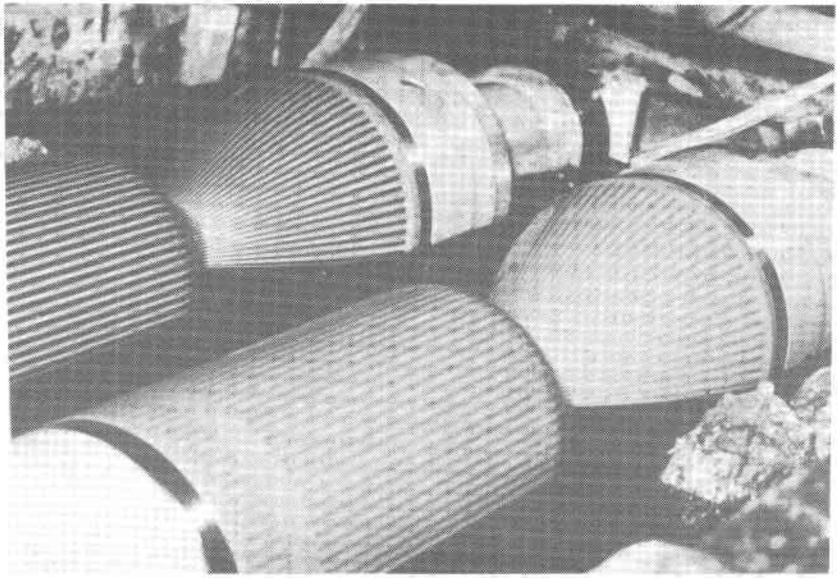


Fig. 11 THRUST CHAMBER MANUFACTURE PROCESS

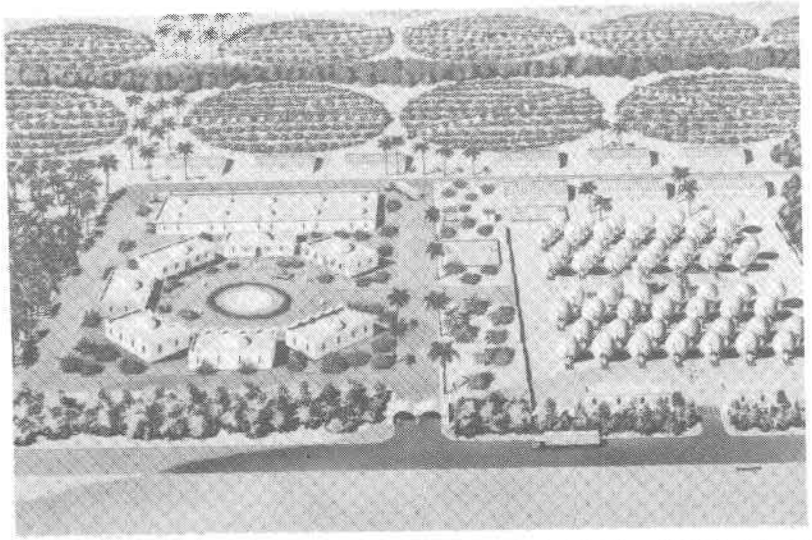


Fig. 12 SOLAR FOOD-WATER-POWER SYSTEM IN KUWAIT

Fig. 14 TABLE OF CONSTRUCTION

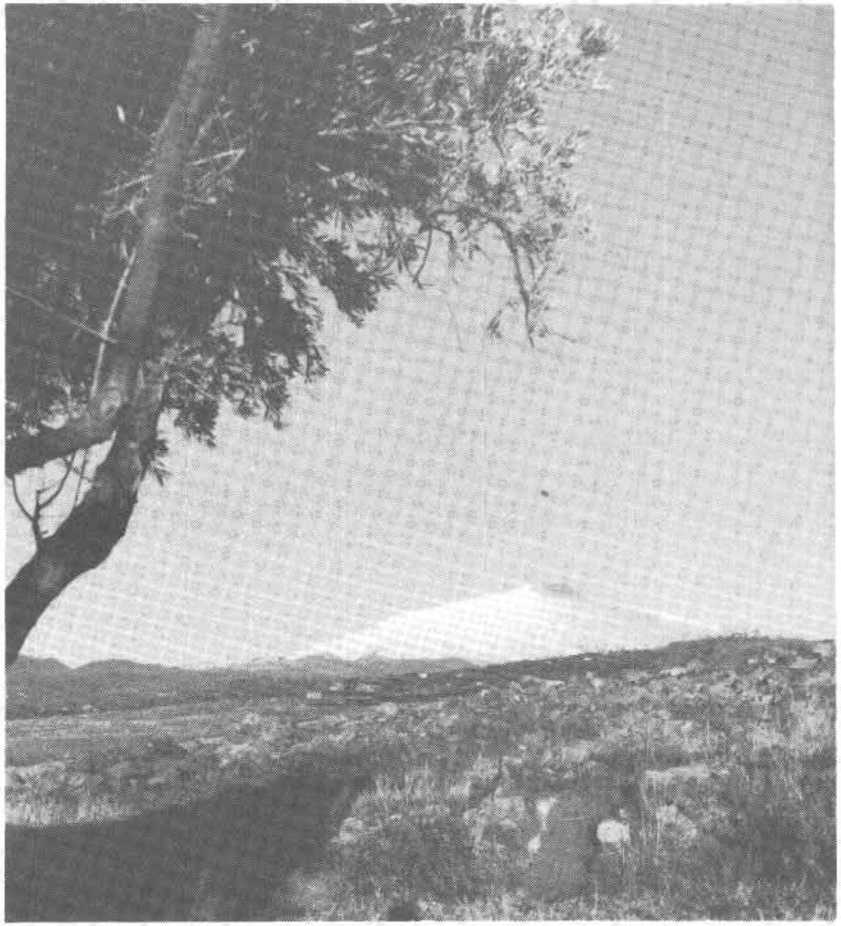


Fig. 13 EURELIOS SITE AT ADRANO/SICILY

Fig. 15 CENTRAL RECEIVER FIELD AT S. ILARIO/GENOVA

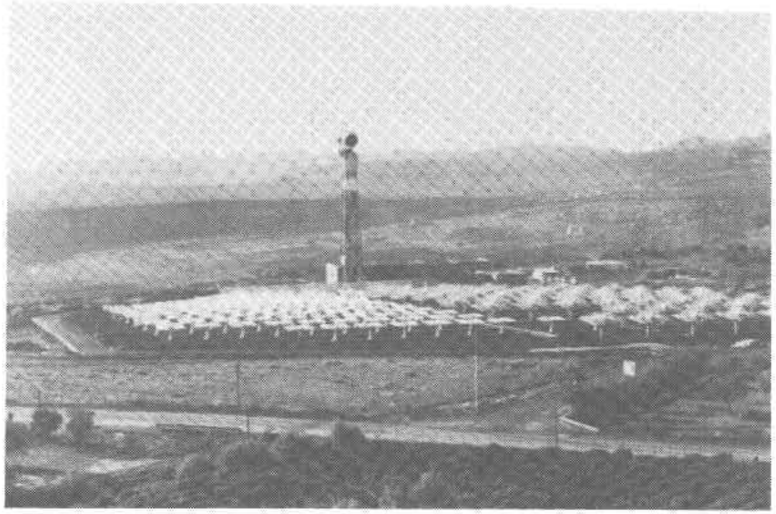


Fig. 17 PROSPECT OF THE EURELIOS PLANT

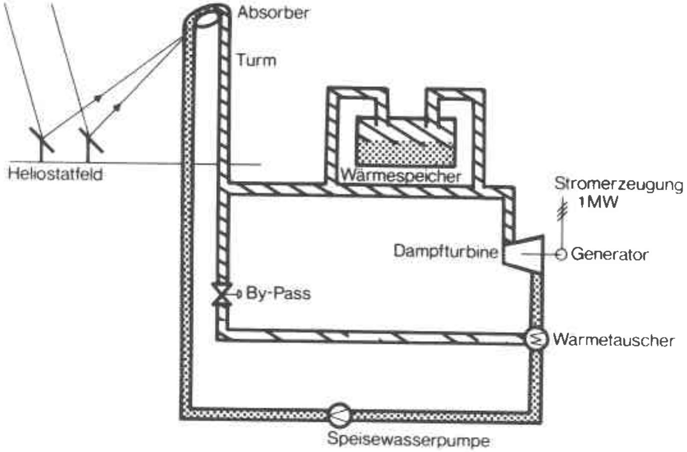


Fig. 16 SIMPLIFIED FLOW SCHEME

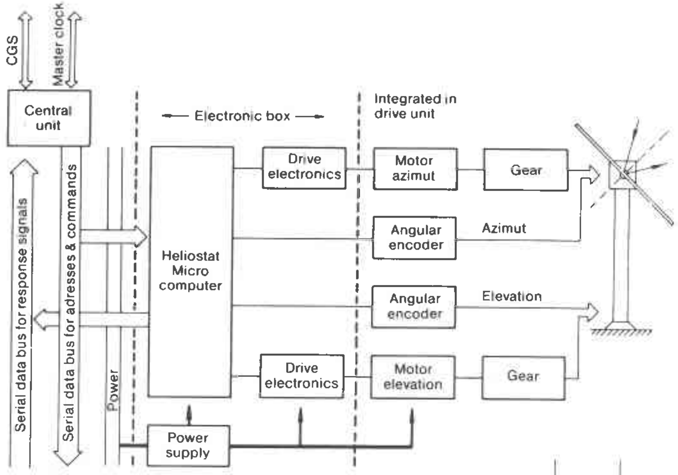


Fig. 18 BLOCK DIAGRAM OF THE TRACKING SYSTEM

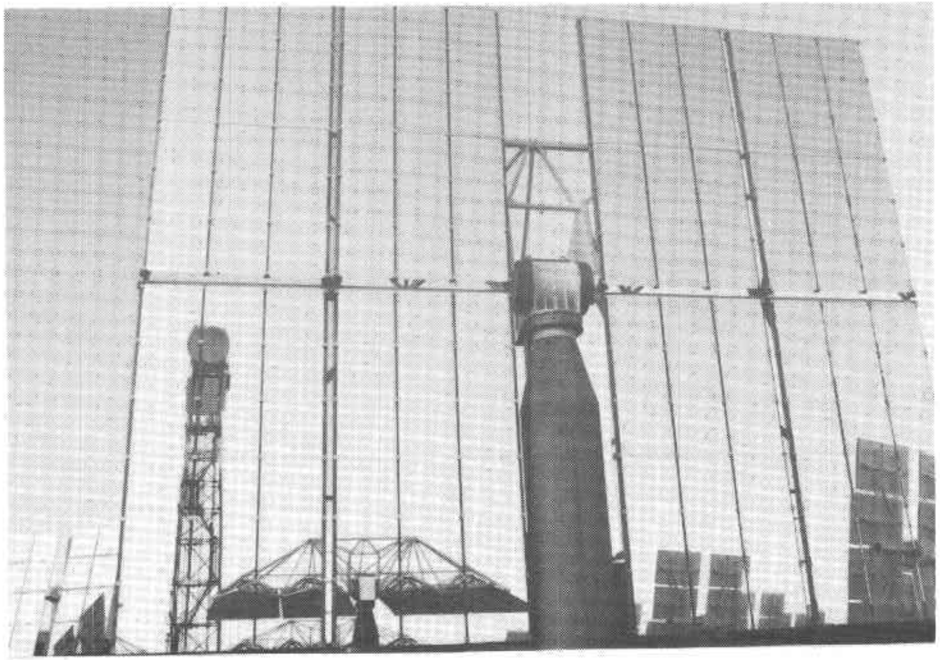


Fig. 19 CETHEL HELIOSTAT FIELD

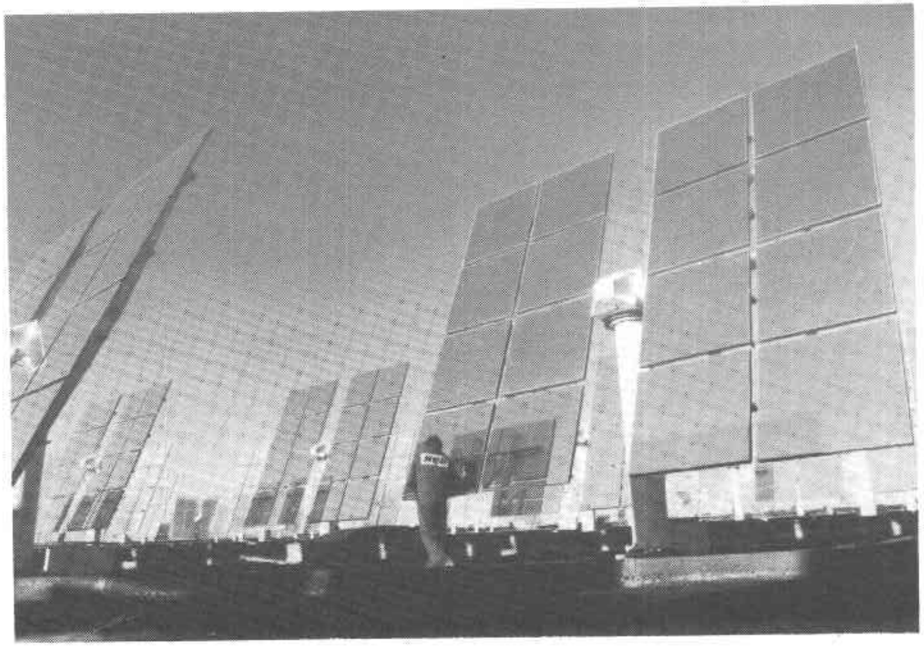


Fig. 20 MBB HELIOSTAT FIELD

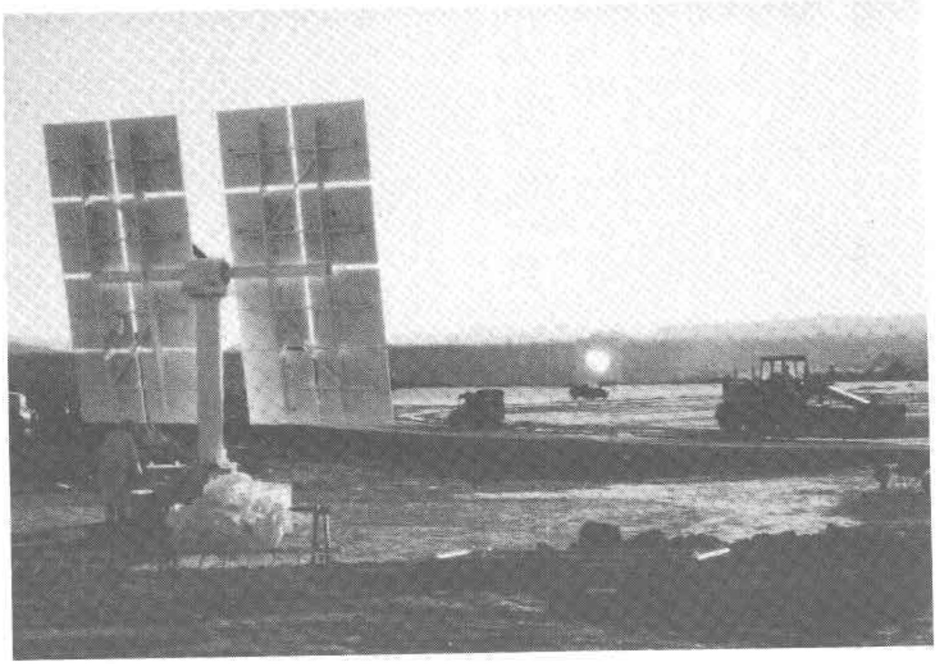


Fig. 21 BEAM POINTING ACCURACY; DISTANCE 190 M

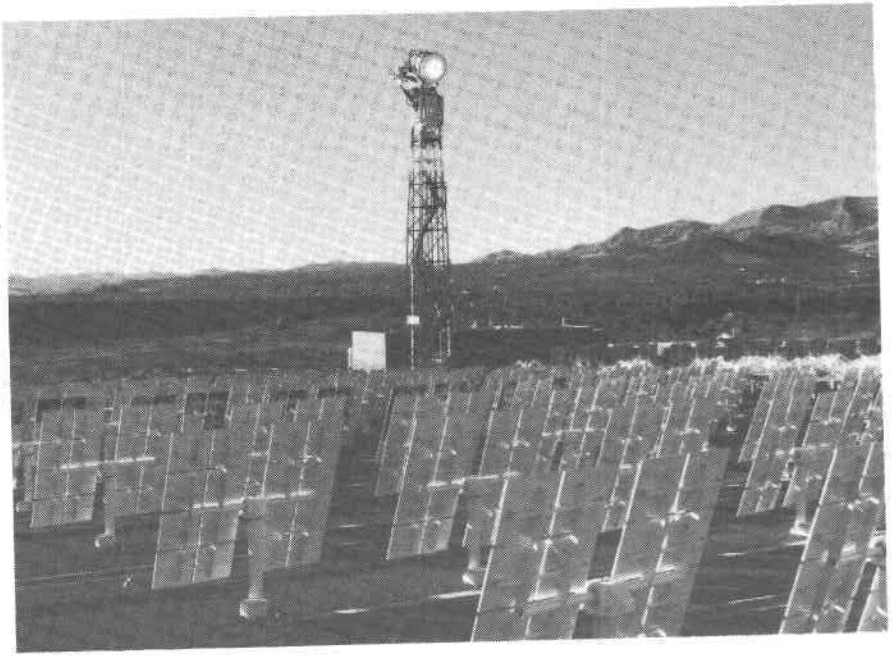


Fig. 22 HELIOSTAT FIELD ALIGNMENT

A SOLAR COAL GASIFICATION REACTOR FOR HYDROCARBON-FREE SYNTHESIS GAS

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ABSTRACT

In many applications, the hydrocarbon content of the synthesis gas produced in coal gasification is very valuable. In SNG production, the end product is a high BTU gas composed of methane and higher hydrocarbons. Futhermore, the liquid hydrocarbons can be even more valuable as feedstocks for other processes. In other applications such as methanol production, the hydrocarbon content of the synthesis gas is a non-reactive diluent that must be bled away from the product synthesis area to keep its concentration from building up. The liquid hydrocarbons that are a valuable product in a large-scale plant can cost more to remove from the synthesis gas than they are worth in a small-scale plant. In addition to the above benefits, this reactor requires substantially less steam in the coal gasification process.

The reactor is able to produce hydrocarbon-free synthesis gas because it withdraws the pyrolysis gases from the reactor as they are formed and reinjects them above the char gasification zone where they are steam reformed into CO, CO_2, and H_2. Since almost all of the hydrocarbon released in coal gasification come off with the pyrolysis gases, the reactor will produce nearly hydrocarbon-free gas.

An edited transcript of the presentation given at the meeting along with the viewgraphs used is printed herewith.

"Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48."

(Viewgraph 1 Presented)

DR. AIMAN: I am going to tell about a new idea. We applied for a patent on this concept on the 6th of this month. It is a solar coal gasification reactor for hydrocarbon-free synthesis gas.

(Viewgraph 2 Presented)

The first thing to discuss is why would anyone want such a thing. Normally, in coal gasification, we want the hydrocarbon in the product gas because we are talking about making synthetic natural gas to put into a pipeline, and all of the hydrocarbons are valuable. However, in some syntheses, the hydrocarbons are a nonreactive diluent, which must be removed in order to prevent build-up in the product synthesis reactor. Methanol is one example. The methane is nonreactive on the methanol-forming catalyst. A second advantage of this reactor would be the absence of tars and phenols. Even though they are quite valuable, they are difficult to remove from the product stream. In a small plant, they cost more than they are worth.

A third advantage is that this reactor uses less steam in the feed because the bound water in the coal is recycled in the process to react with the char. In countercurrent processing, the water that came in with the coal goes away with the pyrolysis gases, never contacts the char, and is not usable in the char gasification reaction. Energy is required to generate this steam and, in the Southwest United States, providing water is a problem.

(Viewgraph 3 Presented)

This process is based on the coal chemistry that I discussed in my earlier paper in this conference.

(Viewgraph 4 Presented)

Coal gasification occurs in two steps: pyrolysis and coal gasification. The hydrocarbons are released in the pyrolysis step. These pyrolysis gases can be recycled into the char gasification zone where they are steam-reformed in a process similar to the char gasification reaction.

(Viewgraph 5 presented)

This is the reactor. I will go through this reactor from three different standpoints. What becomes of the solid phase, what becomes of the gas phase, and where the energy goes.

Coal enters the reactor at the bottom through a coal-feed device. This might be an auger or something else that forces the coal up into the reactor. The coal then comes to the pyrolysis front where the coal is converted into char, pyrolysis gases, and tars. These gases and tars are the hydrocarbon species from the reaction. The char is forced on up through the reactor to the gasification front where the steam-char reaction occurs with the energy supplied by the focused solar energy. The char is gasified and the remainder, the ash, is removed by an ash removal process, not currently specified. That is what becomes of the solid phase.

Now, the gaseous phase, starting with the pyrolysis gases released in the pyrolysis front. They are removed from the reactor with the blower. Steam is added to this stream, and it is reinjected at the top of the reactor. The steam reacts with the char endothermically to produce synthesis gas. The hydrocarbons in this stream are steam reformed on the hot char. The reforming reaction is very similar to the char gasification reaction. The hydrocarbons are simply ripped apart and turned into CO, CO_2, and hydrogen. The gases from the gasification front flow down through the reactor. Part of these gases are removed as a product gas. The remainder of the gases flow on down into the pyrolysis front. That covers what becomes of the gas phase in the reactor.

Now, the energy distribution in the reactor. The focused solar energy comes in the top, supplying the endothermic reactions with energy at the gasification front. The hot gases out of the gasification front contain more sensible energy than is required to pyrolyze the coal that supplied the char that was gasified. You may recall from my first presentation that if you allow the coal to pyrolyze freely, using up all of the sensible energy in the gas phase, you only gasify 70 percent of the char. That means there's more sensible heat in the gas phase than you really need, and we can withdraw part of the gas as product gas and still have enough sensible heat to drive the pyrolysis reactions down at the botton of the reactor. That's the key concept of the whole scheme. Because those gases have more energy than is needed to pyrolyze the coal, these two fronts will separate in the reactor. This reactor now will produce hydrocarbon-free product gas.

(Viewgraph 6 presented)

In summary, a clean, tar-free synthesis gas is produced. This can be a major economic advantage for small plants. Because the water that came in with the coal was vaporized and recycled up to the top of the reactor, this water is available for gasifying the char, and a minimum amount of steam need be added to the reactor. The hydrocarbon-free synthesis gas is a more desirable feed for certain processes such as methanol synthesis.

DR. COLE: Questions or comments on this paper? Would you identify yourself, please.

MR. DAVIS: Sam Davis, Sanders.
What is the impact of coal impurities such as sulfurs and the like on the process, and what temperatures or pressures do you run in the reactor?

DR. AIMAN: Well, the primary impurity that would survive the process is the sulfur. The other species in coal that we worry about, such as phenols and such as that, would be steam-reformed on the hot char, and they would simply be gone. The hydrogen sulfide would be present. You would have to deal with it at a later point in the process. In methanol synthesis, I think sulfur-tolerant methanol synthesis catalysts are coming along; so it might be that you could separate the hydrogen sulfide after product synthesis, which would be very desirable.

As far as pressure is concerned, the primary reason why you run at pressure in a coal gasification reactor is to reduce the size of your downstream processing. As far as the effect of the pressure on the reactor, it is just a matter of making it strong enough, building a window that will stand the pressure. If you go to really high pressures, you can start forming methane on the char from the hydrogen produced in the char gasification reaction. Other than that, it would have little effect.

DR. COLE: Will Beattie?

DR. BEATTIE: Beattie, Los Alamos.
When you pyrolyze the coal, you will get some very heavy (unintelligible) compounds that are tars. How do you plan to move those up to the top since they'll condense on the walls of your blower and everything else?

DR. AIMAN: Well, I have a quick, easy answer for that. Keep them hot. Don't let them get cold.

DR. BEATTIE: Some of them, I think, will deposit the char on the blower rather than move up.

DR. AIMAN: That is a possible difficulty. It depends on just how the pyrolysis occurs.

DR. COLE: If there are no more questions or comments, let's thank our speaker.

A Solar Coal Gasification Reactor for Hydrocarbon-Free Synthesis Gas

William R. Aiman and David W. Gregg
Lawrence Livermore National Laboratory

FIGURE 1

- In some syntheses, hydrocarbons are non-reactive diluents, nuisances that must be bled away to prevent build-up.
- In a small plant, not having tars and phenols would be an advantage.
- Less water would be needed because the "bound" water in the coal is recycled to react with the char.

FIGURE 2

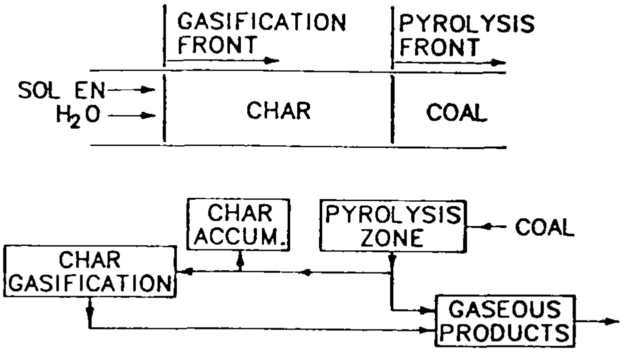

FIGURE 3

- Coal gasification occurs in two steps:
  1. Pyrolysis.
  2. Char gasification.
- The hydrocarbons are released in the pyrolysis step.
- The pyrolysis gases can be recycled into the char gasification zone where they are steam-reformed.

FIGURE 4

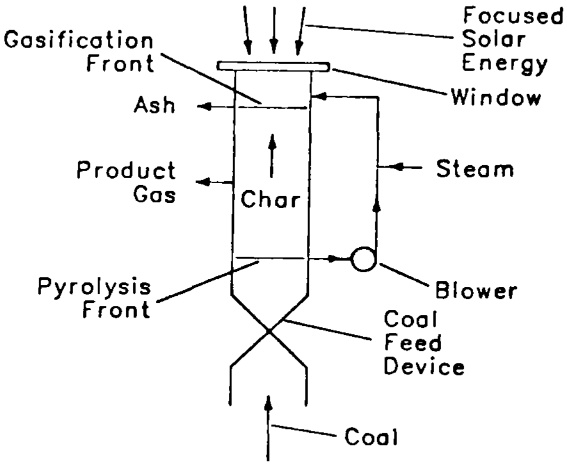

FIGURE 5

SUMMARY

- A clean tar-free synthesis gas is produced, an advantage for small plants.
- A minimum amount of water is required, an advantage in dry Western areas.
- The hydrocarbon-free synthesis gas is a more desirable feed for certain processes such as methanol production.

FIGURE 6

WORKSHOP SUMMARY DISCUSSION

Gottfried Besenbruch, Chairman

Besenbruch - From Bill Kaspar's very interesting talk, it is clear that DOE is looking for a program where the development effort will result in a successful demonstration of a solar thermal fuels and chemical project similar to Barstow.

The primary problem is that the funding decision is to be made within the next three months. Even with the best qualified people involved, the time frame, in my view, is insufficient. I think the Users Association should carry some weight in the decision because of the potential contribution of those who have performed experiments at the CRTF, ACTF, and WSSF. However, I know they are not being utilized, and I think this is a mistake.

Since money is becoming more scarce, perhaps we should have several R&D categories in which the first step would be to demonstrate the feasibility of the system itself. This could be accomplished at a much lower cost without using the solar facility. The next step would involve going to the facility and demonstrating the solar process interface.

This brings me to another thing I've mentioned a couple of times during this meeting. We have heard much talk about the demonstration of the feasibility of processes in the solar environment. I'm not sure whether feasibility has been demonstrated in 10- or 30-minute experiments, especially since each experimenter reported some type of materials problem. I believe the interface between the process and the materials is going to be one of the critical problems. In the area of industrial development, the developmental phase for a pilot plant is generally between two and four years, with an additional year of operation to establish all process parameters. We are talking about something like this in the solar field. The solar users, the facilities themselves, have seen only a very small fraction of their potential use.

I agree with others who feel that the Users Association should take a prominent role in compiling a worldwide list of solar facilities, establishing a central point for obtaining information about the facilities and the work being accomplished.

Frank mentioned that all the Users' work should be gathered into a comprehensive publication in order to demonstrate what we are doing.

Also, we need to broaden our audience by taking our message to meetings which are much more public; for example, we might persuade the ACS or the Gordon Conference to have a special session on solar systems.

Another possibility would be to compile a report on facility operations as a function of time. The mirrors have been in operation at some of the facilities for five or six years. Industry is always saying, "Your mirrors are not going to last; what is going to happen with all the storms going on?" There should be some way of publicizing the fact that those mirrors do last (assuming that they do). This information should give industry some confidence in the work we are doing and in the systems we are testing.

I definitely feel that the Users Association should be assertive about helping the DOE in its decision-making effort. If they make a choice without us, all our knowledge and operator experience will not be taken into account.

Another point was apparent in several papers presented at this workshop: Aiman and Ehrhardt said the same thing: If we want to talk about fuels and chemicals, those processes are generally 24-hour processes. They don't want to run 4 hours with a 2-hour startup and a 2-hour shutdown. We will never make an economical or even a feasible system of it. We must find a way of hooking up a chemical 24-hour process to an 8-hour process. This is a key problem, and if we can't answer that, I don't think we will ever have a solar fuel and chemical system.

For example, Bill Aiman talked about a solar plant costing $2 billion as compared with $5 million for a coal-fired plant. Industry just won't buy this initial capital outlay for a solar system, despite the fact that in the long run they are better off than at a coal cost of $2 or $3 or $4/gigajoule. An effort must be expended in the area of heat storage, of energy storage, and we must find innovative ways of hooking up the sun to something which runs 24 hours.

This is an open discussion period. Please feel free to comment if you wish.

Walton - I disagree with your last statement. We should be aware of two points that were brought out at this meeting. One is that we must look at high-cost, small-volume markets, as Jean-Pierre mentioned today. In this situation, where the product is expensive and the market is limited, a 24-hour-day operation is not needed.

Mike Antal mentioned that there is no start-up time on his process. If a cloud comes along, he simply stops until it has passed by. Therefore, I think that in regard to small-scale work in particular, we would be mistaken in saying we are going to have to develop solar systems with long-time energy storage capability.

The second thing is, if heat is all we want, I believe we are going to defeat ourselves. If we only want Btus at 1200°C (or the like), we're going to lose out, because of our cost disadvantage. We should not be attempting simply to replace high-temperature thermal energy with solar energy. Concentrated solar energy is high-temperature radiant energy, and that is unique in the high-temperature field. Because it is unique and because it has not been widely studied in the past, we know very little about its use in developing new high-temperature processes. Mike Antal has emphasized the need to take advantage of the unique characteristics of solar energy. Of course, we will need transparent reaction vessels to contain the materials we want to react; then the experimentation begins. When we start doing these kinds of experiments on a large scale we may discover that we can produce chemicals or processes using high-temperature radiant energy processes that we may have done inefficiently in the past, or may never have done at all.

If we are going to look at things that are unique to solar, we can also use solar simulation. Xenon lamps are pretty good simulators; there are high-pressure xenon arcs and other systems in use in the Ultra-Refractaires Laboratory at Odeillo, where they never worry about sunshine.

Again, I would like to see a large number of small 5-foot diameter concentrators located at various places around the country, so experimenters can test their ideas without having to travel to Georgia Tech or Sandia or somewhere else. When the experimenter gets an idea he can go up on the roof of Mechanical Engineering or Chemical Engineering and try it. (Georgia Tech has two of them--a vertical axis and a horizontal axis.) I think this is the best way to get the new ideas and discoveries we are looking for.

My final comment concerns a statement made earlier today about the criteria that are going to be used to select existing processes for solar chemicals and fuels demonstration. There are no existing solar process, and I feel that if we accept those criteria, we will also accept a penalty, because none of the processes I know of use concentrated radiant energy. That means we are going for Btus, and to me, this means we are in trouble. I agree that the people establishing these criteria must be extremely knowledgeable on these points. Otherwise, they will set up criteria which will penalize solar and prove five years from now that it costs more to get 1200°C using solar energy to carry out some process than the way its being done using conventional fuels. There are all kinds of traps built into these criteria because the high temperature industrial processes in use today have tremendous resources and a long time of development and optimization behind them, based on traditional energy sources.

Ehrhardt - If we can produce high flux radiation, even for only six hours per day, we can probably run a process which has never been run before. The petrochemical industry did not exist 200 years ago, and now they are giants of the world.

A great deal might be accomplished with suitable experimentation, but I don't know where the funds will come from. It probably won't come from industry, because they are interested in preserving and making more economic products than they presently do. It appears that money is not forthcoming for the fuels and chemicals area. This is an entirely separate problem. I am speaking of money to look at processes which are primarily photolytic in nature, which do something with this beam and make a product that cannot be produced by any other means. It makes no difference whether you run 1, 2, or 20 hours/day because you are making something that nobody else can make. I think Mike was alluding to this in his talk. The original concept behind his experiment was to produce something that was being produced in another way, and in the process of experimentation, he discovered products that cannot be produced any other way to make his process economical, almost regardless of the cost input.

Besenbruch - If I understand you correctly, you are saying you will go back to the very basics and try to invent some new processes that are solar-specific. I don't think that's realistic anymore. It's going to be extremely difficult and time consuming, taking 5 to 10 years. We are talking about providing funding to some existing systems. You are telling me to go back to basic research.

On the other hand, the Germans go to Kuwait, build a 700-kW facility, and they are going to operate it. A lot of information will come from that, and they will discover how to improve it and make it more valuable.

I'm not sure which is the right concept.

Ehrhardt - They are two different things. One is the generation of electricity and the other is the generation of fuels and chemicals.

Besenbruch - Their facility is hybrid--700 kW for electricity and 500 for thermal. It uses the thermal energy as we have been talking about.

Silverstein - I understand J.D.'s point, but we must not forget that our interest in producing fuels and chemicals is to assure that products currently produced based on the availability of oil and gas will continue to be available in the event that existing natural supplies are curtailed. We can't afford to forget that.

It's fine to talk about selective, specific processes which are unique in their capability, but I don't think a program can be established on that basis. The program must be developed on the basis of meeting a specific national need, addressing the critical energy problems facing the country right now. To the extent that Mike Antal comes up with a better process that does something unique with solar energy, that's excellent. It should be included as part of the program, but I don't think it can be the one central theme of the program.

Hildebrandt - I agree that the national aspect is important. If you look at the fuels and chemicals program, I have a few comments on why it wouldn't succeed if it takes certain paths.

If you make a particular very small company rich by that particular technique, then to a certain extent the problems will be the same as in other areas. You get almost there, and then it's an industry problem that they are supposed to develop. We do need the kind of thing J.D. mentioned; we need a number of the small things that will ultimately make companies rich. On the other hand, I don't think that will be the big project of national scope that Kaspar was talking about.

I believe the national problem on fuels and chemicals must place emphasis on a very general problem like production of hydrogen or ammonia, in contrast to heating rockwalls and making portland cement, for example. To a certain extent, the IPH market has been looked at in detail, case by case, and there really hasn't been a breakthrough for going in this system's direction because it is on an individual case-by-case operation rather than being a national problem.

How does one address a national problem? Let's center on discussing, say, 600°F steam. In the case of IPH, we have avoided steam delivery systems, hot oil delivery systems, or the chemical heat plant system. Why? I don't understand the reason, because if we draw a parallel and look for a large program, I think it will have to be along the utility line because that can be termed a national problem. Barstow is there because it is tied in with electric utilities. Although utilities, both public and private, are profit regulated, it was accepted that they need some support. This is a problem of national scope, not limited to just one small sector. So, I still think developing the utility concept to the IPH-type market has been repeatedly overlooked. Why does DOE continue to avoid saying yes or no to something like the Germans are doing on EVA/ADAM. I am an advocate of doing something specific, but if these reviews are going to be meaningful, like in the Veda Corporation, they should answer why something like the EVA/ADAM system is not followed. I mention this because they have been looking into this system, have invested a lot of money, and are trying to go down that path. I think this could be connected to our type of utility system.

Furthermore, I think it is possible to get some financing, some federal participation. If it is a national problem, you can get IPH heat in a uniform way, but if it is done case by case, you will stop far short of even a factor of two. Going back about five years or so, I think the approach of Hank Marvin and the DOE was very much on target. Tom Springer and I were looking at some specific graphs, and I think that in many cases we can look at being within a factor of two for some of the electricity delivery systems. There is still the problem of getting to the public sector, but in going case by case, looking at photolytic reactions and electrolysis and sheetrock, etc., the testing will not proceed within a factor of two. I am afraid that five years from now, we would have all these batons sticking out of DOE with nobody to pick them up. In a way, it's been hard enough getting into the utilities. Perhaps I should ask the question: Should there be something besides a uniform utility product, some temperature delivered in hydrogen and ammonia? Is there something else that really presents a national problem?

Silverstein - I think the national problem at the moment is not hydrogen or even ammonia. The national problem is how to make sure that there will be enough gasoline for our cars the next time there is an oil cut-off. The most apparent national need is the ability to produce synthetic fuels. This can be done with solar.

Hildebrandt - Which system?

Silverstein - That's not material at this stage. There are a number of systems. If solar energy is made available to provide the feedstocks needed for synthetic fuels--hydrogen in particular--and if it is also made available to provide the heat of reaction, then there is a very significant impact on national need.

I think we have to be very careful when talking about hydrogen because hydrogen is fine, but at the moment hydrogen, per se, is not an end product. In virtually all its uses, hydrogen is used for a feedstock to make something else. I think hydrogen is an essential, and it's going to have to be an essential part of any of these solar fuels and chemicals programs; but I think you can run into problems if you talk about producing hydrogen, per se. It must be thought of as a means to producing a desired end. Today's energy problems will not be solved by the production of infinite amounts of hydrogen.

Besenbruch - We have to throw them away.

Silverstein - That's right, and if you look at the way hydrogen is used today, whatever it is, it is the equivalent of 300,000 or 400,000 barrels a day. And very little of that is virgin hydrogen which is produced and shipped to someone. It is used as part of the dedicated plan, and most of the time it doesn't even appear as a separate stream. It is mixed in with carbon monoxide in most cases. I agree that there must be a national approach, but be very careful about highlighting hydrogen. It is a means to an end, and I think that end is some sort of fuel. I'm sure there's room for discussion as to what that end should be.

Hildebrandt - I agree with you basically, but again, it's in the concept of having a national impact because it's not just solving one specific problem.

Silverstein - Right, and as I said before, there is room in the program for looking at a specialized situation in which solar can do something unique. That's fine; let's push it and develop it. But as you say, that is not going to have the national impact, and you can't sell a program on that basis.

Besenbruch - Yes. If we go back to square zero to the funding level, we'll just slowly dribble off into oblivion.

Silverstein - Gottfried, your point about the 1985 goal is well taken. It deserves a lot more thought, and I don't think it necessarily follows that just because Bill Kaspar said they are thinking in terms of 1985, that it has to happen that way. I also agree that if they get additional input, let's get our thinking in order and determine what we want to do before we start deciding now that we are going to have a major demonstration grandstand-type program. If these things are made known, there is a possibility of impacting that thinking.

Besenbruch - I don't know what we can do. Since Frank has done a lot of work with Gerry Braun on the Multi Year Program Plan, perhaps we should suggest that he approach Kaspar, requesting that he (Smith) or someone like him be permitted some input toward DOE's decision-making effort.

Springer - I think it would be better for us as an organization and association to agree on some good, solid recommendations before asking Frank to approach Kaspar.

Besenbruch - I hate to finish this meeting with saying, "Yes, we should do something," and then we'll never do a thing about it.

Smith - I'd like to mention several points. First, I'm delighted to hear this discussion because I don't think we will come up with an answer this afternoon. Also, if given a choice, I would have to agree with J.D. because I believe we are not going to win against the traditional fuels. From the standpoint of economics, I don't believe we are going to win in the 5-year time period. However, we cannot ignore it if this is the way DOE is going. We face a dilemma, which is just what we were discussing, and I do not know the answer. If the Users Association takes it upon itself to jump in and try to decide for Braun or Kaspar just which program is going to be the big winner, it's great if we win; but I think the cards are stacked against us. In the longer run, we are likely to come up with some process such as J.D. mentioned, but more to the point, we must be careful not to box ourselves in. If we put all our support into one particular process, we lose sight of all other things.

One of the reasons our program has been viable for the past five or six years is that we have been left alone. We were allowed to go ahead with things that looked interesting. We need to retain that ability, and we need to retain sufficient budget to continue. Regardless of what we do (or do not do), this would be the big national demonstration plan.

I don't know what advice we should offer Kaspar at this point. I'm sure they would like us to say, "Here's what you should do, and to build it by 1985."

Besenbruch - I think it would be an acceptable criticism to tell them we think their time frame is unrealistic without saying what they have to do.

Silverstein - I see nothing wrong with going to them in a spirit of cooperation and letting them know what our thinking is. They are to free to accept it or not.

Smith - Even though it's less than complete at this point?

Silverstein - Certainly it would be even better to wait until we have developed a rational approach, if you will; but I don't see why this should have an impact on the Users Association, if it, as one of the leading organizations in the field, presents its thoughts on the matter to DOE. It would be clearly stated that the decision is still up to them.

Smith - We will do that. We don't have any choice about not doing it.

Coutures - Returning to the gasoline problem, this could be solved by decreasing the fuel consumption of your car, but have you enough data? For example, do you have cost comparison data for gasoline produced by solar process as opposed to gasoline produced from coal?

Silverstein - No, we don't.

Besenbruch - There's more to solar than just the pure industrial economics of now. The economics of solar may have a further-reaching national impact than its direct impact on the industry. I think we need not be that defensive, worrying about solar being more expensive than an existing process.

Voice - I agree with that for now, but it's extremely important to look ahead and, by some reasonable assumptions, find that it will be economical within a reasonable time, because I have been very impressed by what's happened in electric. The utilities are very cost conscious, and they are not going to buy things that cannot be expected to be competitive within a short time. That's even more true of industry. They're not giveaway organizations; they don't manufacture money.

Davis - It all boils down to energy. We need energy and we are going to provide something that is economical; otherwise it will not fly. Also, the one facet of economic electric power that is often overlooked is its social implication. In other words, if I want to increase my manufacturing capability in the Los Angeles basin, I must displace an equal or larger amount of pollution in order to have a process which, on its face, provides me with expensive power; but it also provides me with accessible power--power I can get that might not be available if I'm running a fossil plant. So there are a couple of areas in the economics of it that can be considered direct cost and social costs.

We're not going to get there unless we become economically viable, but solar energy is one way of doing that. The solar aspect only needs to be part of an overall power generation or heat generation system, but then we're only paying for the fossil input or solar increment of the system. We can get our foot in the door and start producing energy and start offsetting the use of fossil fuel.

A number of us fail to consider the fact that many of the hydrocarbons that were built on this earth were formed before it was suitable for our habitation, and if we put them all back into the air, the earth might not be suitable for us anymore. This might be a driving force for going toward the hydrogen economy because we know we will need water, and water is a by-product of burning hydrogen.

What most of us are attuned to do within the area of our expertise is in developing technology. I would like to see that continue. Large corporations are going to jump on technology and they will ride us for economic exploitation. It makes sense to me to continue the push for development of technology and let the economic forces in industry strive for the overall deployment.

Ehrhardt - Bill (Kaspar) gave us part of the picture in his speech yesterday. Two weeks ago in Oakland, Sunny Cherian talked about dividing the new program into two parts. Bill Kaspar is handling one of those parts. A lot of work is to be done in the materials area, which may answer some of your questions.

Sunny also stated that unless the fuels and chemicals program produces something interesting to Congress within the next couple of years, he might as well terminate it himself before Congress knocks him off his feet. Against that operational philosophy, I think two weeks later we've seen the policy defined a little more in the way Bill stated.

Cherian also stated that he was going to try to put more money back into universities for research purposes. Before we make specific recommendations, perhaps we should try to determine how he is planning to apportion his budget. That is, will all the money that has funded his type of work (that we have been doing) go into this demonstration plan, or will there be some reasonable mix of other work that's still being carried by the program?

Besenbruch - What worries me most is that the decision will be made on a very limited amount of information and within an extremely short time period--that can't go right.

Ehrhardt - It will be done whether or not we make an input.

Silverstein - If the solar program can't be sold on the basis of national interest in energy self-sufficiency, it will be tough to sell it on the basis of economics, because I don't think anybody will believe us. I believe the reason for the two-thirds cut in the solar program this year is that people are overselling. Optimism is blossoming like weeds in the field. In support of this, let me illustrate. In South Africa, SASOL I plant is finished and they are building SASOL II. They are building this for energy self-sufficiency, not because the gasoline produced is cheaper than gasoline they can refine from petroleum imported from Saudia Arabia or some other OPEC country.

In Brazil, cars are being manufactured to run on alcohol, and they are planting sugar cane to provide that feedstock, not because it is any cheaper than what is available. They are doing it for energy self-sufficiency.

If energy self-sufficiency is a reasonable goal. . . Tom, you were concerned about economics. The economics will take care of itself because subsidies and whatever else is needed to make it attractive to the customer or user will be provided. For example, in Brazil, the government decreed that the price of alcohol cannot exceed 70 percent of the price of gasoline. So far as the user is concerned, he has a product that is in fact economically sound.

Besenbruch - It's contrary to our national thinking, but maybe that's one thing we have to . . .

Springer - I disagree. In fact, I think it's very much further from being a possibility since the Reagan administration has stated clearly that it doesn't want to get involved in that kind of thing anymore. They don't want to tell anybody what they have to do or what they have to buy. Therefore, I am even more afraid of the economics. I'm not necessarily saying I like it, but in dealing with utilities recently, and with some industries, they are extremely sensitive to the cost of things.

Silverstein - True, but we must recognize that their cost is not necessarily the cost of the product. I do not minimize the need for trying to cut costs as low as possible, but keep in mind the fact that if the national interest is great enough, the government will see that the cost is made attractive through subsidies, tax breaks, etc.

Springer - But, for example, right now we really have a serious problem with oil because the government is not doing anything. We're spending billions and billions . . .

Silverstein - They'll change it. Give them a chance, they've only been in office about three months. Six months from now their position will not necessarily be the same as it is at the present time.

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Silverstein - They'll change it. Give them a chance, they've only been in office about three months. Six months from now their position will not necessarily be the same as it is at the present time.

Voice - Again, I want to stress that it has to be a national problem, and I don't think it is our solution they are really looking for.

Hildebrandt - I agree with J.D. that we must deal with the small experiments, and I think that's what we're interested in. In other words, if there were just one experiment to do, then the Users Association really should become defunct because the programmatic aspects of it would cover it. But I don't think we have been asked what the Users Association should do. I think Kaspar was talking about his need for a national program, and I would argue that to a certain extent I think we would not have been left alone and that we would have the Users program if there had not been a program. For example, a lot of battles were taking place concerning Barstow, and if Barstow were not going to go forward, then many other things--the Users Association, etc., would have had a completely different outlook. Others may have a different viewpoint, but I think we are being asked to give a national focus to something, and when we provide that national focus, there will be a continued need for us in the background research area. It's all right if we say we are going to do research and nothing but research, but we are not answering their questions. Kaspar needs something of national impact, and I hope that with this new opportunity the UA, as an organization in the solar community can get behind something fairly early in the program and stick with it instead of simply saying, "Well, we assume it's Barstow," and therefore I can do it ten times better by this or that technique, or whatever, right on through Congress to the point of view that there is no single solution. In other words, because you did ten experiments this year, you know you will have to do 100 next year.

Again, I think as the Users Association we will do and should do exactly that. But as far as the programmatic aspect is concerned, we should try to help Kaspar and DOE have something called a program, because if they do not have a program I think it will be relegated to basic research, and the funding of basic research will be cut by 50 percent the following year. I think DOE needs the fuels and chemicals and IPH program, and they haven't settled on it. They are going case by case.

Voice - The key point that was raised earlier about solar's being a nonpolluting energy source could be part of the basis of this national program. The cost of pollution is a very real economic thing. The fiberglass industry is a good example. At a time when electric rates were going out of sight, that industry has gone almost completely to electric mounting instead of gas mounting (as they had in the past) because they had to eliminate their pollution problem.

Smith - May I come back to another point, because I think this does get pretty close to where we are. First, I don't think any of us felt that we might not give any advice to Kaspar and Braun. But I am concerned that we might get on one bandwagon, hell-bent for leather, excluding anything else; I'm not sure we want to do that. To draw a parallel, some years ago I was associated with something called CCIR in the business of international radio frequency allocation, which was set up in a very sensible way.

There were two groups: One group made the decisions which involved a lot of international political interplay, and the other group, called the International Radio Advisory Committee, made up of technical experts, "massaged" the technical problems to assess all the technical options and possibilities. That's what I meant this morning when I said I think the UA first needs to retain its technical integrity. Others can take those facts, which are not always conclusive in themselves, and do the political "massage"

We might view that sort of a division of roles in which we are the technical advisors to whatever program the DOE comes up with, without necessarily wedding ourselves to that exclusively.

In other words, suppose the UA said hydrogen or biomass pyrolysis. First thing you know, that's all we are doing. Then when others come up with new ideas that happen to be outside our particular thing, we might be too preoccupied with going down that one main road.

Silverstein - I agree.

Smith - The parallel is that certainly we have never opposed Barstow, but on the other hand we have not really been a lobbying group for solar energy. Several people individually have supported it, and that's fine. Al Hildebrandt especially has damn near kept the thing alive, but the Users Association as an organization has not been a lobbying group for Barstow. I'm just suggesting that we try to retain that sort of identity--that of a technical advisory professional group, if possible above the day-to-day politics. We should look at all possibilities evenly and equally within the extent of limited resources.

Hildebrandt - That answers the question of the test facilities, which is our real charter. On the other hand, I think Kaspar asked for a program of national impact. Are we addressing that with what you just said?

Smith - I don't know. If Kaspar says he wants you to recommend a program, I want to give it a lot of thought before deciding whether I want to recommend a single process or not.

Silverstein - The program doesn't necessarily mean recommending a specific process.

Smith - No. As a matter of fact, he did say he may look at five or six options. I think that's good because we should be a background technical advisory group to him on all five or six rather than singling one out--maybe those five or six plus another eight or ten that maybe aren't quite on the front burner.

Hildebrandt - Basically, all I'm saying is that we should be thinking about those things that have a potential national impact.

Smith - I don't disagree with that. I'm just saying, let's not become too wedded to one particular thing. It's premature to do that.

Moore - Among the things the Users Association has been doing so far is looking at the R&D aspects. We could probably be helpful to Kaspar or Sunny by reviewing some of experiments and state which types we think are ready for development and can be done with the existing facilities.

Besenbruch - That's a good idea.

Moore - In the past, DOE has forbidden practically any change in the procedure for development of a new process.

Bowman - Getting them to change that approach might be the most valuable thing we could do.

Moore - I possibly agree with that.

Christensen - This is the first time I have attended a Users Association meeting, but I'm sure all of you recognize that the political process is in place, with Kaspar coming down here, and that DOE is going down the road with or without the UA. I think if the political mechanism is such that something must be demonstrated within a couple of years or nothing, then it's meaningless. Kaspar's coming here is evidence that he recognizes the import of this group, and he would like your help. Frank Smith's comments really hit the nail on the head. If the UA gets involved in a programmatic structure setting or in the political process which is occurring, it will probably get chewed up--not because you are not politically smart, but because of the way you are structured. You can't possibly respond to politics which changes on a day-to-day basis. The absolute best use of this group is to do as Frank has said: Stand back until you become an active partner in an advisory role because your technical strength is here. You are the users; you have the experiments. I don't see how they could proceed without that input, but it should be input only, letting the DOE make the choices and selections with contracts, relying on the UA's advice regarding the hazards you view from your experiments.

Smith - I guess I agree with him because he agrees with me. You always agree with somebody who agrees with you. But I would like to draw one other analogy, and that is, I think we've observed over the past 20 years the dichotomy between the manned-space program, the big part of the space program, and the space scientists. To this day, many space scientists have failed to realize that although the manned-space program took the big dollars and got a lot of the publicity, the space scientists probably got two orders of magnitude more support because of the manned-space program than they would have if the program had not existed.

So I am not suggesting that we oppose a solar fuels and chemicals program. Far from it, because I think our portion of the spending is peanuts when compared to the whole, and will continue to be. They will probably spend more on one thing than we will ever spend. Nevertheless, the fallout from that will provide a lot more support for continuing the kind of R&D that J.D. is talking about, and that Jean-Pierre is talking about. If we are reasonably intelligent about it, I think we can almost have our cake and eat it too.

Besenbruch - We'll close the session at this point. Frank mentioned this morning that he would take all the credit if if everything went right, but that if anything went wrong it would all be my and Marylee's fault. In reality, it was that if anything went wrong it would all be Marylee's fault. But things seem to have run very well and, to me, it was a very enjoyable meeting, especially the three speakers at the luncheons and the banquet. I think we should give Marylee a hand for all the work she has done. Now, Tom Springer will make the closing remarks.

Springer - Let me exercise my prerogative as President and suggest that a committee be appointed to make some sort of recommendation, or perhaps we could use the Executive Committee, but we will do something about this. Obviously, it is of interest to everyone, and it will be accomplished in a manner which will allow everyone in the Users Association to have some input, or at least be aware of it. We will either appoint a committee, with the members not necessarily a part of the Executive Committee, or it will perhaps be made up partially of Executive Committee members. In any case, we will have a meeting of the Executive Committee to reach a decision on procedure concerning the future.

Silverstein - In light of the tight schedule you are facing, it should be done soon.

Springer - Right. Gottfried, we thank you for an interesting, well-run program. We appreciate the fine job all the speakers did. I believe everyone else has been thanked at one time or another during the meeting, and I declare the meeting adjourned. Thank you very much.