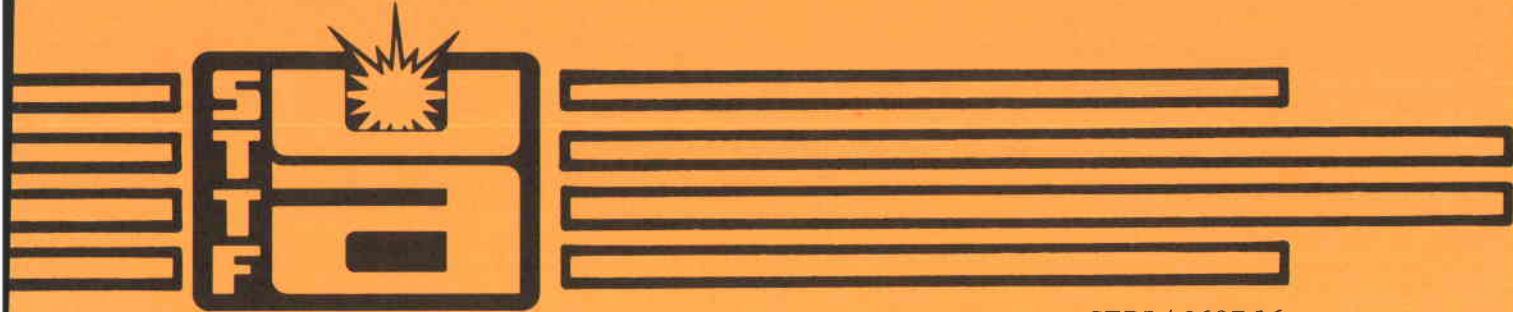


**Solar Thermal Test Facilities
USERS ASSOCIATION**



SERI / 0637-16

PROCEEDINGS OF
FACILITY OPERATORS
AND EXPERIMENTERS
WORKSHOP

MAY 3-4, 1979

ALBUQUERQUE, NEW MEXICO



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Solar Thermal Test Facilities
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OPENING REMARKS

A. F. HILDEBRANDT: I am happy to welcome all of you to this Users Association Facility Operators and Experimenters Workshop. It is apparent from recent national and international energy headlines that solar has an obvious role. In the areas of fuels and chemicals and energy transmission there are many things that still need doing to make solar thermal a viable and acceptable form of energy. There are many challenges and problems yet to be solved.

I would like to recognize several individuals who have come from abroad: Claude Royere and Jean-Pierre Coutures from Odeillo; and Peter Carden from Australia. Also, I would like to recognize the Executive Committee members: Terry Cole, John Gintz, Fred Manasse and Tom Springer. Dick Blieden was unable to attend.

At this time, I would like to introduce Dr. Charles Grosskreutz, Assistant Director of Research at SERI. Most of you know him as he has been in the solar thermal or solar tower work since its inception.

GROSSKREUTZ: I told Frank and Al I came down here to listen so I am just going to say a couple of words. It is a pleasure to be here. The real pleasure, however, is to look back a few years to when the Users Association and the test facility were in their embryo stage and some of the men whose names were just called for the Executive Committee were involved with me in getting it started. I see there are now 36 proposals in review and note it has been an active year. It is really gratifying to me.

One of the kicks I get out of solar energy is watching things grow from nothing to something, as happened here. I wish you well on this particular occasion and on your meeting in Atlanta. I am looking forward to a good meeting. Thank you.

HILDEBRANDT: It is especially gratifying to see the large number of proposals we received. One of the problems we now face is analyzing those proposals to make sure we fund high-quality proposals. It is obviously delightful to compare good proposals.

At this time, I would like to turn the meeting over to Frank Smith who will discuss the organizational part of the workshop.

SMITH: I would like to add my welcome to those of Al Hildebrandt and Charlie Grosskreutz. It is indeed satisfying to see how interest in the Users Association and solar thermal research has grown over the past two years since we began. We have now had four workshops and have had a larger attendance at each. As a matter of fact, each time we anticipated a small meeting but always ended up with two or three times as many people as anticipated. That is good because it shows there is significant technical interest in what we are doing.

Our Fall 1978 Atlanta workshop, which many of you attended, addressed many of the theoretical aspects of high-temperature fuels and chemical programs.

I would again like to thank those who participated in that meeting because the proceedings have become a ready-reference for much of the fuels and chemicals planning that has taken place since the Atlanta meeting.

By contrast, this meeting, will be more of a nuts-and-bolts session. We particularly want experimenters and would-be experimenters to have the opportunity to discuss problems of mutual interest with the people who will be running the facility where experiments will be run. Those people will be John Holmes from Sandia; Richard Hays, William Williams and Steve Illichmann from White Sands; Tom Brown and Hamp Teague from Georgia Tech; Claude Royere, operator of the 1-megawatt facility of Odeillo, France; and Jean-Pierre Coutures, who works with the Laboratory Scale Facilities at Odeillo. Jean-Pierre has been acting as a consultant to the UA in Albuquerque for the last couple of months and has been very helpful.

First, we will hear from the facility operators, who will update the status of their facilities and describe any changes that have been made, or are anticipated in the near future. After the facility operators' presentations, we have several experimenters who will be talking about the experiments they have run.

Following those talks, we will break into four panels as shown on the agenda: Hydrogen, Pyrolysis and Coal Gasification; Chemical Conversion and Transmission; Central Receivers, Windows, and Materials; and Chemical High-Temperature Processes. I have asked an individual to chair each panel but they will be fairly informal. I have also asked that a facility operator be included in each panel to answer your questions or discuss operating problems.

We will continue those panels in the morning, followed by a summary session where the Chairman will give us a report of each panel discussion. Thank you.

U. S. DEPARTMENT OF ENERGY ADVANCED COMPONENTS TEST FACILITY[†]

Ralph F. Altman, C. Tom Brown
and Hampton L. Teague

Georgia Institute of Technology
Engineering Experiment Station
Atlanta, Georgia 30332 U.S.A.

ABSTRACT

Installation of the U. S. Department of Energy's Advanced Components Test Facility has been completed. The facility is operated by Georgia Tech's Engineering Experiment Station and is located on the Georgia Tech campus in Atlanta, Georgia. The principle feature of the facility is a hexagonal array of 550 mirrors or heliostats that are mechanically driven so that they focus sunlight at a point 21.3 meters above the center of the field. A tower for test apparatus stands in the center of the field and a computerized data acquisition system is housed in the control building adjacent to the field. The mirrors are capable of delivering a total flux of 400 kW to the focal zone with a peak flux density of approximately 220 W cm^{-2} .

The facility is designed to serve as a test-bed for solar components that require concentrated solar energy for their operation. New systems and components can be tested at the facility on a moderate scale. It is particularly well suited for the testing of high temperature solar receivers and components, photovoltaic conversion systems, and total energy systems. This paper describes the facility, its intended uses and capabilities. A report on the current goals and accomplishments is included.

[†]This work supported by the Division of Solar Technology of the Department of Energy.

I. INTRODUCTION

The Advanced Components Test Facility, which is located on the Georgia Tech campus in Atlanta, Georgia, is a solar energy concentrator design by Professor Giovanni Francia of Genoa, Italy. A photograph of the facility is contained in Figure 1. Concentration is achieved by aiming sunlight reflected from 550 mirrors at a point located above the center of the field. The mirrors are arranged in a hexagonal array and are mechanically driven so that the sunlight reflected from each mirror passes through the stationary point or focal zone throughout the day.

The facility is operated for the U. S. Department of Energy by the Georgia Tech Engineering Experiment Station. It is designed to serve as a test bed for promising high temperature solar components and materials. It is a flexible and convenient test facility accessible to all research

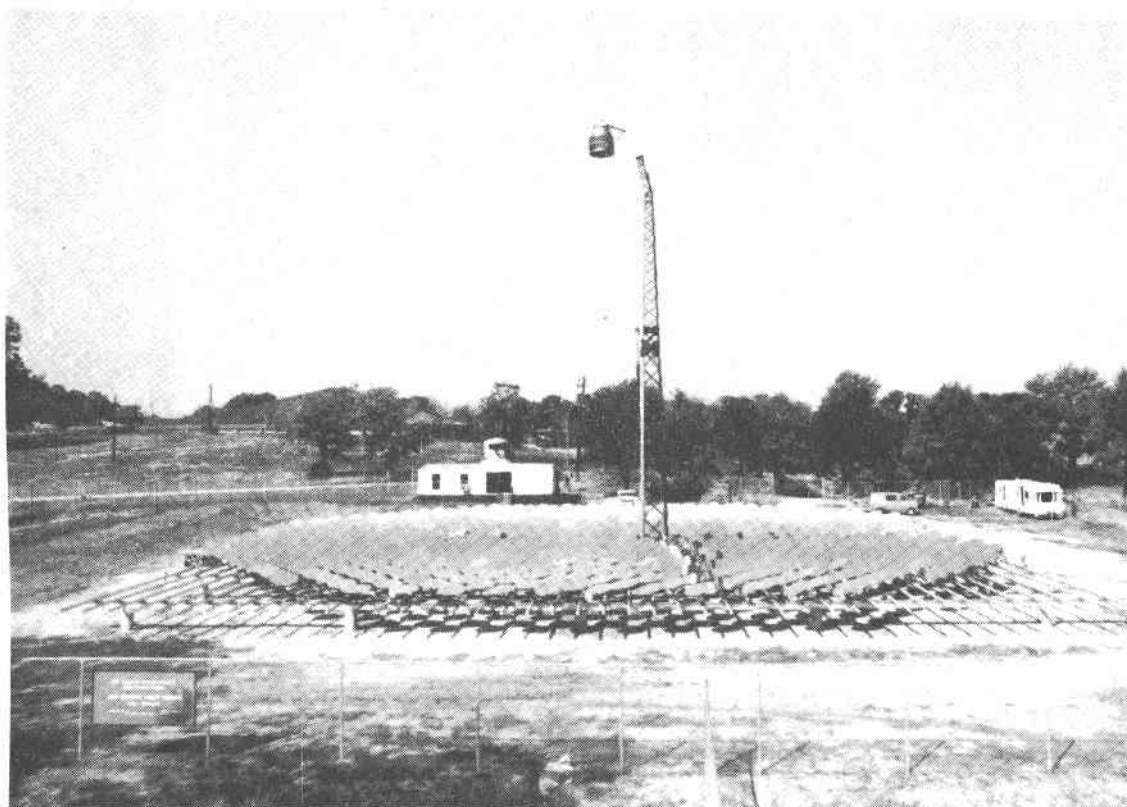


Figure 1. Photograph of the Advanced Components Test Facility.

and development organizations -- large and small, public and private. The facility is particularly well suited for the testing of solar heat receivers and components, high temperature materials and high temperature chemical reaction system components.

II. BACKGROUND

In 1965, Francia built and operated the first of several solar powered steam generators in Italy (1). The solar collector was a tracking mirror field that focused sunlight into a cone shaped receiver located above the center of the mirror field. The mirror tracking mechanism was a unique feature of the field. This mechanical coupling, which Francia called a kinematic motion, moved the mirror it supported in such a way that sunlight reflected from the mirror passed through a stationary focal zone throughout the day. The tracking system required no feedback, either mechanical or electrical, in order to operate. A second unique feature of the system was the antiradiating structure located in the receiver. This structure was constructed of pyrex tubes, closed at the top and open at the bottom, mounted vertically in the lower portion of the receiver.

Since the operation of this first system, Francia has refined and enlarged the design through three generations of systems. The largest and latest test system was first operated at St. Ilario, Italy, in 1972 (2). The mirror field contained 271 tracking mirrors with a total surface area of 135 m^2 (1450 ft^2). The mirrors were round, second surface reflectors with a diameter of 78 cm (30.7 in.). The receiver for the system has generated 150 atm (2200 psi), 600° C (1110° F) steam with an overall collection efficiency of 78 percent.

In 1975, the Energy Research and Development Administration purchased a solar powered steam generator of the Francia design through the Italian firm of Ansaldo, SpA,[†] with the intent of installing and operating the system in the U. S. The operation of the facility would accomplish two objectives. The first objective was the transfer of the technology that Francia has developed in Italy. This objective would be accomplished by

[†]Ansaldo, Societa Generale Elettromeccanica S.p.A., Divisione Impianti Elettrici, 16152 Genova-Cornigliano, Via N. Lorenzi, 8 ITALY.

installing and operating the mirror field and central receiver and documenting their performance. The second objective, to provide a place to test innovative solar receivers and systems on a moderate scale, would be accomplished following the system characterization by converting the system to a general purpose test facility. Georgia Tech's Engineering Experiment Station would be responsible for the characterization of the original facility, the conversion to a test facility and the operation of the facility after conversion.

III. CHARACTERIZATION PROGRAM

The solar steam plant was installed at Georgia Tech in 1977 and became operational in November 1977. Figure 1 shows the facility in the "steam plant" configuration. The mirror field contains 550 Francia type heliostats or kinematic motions. These devices are mechanically interconnected by torque tubes, and the entire field is driven by one 1.1 kW (1½ hp) electric motor. Each kinematic motion supports and manipulates a 111 cm diameter circular, second surface, low iron glass mirror which can be operated either flat or focused. The receiver shown in Figure 1 is a once-through steam generator. It is located at the geometric center of the field at an elevation of 21.46 meters above the mirror plane. This height combined with the extent of the field, gives a nominal rim angle for the field of 45 degrees.

The principle of operation of a kinematic motion is diagrammed in Figure 2. Point A is the center of a sphere of fixed radius. Point B is the point at which the extension of a line drawn from the sun through Point A intersects the sphere. Line RA is a line drawn from the center of the sphere to the receiver and Point C is the intersection of this line with the sphere. Lines CA and AB are of equal length and form the equal sides of the equilateral triangle ACB. A mirror is placed at point M perpendicular to line MCB. Since line MCB is parallel to the bisector of angle SAR, the mirror surface will reflect the light from the sun (point S) onto the receiver (point R). Point B rotates about axis TA, (parallel to the earth's axis) at 15°/hr and MCB rotates around the fixed point C. This rotation forces point B to follow the sun throughout the day, and keeps the sunlight reflected by the mirror centered in the receiver.

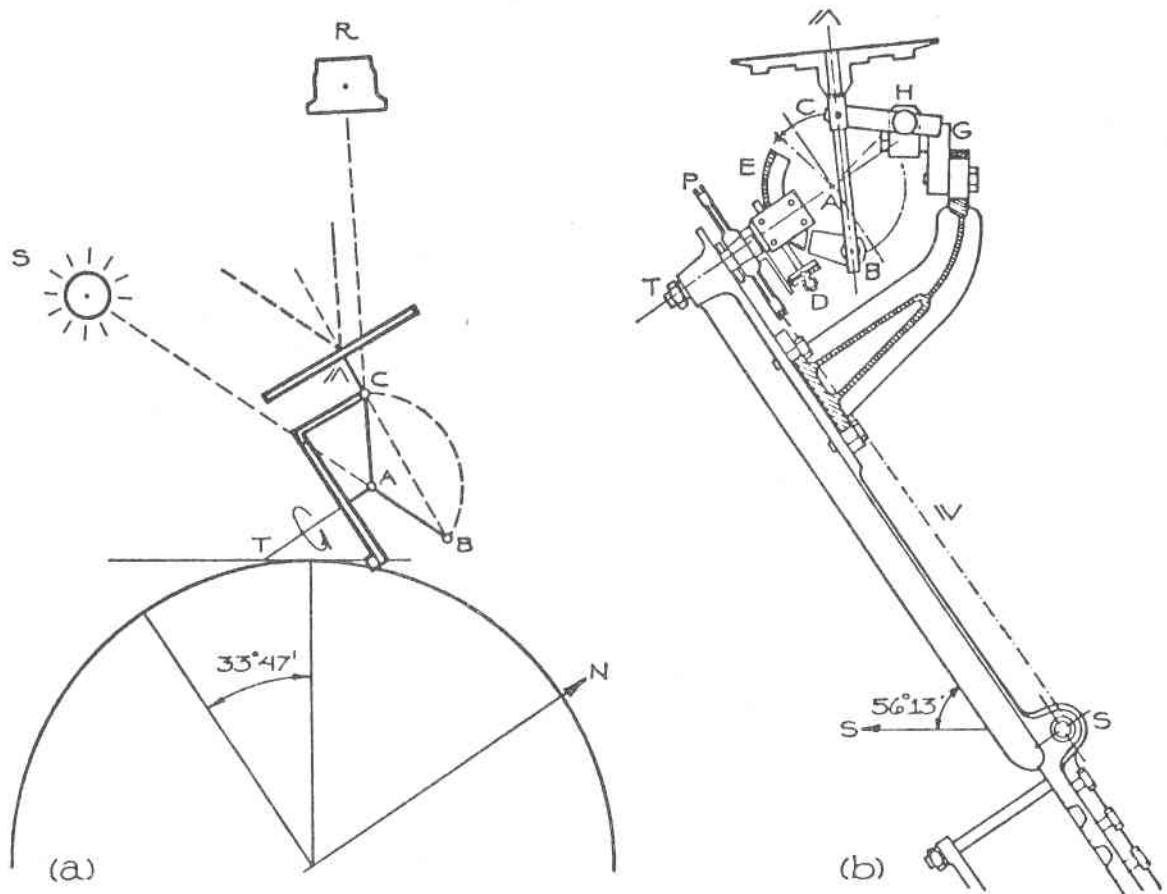


Figure 2. Principle of Operation of Kinematic Motion.

A drawing of an Advanced Components Test Facility kinematic motion is also shown in Figure 2. The relevant points are indicated on the drawing of the kinematic motion. The axis of rotation is shown by line AT which is located parallel to the earth's axis. Rotation is provided by a cable W around the pulley at P and driven through the shaft S. Alignment with the sun (line AB) is provided by a worm gear at D acting on the circumferential gear arm F. Declination adjustments also are provided through D. Alignment with the receiver (line AC) is provided through point H attached to a movable collar on the fixed rod G.

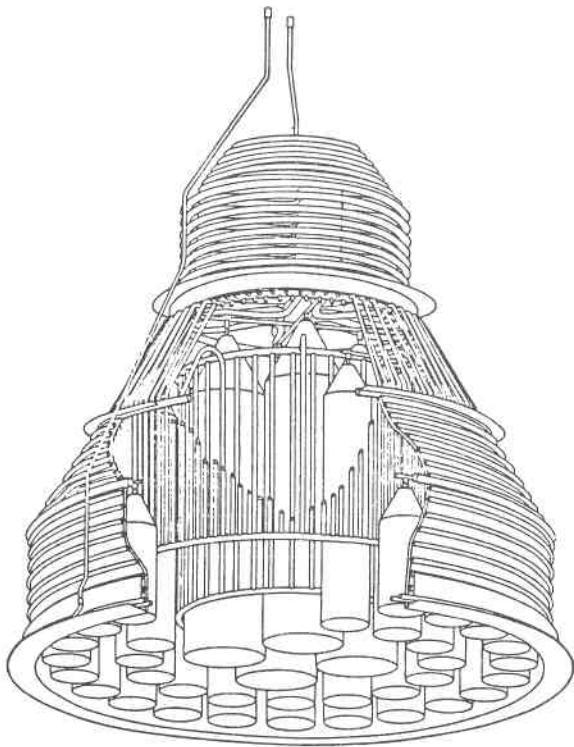


Figure 3. Francia Once-Through Steam Generator.

The receiver supplied with the system is depicted in Figure 3. It is a once-through steam generator constructed entirely of stainless steel. Chemically treated water is first circulated through the tubes that curl around the shell of the receiver. The preheated water then flows into the inner ring of boiling tubes. The boiling sections are in the middle of the receiver. Steam leaving the last boiling section flows through the serpentine superheater tube in the top section of the receiver. The receiver is designed to generate 600°C (1110°F) steam at 120 atm (1700 psi). The large cylinders shown in Figure 3 are the pyrex tubes that make up the antiradiating structure.

The characterization of the basic Francia type facility has been partially completed. The focusing capability of individual mirrors has been determined and the tracking errors of the kinematic motions have been measured. The steam generator has been operated at its design temperature and pressure. The tests to date have been of a preliminary or shake-down nature. Flux measurements in the focal zone are scheduled to take place in July 1978, and the performance of the receiver will be determined in late 1978.

IV. FACILITY CONVERSION

The conversion of the Francia steam plant to a general purpose test facility is proceeding while the characterization tasks are being completed. The conversion process started in December 1977, with the design of a new central tower to replace the articulating tower supplied as part of the Francia solar steam plant. An artist's concept of the new tower appears

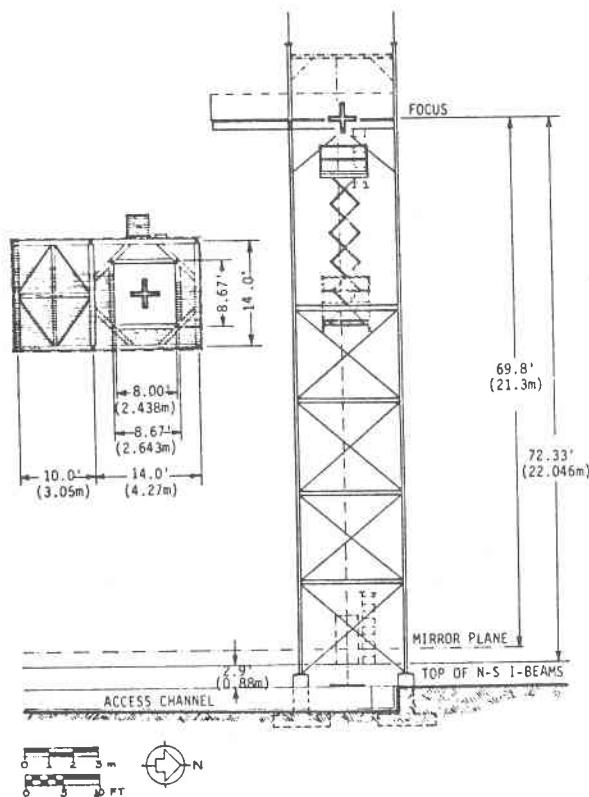


Figure 4. Drawing of New Central Tower.

in Figure 4. The new tower provides an increased load capability and better access to the experimental area. The old tower had a capacity of approximately 680 kg (1500 lb). The new tower has a capacity of 9072 kg (20,000 lb). The focal point for the mirror field is centered on the tower legs and located at the floor level of the experiment platform. Access to the top of the platform is provided by ladder and man/material work hoist; access to the area below the platform is by scissors lift. The scissors list can be withdrawn to the 15.2 m (50 ft) level during a test so as to minimize the blocking of

radiation incident on the focal plane. The cantilevered part of the platform will house an instrument building. The facility in its present configuration is shown in Figure 5.

Support equipment at the DOE Advanced Components Test Facility includes a computerized data acquisition system, a scanning flux calorimeter, pyrhemeters, a pyrometer, and a solar blind infrared TV camera system. The computerized data acquisition system consists of two minicomputers.

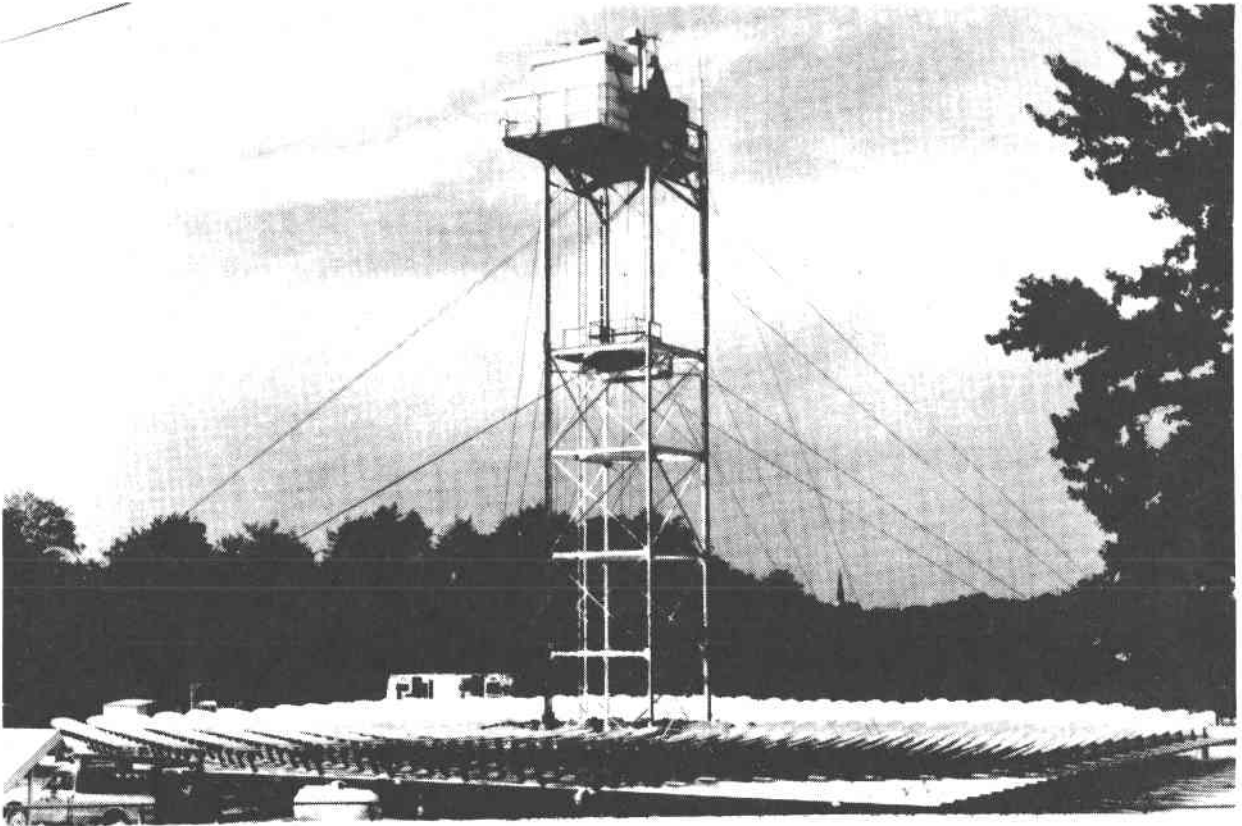


Figure 5. Photograph of ACTF Central Test Stand.

One will be located atop the tower and will control a 120 channel multiplexed A-to-D system. The second computer will be located in a control room adjacent to the mirror field. This processor manages the tower top computer and also manipulates, stores and displays data according to the needs of the experimenter. Data output from the system includes strip chart recorder type displays on a video terminal, line printer listings of selected channels, magnetic tape copies of both raw and processed data, and diskette copies of data. Data input to the computerized data acquisition system can be from virtually any type of analog output transducer.

A scanning flux calorimeter will be used in the characterization experiment and will be available for use by the experimenter. This device is a water cooled bar housing 37 Gardon gage type calorimeters on 5.08 cm (2 in.)

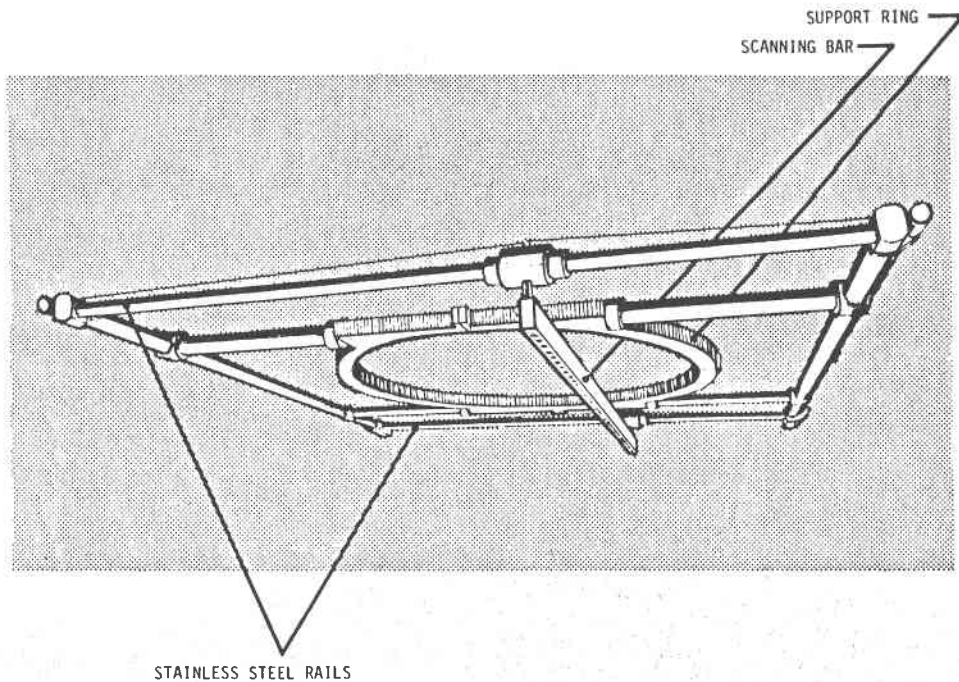


Figure 6. Perspective of the Scanning Flux Calorimeter.

centers. The bar is mounted on a water cooled structure that can in turn be mounted to the tower or an experiment. The device operates under computer control in such a manner that a 5.08 cm x 5.08 cm (2 in. x 2 in.) grid of the incident flux distribution can be produced by scanning the bar through the distribution. The output of the calorimeter is stored by the data acquisition system. A drawing of the flux scanner is contained in Figure 6. The central support ring in Figure 6 was designed to attach the flux scanner to a specific experimental receiver. This ring can be modified or replaced to adapt the scanner to other experiments, or the scanning flux calorimeter can be mounted directly to the central tower.

Presently, two major Department of Energy contractors have tests scheduled at the Advanced Components Test Facility. In the first series of experiments, a prototype of a high temperature ceramic air cooled receiver

will be tested. This receiver is designed to be used in an open Brayton cycle to produce electricity. Testing will begin in July 1978. A sodium heat pipe receiver is scheduled for testing in 1979. It is anticipated that additional tests of new receiver concepts or experiments will be added to the facility's schedule in the near future. A manual that contains a detailed description of the Advanced Components Test Facility, its policies and procedures is available. Copies of this Users Manual can be obtained by writing or calling:

Director, Advanced Components Test Facility
SEMTD/EES
Georgia Institute of Technology
Atlanta, Georgia 30332
(404) 894-3650 (Commercial).

V. REFERENCES

1. G. Francia, "Pilot Plants of Solar Steam Generating Stations," Solar Energy 12, No. 1, p 51-64 (September 1968).
2. G. Francia, "The University of Genoa Solar Furnace," Presented at the NSF International Seminar on Large Scale Solar Energy Test Facilities, New Mexico State University, Las Cruces, November 18-20, 1974.

WHITE SANDS MISSILE RANGE SOLAR FURNACE TEST FACILITY

Richard Hays

Abstract

A description of the 30,000-watt thermal White Sands Solar Furnace Test Facility located at the Nuclear Weapon Effects Laboratory, White Sands Missile Range, New Mexico. The White Sands Solar Furnace (WSSF) is primarily used for nuclear weapon thermal effects testing, but is also used for solar energy research. The WSSF is capable of providing a maximum solar flux in excess of $80 \text{ cal/cm}^2 \text{ sec}$ over an exposure area of approximately 5 cm in diameter. The solar flux of the WSSF can be modulated to provide thermal pulse shaping, such as rectangular and nuclear, or operated in a steady-state exposure mode.

Introduction

The WSSF was originally constructed in 1958 and operated by the Quartermaster Research and Engineering Center at Natick, Massachusetts. In 1973 the WSSF was relocated at the White Sands Missile Range, New Mexico. The WSSF is available for use by the Department of Defense and its contractors, or other Government agencies and private industry.

The facility is operated by the Army's Nuclear Weapon Effects Laboratory primarily for nuclear weapon thermal effects testing but is also used for solar energy research by numerous Government agencies and universities.

Description of the WSSF

The WSSF is comprised of four main parts: the Heliostat, Attenuator, Concentrator and Test and Control Chamber, see Figure 1.

The Heliostat consists of 356 flat plate mirrors, each 0.635 cm in thickness and 62 x 62 cm square, mounted on a steel framework 1.2 meters wide and 11 meters high. The heliostat moves in azimuth ± 60 degrees and about 180 degrees north-south orientation and 0 to 90 degrees in elevation. The heliostat is an elevation over azimuth mounting with the drive systems located in the vertical and horizontal turret sections. The heliostat mirrors are front-surfaced standard

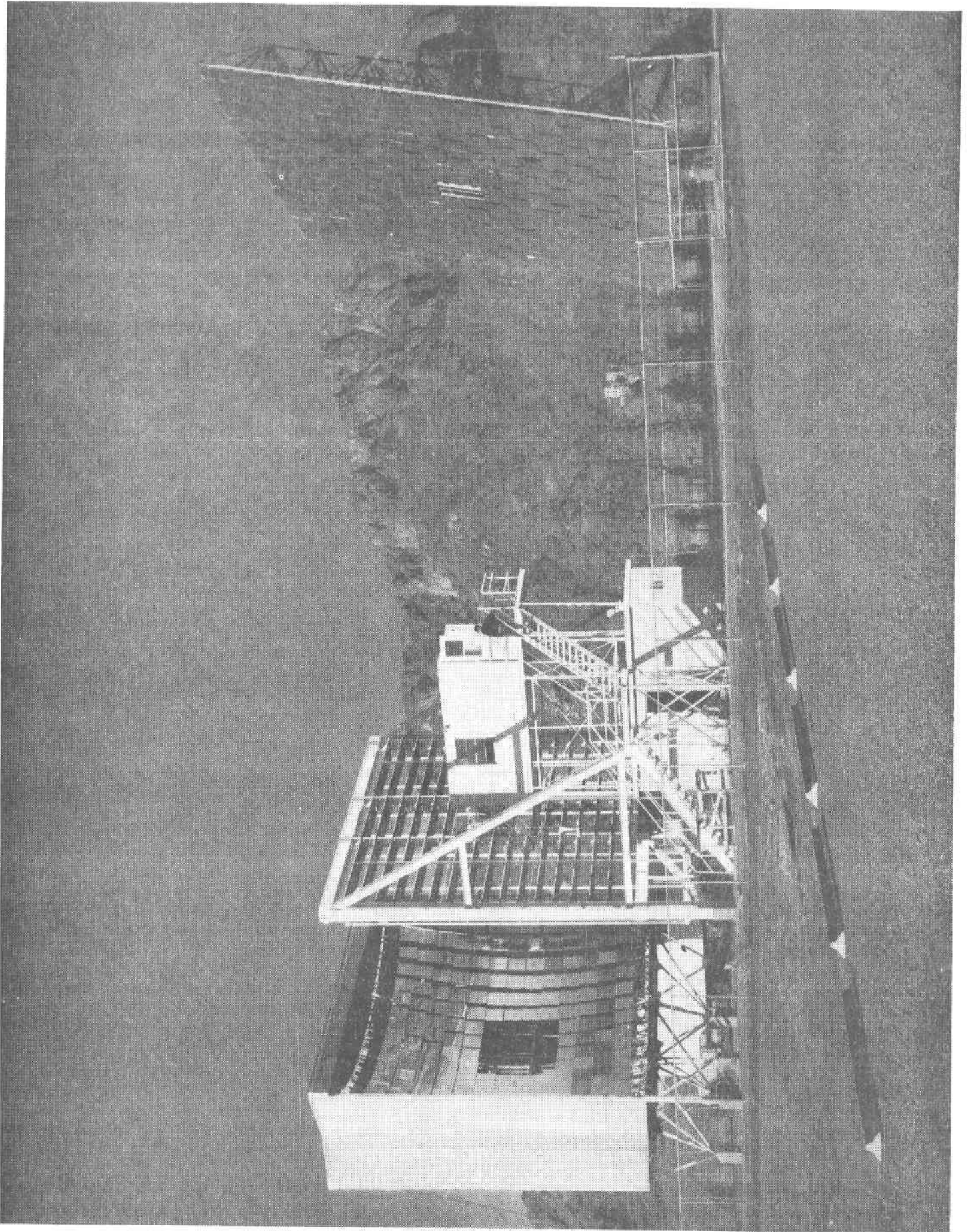


Figure 1

flat plate glass. The reflective surface consists of vacuum-deposited aluminum with an overcoating of silicon monoxide. Each mirror is mounted on three compression springs with stainless steel bolts through the mirror and spring and attached to the heliostat framework.

There are three modes of movement of the heliostat: slew, manual track and auto track. In the slew mode, two 1/2-hp AC motors (one AZ., one EL.), operating at 1725 rpm, are used to move the heliostat at rates of 7.2 degrees per minute in azimuth and 6.5 degrees per minute in elevation. The slew mode is used to bring the heliostat from the stow position to sun acquisition. In the manual mode, the same mechanical drive systems are used as in the slew mode. The difference between the slew and manual track modes being a further gear reduction and a variable-speed, 1/15-hp, 0-1725-rpm, DC motor coupled to the drive system through an electro-mechanical clutch. In the manual track mode, the heliostat is moved in azimuth at a maximum rate of 11.6 degrees per hour and in elevation at a maximum rate of 7.8 degrees per hour. The third mode of movement is auto track, which is the same as the manual track mode with the exception that the motor speed is controlled by position feedback from a photo detector. In this mode the heliostat automatically tracks the sun, keeping the heliostat positioned within 30 seconds of arc. The auto track system keeps the solar image at the focal plane positioned within 0.25 cm. Gusty winds above 15 knots and clouds passing between the sun and the heliostat can cause tracking instabilities with up to 1.25 cm of movement of the solar image or loss of track. If required, moon tracking can be accomplished with the same auto track system. By using the moon as a source, precise alignment of optical experiments can be performed without the intense concentrated solar heat and light associated with the sun.

The Concentrator consists of 180 spherical mirrors mounted on aluminum rings 59.7 cm in diameter, which are attached to the 9.1-meter square concentrator framework so that a solar image is positioned at the WSSF focal plane 10.7 meters away. All the concentrator mirrors are front-surfaced with vacuum-deposited aluminum and overcoated with silicon monoxide.

The Attenuator controls the useable thermal power of the WSSF, varying the power from zero to maximum within two minutes. The attenuator consists of 17 rows of rotatable horizontal blades. The blade angle is controlled by the solar furnace operator and varies from 45 to 90 degrees from vertical for complete to minimum

attenuation of the solar energy. If a hazardous condition occurs during testing, automatic safety circuits are coordinated with the attenuator drive circuits so that the attenuator may be closed within 0.5 second. The attenuator can operate in an auto control mode, compensating for changing atmospheric conditions, and thus keeping a constant flux level at the focal plane during long steady-state exposures. See Figure 2 for attenuator transmission characteristic. The test and control chamber is 2.4 by 2.4 meters in cross section presented to the solar energy reflected from the heliostat and 4.8 meters in the direction of the optical axis and houses the experimental area, the control console and the fast shutter system. Cooling water and high-pressure air supplies are available in the test and control chamber.

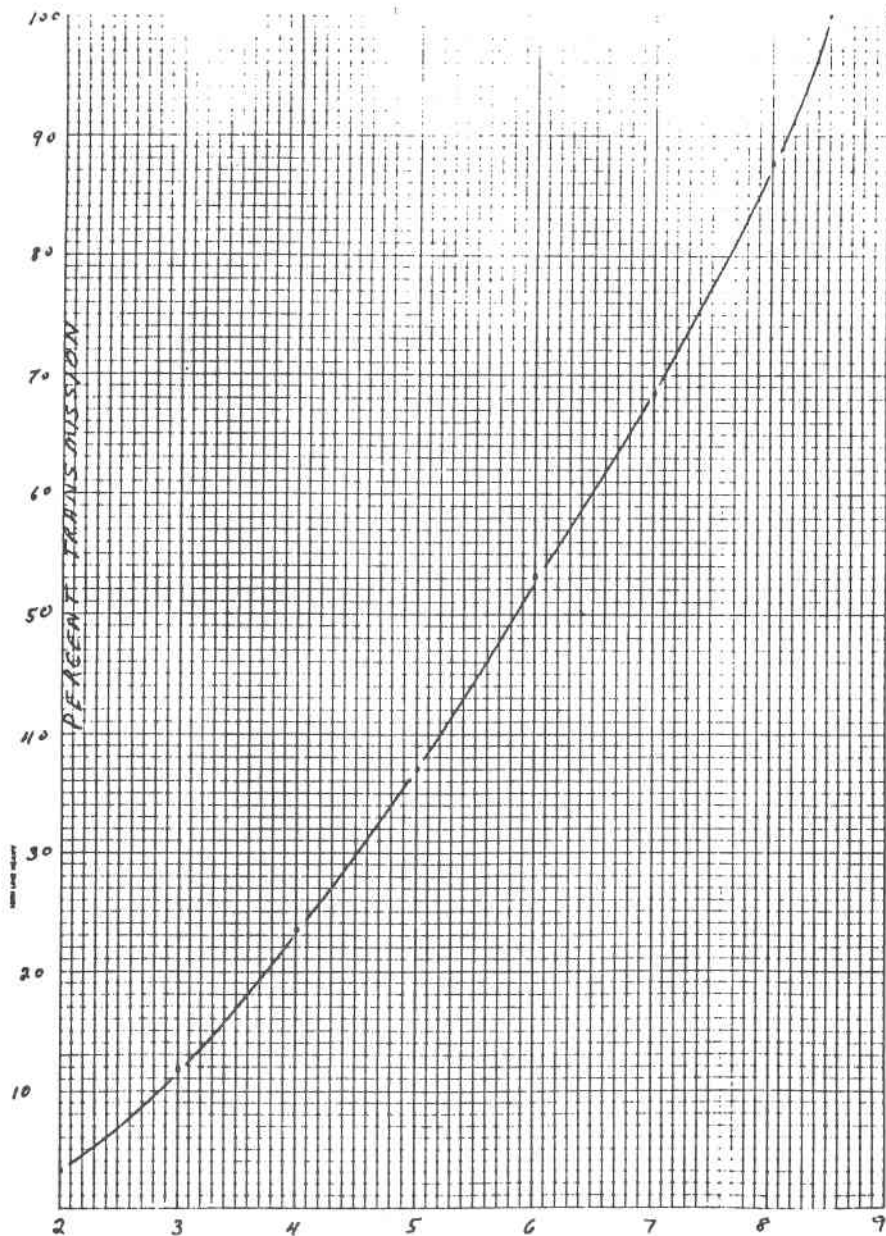


Figure 2

The Fast Shutter System consists of a water-cooled shutter, exposure shutter, and a limit shutter. The water-cooled aluminum shutter is 45.7 cm in diameter and protects the fast shutters and experiment from the 30,000 watts of thermal energy during nonexposure. The exposure and limit shutters have rise and fall times of 25 milliseconds and are mounted 5.1 cm in front of the focal plane. These two shutters produce a rectangular pulse duration as short as 100 milliseconds. The thermal pulse shaper for nuclear weapon simulation is mounted behind the fast shutters and can be for steady-state operation. Also, a wind tunnel which will accommodate 7.6 by 10-cm test specimens can be used in conjunction with the WSSF to provide air flow with velocities up to a maximum of 40,000 feet per minute.

Exposure Characteristics

The thermal exposure area is approximately 16 cm in diameter at the focal plane located 81.25 cm from the south wall of the test chamber and 1.06 meters above the test chamber floor. Larger exposure areas can be obtained by moving out of the focal plane but with reduced flux levels. The maximum available flux at the focal plane to date is 100 cal/cm² sec (90 cal/cm² sec readily obtainable), with a total available power of 30,000 watts thermal. Maximum flux levels with a 10% uniformity are obtained over an exposure diameter of 5 cm. The thermal flux profile at the focal plane has the 50% flux points occurring at a 5-cm radius from the center of the solar image as shown in Figure 3. Table I gives some of the important exposure characteristics of the WSSF.

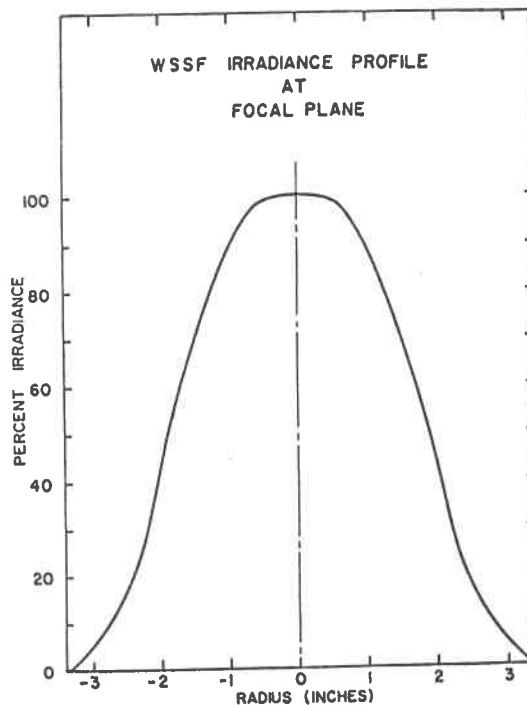


Figure 3

Table I

<u>Diameter (in.)</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>6.5</u>
Percent Total Power	6.5	24.6	49.5	74.5	91.5	99.1	100.0
Power, kilowatts	1.89	7.21	14.56	21.91	26.97	29.17	29.47
Min. Flux, cal/cm ² sec	88.2	79.2	59.4	39.7	14.4	4.5	0
Mean Flux, cal/cm ² sec	89.1	83.7	69.3	49.1	26.6	9.4	2.2

Operational Characteristics

Since the WSSF is dependent upon weather conditions for operations, the following weather data is used to help schedule experiments to be conducted at the WSSF. Wind and cloud cover data taken over a period of 22 years, by the Atmospheric Sciences Laboratory, indicates WSMR is a good location for the WSSF in regard to availability of usable operational hours. 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. This is based on a 2080-hour work year, 5-day work week, and an 0800 to 1600-hour work day, see Tables II and III. It must be remembered that the WSSF has two operational constraints, cloud cover and wind, when planning thermal tests.

Table II

<u>Category</u>	<u>Cloud Cover</u>	<u>Winds</u>	<u>Available Hours</u>
I	Clear	< 5 knots	395
II	Clear	< 14 knots	666
III	< 50%	< 5 knots	666
IV	< 50%	< 14 knots	1200

Table III lists the month of the year according to percent operational time available for that month in Category IV of Table II.

Table III

<u>Month</u>	<u>% Operational Time</u>
September	71
October	70
June	70
May	61
November	60
August	59
July	57
December	53
April	51
January	50
February	50
March	48

LABORATORY SCALE FACILITIES AT ODEILLO

J. P. Coutures
Laboratoire des Ultra-Refractaires, CNRS

The laboratory currently uses ten laboratory scale solar furnaces (LSSF), double reflection, for the following work:

- High-Temperature Physical Chemistry
- Solar Engineering
- Solar Energy Storage

For these purposes, eight LSSFs have vertical axes and two have horizontal axes.

Six of these furnaces are 2 kW and four are 1.6 kW. In each case, the flux density at the focal point is 1600 W/cm^2 and the focal points are, respectively, 8 and 6 mm. In both cases, work under controlled atmosphere or primary vacuum is possible by using quartz or Pyrex windows.

1. Horizontal Axis

We use rotating kilns of different volume (10 to 100 cm^3). The following work is performed:

- High-Temperature Physical Chemistry
 - Thermal analysis in blackbody conditions phase diagram studies (T_{max} : 3000°C)
 - Vaporization measurements with a transpiration technique ($T_{\text{max}} = 2600^\circ\text{C}$)
 - Solar Engineering: stirred bed studies, and temperature distribution inside a cavity

2. Vertical Axis

All of these facilities are associated with cooled-hearth devices. The following work is performed:

- High-Temperature Physical Chemistry
 - gas dissolution (O_2 , H_2O , CO_2) in liquid oxides (T_{max} : 2500°C)
 - splat cooling
 - vapor quenching
 - synthesis
- Solar Engineering
 - fluidized bed studies
 - ore processing
- Solar Energy Storage
 - hydrogen thermocycles by decomposition of various oxides

3. Examples of Actual Research Fields

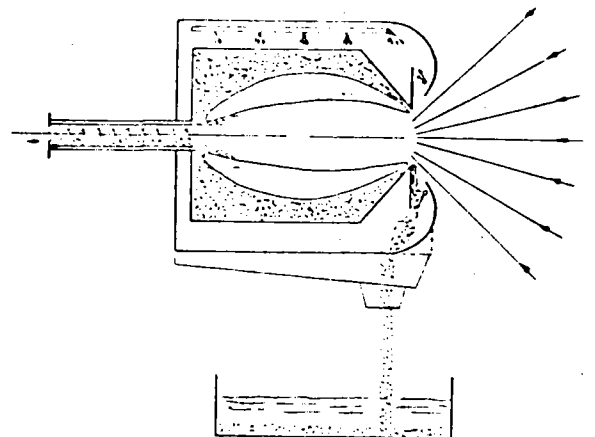
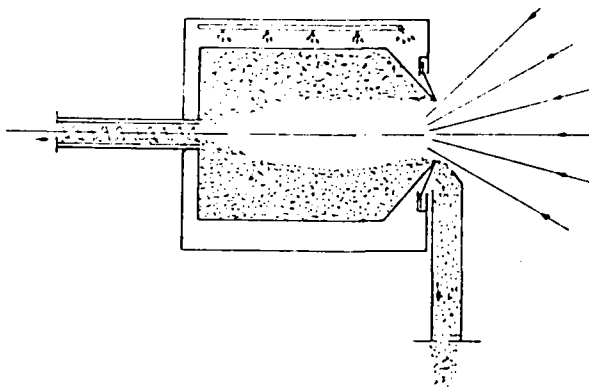
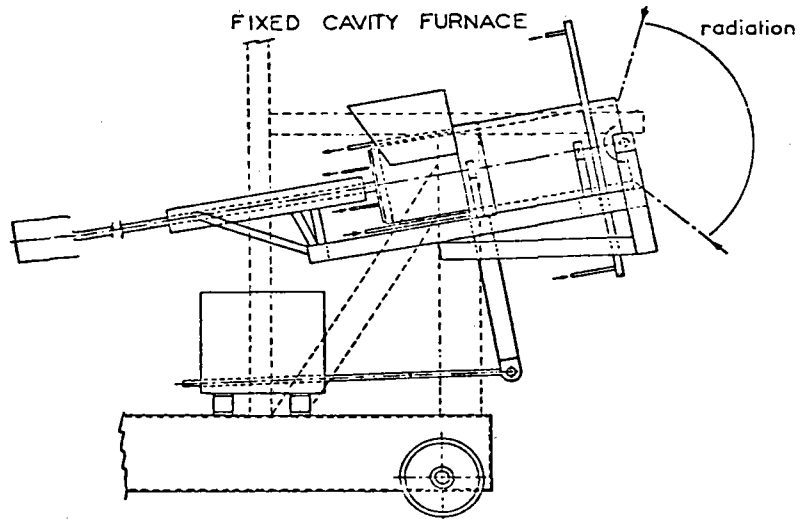
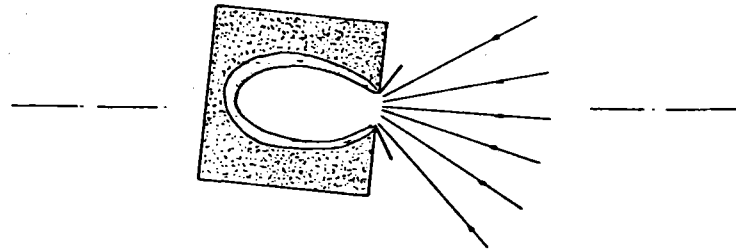
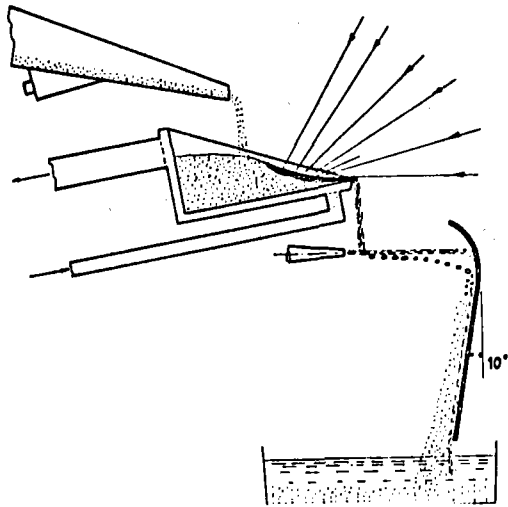
- High-Temperature Physical Chemistry: water vapor dissolution in liquid silicates: binaries CaO-SiO_2 ; $\text{Al}_2\text{O}_3\text{-SiO}_2$ and ternary $\text{CaO-Al}_2\text{O}_3\text{-SiO}_2$
- Ore Processing: molybdenite ore processing (with support of PIRDES/CNRS and STTFUA/DOE): combustion of raw ore and MoO_3 collection
- Solar Engineering: fluidized bed techniques for solar energy storage in the case of decomposition of CaCO_3
- Solar Energy Storage: oxide decomposition (Fe_3O_4 , ZnO) which could be used as a step in hydrogen thermocycles

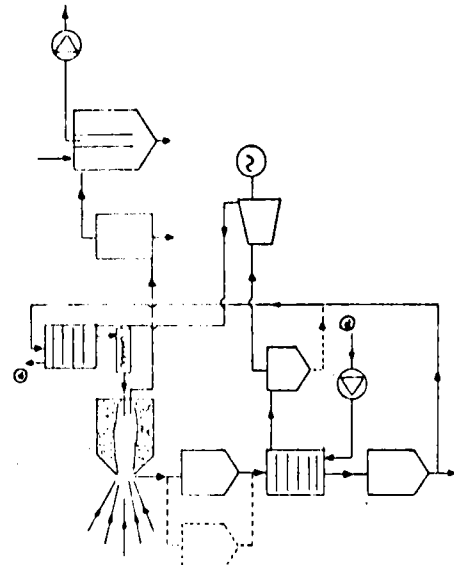
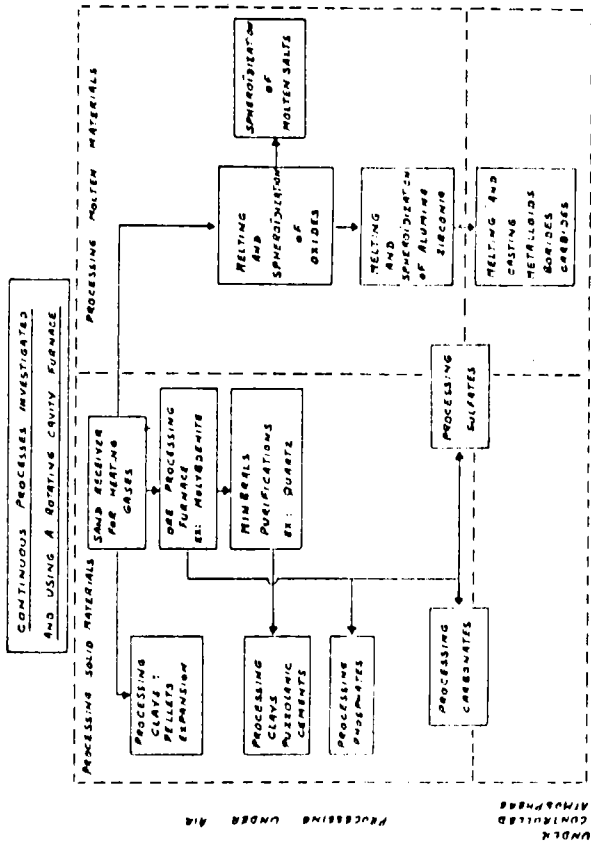
4. Remarks

For all of the above work, it is necessary to use the other high-temperature technique and analytical apparatus developed at the laboratory, such as:

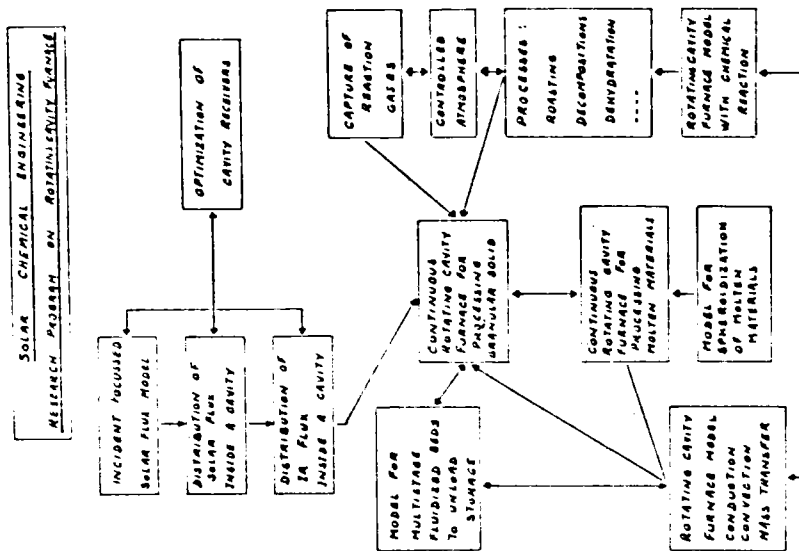
- high-temperature thermogravimetry (up to 1850°C in oxidizing conditions) for some kinetic measurements
- high-temperature calorimetry (drop calorimetry or scanning up to 1500°C) for heat content

Characterization of reaction products, solids and gases, are made, respectively, by X-ray diffraction and by gas chromatography or mass spectrometry





SOLAR HIGH TEMPERATURE HEATING ENERGY STORAGE AND ORE PROCESSING



SOLAR CHEMICAL ENGINEERING RESEARCH AND TEST
ACTIVITIES USING THE 1MW_{TH} SOLAR FURNACE AT CNRS

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SUMMARY

The purpose of this paper is to give a short summary and general overview of a broad program which is currently underway.

The objective of the program is to investigate and test the possibilities of a way proposed by the author to use thermal energy from focused solar radiation at high temperatures in the range of 700 to 1000°C for thermal storage, heating solids and gases and ore processing in energetics and chemical processes.

As a matter of fact, this paper is a follow-on of the previous presentations of the author at the STTFUA*. The present status of the scientific and technical acquisitions for the utilization in various fields at high temperatures (above 1000 up to more than 3000°C) of the 1MW_{th} CNRS solar furnace was described in some details. A short note on optimization of cavity receivers showed in a summarized preliminary attempt that there is a temperature limitation in efficient use of single reflection solar point focusing facilities (in the vicinity of 1000 to 1300°C) above which it becomes necessary to use double reflection facilities.

So the program described in the present paper is mainly devoted to investigations and tests of possible applications of single reflection point focused solar radiation in the upper range of capabilities of central receiver tower facilities, that is to say from 700 to 1000°C (although some double reflection solar furnace type facilities applications are pointed out).

The entire program is aimed at objectives in tight connection with each other: heating solids (or liquids) and gases, storage of thermal energy for energetics or chemical applications. It relies mainly on the main following key points:

- the technology of the rotating cavity solar receiver developed and extensively used for MONTLOUIS and ODEILLO solar furnaces applications at very high temperatures on a batch process basis needed to be improved to allow continuous processing of solid (or liquid) materials at lower temperature.

* See Golden April 78 STTFUA workshop proceedings, pp. 38 to 90

These tests on the new equipment are scheduled for this year. The centrifugal furnace used until now allows to take advantage of the self-container, effect. This point has led the author to think that it is necessary to investigate the possibility of using the rotating cavity in a precentrifugation regime to keep mainly the self-container advantage (saving in this way insulating refractory materials). The theoretical study shows this is possible and the tests should verify this possibility.

The two first applications being studied and designed for pilot scale experiments at about 200KW_{th} level are:

- the "sand receiver" with storage and heating of a gas. In the first step only the receiver, the storage and the fluidized bed are going to be tested to determine the conditions of operation, the efficiencies and the possibility to increase the size up to the scale of a central receiver tower facility and for power generation through a gas cycle.

- the ore processing reactor which uses part of the equipment plus a filter and a humid cyclone to collect the reaction product (in the case of volatilized product) and the gas from reaction. This one is going to be tested for roasting molybdenite ore. In this case the ore to be processed is a low grade ore. It is necessary to save the sensible heat from the processed ore to find if there is any chance of economical feasibility for this particular ore process.

The "sand receiver" program is developed by the author and co-workers in close connection with a second team under Dr. LAGUERIE, Chemical Engineering Institute in TOULOUSE, well known for their experience in the theory and practice of multistage fluidized beds. The program is approved and funded by Engineering Physical Sciences in CNRS under a large program on "Thermodynamics 78" and also by PIRDES.

The program concerning molybdenite ore processing is in collaboration with a team under Dr. J. P. COUTURES from the CNRS Ultra Refractory Laboratory at ODEILLO, in particular doing the thermodynamics and kinetics studies. This program is funded by PIRDES in CNRS among others under the name Chemistry and Solar Chemical Engineering 78.

Concerning the "sand receiver" program the author has also initiated an investigation on materials in the granular solid state for use in the receiver and to store the heat at high temperature.

The name "sand receiver" is, in fact, a kind of a nick name. Actually "sand" covers a granular solid material with the appropriate properties for the investigated purpose. The volumetric heat capacity varies by a factor of 2, 5 to 3 depending on the material.

The author is investigating the possible capabilities of solar furnace melted spheroidized bauxites in tiny properly sized grains (this material was developed in '71-72 with the spheroidizing process). It is expected to offer some attractive properties for the optimization of the "sand receiver".

Another investigation suggested by the author and being performed concerns the evaluation of the possibility of recuperating thermal energy from the heat

- the rotating cavity solar receiver is a good candidate to solve the problem of heating a granular solid directly by solar focused radiation without wall effect on heat transfer in such a way that it allows high heat transfer rates with much less limitations than with tube walls and such means.

- the material heated in the cavity receiver absorbs directly the radiant energy and converts it to thermal energy stored in it at high temperature as sensible heat.

- the heated material can be stored and this storage can be unloaded through multistage fluidized beds when necessary to heat a gas under desired pressure.

- the same technology can be applied in the case of ore processing to save thermal energy from the processed material.

Heat transfer rates through tubes walls for heating gases are limited well below those which would be necessary to use the flux densities above $40W/cm^2$ which can be achieved easily in the focusing area of the central receiver tower facilities.

On the other hand controlled atmospheres are difficult to achieve except presently inside tubes (although quartz windows have been used on a pilot scale chamber for the ODEILLO furnace but under normal pressure).

On the contrary the proposed way of using point focused solar radiation is an attempt to accommodate high fluxes with limited problems on materials and to separate the absorption of solar radiation and the controlled atmosphere which is achieved down in the process after the receiver.

There are several different objectives in the investigation of the rotating cavity furnace for the different applications to be tested on pilot scale.

The applications to be tested are classified into four quadrants depending on whether they necessitate processing the material in solid (or liquid) state, under air (or controlled atmosphere). Except for molten salts the level of temperature increases and in most applications necessitates use of double reflection, high concentration ratio facilities.

Three different technologies have been developed and used to melt materials with the $1MW_{th}$ solar furnace.

The rotating cavity furnace has been used with the solar furnace until now only for batch processes at high temperatures for making large crucibles.

Modifications are being made on this equipment to melt materials continuously (in connection with the spheroidization process) and to heat a divided solid (also continuously).

content of the exhaust gas turbine outlet (in the case of an open air cycle) and to transfer this energy to the solid under normal pressure via a fluidized bed prior to entering the "sand receiver".

In conclusion the author has tried in this paper at the Solar Energetics Laboratory, in a cooperative effort with two different teams from PIRDES* at CNRS,* to investigate the possibilities of a new way of utilizing point focused solar radiation in the fields of energetics and chemical processes: storage at high temperature, direct absorption of radiant energy on to a granular solid material, heating of gases for chemistry or power generation using open air cycle, and ore processing based on the use of the rotating cavity furnace utilized until recently only for high-temperature batch processes.

*CNRS: Centre National de la Recherche Scientifique
PIRDES: Programme Interdisciplinaire de Recherche et Developpement de
l'Energie Solaire



OPERATION OF THE
CENTRAL RECEIVER TEST FACILITY

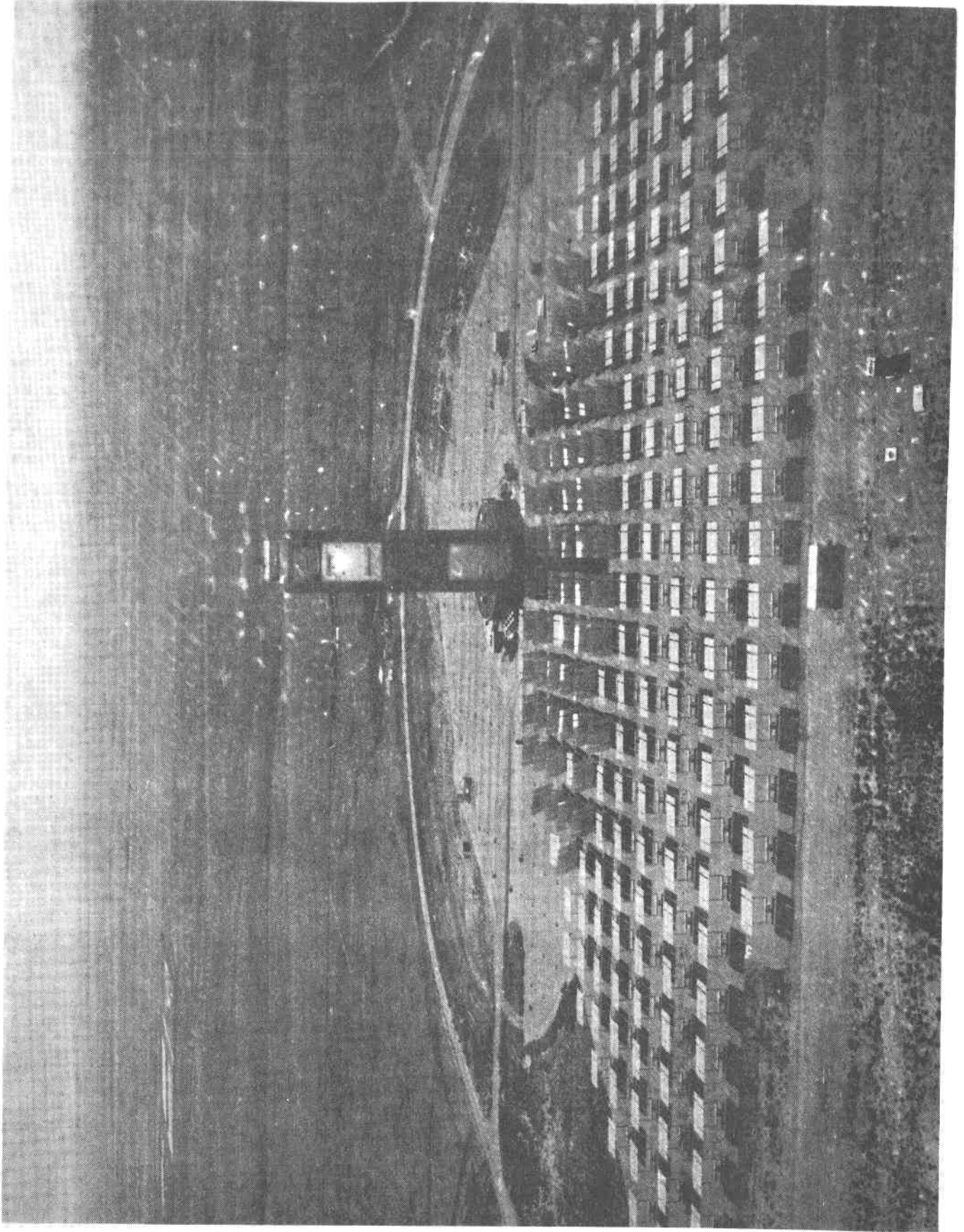
STTF-UA WORKSHOP MAY 3, 1979

ALBUQUERQUE, NM

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Abstract

The world's largest high intensity solar experimental facility became fully operational October 1978. The Central Receiver Test Facility is capable of delivering 5 million watts of thermal power to experimental equipment. The primary CRTF testing programs will involve prototype components (receivers and heliostats) for central receiver solar electric power plants. The CRTF also provides unique capabilities for other high solar flux and high temperature research and development work. Two hundred twenty-two sun tracking heliostats are used to concentrate the sun's energy to an experiment located on the 61 meter tall concrete tower. Testing of the first gas cooled receiver was completed in March 1979. The first steam cooled receiver and prototype power plant heliostats are currently under test at the CRTF.





OPERATION OF THE
CENTRAL RECEIVER TEST FACILITY

John T. Holmes

INTRODUCTION

The 5MW Central Receiver Test Facility (CRTF) provides for the testing of prototype components for central receiver solar electric power plants and to provide a high solar flux, high temperature test bed for other research and development work. The CRTF has been built by the USA Department of Energy and is operated by the Sandia Laboratories.

The CRTF conceptual design was begun in the fall of 1975. Construction started in the summer of 1976 and completed about 24 months later in mid-1978. The facility consists of a centrally located, 61m tall, experiment tower, 222 computer controlled heliostats capable of directing about 5MW_t to an experiment on the tower. The total design and construction cost for this versatile, high intensity solar test facility is 21.25 million dollars.

EXPERIMENT CAPABILITIES

Tower

The primary purpose of the centrally located tower is to provide locations with support utilities where experiments may be placed to receive high intensity reflected sunlight from the facility heliostats. The tower rises 61m (200 ft) above ground level and extends 15.2m (50 ft) below ground. Four primary experiment locations are provided on the tower. Large experiments are located atop the tower which will be the most heavily used experiment location. Three test bays for smaller experiments are located on platforms at the 36.6m, 42.7m, and 48.8m (120, 140 and 160 ft) levels as shown in Figure 1. The two lower test bays are configured as rooms and the upper test bay is an outside shelf.

Elevators and Hoists

The tower interior contains a large elevator that can be positioned with its roof anywhere between ground level and the 61m (200 ft) level. The roof of the elevator is the location where large experiments are mounted. Ground level access to the roof is by a 9.8m (32 ft) wide by 16.8 (55 ft) high door on the north side of the tower. The elevator will lift 90,700 kg (200,000 pounds). It contains support equipment for the experiment including instrumentation terminal panels, computer control and data acquisition hardware and a light machine shop.

Equipment and material can also be lifted into position up the outside or inside of the tower with a number of 4536 kg (10,000 pound) jib cranes. The test bays at the 36.6m and 42.7m (120 and 140 ft) levels are serviced by 4536 kg (10,000 pound) hand-gearred bridge cranes.

Heat Rejection System (HRS)

Most of the CRTF heat rejection equipment is housed in the tower. The heat rejection system is capable of handling water or air as the coolant fluid.

Figure 2 shows the water/steam heat rejection system. This system is composed of dry cooling towers, a condenser, pumps, heat exchangers, and other necessary equipment.

The HRS can supply demineralized water at the maximum rate of 4.7 l/s (75 gpm) and a maximum temperature and pressure of 288°C (550°F) and 15.5 MPa (2240 psi), respectively. 9000 Kg/hr (20,000 lbm/hr) of 518°C (965°F) steam at 13.8 MPa (2000 psi) can be accommodated by the HRS.

To assure the experimenter of high quality demineralized water, a water quality monitoring system is used. This system measures temperatures, specific conductance, cation conductance, and pH and a number of selected anions. Hydrazine and a deaerator are used to control the oxygen content.

A closed-loop dry cooling tower system provides coolant to dissipate the excess energy in the feedwater/steam loop. A 25.2 l/s (400 gpm) pump also brings coolant from the cooling tower and pumps it through a tower manifold to provide low temperature cooling capabilities throughout the tower.

The air heat rejection system (Figure 3) supplies 2.7 kg/s (6 lbm/s) air at a maximum temperature and pressure of 121°C (250°F) and 1.0 MPa (150 psia), respectively.

STEAM/WATER HEAT REJECTION SYSTEM

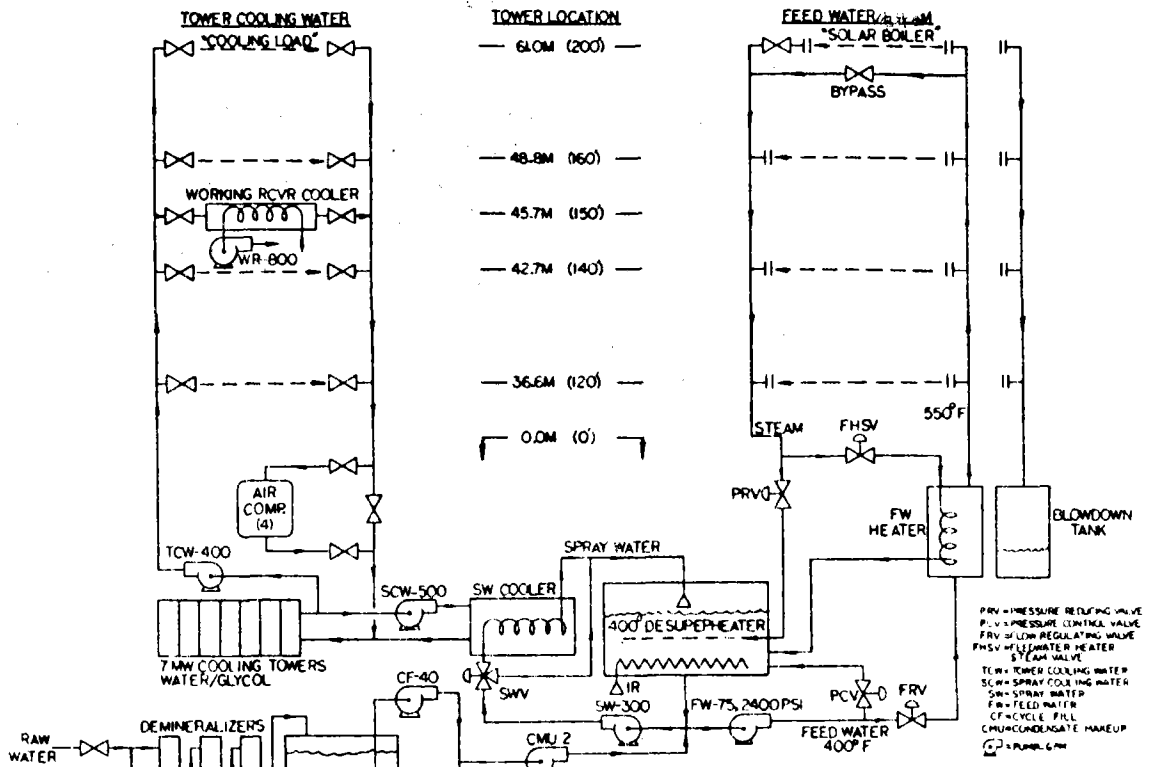


FIGURE 2

CRTF AIR HEAT REJECTION SYSTEM

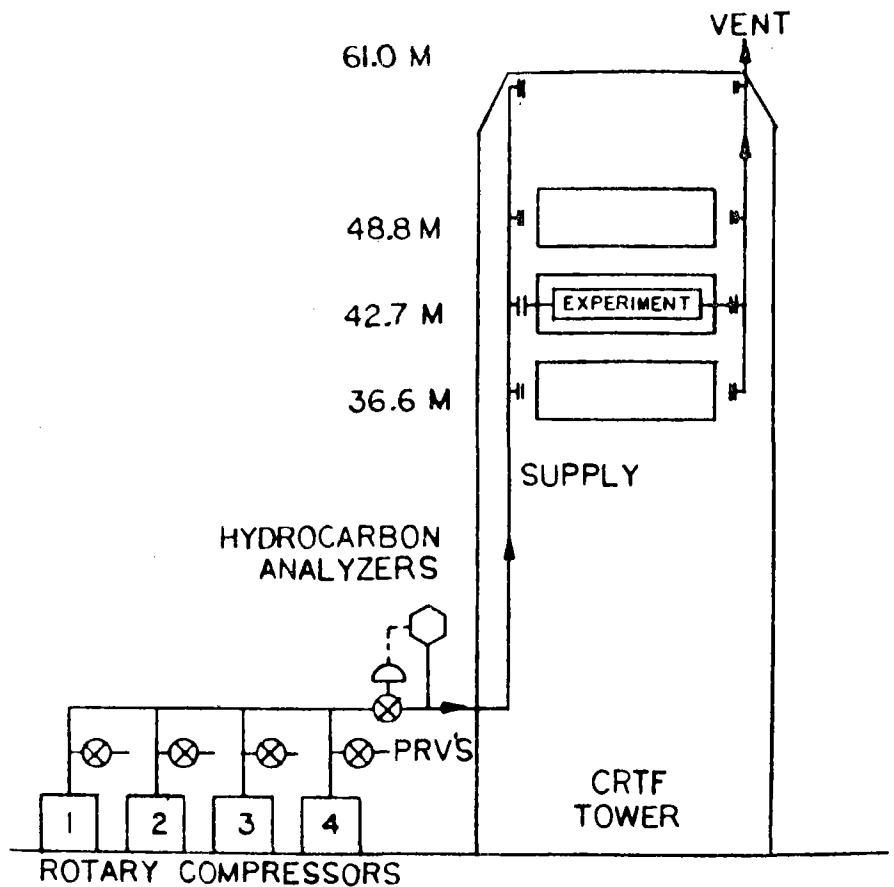


FIGURE 3

Four rotary type diesel driven compressors provide the air supply. Two hydrocarbon analyzers are used to monitor the hydrocarbon content of the compressed air. One is used to monitor and display hydrocarbon content for the experimenter and the other is used to stop the input to the system if the air becomes contaminated. The hydrocarbon content is less than 5 ppm. As is true for the water heat rejection system, the air system can be used at any tower location.

Master Control System

Coordinated control of all CRTF operating and data systems is provided by a Master Control System (MCS). The MCS is an overall command, control, and data system performing control management and supervision as well as data collection, analysis, and presentation.

The MCS uses three digital minicomputers in a modular, function-oriented network as shown in Figure 4.

1. MCS-Control is the interface for the facility operator's and experimenter's consoles through which the entire CRTF can be controlled.
2. MCS-Data is used to control and acquire data from the heat rejection system, four meteorological stations, and from the MCS-Tower minicomputer.
3. The MCS-Tower minicomputer acquires data from experiments in the tower and generates control signals.

Up to 480 channels of analog data can be connected to the MCS measurement equipment multiplexers at any tower elevation. Control signals are either digital, for on-off control, or analog, such as proportional voltage or current to adjust set-points for analog proportional controllers.

The facility operator will be able to display any of three color coded data or status pictures stored in his console's refresh memory. One display is the heliostat field status and other current information such as time and weather data; another is the Heat Rejection System status display. A third picture will be tailored for experimental data, such as a color image depicting temperature or stress regions within the boiler. The facility operator's keyboard is used to enter real time, on-line commands which are analyzed and tested for validity, then passed to the HAC's for immediate execution or to the MCS-Data minicomputer to change the data acquisition configuration or to the heat rejection system controller set points.

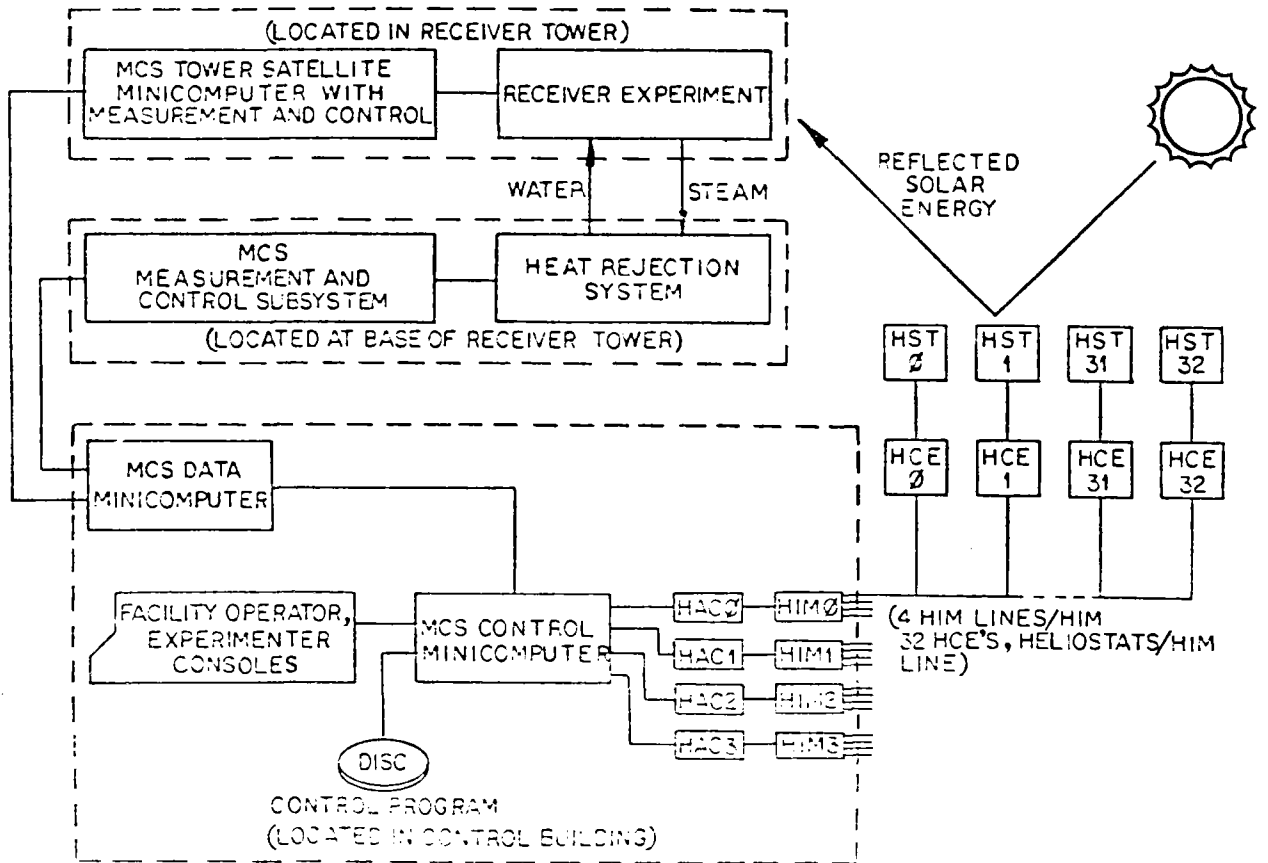


FIGURE 4

The experimenter sits at a console identical to the facility operator's and may look at the same three data or status pictures, but cannot change the contents of any but the experiment data picture.

Off-line post-test programs allow (1) reformatting the data for subsequent processing, (2) replaying the test data with time-scale changes for analysis, (3) analyzing and presenting data for more channels or with more time consuming analysis than possible in real time, and (4) archiving data.

Heliostat Array Subsystem

The STF energy collection field consists of 222 heliostats, see Figure 5. The total heliostat field is capable of concentrating in excess of 5 million thermal watts of power and produce a peak intensity of 2.4×10^6 watts/m² under favorable sun, heliostat, and target conditions. This is equal to a maximum black body absorber temperature of about 2530°K. Figure 6 and 7 give the calculated total power and peak flux expected at a tower top target as a function of time of day and day of year using the 222 heliostats located north of the tower. For test flexibility, the heliostats can be located on either of two general foundation arrays which form a northern or circular distribution with respect to the central tower (Figure 8).

The reflector surface of the heliostat is made up of 25 back-silvered glass mirror facets that total 37.2m² in area. The 25 facets are assembled into a mirror module. The mirror module is moved about by an azimuth and elevation mount and drive system. Each axis gimbal is driven by a dual motor system which provide angular rates of either 5.6 milliradians/sec or 0.3 milliradians/sec. The high gimbal rates are primarily used to move the mirror module rapidly for emergency, start-up and shut-down operations. The low rate is used for sun tracking operations. The position of each gimbal is known by a digital-output optical encoder.

The facets of each heliostat can be focused by mechanically shaping the mirror. This is done in the facet assembly process. Each reflected facet beam is aligned with each of the other beams so as to produce 25 coinciding facet beams. This focusing and aligning process produces concentrations of 10 to over 50 depending on the focal length.

The alignment is accomplished using a collimated laser light beam the size of a facet which is directed to the facet of interest and the reflection is returned to a target. The control system positions the heliostat properly to create the required facet-to-facet orientation. The operator adjusts each facet support until

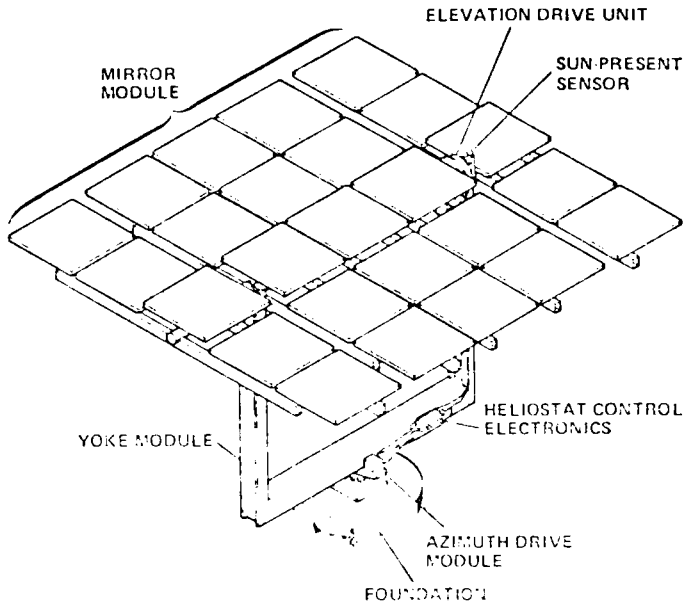


FIGURE 5

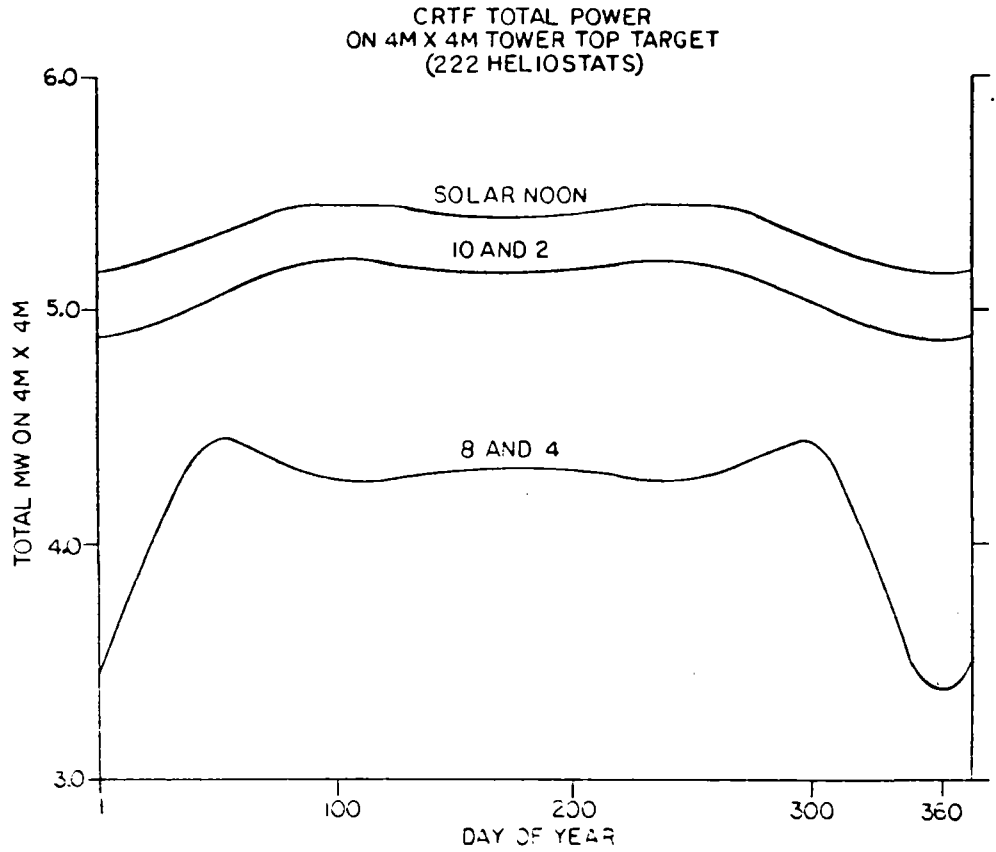


FIGURE 6

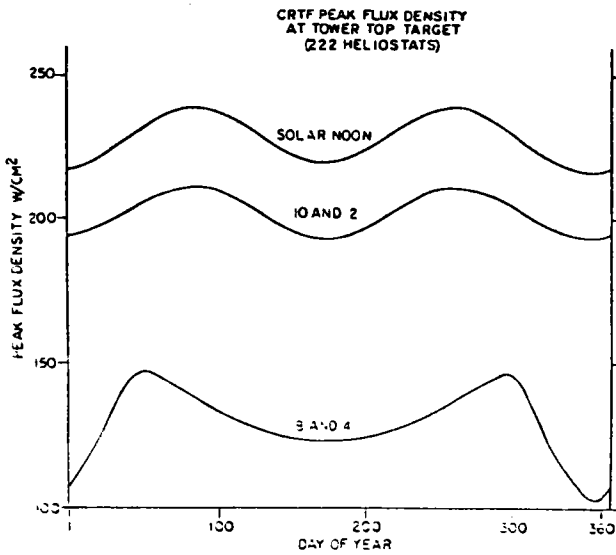
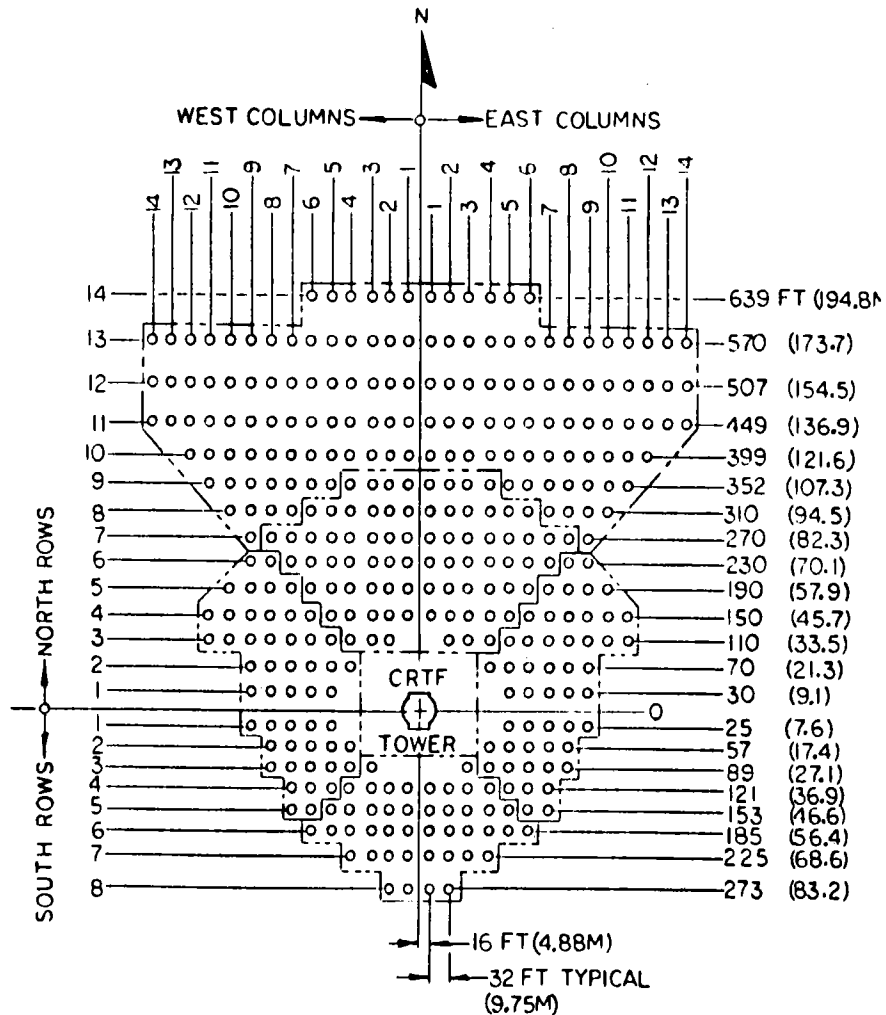


FIGURE 7



CRTF HELIOSTAT LAYOUT
FIGURE 8

the reflected beam returns to the target center. The geometry created by alignment is optimized for any solar day and hour, heliostat field location, and target location on the tower. Considerable beam spreading occurs when the overall geometry is much different than the chosen alignment condition. About eight man hours are required to align each heliostat.

A secondary concentrator is being designed that is a paraboloid of revolution in shape. It will produce a beam concentrated by about four to five times and about 0.23m in diameter. Achieving a flux density of about 10,000 kW/m² will give a maximum theoretical temperature of 3630°K using the secondary concentrator.

Heliostat Control System

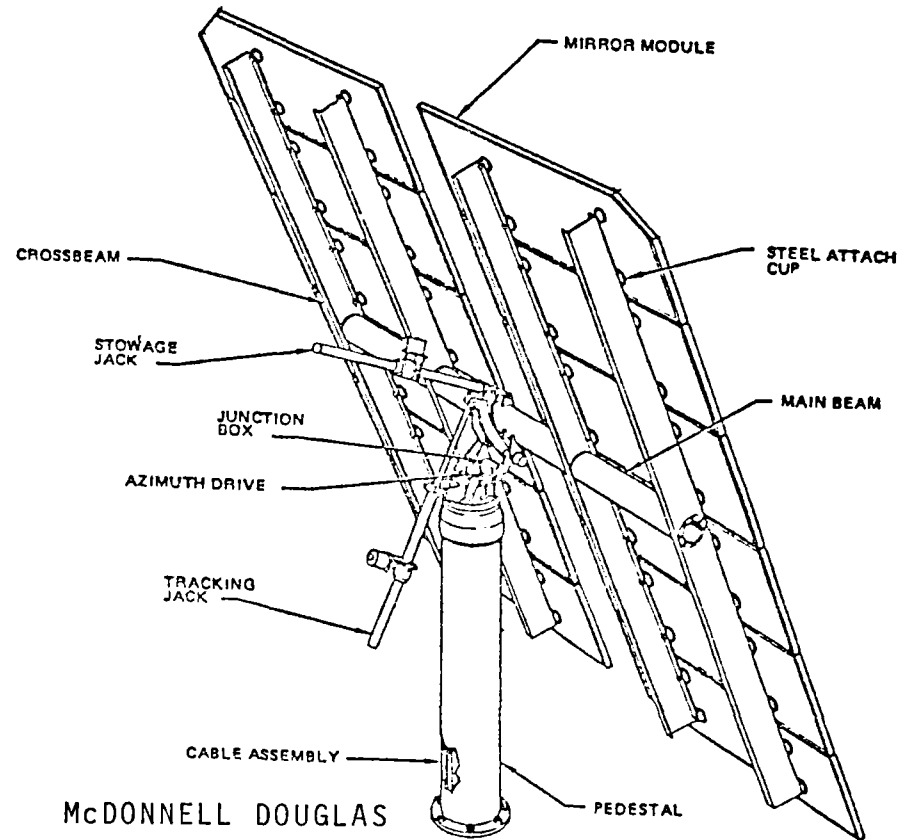
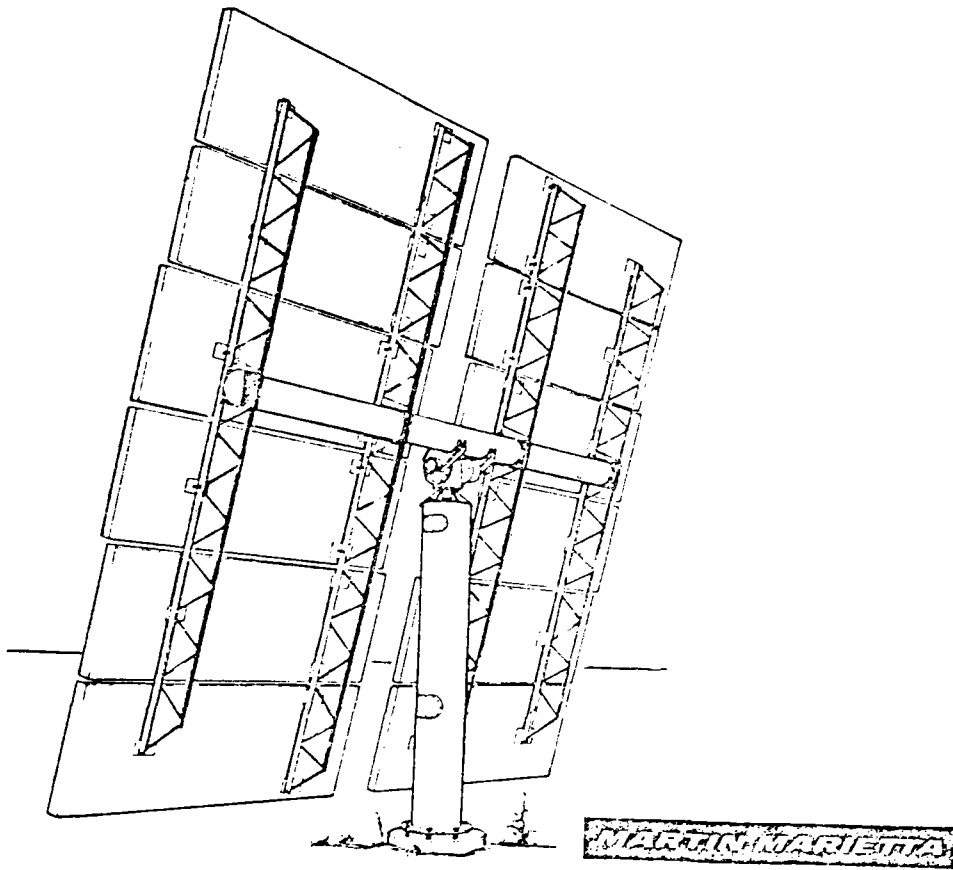
The overall heliostat control system is shown as it interfaces with the Master Control System in Figure 4. The heliostat pointing commands from the preprogrammed test sequence or from the facility operator are analyzed by Master Control System (MCS) and distributed to the heliostats for execution. Heliostat Array Controllers (HAC) communicate with up to 128 heliostats in their jurisdiction. The HAC's send MCS-generated commands, and HAC-generated azimuth and elevation pointing information to its four associated Heliostat Interface Modules (HIM) to be transmitted to the appropriate heliostats. Each heliostat receives these pointing vector updates once every second and responds with its own status. The HAC's also process alarm messages such as tracking or communication errors.

The commands and data transmitted to the individual heliostats are received and executed by the Heliostat Control Electronics (HCE's). The HCE provides the proper drive motor power until the gimbal axis encoders indicate that the appropriate heliostat attitude has been attained. The HCE and heliostat motors then await the next command.

Heliostat Characterization Systems

The CRTF has a system for the complete performance evaluation of prototype heliostats. The two basic systems used during heliostat evaluations are the BCS and the PCS. These systems will be used first to evaluate prototype heliostat designs for the 10-MW^e Pilot Plant in Barstow, California. Two designs have been selected for testing at the CRTF: one by the Martin Marietta Co. and one by McDonnell Douglas Astronautics Co. as shown on Figure 9.

Figure 9
PROTOTYPE HELIOSTATS FOR THE
10MW_e SOLAR PILOT PLANT



1. Beam Characterization System - The BCS uses video radiometer techniques to measure the reflected solar power of a heliostat. The system consists of a (9.1x9.1-m) 30x30-ft. beam target, video camera, analog image analyzer, calibration system, video digitizer, and a minicomputer. Figure 10 shows this basic system configuration.

The BCS provides the following basic tabular and graphical outputs: a 256x256 matrix of spatially located heat-flux density values (W/cm^2), total power incident on the BCS target, beam power centroid location relative to the desired aimpoint, 2-D beam profiles, isoflux density contours, 3-D flux distributions, and plots of power vs radius from the centroid location. Ancillary equipment interfaced to the BCS provides measured insolation levels, sun shape, and meteorological data.

The BCS also has an operating mode that will be used to evaluate wind loading (heliostat vibration effects) and short-term beam pointing errors.

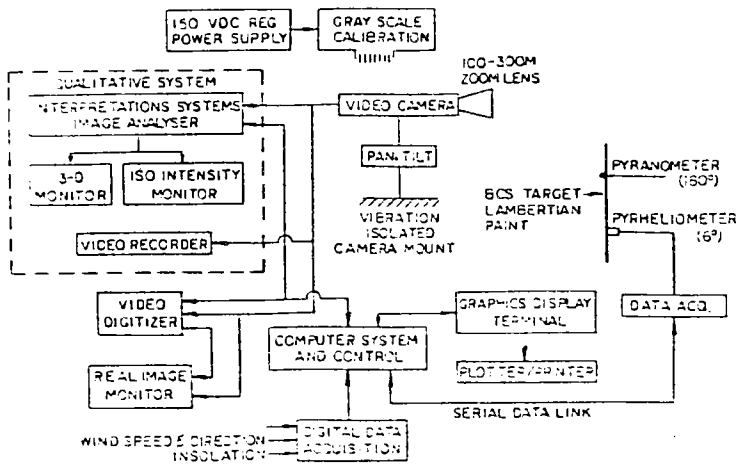
2. Pointing Characterization System - The PCS consists of a helium/neon laser mounted on the test heliostat, a laser target, a video camera, a time-display input and a video recorder (Figure 11). The general purpose of the system is to resolve the pointing characteristics of the heliostat control and drive mechanism from the structural and optical response of the entire heliostat.

The PCS provides four basic outputs: measured track and slew rates, heliostat pointing repeatability, electronic control stability, and a direct assessment of control/drive pointing accuracy during heliostat operation.

Heliostat Maintenance

A number of problems have been encountered with the CRTF heliostats that have required concentrated maintenance efforts. The problems, in part, have been related to moisture intrusion into the heliostat control electronic boxes and into the optical encoder chambers. There have also been numerous component failures and poorly tuned electronic components. The moisture problems have been solved by improved sealing techniques. The electronic problems are being solved using higher quality components and more sophisticated techniques for adjusting the optical encoder bit thresholds.

Over 64,000 heliostat hours were accumulated through April 1979. Maintenance efforts have over 95% of the field operational. After the basic problems were rectified by the heliostat maintenance crew, the problems have not reoccurred, and heliostat maintenance efforts at the CRTF are decreasing.

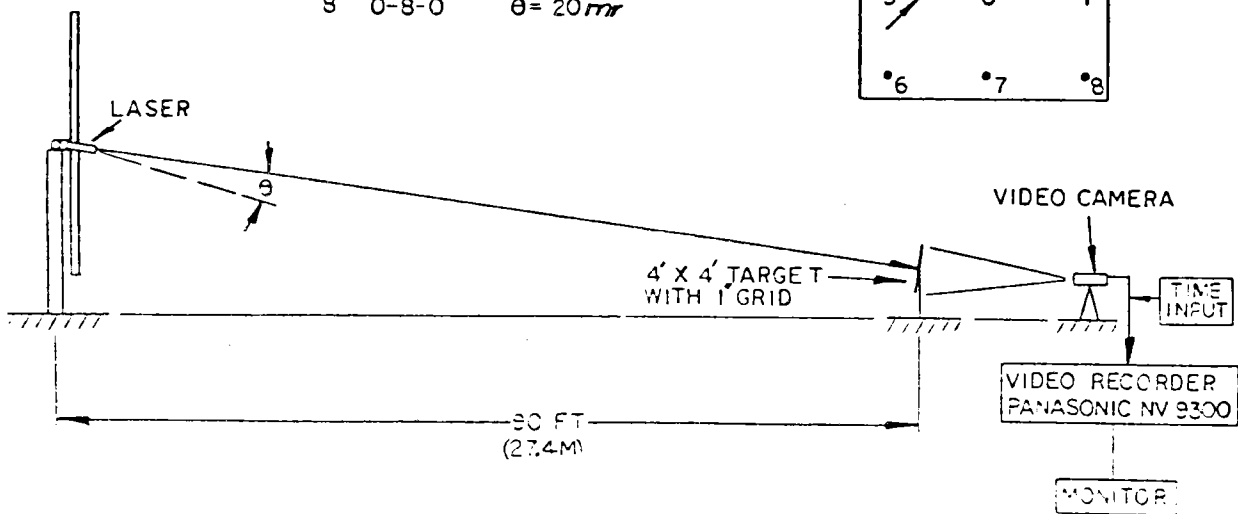
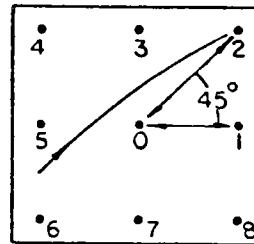


BEAM CHARACTERIZATION SYSTEM
Figure 10

POINT SEQUENCES

- 1 0-1-0 $\theta = 20\text{ mr}$
- 2 0-2-0 $\theta = 20\text{ mr}$
- 3 0-3-0 $\theta = 20\text{ mr}$
- 4 0-4-0 $\theta = 20\text{ mr}$
- 5 0-5-0 $\theta = 20\text{ mr}$
- 6 0-6-0 $\theta = 20\text{ mr}$
- 7 0-7-0 $\theta = 20\text{ mr}$
- 8 0-8-0 $\theta = 20\text{ mr}$

LASER PATHS ON TARGET



POINTING CHARACTERIZATION SYSTEM (PCS)

Figure 11

The reflectivity of the CRTF heliostats is being monitored on a routine bases. The reflectivity is slowly decreasing from the original, over 80% to about 75% at the present time. Figure 12 shows the effect of the non-operating orientation on the reflectivity. The reflectivity of the entire field has been improved by using a number of opportunities to allow natural rains to clean the glass. The reflectivity improves within 1% of clean by the rain washing. No artificial techniques have been used to clean the CRTF heliostat mirrors.

CRTF TESTING PROGRAMS

US Department of Energy (DOE) Receiver Experiments

The US DOE commitment to a 10-MW_e central receiver pilot plant has produced solar receiver hardware to be tested at the CRTF. The pilot plant concept uses a Rankine cycle with water/steam cooled receiver.

The first of these receivers to be tested at the CRTF is a prototype module of the once-through external absorbing receiver designed by a McDonnell Douglas/Rocketdyne team. The receiver module is .89m (35 in) wide by 12.5m (41 ft) high and requires about 4-MW_t of incident solar power to operate at the maximum nominal design conditions. The CRTF will supply 288°C (550°F) feedwater and the receiver will output 516°C (960°F) steam at 10.4 MPa (1515 psia) pressure. The solar testing began in February 1979 and is expected to last four to six months (See Figure 13).

The second of these prototype receivers that may be tested at the CRTF is an approximately 5-MW thermal capacity scale model of a cavity type receiver using separate boiler, steam drum, and superheater sections. This receiver is a product of the Martin Marietta/Foster Wheeler team. The receiver including its support structure measures approximately 9.1m (30 ft) wide by 5.8m (19 ft) deep by 14.3m (47 ft) high and will weigh 77,300kg (170,000 pounds). The CRTF will supply 205°C (400°F) feedwater to the receiver and the receiver will output 516°C (960°F) steam at 9.1 MPa (1325 psia) pressure.

1-MW_t Gas Cooled Receivers

The Electric Power Research Institute (EPRI) has initiated a program with Black & Veatch Consulting Engineers and Boeing Engineering and Construction Company to develop gas cooled receivers for Brayton cycle power plants.

The Boeing concept involves a closed helium cycle that will operate at a temperature of 816°C (1500°F). The Boeing 1-MW thermal

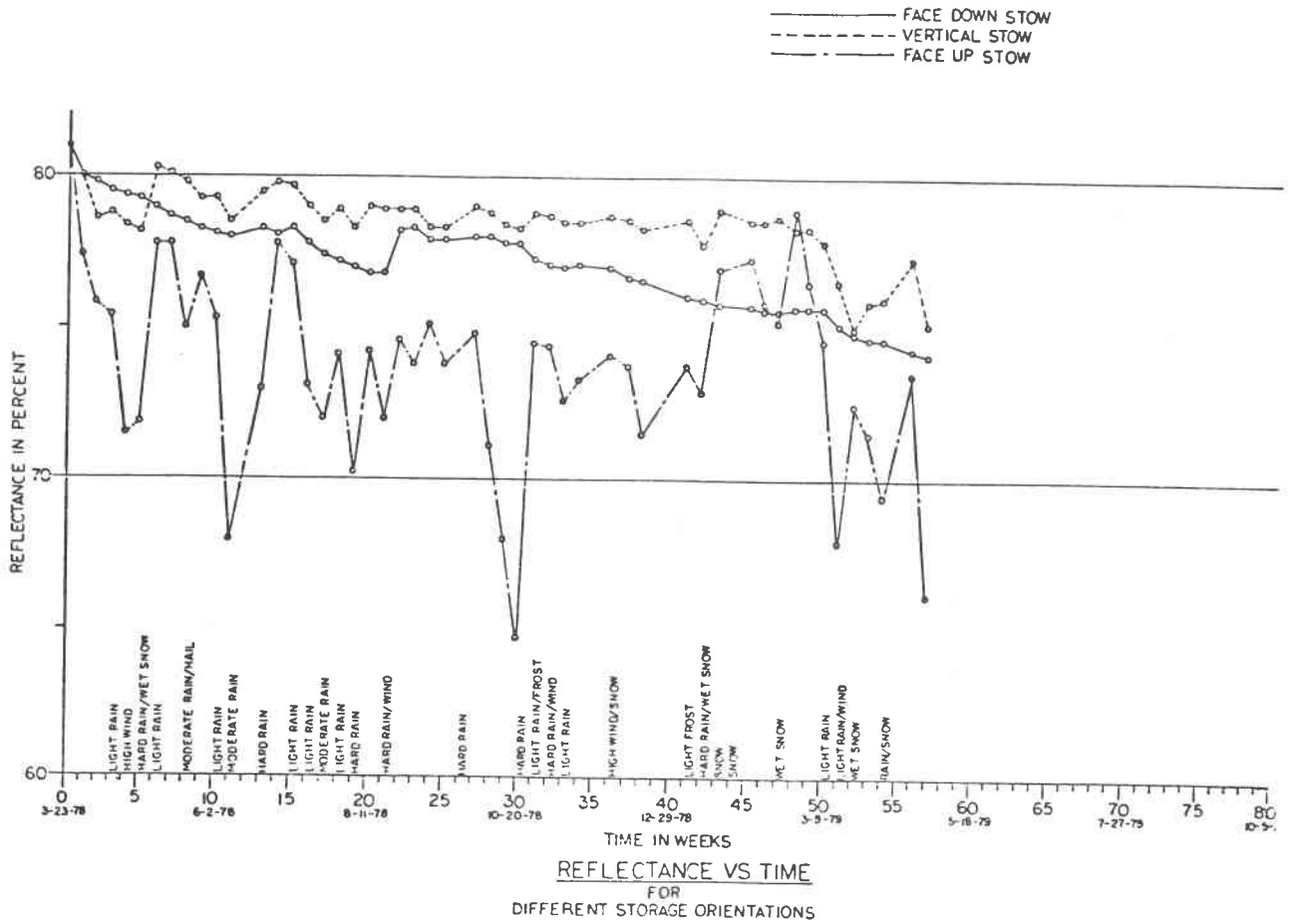


FIGURE 12

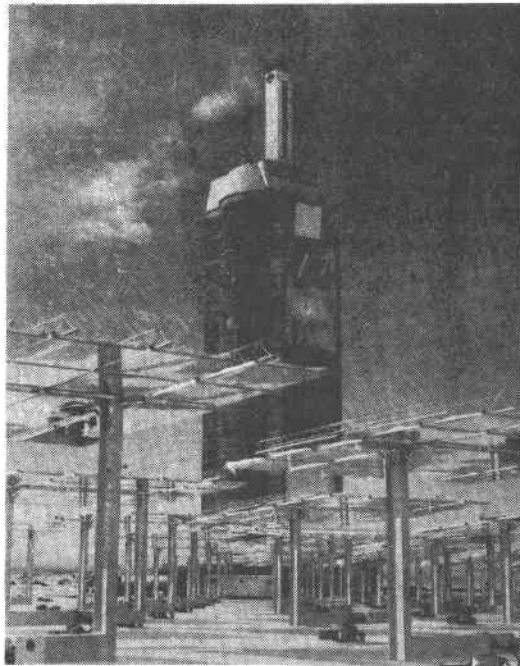


FIGURE 13

capacity prototype receiver was tested at the CRTF from October 1978 to March 1979. Figure 1 shows the Boeing receiver in test at the CRTF. The receiver used air as the coolant during the STTF tests. Although the test results are not completely analyzed, the Boeing receiver operated at efficiencies (light to heated working fluid) of over 60%. A serious degradation of the ceramic reflector inside the cavity was encountered. Improved materials for that application are being evaluated.

The Black & Veatch solar receiver will be used in an open cycle with a conventional combustor in parallel for added plant reliability. This system will operate at 1038°C (1900°F) using a ceramic receiving surface. A 1-MW thermal capacity Black & Veatch prototype receiver will be tested at the CRTF towards the end of 1979.

STTF Testing Schedule

The STTF tower top test location is committed to DOE solar receiver testing for the next year, the test bays are only partially committed, and additional experiments are being sought. DOE-sponsored high intensity photovoltaic arrays are anticipated for testing in 1979. A test of the accuracy of a radar device in a missile nose cone undergoing simulated aerodynamic heating will also be performed in 1979. In the conceptual stage are experiments on:

- Liquid metal, molten salt, oil, or gas cooled receivers or storage systems.
- High intensity photovoltaic or thermionic array evaluations.
- High temperature material performance studies and material process development.
- High intensity photochemical, photoelectrochemical and high temperature chemistry process development.

POTENTIAL EXPERIMENTERS

An active Users Association including universities, government contractors, research institutes, private companies, and foreign interests has been founded to assist experimenters and to encourage utilization of the CRTF. Prospective experimenters are invited to contact the STTF Users Association, Suite 1204, First National Bank Building, East, Albuquerque, NM 87108. Detailed technical questions will be answered by direct contacts to the CRTF Liaison Engineer. A publication, "Solar Thermal Test Facility Experiment Manual," SAND 1173, defines the services provided by the CRTF and the requirements that experimenters must fulfill in order to implement an experiment at the CRTF.

TREATMENT OF MOLYBDENITE ORE USING A 2-kW SOLAR FURNACE--
1978 EXPERIMENTS AT ODEILLO

S. R. Skaggs and J. P. Coutures

Introduction

The emphasis in this presentation is on the details of performing the experiment including design, installation, instrumentation, and control. Basically the experiments we performed in the summer of 1978 duplicate those done in 1977 using the same apparatus, and I would like to spend just a few minutes presenting results of both experiments. Then I will describe the experimental apparatus, the ease with which this experiment was conducted and the instrumentation we used. Primary emphasis is on the solar experiments conducted in the 2-kW furnaces described elsewhere at this conference by Coutures. Finally, I would like to finish with a brief description of the experiment we expect to conduct this year at White Sands.

1977 Experiment

This experiment was conducted on crushed rock of 0.2-0.5 mm dimension containing 5-6% MoS₂ in the alumino-silicate (granite) rock matrix. Separation of the Mo from the rock was accomplished in one heating step, and the MoS₂ was oxidized to MoO₃. This is the form in which it is used in steelmaking and as a first stage for the manufacture of molybdenum metal. Impurity levels were 4000 ppm, most of which was silica, in the MoO₃; and the silica that was collected had a very low impurity content. Other elements were separated quite completely also. The low impurity level in the molybdic oxide has had a significant influence on the experiment to be run in 1979, and this will be discussed later.

1978 Experiment

The experiments run during August and September were conducted on raw ore and a mixture of raw ore and 10% MoS₂ concentrate primarily to study the kinetics of oxidation of MoS₂ to MoO₃. The data sought were the reaction temperature, the production rate of SO₂, and the mass balance or conversion of the sulfide to the oxide. Allied information that was obtained in a TGA microbalance was the specific heat of the raw ore. Due to the difficulty of measuring the reaction temperature during direct heating in the solar furnace, we moved this measurement to the micro-TGA apparatus.

Reaction temperatures for removal of water from the raw ore, reaction of FeS₂ to FeO-Fe₂O₃, and reaction of MoS₂ to MoO₃ are shown in Figure 4. We found that the last reaction could be made to occur as low as about 800°C; however, in order to make it proceed at an acceptable rate for commercial conversion, it must be driven at about 1000-1100°C. At these temperatures the MoS₂ oxidizes and sublimes, but the matrix material remains solid. At about 1250-1300°C the alumino-silicate powder begins to melt and agglomerate into glass beads. The optimum temperature to react this material is around 1100°C. In a continuous flow process there will have to be a balance between solar insolation incoming and energy conducted out of the system by powder being heated and/or sublimed in order to stay near this desirable temperature.

Mass balance measurements produced quite favorable data when compared with the other measurements. These data, shown in Figure 5, were obtained in a very crude fashion by starting with 0.5 g of material and collecting both the reacted product of oxidized material and the residue left behind on the hearth.

The production of SO_2 was measured by observing the concentration of SO_2 in the oxygen or air sweep gas through the reaction chamber. The data shown in Figure 6 confirms observations made on other parameters. Reaction times using the SO_2 measurements indicated that the MoS_2 to MoO_3 reaction was essentially complete in about 1 minute. This was confirmed by the mass balance measurements made as a function of time.

Description of Apparatus

In Figure 7 the apparatus is shown schematically. We controlled the atmosphere by surrounding the hearth with a globe and allowed the gas to flush through the chamber for several minutes before heating. The entire hearth, globe, inlet and outlet gas tubes, etc., is mounted on a trolley which can be pushed into the focus and withdrawn rapidly.

We attempted to measure the temperature of the reacting pile of powder but encountered two problems:

- 1) The pyrometer filter first employed was not in the solar blind portion of the spectrum; and after this problem was solved,
- 2) the reacting vapor species which sublimed from the pile of powder diffused the light and created a false reading of reaction temperature of around 2500°C .

The conversion of MoS_2 to MoO_3 was monitored by observing the concentration of the effluent gas for SO_2 using an infrared gas analyzer at $8.6 \mu\text{m}$. All of the gas was passed through the chamber of the analyzer so we had a measure of the total reaction product to check against the mass balance. The agreement was quite good. The mass balance was performed by very carefully collecting the reacted powder which was in the form of a yellow-green crust on the surface of the pile of powder. The unreacted residue was collected afterward, and the fraction of each related to the total amount was calculated.

Proposed Experiment

Several members of one of the investigating teams at Odeillo, directed by Dr. Claude Bonet, have studied the behavior characteristics of powders in rotating kilns under direct solar heating. We intend to fabricate a similar device here at LASL, confirm the data of their study which is available in the thesis of Gilles Flamant, and then install this apparatus at or near the focus of the White Sands facility.

The major focus of the effort at White Sands will be to convert MoS_2 to MoO_3 and sublime it in air flowing through the rotating kiln while leaving behind the alumino-silicate rock residue. For doing this we have obtained some MoS_2 from the "rougher concentrator" at Climax which is reported to be 5-7% MoS_2 with the balance being rock, 35% of which will pass through a 100-mesh screen. We expect this part of the experiment to take 15 solar working days.

In recent discussions with people of the Climax Division of AMAX we determined that they require very pure MoO_3 for the manufacture of Mo metal. From the results of our 1977 experiment we found that we could produce MoO_3 of such quality that the intermediate process of forming ammonium molybdate and subsequently calcining it so the oxide might be bypassed. As a direct result of our 1977 experiments and our discussions during the last week of April 1979 with members of the research staff of AMAX in Golden, CO, we have obtained about 20 kg of "rougher concentrate" which is supposed to contain 5-7% MoS_2 . This is the material that will be treated at White Sands this year.

The engineers and metallurgists at AMAX have not been too impressed with our results to date, because 1) the sun shines only about 8 hours per day, and ore is mined on a 24-hour basis; and 2) it is difficult at today's price for electricity to compete with concentrate cost figures of 25¢ per pound. On the other hand, they are interested in the results of making very pure MoO_3 directly with solar heat because it is much less expensive than going through the intermediate ammonium molybdate. Their annual production of the very pure concentrate for metal production is about 3×10^6 pounds, which is certainly within the magnitude of production that could be accomplished with a solar heating unit.

Conclusions

The chemistry of processing molybdenite ore is straightforward, the kinetics and other parameters have been determined, and it was found that the major effort is in handling powders on a continuous basis in a solar furnace. Once this problem is solved there seems to be no reason why this technology cannot be extended to the treatment of the other common ores in North America, e.g. iron.

SECRETARIAT D'ETAT AUX UNIVERSITES
CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE
LABORATOIRE DES ULTRA-REFRACTAIRES
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LOS ALAMOS SCIENTIFIC LABORATORY
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TREATMENT OF MOLYBDENITE ORE USING A 2 KW SOLAR FURNACE

S. R. SKAGGS, J. P. COUTURES, AND R. RENARD

1977 EXPERIMENT

0.2 - 0.5 MM CRUSHED ROCK

5-6% MoS_2

HEAT ONLY

ANALYZE SEPARATE PRODUCTS

YIELDED EXCELLENT SEPARATION
> 99% MoO_3 (< 4000 PPM IMPURITY)
ALMOST PURE AMORPHOUS SILICA

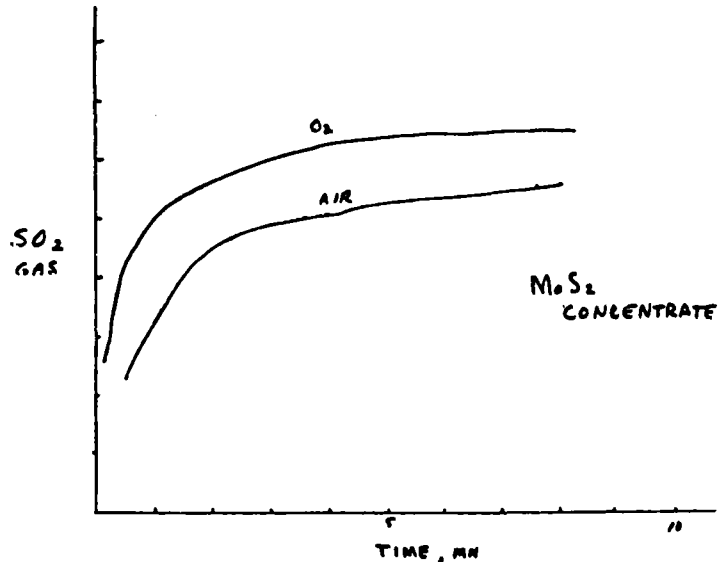
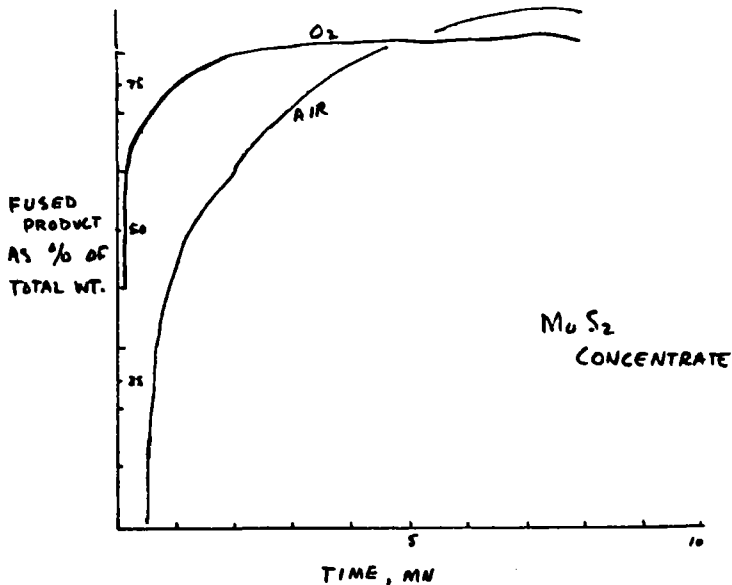
1978 EXP'TS

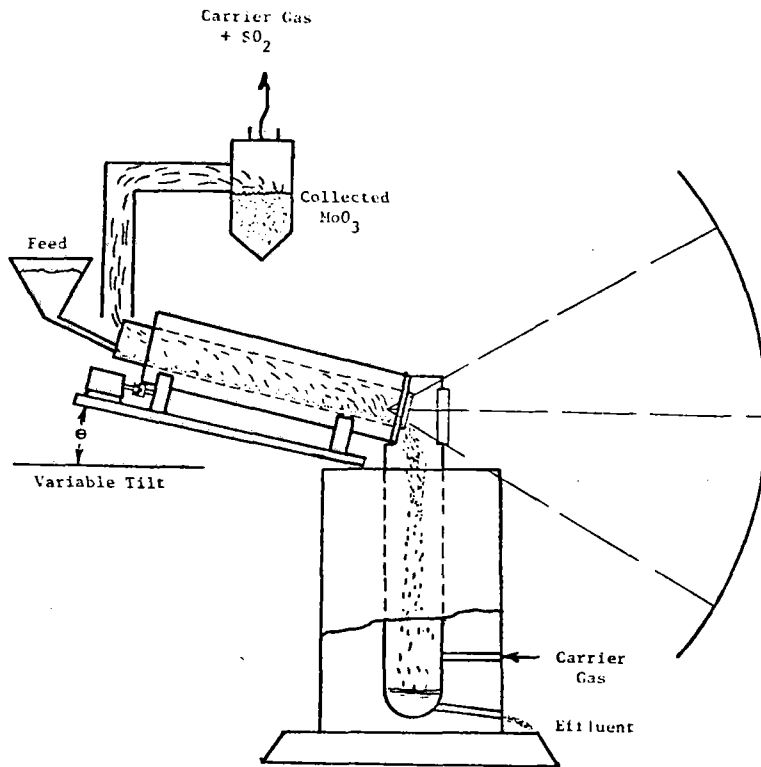
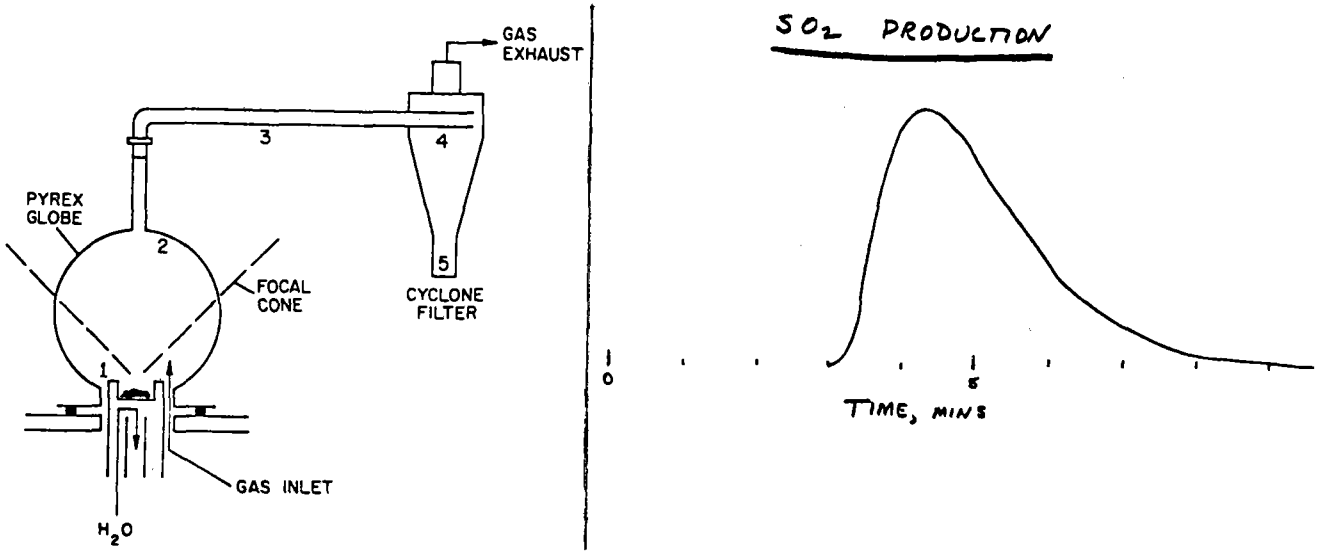
RAW ORE and 10% CONCENTRATE

- 1) REACTION TEMPERATURE
- 2) SO_2 PRODUCTION
- 3) MASS BALANCE
- 4) C_p FOR RAW ORE

REACTION TEMPERATURES, °C

H_2O	100 - 125
FeS_2	400 - 520
MoS_2	700 - 800 CONCENTRATE 900 - 1000 RAW ORE
SILICATE MELTING	1250 - 1300





Schematic of Solar Kiln for Ore Treatment

STABILITY OF PLASMA-SPRAYED COATINGS TESTED
AT WHITE SANDS SOLAR FACILITY*

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ABSTRACT

A research proposal was funded through the Solar Thermal Test Facilities- Users Association and the Solar Energy Research Institute for testing plasma-sprayed coatings in the White Sands Solar Test Facility. The study involved a screening program under a solar flux producing plate temperatures of 600°C to 1000°C. This screening program was designed to demonstrate the survivability of plasma-sprayed coatings in a solar furnace environment and to select favorable candidates for further study.

Duplicate stainless steel test plates (4" x 4" x 1/4") were plasma-sprayed with materials listed in Tables 1 and 2. Chromel-Alumel thermocouples were spot-welded at the center and back of each of the seven plates to be used in the air-cooled test but not to the seven specimens to be water-cooled.

A stainless steel specimen holder was fabricated so that the back of the plates could be air-cooled during solar testing. Also, a copper specimen holder was fabricated for use while solar testing with water-cooling.

* This research is funded by the Department of Energy through STTF Users Association and Solar Energy Research Institute.

** Operated by Union Carbide Corporation under contract W-7405-eng-26 with the U.S. Department of Energy.

Table 1. Solar Tests at White Sands Solar Facility
(Air-Cooled Specimens)

Run Number	Sample Number	Coating	Density (g/cm ²)	Exposure Time (min)	Flux (Cal/cm ² /sec)	Pyrometer Readings (°C)	Thermocouple Readings (°C)
1-6	550A	Cr ₂ O ₃	0.010	Calibration	2.0	672	656
7	579B	ErB ₁₂	0.010	18	2.0	600	645
8	576A	WC	0.015	15	2.0	645	655
9	577A	YB ₆	0.008	12	2.0	610	674
10	578A	Ta + Cr ₂ O ₃	0.006 0.008	11	2.0	700	625
11	575B	TaC	0.01	16	2.0	655	613
12	581B	Ta + V	0.004 0.007	11	2.0	688	639

Table 2. Solar Tests at White Sands Solar Facility
(Water-Cooled Specimens)

Coating Composition	Thickness (g/cm ²)	Insolation (Cal/cm ² /sec)	Water			Insolation		Recovery (%)
			Inlet (°C)	Outlet (°C)	Flow (ml/sec)	Received (Cal/sec)	Collected (Cal/sec)	
ErB ₁₂	0.009	13.4	12.9	57.4	22.7	1086	1019	94
		14.6	12.9	61.8	22.7	1184	1120	95
		15.5	12.9	66.2	22.7	1257	1221	97
ErB ₁₂	0.012	6.9	12.0	36.0	18.9	559	454	81
		8.0	12.1	41.1	18.9	649	548	84
		9.5	12.2	51.7	18.9	770	558	72
YB ₆	0.008	5.5	11.0	30.6	18.9	446	370	83
		6.8	11.3	36.2	18.9	551	471	85
		8.0	11.3	44.1	18.9	648	620	96
Ta (undercoat)	0.005	8.2	12.0	40.0	18.9	665	529	80
Cr ₂ O ₃ (overcoat)	0.010	9.2	12.0	42.5	18.9	746	576	77
		9.1	12.0	47.7	18.9	738	675	91
		9.7	12.0	49.6	18.9	786	711	90

A brightness pyrometer was used for temperature measurement on the front surface during testing. The pyrometer was focused on a 1-in. area at the center of the test specimen. This is the location of the maximum flux level at the focal plane. All pyrometer readings were taken at an emissivity setting of 1 on the instrument. The pyrometer used in this test was calibrated against a black body when the emissivity control was set on the position 1.

Data collected on the plasma-sprayed coatings, while air-cooling the back of the plates, are shown in Table 1. Data collected on water-cooled specimens are shown in Table 2. Analysis of the specimens before and after testing showed erbium dodecaboride (ErB_{12}), yttrium hexaboride (YB_6), titanium diboride (TiB_2), and chromium oxide (Cr_2O_3) to be stable above 600°C . A heat balance on the water-cooled specimens of these coatings showed 72% to 97% heat recovery efficiency.

PHOTOTHERMAL CHANGES IN CHROME BLACK EXPOSED TO HIGH SOLAR FLUXES

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Houston, Texas, 77004

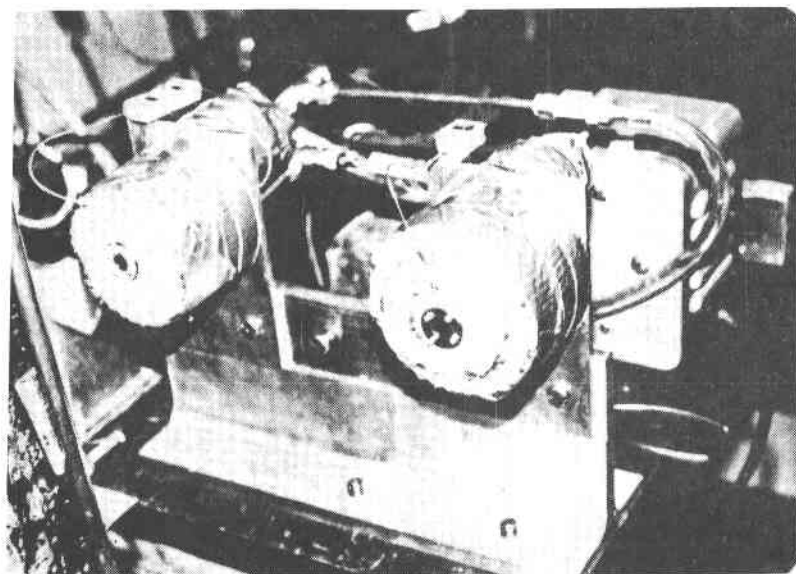
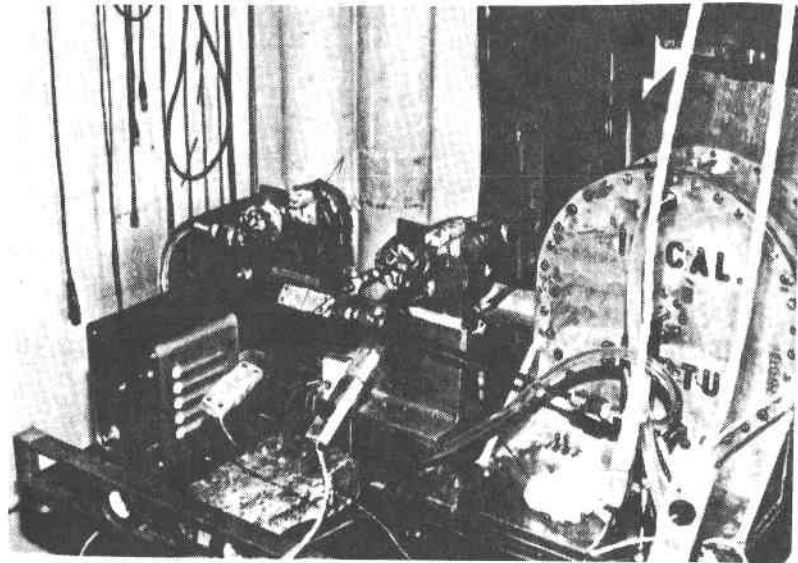
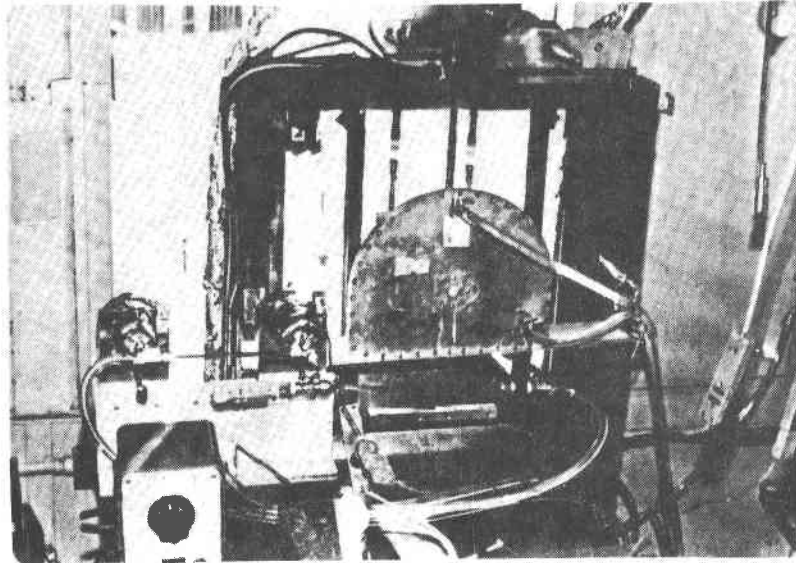
Chrome black deposited onto 1/2" diameter nickel discs with different thicknesses, different current densities and different solutions were exposed to intensities in the vicinity of 250 kW/m^2 and 2.5 MW/m^2 ; each for periods of about one hour, at the White Sands Solar Furnace early in April, 1979.

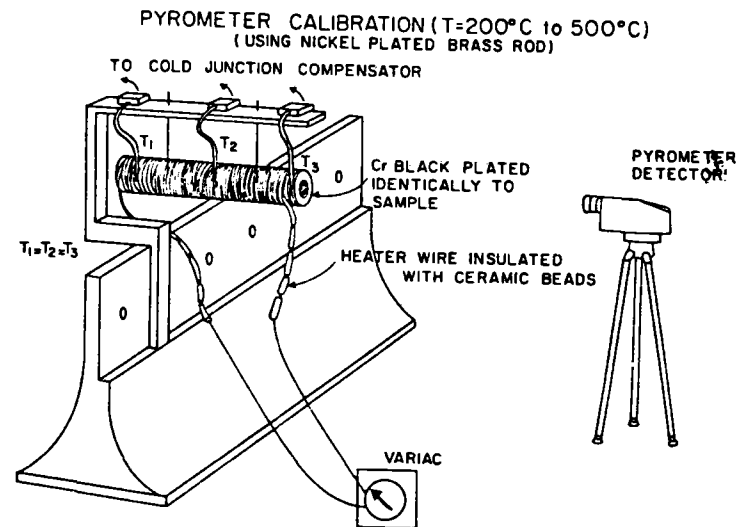
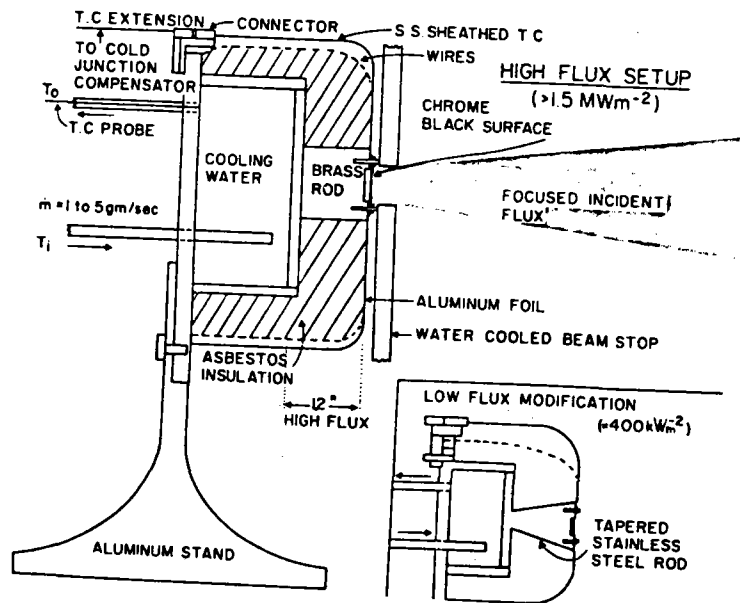
Special sample holders were constructed, one type for each flux range, to yield similar steady state surface temperatures between 300 and 400°C at both intensities. Energy drainoff was provided by water flowing at low pressure and average temperature below 50°C. Monitoring of inlet and outlet water temperature and flow rate provided real time measurement of absorptivity with particular interest in changes occurring during exposure. Surface temperature was monitored throughout exposure. Total flux on the sample face was measured at the beginning or end of each run, while the flux on the plane of the heliostat was monitored continuously.

Identical samples were subjected to the same thermal history as their counterparts at White Sands by heating in a horizontal furnace open to air. This enabled a detailed comparison between thermal and photothermal changes at the same temperature.

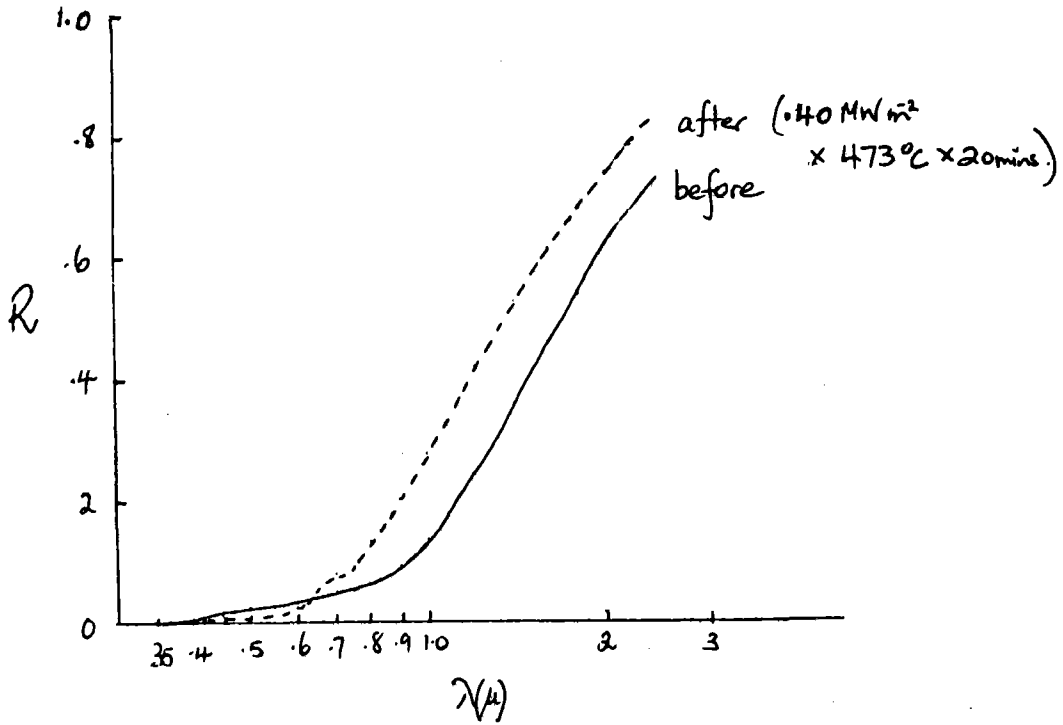
Various measurements are now being carried out to study and compare the physical and chemical changes which have occurred. Significant and consistent differences have already been observed between thermal and photothermal effects on optical properties.

* On leave in 1979 from Physics and Materials, N.S.W. Institute of Technology, Broadway, N.S.W., 2007, AUSTRALIA.

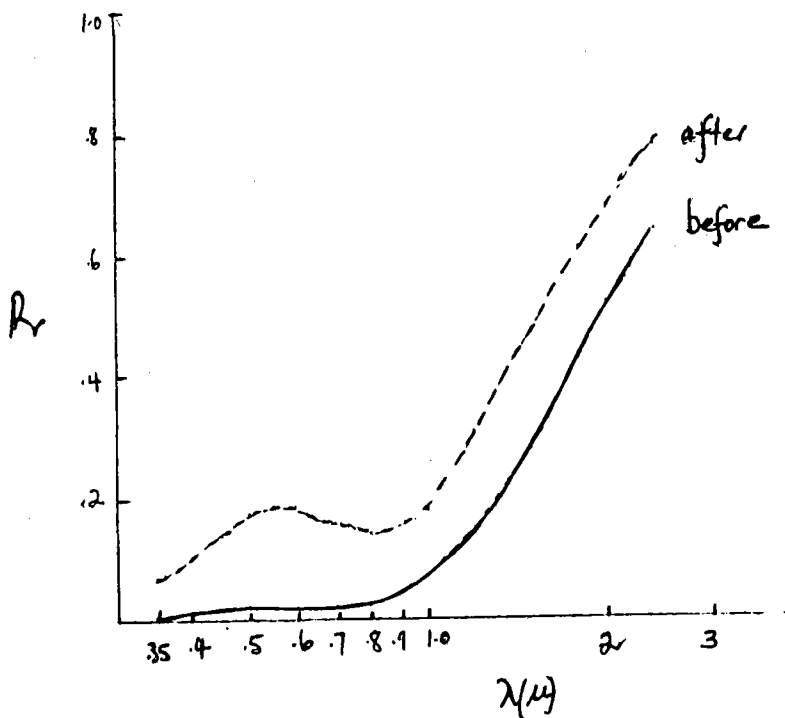




Standard 'Chromonyx' Chrome Black - Exposed to $.400 \text{ MW m}^{-2}$
at 473°C for 20 minutes

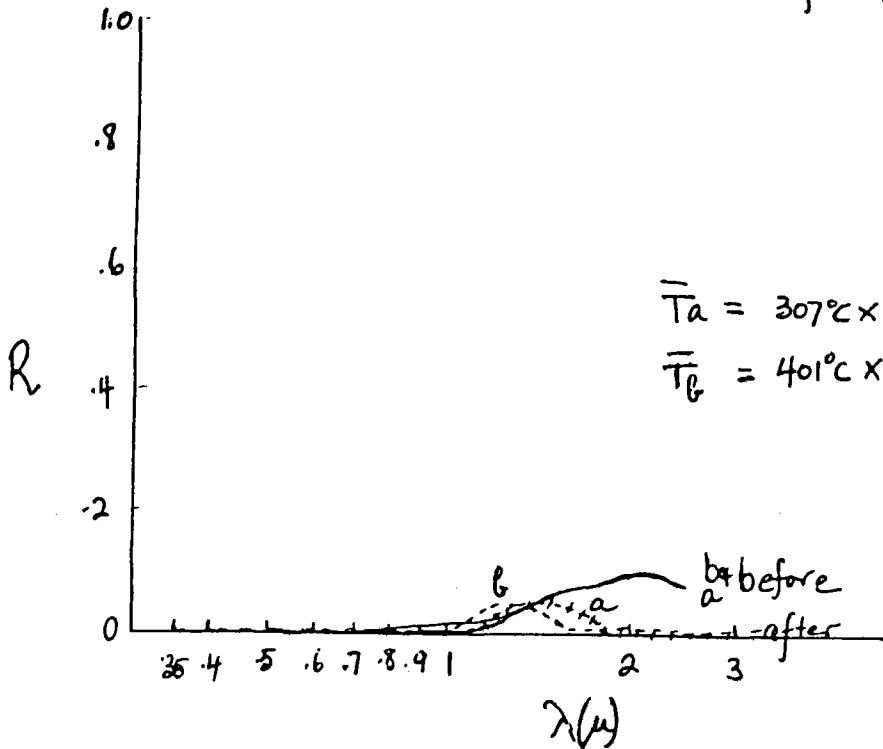


'Chromonyx' Chrome Black - Standard - (Oven heated to
[match one low flux exposure
(473°C x 20 minutes)



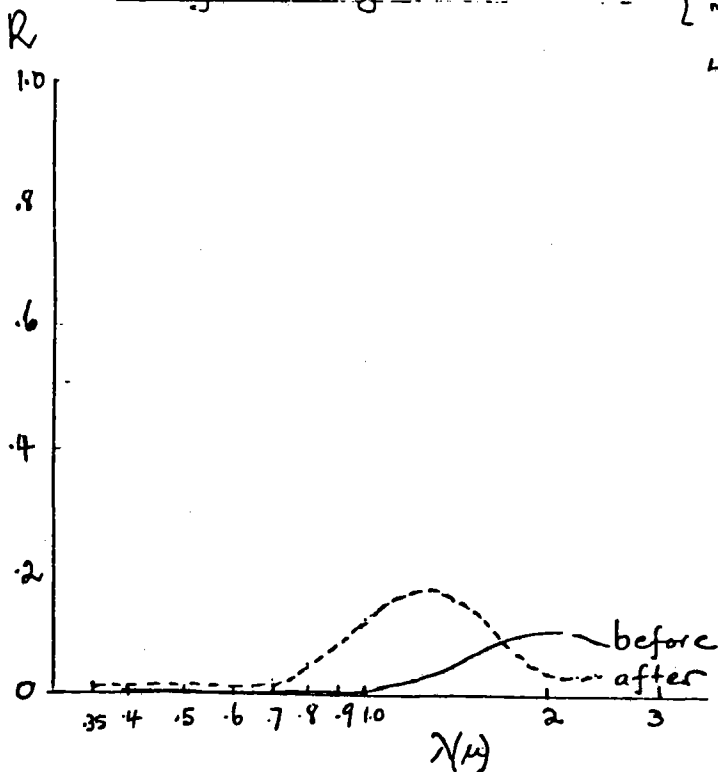
Heavy 'Chromonyx' Chrome Black - Exposed at

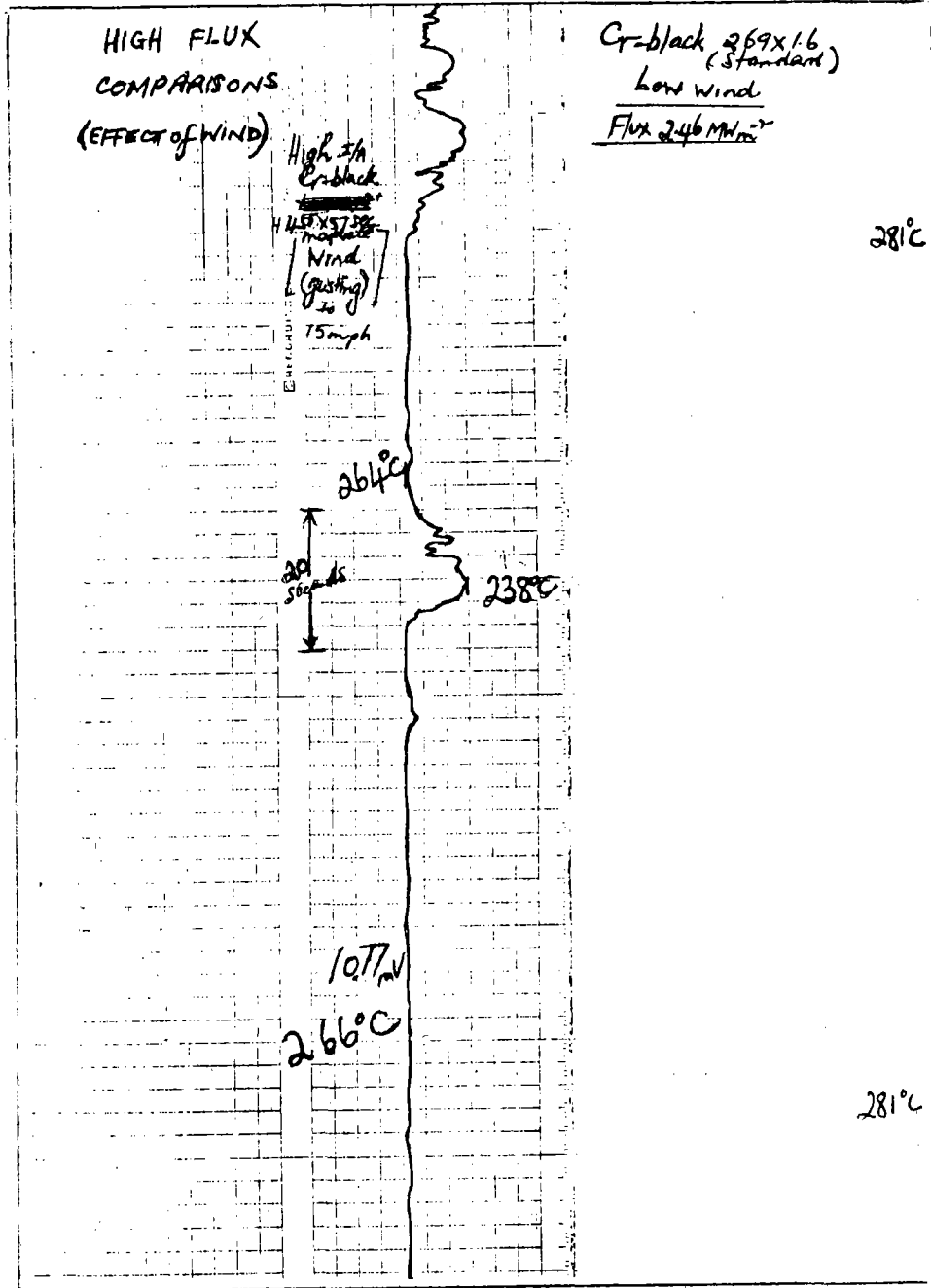
- (a) 2.30 MWm^{-2} for 56 minutes at 307°C
- (b) 326 MWm^{-2} for 64 minutes at 401°C



Heavy 'Chromonyx' Chrome Black -

{ Oven Heated to
 match one low flux
 exposure
 $401^\circ\text{C} \times 64 \text{ minutes}$





Engineering Design Study of
Conversion of Solar Energy to
Chemical Energy Through Ammonia
Dissociation

Dr. Terry G. Lenz
Colorado State University

Presented at Solar High - Temperature Workshop

Albuquerque, New Mexico

May 3, 1979

Summary

This paper deals with the design of an experimental solar absorber-ammonia dissociation reactor-heat exchanger. Such a composite absorber-reactor-heat exchanger would be at the endothermic end of a closed cycle process for conversion of solar energy to high-quality process heat or electric power, as shown on Figure 1.

The 10 kW_{th} unit designed for our anticipated experimental studies is of cylindrical-cavity geometry, being about one foot in diameter by one foot long, and contains 43, 0.375-inch OD, 0.245-inch ID catalyst-filled tubes, arranged as shown in Figure 3. Candidate catalysts are 10-12 wt % Ni on Al₂O₃, 2-3 wt % Fe on Al₂O₃, and 0.5 wt % Ru or Rh on Al₂O₃. The reactor would be fabricated from a high-nickel alloy (most likely Inconel 617). Total pressure drop (reactor plus heat exchanger) has been calculated to be about 4.6 psi for a 4000 cm³/min average flow (650°C, 300 atm), with a conversion of 87 mole % of the fed NH₃ to N₂ and H₂. The dissociated gas temperature exiting the heat exchanger is predicted to be within 10°C of the incoming NH₃ temperature.

Introduction

The process for closed loop conversion of high temperature solar energy to chemical energy through ammonia dissociation is shown in Figure 1. Ammonia is dissociated into nitrogen and hydrogen in a catalytic reactor located at the focus of a concentrating collector. The incoming ammonia is heated by the exiting dissociated mixture in a countercurrent heat exchanger to recover the sensible heat in the products before they are piped to a central use area where ammonia is resynthesized, high quality heat liberated, and the ammonia returned to the collectors (1).

Work at Colorado State University, which is currently centering on the design of the solar absorber-chemical reactor-heat exchanger unit, has been divided into two phases. Phase I of the program which is now complete, was aimed at specifying an appropriate scale for the experiment, identification and characterization of catalysts suitable for ammonia dissociation, selection of an integrated design for the solar absorber-chemical reactor-heat exchanger, and analysis of predicted unit performance. Detailed designs for the reactor unit and supporting test equipment have been prepared.

Materials

Materials are substantially weakened by elevated temperatures. The loss of strength varies with time, so that the useful strength at elevated temperatures is less for long service time. Creep, a time-dependent deformation that occurs under stress at high temperatures, is another consideration in high temperature design and also affects service life. A third phenomenon which must also be considered for long-term design life is adequate resistance of the material to corrosion, oxidation and other types of chemical attack by the surrounding atmosphere. For our design problem, attack of the base metal by the formation of stable nitrides appears to be the most serious corrosion design constraint (5).

The design parameters which we have selected for our reactor are as follows. Complete details of the reactor design are discussed in section VII. The receiver is designed to operate at an interior cavity temperature of 700°C. The reactor consists of a series of 43 catalyst filled tubes (0.375 in OD, 0.065 wall) located around the perimeter of a 1 foot diameter cylindrical cavity. The tubes are 12 inches long and run parallel to the cavity axis. Ammonia at 500-650°C enters the tubes and is dissociated into nitrogen and hydrogen at 300 bars (4350 psia) pressure. The design stress as a result of pressure on the tube wall at the interior surface is 10,800 psi. Thermal stresses may range from 2000 to 20,000 psi. Although a commercially acceptable reactor design would probably have to be designed for a 50,000 - a 100,000 hr. life, our initial experimental unit will be designed for a 1000 hour life. The final commercial design would also experience on the order of 10,000 thermal cycles, whereas, our experimental design will not address fatigue criteria.

We have discussed our material requirements with several alloy manufacturers. An initial recommendation which we received was to use Inconel 600 which is currently used in high temperature ammonia dissociation reactors for metallurgical processing. Although Inconel 600 has demonstrated high resistance to nitriding in this application, it has not been required to provide the strength values which we require for long term service in high temperature-high pressure tubing. High temperature-high strength materials that have been considered include Inconel 617, Haynes 188, and Hastelloy X. Nominal chemical composition and physical properties for these alloys, as furnished by suppliers, are given in Table 2.

Nitriding resistance of the three candidate materials is expected to be adequate due to the high nickel content of all the alloys (6). Information supplied by the manufacturer showed Hastelloy X to have an apparent nitride layer thickness of 0.4 mils after exposure to an atmosphere of hydrogen, nitrogen and ammonia at 593°C (1100°F) and 1030 bars (15,000 psi) for 64 days with no intergranular attack. Nitriding data for the other materials was not available.

Thermal cycle tests and elevated-temperature rupture tests have been performed on Haynes 188 and Inconel 617 material under an EPRI-sponsored program to evaluate high-temperature central-receiver concepts for solar electric power (7). The thermal cycle tests indicated that the materials and weld joints could survive 30 years of cycling at 500 psi helium pressure from 483°C (900°F) to 830°C (1525°F). Oxidation resistance of the material was rated as excellent. The elevated-temperature rupture tests subjected the tubing to overheating at 500 psi helium pressure. The tests showed that the material could stand much higher

temperatures than 830°C (in the range of 1037°C to 1092°C) for a period of time. All failures were noncatastrophic with relatively small fissures in the tubes. This characteristic indicates that if failure occurs, there should be no adjacent tube damage or safety hazard from shrapnel. The welded tubing used in the tests performed satisfactorily. Welds were not involved in the stress-rupture failures, and defects in the manually welded tube-to-header joints did not propagate during the tests.

Information on Inconel 617 weldments is currently being developed and a presentation to the ASME Code Committee is planned by June for welds at temperatures up to 1500°F by Huntington Alloys, Inc. (8). Wire for welding is currently available, and coated electrodes are expected to be available within several months (8).

Inconel 617 has been selected as the reactor construction material for our tests, primarily because of its availability as tubing in the size required for construction of a 10 kW_{th} reactor.

A small-scale single tube experiment which will test a tube made of Inconel 617 under actual conditions of temperature, pressure and a dissociating ammonia environment has been designed. Details of the experiment are contained in a proposal prepared for the STTF User's Association, a copy of which has been provided to SERI (October 27, 1978). Metallurgical sectioning and examination of the tube, before construction of the 10 kW_{th} reactor, will help validate the selection of Inconel 617 for the reactor fabrication.

Catalyst Selection

Sizing of the chemical reactor portion of the absorber-reactor-heat exchanger is primarily dictated by catalyst performance and catalyst bulk density. Conventional ammonia synthesis is carried out at high pressure (about 300 atm), but generally at 450-500°C, or some 200°C lower than our target dissociation temperature. Since the conventional promoted-iron synthesis catalyst activity is destroyed at temperatures above 500°C (presumably due to surface area loss via sintering), special high-temperature ammonia dissociation catalysts are required.

In approaching catalyst selection, we first conducted a thorough literature search (by computer) for references on ammonia dissociation catalysis and kinetics. Traditional catalysts, such as nickel on alumina, and iron on alumina were quickly identified. However, reactor size for our design likely will have a more pronounced effect on overall economics than is true for conventional ammonia dissociation reactors (which are operated at less severe pressure-temperature conditions to produce H₂, or to reduce ammonia levels in effluents to low levels). We therefore identified additional catalysts which may be more active than the nickel or iron catalysts, although more costly, but which would permit an economic trade-off opportunity for commercial-scale design. The following catalysts are those we feel merit study as ammonia dissociation catalysts for our solar thermochemical application:

- 1) Ni on Al₂O₃ (10-12 wt % Ni)
- 2) Fe on Al₂O₃ (2-3 wt % Fe)
- 3) Ru, Rh, or Pt on Al₂O₃ (about 0.5 wt % metal)

The nickel catalyst is a conventional ammonia dissociation catalyst, and is the one employed thus far by P. O. Carden et al. in limited

experimental work in Australia (9). Carden (9) suggests that more active ammonia dissociation catalysts should be sought, and the precious metal catalysts above are such candidates. The 2.5 wt % iron would provide evaluation of a low-cost catalyst for ammonia dissociation.

Catalyst suppliers have been contacted relative to availability of the above catalysts. We have obtained one gallon samples of Ni-Al₂O₃ rings and 2.5 wt % Fe on Al₂O₃ spheres from United Catalyst Industries. In addition, Engelhard Industries can supply ruthenium, rhodium, or platinum on 5/64" Al₂O₃ spheres.

Detailed calculations based on the equations shown in Table 3, as well as space-velocity calculations based on vendor data for ammonia dissociation catalysts resulted in the catalyst volume requirements given in Table 1. Further details of these calculations are given in Appendix E. Our catalyst volume results have been reviewed by P. O. Carden (10), and he concurs that they are reasonable.

Reactor Design

A. Design Criteria

The basic design criteria which were formulated to assist in the design procedure are as follows:

1. 10 kW_{th} conversion of thermal solar energy to chemical energy through the dissociation of ammonia. The rationale for the choice of the 10 kW_{th} scale is given in Section II.
2. 700°C maximum material temperature in the reactor cavity. Initial design concepts envisioned a 750°C maximum material temperature, but further analysis of the pressure and thermal

stresses has shown them to be greater than the maximum allowable stresses for available materials at the higher temperature.

3. A 650°C gas and catalyst temperature in the exit region on the reactor to assure high ammonia dissociation rates and 87 mole % conversion of NH_3 to H_2 and N_2 . The 650°C design temperature is based on a 50°C temperature difference between maximum reactor material temperature and the gas flowing within the tube as a result of conduction through the tube wall and the convective film temperature difference.
4. Total pressure drop through the reactor and heat exchanger shall be less than 20 psi (based on limiting the pumping power required for moving fluid through the unit to less than 0.1% of solar power absorbed).
5. Design stresses in the catalyst-filled reactor tubes exposed to the solar flux shall be limited to 16,000 psi (2/3 of rupture strength for 10,000 hours for Inconel 617 @ 700°C). Design stresses in materials containing the hot gas (such as the exit manifold) shall be limited to 20,000 psi (2/3 of yield strength (0.2% offset) of Inconel 617 at 650°C which is less than the allowable stress determined by 10,000 hour rupture criteria).

B. Design Description

Three basic dissociation reactor configurations were developed and analyzed. Performance parameters for each design and its variations are given in Table 3. Computational methods which were used in the design process are detailed in the Appendix.

The first design which was evaluated consisted of a single helical tube which wound around the solar absorber cavity. The concentrated solar radiation impinged directly on the cavity side of the tube. The tube chosen was 0.25 inch ID by 50 feet long. The tube was wound in a spiral fashion to form a cavity 1 foot in diameter by 9 inches long. The tube was to be filled with spherical catalyst particles whose diameter equaled 0.25 of the tube ID. As can be seen in Table 3, the total pressure drop through the reactor would be much higher than desired.

The second type of reactor which was evaluated utilized manifolded helical tubes to provide parallel flow paths to reduce the pressure drop through the reactor. As shown in Table 3, a multiple helical tube reactor with 8 parallel flow tubes satisfactorily meets the design criteria. A conceptual design of the complete receiver-chemical reactor-heat exchanger utilizing this design is depicted in Figure 2.

While the multiple helical tube design appears desirable from a performance viewpoint (low convective film temperature differences and inherently lower stress values at the reactor tube-to-header interface), it may not be well suited to an experimental program because the curved reactor tubes will make replacement of catalyst difficult. Because a key program objective entails testing of various catalysts, adoption of a straight catalyst-filled tube seems necessary so that a catalyst could be easily removed.

Figure 3 depicts a possible straight tube reactor design. A number of configurations were examined utilizing straight tubes and their performance characteristics are given in Table 3. As can be seen, the large number of parallel flow paths results in low pressure drops through the reactor, but at the expense of increased convective

film temperature differences which results in higher reactor tube material operating temperatures.

The final design chosen (bottom of Table 3) utilizes forty-three 0.245" ID Inconel 617 tubes with a wall thickness of 0.065". The active catalyst-filled tube length is 12 inches and the tubes are spaced 0.875 inches apart (center to center). The somewhat wide spacing (0.5 inch spacing between tubes) was chosen for a number of reasons. The wide spacing between the tubes allows part of the solar energy to strike the surface behind the tubes and be reflected and reradiated to the "back" surface of the tubes, thereby reducing the circumferential heat flux variation on each catalyst tube which results in lower material operating temperatures and reduced thermal stresses. The fewer, wider spaced tubes also reduces stresses in the ligaments between tubes in the manifold. Also, access to the tube closure devices is enhanced by the wide tube spacing.

Details of the reactor design are shown in Figures 4, 5, and 6. The catalyst-filled tubes extend through the top and bottom manifolds. The manifolds consist of tubing 0.546 inch ID \times 0.147 inch wall bent into a one foot diameter circle and butt welded to form a closed vessel. Forty-three equally spaced holes are drilled through both walls of the header. The reactor catalyst tubes are inserted through the headers. The top and bottom headers are spaced 12 inches apart. The reactor tubes are closed off on each end with stainless steel "Swagelock" caps.

The reactor catalyst tubes are allowed to extend completely through the headers so that the catalyst reactor tube-to-manifold welds are primarily for sealing purposes and are not required for structural integrity of the pressure vessel.

The reactor tubes extend 10 inches beyond the manifolds to allow a 4 inch extension beyond the 6 inch insulation layer. Convection from the exposed portion of the tubes is expected to keep maximum temperatures at the end of the tube where the "Swagelock" fitting is located to less than 320°C so that standard stainless steel 316 fittings may be used. Total heat loss from the exposed tubes is estimated to amount to about 0.5 kW_{th} at the maximum cavity operating temperature.

The reactor tubes themselves have six 0.040 inch diameter holes drilled in them as shown in Figures 4 and 5 at the manifold locations to allow flow into and out of the catalyst-filled tubes. Conical shaped screen inserts in the tubes at the flow opening locations prevent plugging of the holes by catalyst material. Inert material is used above and below the active catalyst portion of the tube to contain the catalyst and prevent convective heat transfer to end closure caps.

All catalyst tubes are identical except for two tubes located on opposite sides of the header. (Because of the odd number of catalyst-filled tubes, exact symmetry is not possible.) As shown in Figure 4, the catalyst-filled tubes in line with the NH₃ feed tube and dissociation product removal tubes do not extend through the header, but are capped off inside the manifold.

Flow through the catalyst-filled tubes is expected to be self-balancing as a result of locating the feed and product removal tubes on opposite sides of the reactor, thereby equalizing flow paths for all tubes. In addition, the pressure drop through the header is expected to be on the order of 0.02 psi versus a pressure drop of 0.05 psi for the catalyst-filled tubes.

Insulation for the reactor is to be provided by a ceramic fiber insulation (such as Fiberfrax (3)) which is to be contained in an annular space between two light-gauge Inconel cans. The inner "can" will be spaced one inch away from the reactor catalyst tubes and a 6 inch insulation space is to be provided between it and the outer can. Insulation at the top of the reactor will be provided by a 2 inch thick slab of Duraboard (3); Duraboard is a high density (30 lb/ft^3), high temperature insulating material. The silicon carbide heaters will be mounted in 85% alumina terminal tubes which are supported by the Duraboard insulation. Initial testing of the cavity will also utilize a Duraboard insulation cover over the entire bottom cavity opening in order to simplify performing a heat balance on the system. The inside surface of the Duraboard is to be faced with Inconel to eliminate any outgassing of the insulation into the cavity. Additional fibrous insulation will be applied to the top and bottom structural insulation to provide a full six inch thickness. Based on an average insulation thermal conductivity of $0.075 \text{ BTU/hr ft } ^\circ\text{F}$ and an outside convective heat transfer coefficient of $2 \text{ BTU/hr ft}^2 \text{ } ^\circ\text{F}$, thermal losses from the reactor surface are estimated to be about 6% of the total $10 \text{ kW}_{\text{th}}$ reactor power.

Heat Exchanger Design

The heat exchanger design selected for the reactor is a simple concentric tube, countercurrent flow design. Basically it consists of a $3/8'' \text{ OD} \times 0.065'' \text{ wall}$ outer tube with a $3/16'' \text{ OD} \times 0.028'' \text{ wall}$ inner tube. The inner tube is to be dimpled or have "dots" spotted on the outside of the tube to center it in the larger tube. The hot dissociated gas mixture flows from the outlet manifold through the inner tube of

the heat exchanger where it gives up its sensible heat to the incoming NH_3 flowing through the annular passage. Because of a mismatch in the specific heats of the dissociated gas mixture and the incoming liquid NH_3 , the ammonia will be heated to approximately 430°C by the exiting 650°C dissociated mixture.

The use of the inner tube to carry the dissociated gas mixture is advantageous for several reasons. From a materials standpoint, it means that the outer pressure-containing tube only sees a maximum temperature of about 450°C . Therefore, the heat exchanger can be constructed of readily available, lower cost materials such as 316 stainless steel. Because the cooler inflowing ammonia with its higher specific heat is contained in the outer tube, thermal losses from the heat exchanger should be lower. Also, the use of the inner tube for the outlet flow path makes its larger hydraulic diameter available to the increased volume flow rate of the decomposition products and helps to minimize the overall pressure drop.

Heat transfer performance of the heat exchanger was calculated by determining the wall heat transfer coefficient for the inner and outer tubes utilizing the correlation proposed by Dittus and Boelter (11)

$$\text{Nu} = 0.023 \text{Re}^{0.8} \text{Pr}^{0.3}$$

for the inner tube and its modified form

$$\text{Nu} = 0.023 \text{Re}^{0.8} \text{Pr}^{0.4} \left(\frac{d_o}{d_i} \right)^{0.45}$$

for the annular space (12). The heat exchanger length was determined using the logarithmic mean temperature difference assuming that the overall heat transfer coefficient was constant through the entire length.

Based on a 30°C inlet and 430°C outlet ammonia temperature and a 650°C inlet and 35°C outlet mixture temperature, a 9.5 foot long heat exchanger is required if it is assumed that the tubes are perfectly concentric. Because of the uncertainty regarding our ability to maintain the concentric condition for the heat exchanger tubes, a conservative length of 15 feet has been assumed. Pressure drop through the heat exchanger has been calculated to be 0.15 psi per foot in the annulus and 0.16 psi per foot in the internal tube or approximately 4.6 psi overall for the heat exchanger.

The heat exchanger is to be shaped into a helical spiral and located within the insulation surrounding the reactor. The heat exchanger is connected to the reactor as shown in the reactor assembly drawings by a "Swagelock" fitting to the Inconel 617 attachment tube which serves as a pressure containment device for the hot (650°C) 3/16" OD stainless steel line before it enters the heat exchanger.

An alternate heat exchanger design under consideration utilizes tubing with integral inner fins for the outer tube of the heat exchanger assembly. This design could result in a more compact heat exchanger assembly with improved heat transfer performance. The vendor for the finned tubing is currently evaluating his capability for making tubing from stainless steel in our required size and configuration, as well as providing an estimated cost. This design is not the current reference design but only an alternative and, in fact, could be tested at a later date if circumstances indicate the desirability of such testing.

Table 1.

NH₃ DISSOCIATION REACTOR DESIGN PARAMETERS

Reactor Size	6.25 kW _{th}	10 kW _{th}	25 kW _{th}
Mirror Size (100% η)	2.8 m dia	3.5 m dia	5.64 m dia
Aperture Size	10 cm dia	12.5 cm dia	20 cm dia
Mass Flow (87% conv.)	110 g/min	176 g/min	440 g/min
Mean Volume Flow (@=650°C and 300 atm)	2500 cm ³ /min	4000 cm ³ /min	10000 cm ³ /min
Catalyst Volume	150 cm ³	240 cm ³	600 cm ³

(Based on Space
Velocity = $\frac{1000}{\text{hr}}$)

Table 2. Composition and Properties of Candidate Materials

Alloy	Nominal Composition (%)							
	Ni	Cr	Co	Fe	Mo	W	C	Al
Inconel 617	54	22	12.5	-	9	-	.07	1
Haynes 188	22	22	Bal	3	-	14	.15	-
Hastelloy X	Bal	22	2.0	18	9	1	.15	-

Alloy	Physical Properties at 1300°F (704°C)		
	Mean Linear Expansion in/in/°F x 10 ⁻⁶	Thermal Conductivity BTU-in/sq ft-hr-°F	Specific Heat BTU/lb/°F
Inconel 617	8.2	167	.140
Haynes 188	9.0	160	.129
Hastelloy X	8.8	159	.145

Alloy	Structural Properties at 1400°F (760°C)					
	Stress-rupture life (KSI)			Temperature strength		
	100 hr	10,000 hr	100,000 hr	Tensile Ultimate (KSI)	Tensile Yield (KSI)	Elongation % in 2 in.
Inconel 617	22.0	14.5	-	64	25.0	83%
Haynes 188	22.0	15.5	-	95	41.6	54%
Hastelloy X	15.8	11.1	-	63	37.8	37%

Table 3. Reactor design summary.

Design type	Cavity dia. (inches)	Tube ID (inches)	Catalyst dia. $\frac{2}{3}$ tube ID	Cavity length (inches)	Tube spacing center to center (inches)	Re	Nu	$\frac{\bar{h}_w}{\text{hr ft}^2 \text{ } ^\circ\text{F}}$	Average ΔT_{film} ($^\circ\text{C}$)	Δp (psi)
Single helical tube reactor	12	.25	.25	9	.50	5687	212	5294	1.1	512
Multiple helical tube reactor										
3 tubes	12	.25	.25	9	.50	1895	90	2225	2.6	145
5 tubes	12	.25	.25	8	.50	1124	--	--	--	33
8 tubes	12	.25	.25	8	.50	711	41.3	1031	5.6	8.63
Vertical tube										
Straight tube	12	.25	.25	7	.50	65.2	6.6	166	40	.01
Straight tube	6	.25	.25	14	.50	132	11.3	281	24	.093
U-tube	12	.25	.25	7	.50	132	11.3	281	24	.10
U-tube	12	.25	.25	14	1.0	264	19.1	478	14	.62
Straight tube	12	.25	.25	10.5	.75	98	9.0	224	30	.04
Straight tube	12	.25	.50	7	.50	132	11.3	141	47	.002
Straight tube	12	.25	.1	7	.50	26	3.4	211	31	.10
Straight tube	12	.15	.25	12	.30	65	6.6	276	14	.08
Straight tube	12	.15	.25	17	.45	97	8.9	371	11	.27
Straight tube	12	.20	.20	13	.60	79	7.6	298	18	.13
Straight tube*	12	.245	.25	12	.875	116	10.2	284	24.2	.051

* Final design.

Re = $v d_p / \mu$ where d_p is catalyst particle dia.

Nu = $h_w d_p / k$

h_w = wall heat transfer coefficient

ΔT = (tube wall temp) - (fluid mean temp)

Δp = reactor pressure drop

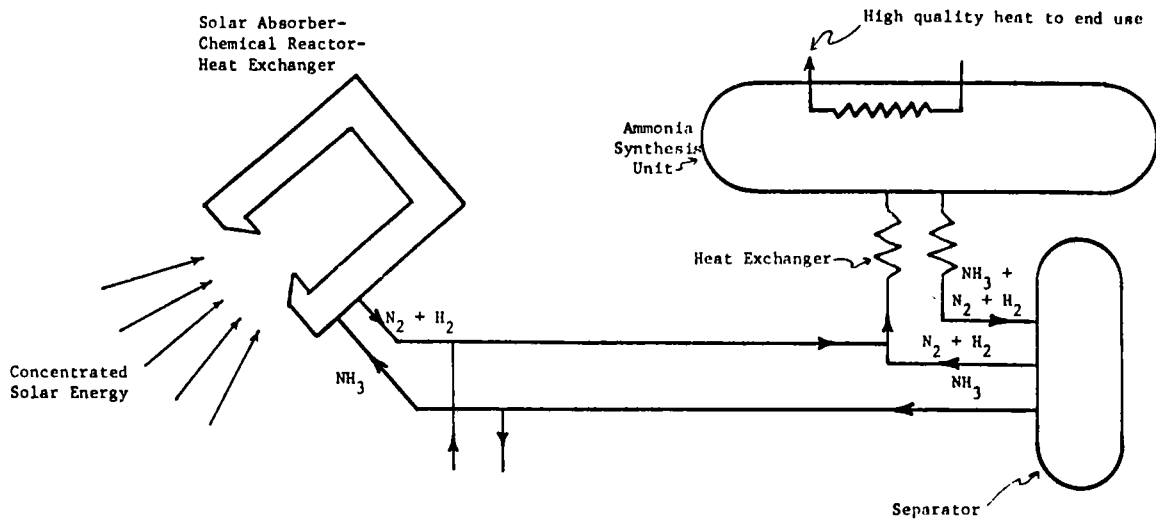


Figure 1. Schematic of Chemical Solar Power Plant

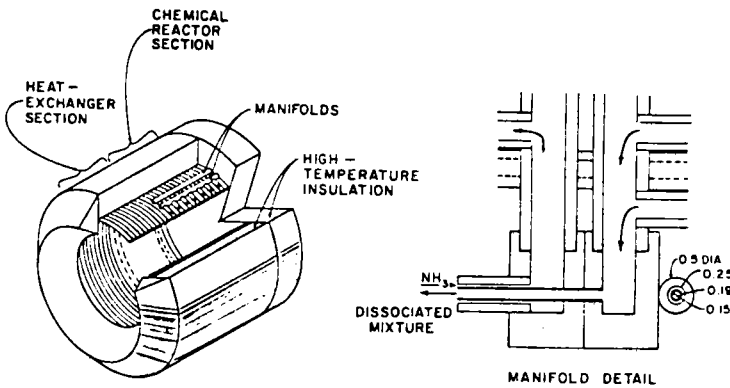


Figure 2. SOLAR ABSORBER - REACTOR HEAT EXCHANGER

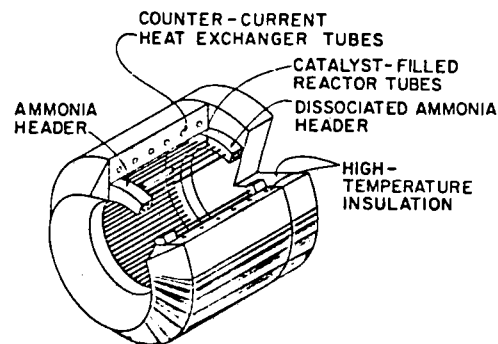


Figure 3. SOLAR ABSORBER - REACTOR HEAT EXCHANGER

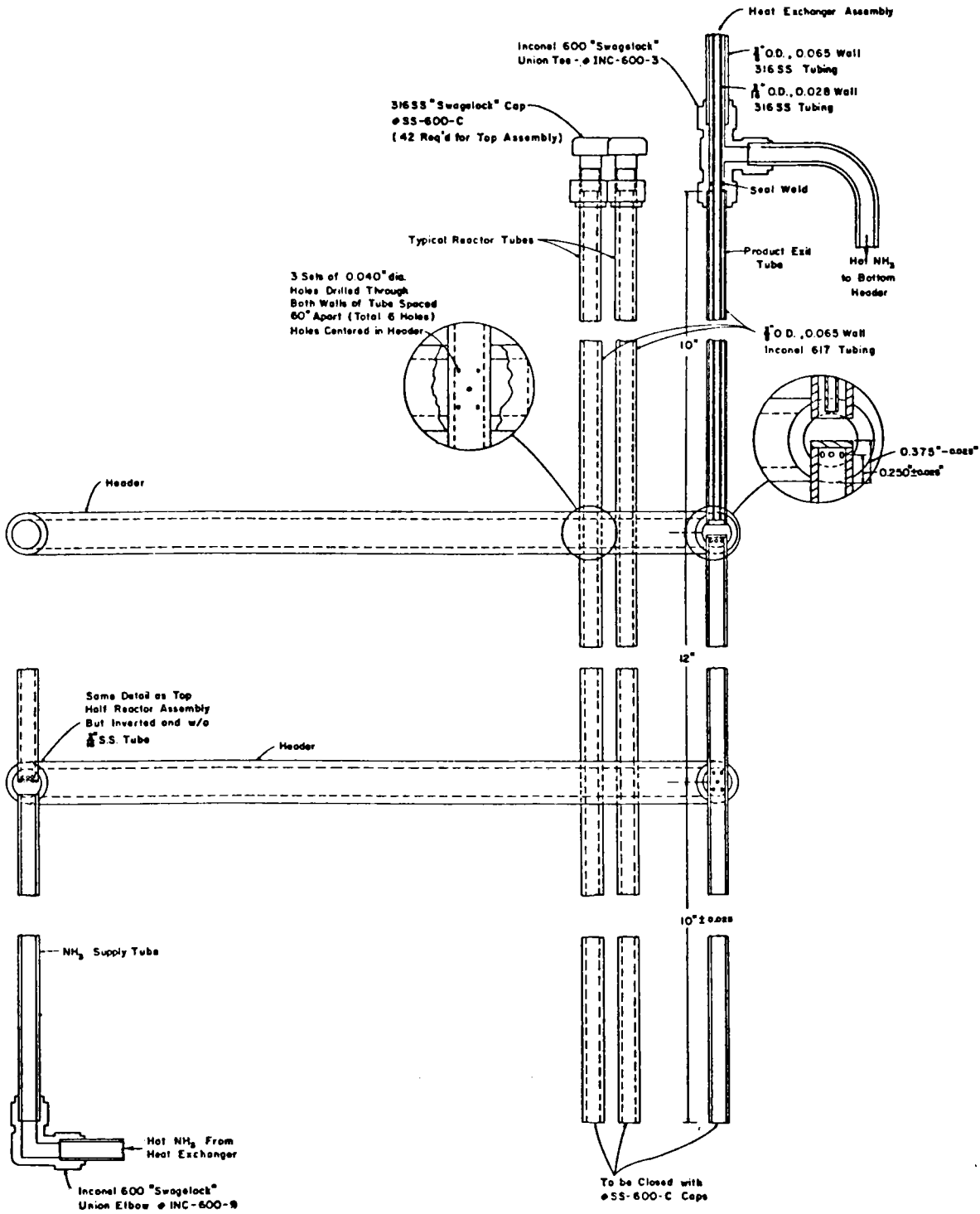


Figure 4. REACTOR ASSEMBLY

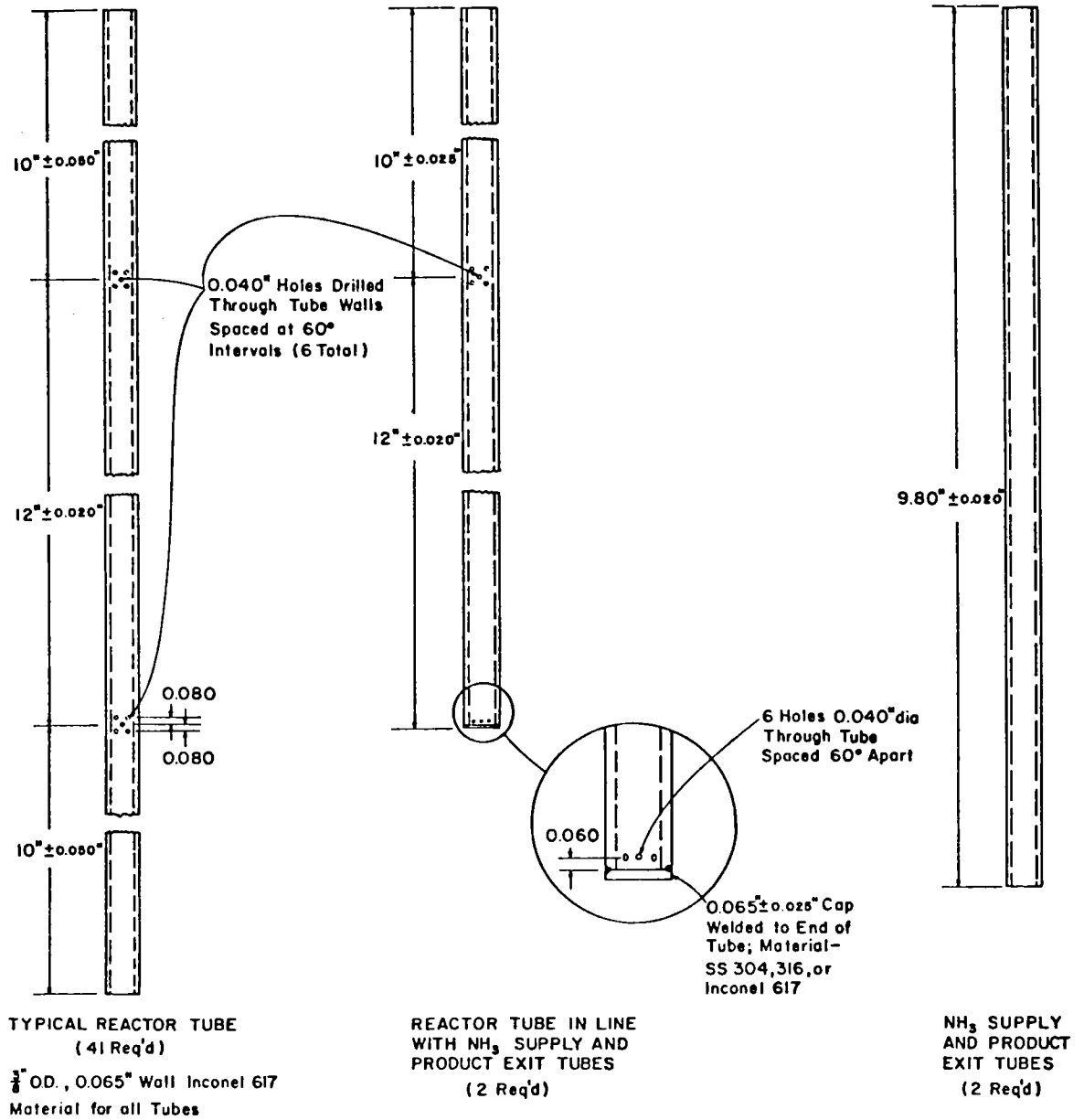
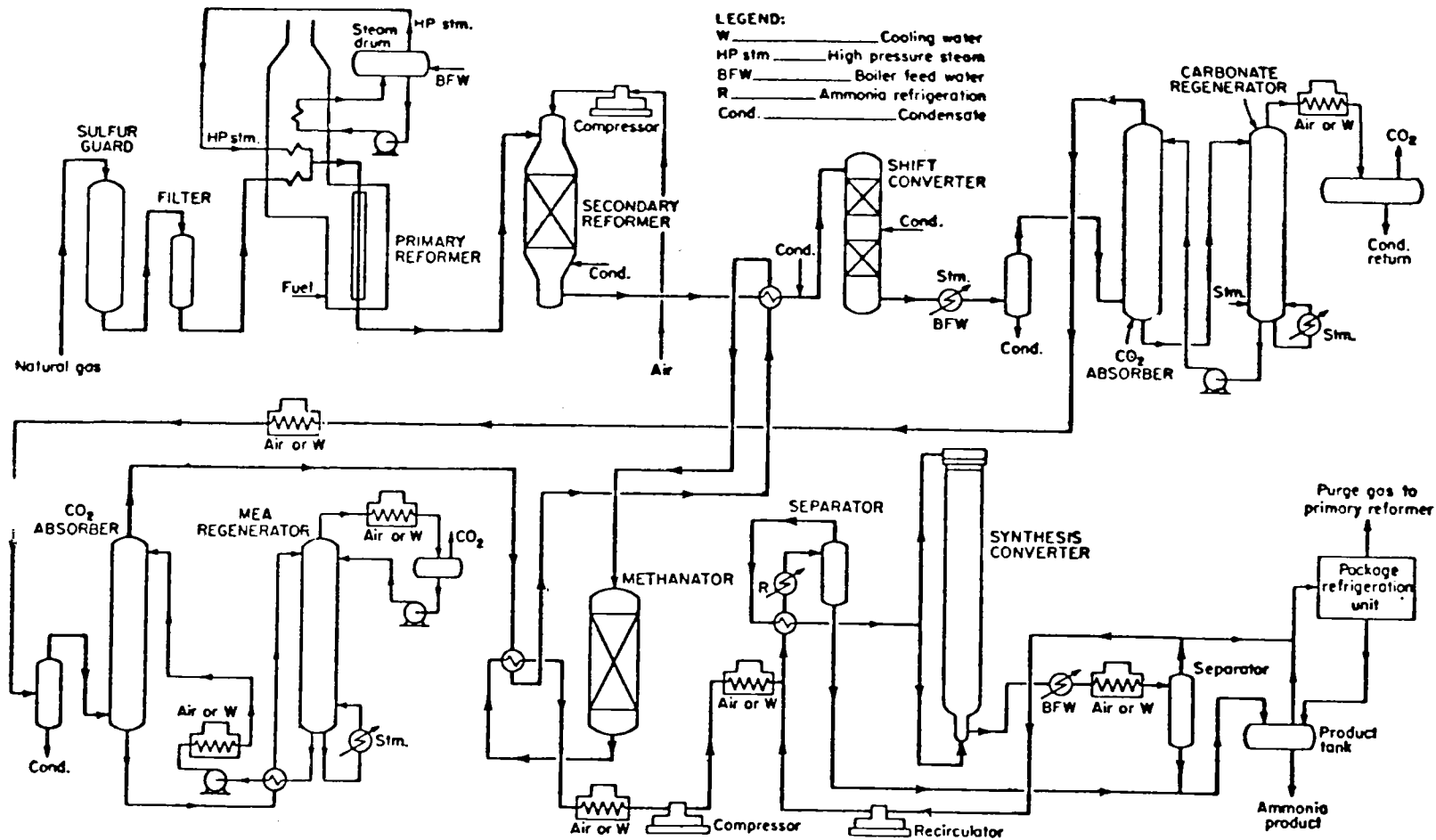


Figure 5. REACTOR TUBE DETAILS



Flowchart for ammonia plant (Lummus Co.)

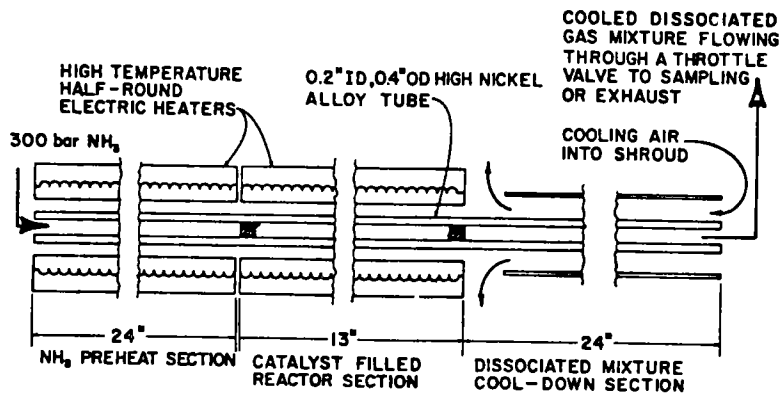
DESIGN OF AN EXPERIMENTAL NH₃ DISSOCIATION REACTOR

FUNDAMENTAL MECHANISMS OPERATIVE

- .HEAT TRANSFER
 - radiative (cavity and reaction zone)
 - conductive (through reactor and heat exchanger tube walls)
 - convective (within cavity and tubes)
 - .MASS TRANSFER
 - NH₃, N₂, H₂ to and from catalyst
 - .CHEMICAL REACTION
 - Heat + 2NH₃ \rightleftharpoons N₂ + 3H₂
 - kinetics
 - thermodynamics
 - catalysis
- The above occurring simultaneously

PRACTICAL ASPECTS OF THE DESIGN

- .MATERIALS OF CONSTRUCTION
 - strength
 - corrosion (nitride formation and hydrogen embrittlement)
 - ease of fabrication
 - allowance for thermal expansion
- .CATALYST
 - composition (Ni, Ru, Fe-Ru alloys)
 - form (metal on Al₂O₃ spheres)
 - reverse reaction possible in heat exchanger
- .PRESSURE DROP
 - reactor Δp controlling (manifold flow)
 - phase behavior in heat exchanger
- .RELATED AUXILIARIES
 - optical design considerations
 - sampling
 - control and instrumentation



SINGLE TUBE REACTOR
EXPERIMENT SCHEMATIC

CANDIDATE CATALYSTS

- Fusion point = 1500°C
- 1) Ni on Al₂O₃ (10 wt % Ni) 5 m²/g
80 lb/ft³ for 1/4" x 1/4" x 5/8" rings
Minimum crush strength = 75 lbs
 - 2) Fe on Al₂O₃ (2-3 wt % Fe)
 - 3) Ru or Pt on Al₂O₃ (= 0.5 wt % metal)

The above are employed as natural gas reforming catalysts

Cost: \$80-\$160/ft³ (\$0.5 - \$1/lb)

Activity: Space velocity typically in the 1000 - 2500 hr⁻¹ range

FINAL REPORT--PHASE I
RECONCENTRATOR FACILITY RECOMMENDATION

. . .

ENGINEERING STUDY OF A SMALL-SCALE FLUX
RECONCENTRATOR TEST FACILITY

. . .

with
STTF User's Association
University of Houston
Houston, Texas 77004

PO 18001
7/18/78

by

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April 1979

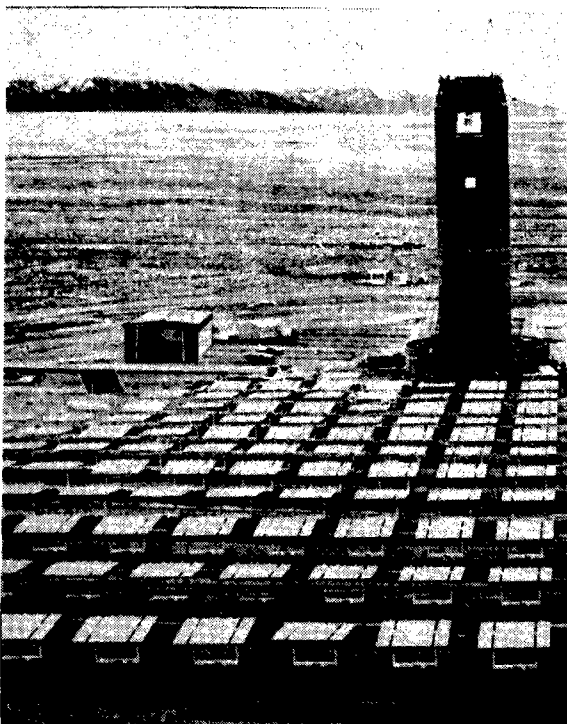
ABSTRACT

Several options for the construction of a small-scale flux reconcentrator test facility at the STTF have been analyzed. It is recommended that a configuration using a nonfocusing heliostat plus Omnium-G paraboloid be constructed. This configuration would permit high-temperature high-flux experiments to be performed for the purpose of evaluating, for example, the slow degradation modes of materials of potential use in solar applications. The proposed addition to the STTF facility will require dedication of a single heliostat for approximately 90% of the sun hours each year when the facility is fully used. A total cost of construction is estimated at \$73,200 exclusive of management overhead. The use of unexpended funds under this purchase order for the design of the focal plane subsystem is recommended.

INTRODUCTION

Failure modes of materials to be used in high-flux and high-temperature solar applications are not fully explored or understood. Rapid failure modes can be identified and studied by experiments requiring very little time of the solar facility involved. Thus the present facilities are satisfactory. However, slow failure modes that have received little study can be of crucial importance for solar application lifetime considerations, where slow can be measured in a day, weeks, or months. One cannot utilize any of the current solar test facility for these extended tests. Thus the question of a small test facility, dedicated to longer test cycles, needs an answer.

In this study we have examined options for using a *single* heliostat associated with the STTF facility to operate a high-flux high-temperature test facility where long-duration tests can be run without adverse impact on the main missions of the STTF.



Aerial view of the STTF showing the proposed high-temperature high-flux (HTHF) installation.

BASIC OPTIONS

We have considered four configurations as options for a high-temperature long-duration test facility.

- (1) Focusing heliostat and reconcentrator (STTF)
- (2) Tracking paraboloid (Omnium-G)
- (3) Small central receiver (Georgia Tech)
- (4) Plane heliostat and Omnium-G

Our original proposal was for the focusing heliostat option, but as discussed herein the other options have points in their favor. The basic optical configuration for each of the above options is shown in Fig. 1.

Focusing Heliostat

The focusing heliostat is attractive because of the availability of the STTF facility at Albuquerque, with many heliostats and a large support team of persons and instrumentation. The fact that *only one* heliostat is needed makes it possible to dedicate one of the many heliostats to a long-term high-temperature materials test program.

Tracking Paraboloid

The tracking paraboloid is interesting since commercial units, such as Omnium-G, the GE, or Atlanta Scientific paraboloids would be usable. These units are small enough to be installed at any of several possible locations at a total cost of approximately \$100,000 per location (including some auxiliary instrumentation). The Omnium-G concentrator is shown in Fig. 2.

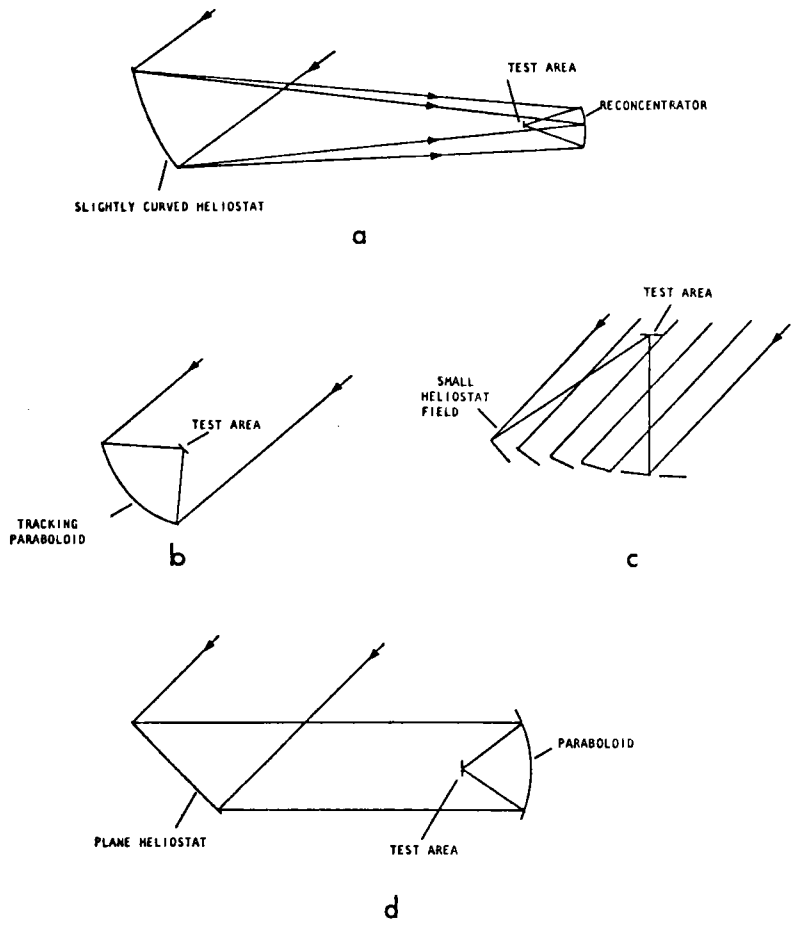


Fig. 1. Four possible options for a small materials test arrangement for long-duration experiments. (a) Slightly curved heliostat, (b) tracking paraboloid, (c) plane heliostat.

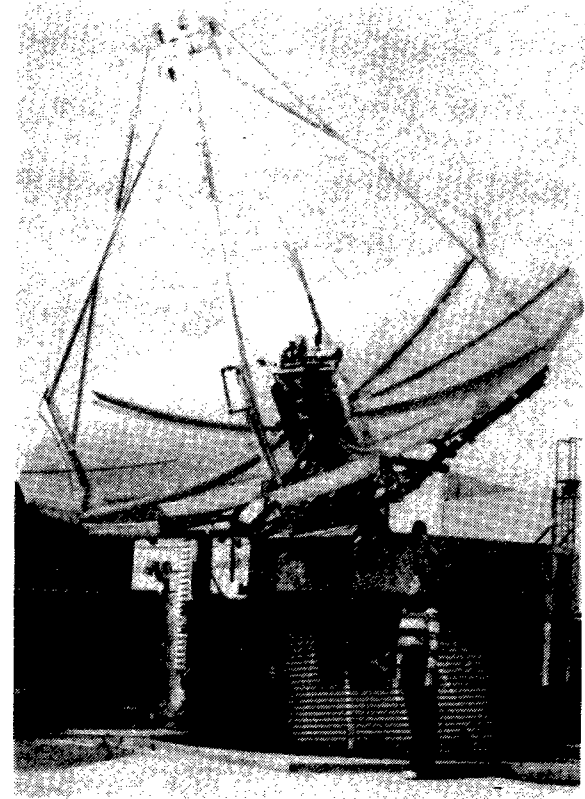


Fig. 2. Omnium-G paraboloid arranged for solar tracking with thermal receiver. All structures above the mirror and the equatorial drive system would be removed for the reconcentrator application, with a fixed pedestal and fixed focal plane assembly added. The resulting cost is therefore unchanged.

Small Central Receiver

The central receiver is attractive since Georgia Tech has revised their unit to accommodate moderate size tests. The principal drawback to use of such an installation is that it has many short exposure experiments in its immediate future, and its use for any long-term experiments is not convenient unless a few heliostats are specifically dedicated to the purpose. One could provide a focal point to the side of the main test area, but one would need a reconcentrator to boost the flux concentration to desired levels of approximately 1000 to 4000 K.

Plane Heliostat

The plane heliostat option requires a parabolic concentrator as large as the heliostat. Its advantage is that differential heating effects and nonuniform illumination of the paraboloid are much reduced over the case of a focusing heliostat. But the following questions arise.

Paraboloid and Heliostat or Paraboloid Alone

If we consider using a paraboloid with a nonfocusing heliostat, the immediate question is "why use the heliostat?" There are several aspects to this question that warrant consideration. The use of a tracking paraboloid eliminates the demand on a heliostat but requires a stand-alone tracking control subsystem and an operator. A roll-off shelter would be required. One does, however, have an option of placing the paraboloid at any acceptable site and not being limited to Sandia.

Paraboloid and Heliostat

A fixed shelter is required, but it is simpler than a roll-off shelter.

The light throughput is lowered by an additional reflection loss. The main advantage is that the tracking part of the system is the heliostat, already tied into the central control station of the STTF.

In view of the above considerations, as detailed in this report, we recommend the paraboloid and heliostat option.

SOLAR FLUX CONCENTRATION FROM HELIOSTAT

The use of a reconcentrator combined with one of the heliostats at the Albuquerque STTF is designed about the fact that the heliostat is focusing. This means that the reconcentrator can be much smaller than the heliostat--an important economic consideration. It also means that a higher input flux can cause some problems with heating of the reconcentrator mirror.

A flat mirror heliostat, when bent to cause a focus to occur, will focus well for only one tilt of the heliostat mirror with respect to the reconcentrator. For all other tilts the heliostat image will be degraded by astigmatism in the resulting image, the amount growing with the square of the off-axis angle.

The result of the astigmatism is that the solar image will spread. Thus the reconcentrator mirror must be larger than the best-focus image diameter.

In order to determine a reconcentrator mirror diameter to minimize spillover of the solar beam, we were provided with three cases measured for a Sandia heliostat, on day 172 for 0.00 hours (noon), on day 80 at 2.00 hours off meridian, and day 80 at 4.00 hours off meridian. The distance from the heliostat to focus was 63.2 m due south. The spot contours are shown for two cases in Figs. 3 and 4. The circle in these illustrations is 2.0 meters in diameter.

The flux contours show that the central brightness is reduced by a factor of about 4 during an 8-hour run centered on noon. They also show that if a 2-meter diameter mirror is used, the flux varies widely from center to edge, especially at noon. This range of brightness means a corresponding

range of energy absorbed by the reconcentrator mirror and resulting warping. We will address this question later.

The actual flux distribution measurements are shown in Tables I, II, and III.

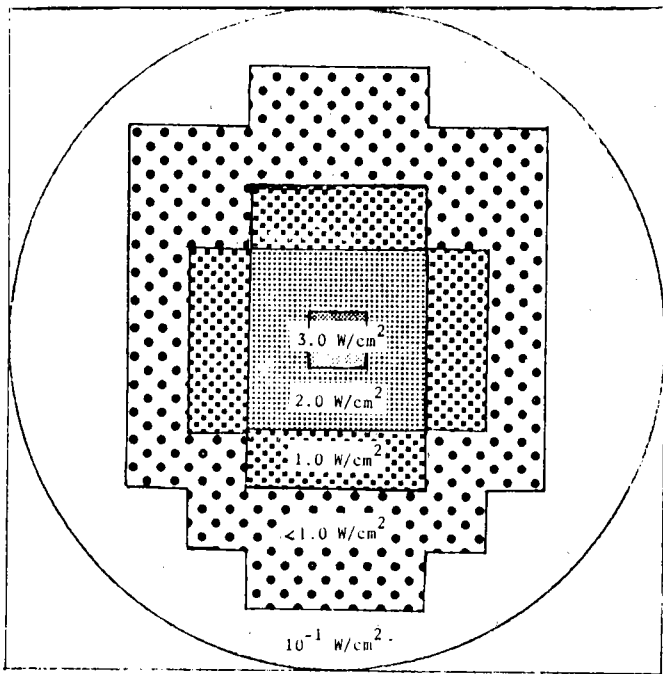


Fig. 5. Flux brightness distribution from an STIF heliostat focused at 63.2 meters due south at noon.

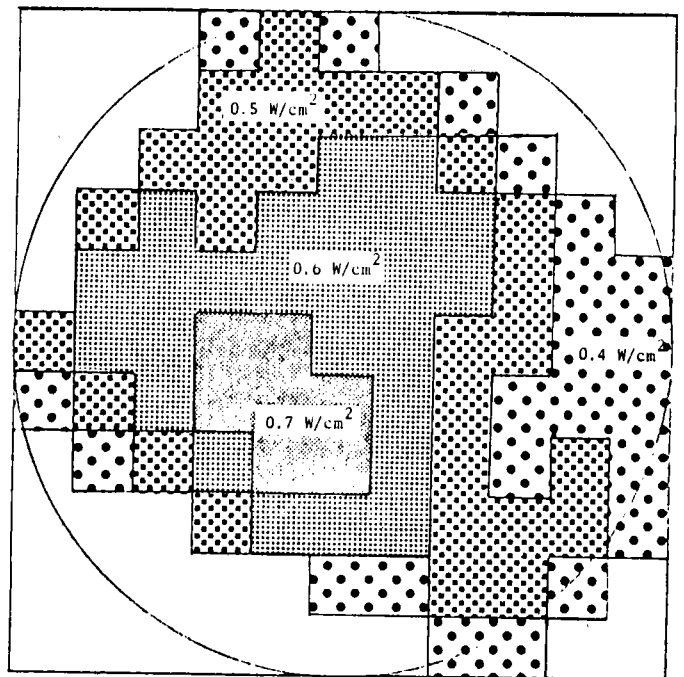


Fig. 4. Flux brightness distribution from an STIF heliostat focused at 63.2 meters due south at ±4 hours off central meridian. Note the astigmatism present in the image. Size of the square is 2 meters on a side. Blank areas are less than 0.4 W/cm².

Table I. Flux Distribution for Noon

W/SQ CM ON TARGET SURFACE FOR DAY 174, AND TIME 0.0000 HOURS.

Z METERS	X(I)=	1.0000	.8000	.6000	.4000	.2000	0.0000	-.2000	-.4000	-.6000	-.8000	-1.0000 M
1.0000		.736E-07	.601E-05	.835E-04	.310E-03	.522E-03	.587E-03	.519E-03	.307E-03	.819E-04	.592E-05	.728E-07
.8000		.235E-04	.610E-03	.545E-02	.172E-01	.275E-01	.310E-01	.274E-01	.171E-01	.540E-02	.604E-03	.234E-04
.6000		.670E-03	.119E-01	.752E-01	.204E+00	.319E+00	.357E+00	.318E+00	.204E+00	.752E-01	.118E-01	.673E-03
.4000		.462E-02	.636E-01	.330E+00	.823E+00	.126E+01	.142E+01	.126E+01	.821E+00	.329E+00	.634E-01	.461E-02
.2000		.109E-01	.138E+00	.855E+00	.154E+01	.242E+01	.272E+01	.242E+01	.158E+01	.655E+00	.136E+00	.109E-01
0.0000		.138E-01	.164E+00	.776E+00	.187E+01	.284E+01	.319E+01	.284E+01	.187E+01	.776E+00	.164E+00	.137E-01
-.2000		.125E-01	.141E+00	.652E+00	.156E+01	.247E+01	.266E+01	.237E+01	.156E+01	.651E+00	.141E+00	.124E-01
-.4000		.749E-02	.833E-01	.354E+00	.919E+00	.140E+01	.158E+01	.140E+01	.920E+00	.384E+00	.831E-01	.746E-02
-.6000		.197E-02	.256E-01	.131E+00	.326E+00	.499E+00	.561E+00	.500E+00	.327E+00	.131E+00	.256E-01	.197E-02
-.8000		.154E-03	.295E-02	.195E-01	.536E-01	.813E-01	.912E-01	.822E-01	.533E-01	.194E-01	.297E-02	.159E-03
-1.0000		.273E-05	.880E-04	.831E-03	.278E-02	.432E-02	.474E-02	.435E-02	.281E-02	.839E-03	.890E-04	.276E-05

TOWER COORDINATES OF TARGET POINTS 1, 11, 111, AND 121.

.838E+02	.200E+02	.406E+01
.918E+02	.200E+02	.406E+01
.838E+02	.200E+02	.206E+01
.818E+02	.200E+02	.206E+01

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POWER MATRIX (INTEGRATIONS OF EACH SET OF 3 X 3 ARRAYS ABOVE)

.6908E+01	.7204E+02	.1238E+03	.7174E+02	.6871E+01
.1640E+03	.1341E+05	.2249E+04	.1339E+04	.1637E+03
.3653E+03	.2739E+04	.4561E+04	.2799E+04	.3653E+03
.1939E+03	.1458E+04	.2447E+04	.1469E+04	.1938E+03
.1607E+02	.1425E+03	.2393E+03	.1430E+03	.1612E+02

TOTAL POWER ON TARGET SURFACE IS .22856E+05 WATTS.

CHECK OF POWER MATRIX

.6418E+01	.7219E+02	.1245E+03	.7186E+02	.6383E+01
.1637E+03	.1341E+05	.2249E+04	.1339E+04	.1633E+03
.3674E+03	.2737E+04	.4558E+04	.2799E+04	.3669E+03
.1937E+03	.1468E+04	.2447E+04	.1469E+04	.1936E+03
.1545E+02	.1426E+03	.2403E+03	.1431E+03	.1550E+02

TOTAL POWER ON TARGET SURFACE IS .22456E+05 WATTS.

FACET AREA = 37.2 M**2
 REDUCED BY COS GIVES 20.0 M**2
 FURTHER REDUCED BY SHBL GIVES 28.5 M**2
 POWER INTERCEPTED BY MIRROR = .2340E+05 WATTS.

Table II. Flux Distribution for ±2 Hours

W/SI CM ON TARGET SURFACE FOR DAY 80. AND TIME -2.0000 HOURS.

Z METERS	X(I)=	1.0000	.8000	.6000	.4000	.2000	0.0000	-.2000	-.4000	-.6000	-.8000	-1.0000 M
1.0000		.699E-06	.382E-04	.688E-03	.602E-02	.305E-01	.796E-01	.970E-01	.538E-01	.144E-01	.175E-02	.552E-04
.8000		.101E-03	.249E-02	.267E-01	.393E-01	.247E+00	.437E+00	.450E+00	.247E+00	.639E-01	.795E-02	.412E-03
.6000		.220E-02	.336E-01	.177E+00	.475E+00	.841E+00	.111E+01	.104E+01	.600E+00	.178E+00	.259E-01	.206E-02
.4000		.116E-01	.136E+00	.355E+00	.116E+01	.162E+01	.179E+01	.160E+01	.101E+01	.382E+00	.741E-01	.833E-02
.2000		.213E-01	.219E+00	.839E+00	.168E+01	.216E+01	.219E+01	.195E+01	.138E+01	.665E+00	.183E+00	.273E-01
0.0000		.173E-01	.177E+00	.769E+00	.168E+01	.226E+01	.232E+01	.208E+01	.161E+01	.943E+00	.351E+00	.701E-01
-.2000		.763E-02	.962E-01	.477E+00	.128E+01	.201E+01	.221E+01	.199E+01	.161E+01	.104E+01	.453E+00	.108E+00
-.4000		.220E-02	.365E-01	.213E+00	.748E+00	.144E+01	.180E+01	.165E+01	.126E+01	.789E+00	.346E+00	.816E-01
-.6000		.535E-03	.766E-02	.659E-01	.318E+00	.785E+00	.110E+01	.100E+01	.663E+00	.347E+00	.130E+00	.258E-01
-.8000		.352E-04	.135E-02	.153E-01	.911E-01	.277E+00	.421E+00	.356E+00	.183E+00	.658E-01	.177E-01	.274E-02
-1.0000		.119E-05	.127E-03	.240E-02	.151E-01	.483E-01	.730E-01	.520E-01	.185E-01	.401E-02	.650E-03	.682E-04

TOWER COORDINATES OF TARGET POINTS 1, 11, 111, AND 121

.838E+02	.200E+02	.470E+01
.818E+02	.200E+02	.400E+01
.838E+02	.200E+02	.200E+01
.818E+02	.200E+02	.200E+01

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POWER MATRIX (INTEGRATIONS OF EACH SET OF 3 X 3 ARRAYS ABOVE)

.1944E+02	.2431E+03	.7364E+03	.4429E+03	.3064E+02
.2978E+03	.1772E+04	.2700E+04	.1594E+04	.1979E+03
.3795E+03	.2502E+04	.3568E+04	.2466E+04	.6244E+03
.1010E+03	.1257E+04	.2674E+04	.1927E+04	.5720E+03
.3116E+01	.2161E+03	.7645E+03	.3887E+03	.6474E+02

TOTAL POWER ON TARGET SURFACE IS .25477E+05 WATTS.

CHECK OF POWER MATRIX

.1955E+02	.2441E+03	.7365E+03	.4431E+03	.3017E+02
.2884E+03	.1772E+04	.2699E+04	.1594E+04	.1982E+03
.3809E+03	.2500E+04	.3569E+04	.2465E+04	.6251E+03
.1004E+03	.1259E+04	.2672E+04	.1927E+04	.5720E+03
.7806E+01	.2159E+03	.7650E+03	.3895E+03	.6419E+02

TOTAL POWER ON TARGET SURFACE IS .25477E+05 WATTS.

FACED AREA = 37.2 M**2

REDUCED BY COS GIVES 32.0 M**2

FURTHER REDUCED BY SHBL GIVES 32.0 M**2

Table III. Flux Distribution for 4 Hours

M/SQ CM ON TARGET SURFACE FOR DAY 80, AND TIME -4.0000 HOURS.

Z METERS	X(I)=	1.0000	.8000	.6000	.4000	.2000	0.0000	-.2000	-.4000	-.6000	-.8000	-1.0000 M
1.0000		.496E-02	.566E-01	.237E+00	.463E+00	.527E+00	.450E+00	.327E+00	.191E+00	.805E-01	.270E-01	.782E-02
.8000		.303E-01	.162E+00	.392E+00	.545E+00	.586E+00	.572E+00	.528E+00	.406E+00	.252E+00	.126E+00	.490E-01
.6000		.109E+00	.333E+00	.522E+00	.572E+00	.584E+00	.626E+00	.635E+00	.560E+00	.454E+00	.311E+00	.165E+00
.4000		.246E+00	.519E+00	.611E+00	.597E+00	.609E+00	.637E+00	.633E+00	.618E+00	.569E+00	.450E+00	.315E+00
.2000		.407E+00	.620E+00	.679E+00	.657E+00	.662E+00	.647E+00	.618E+00	.603E+00	.566E+00	.485E+00	.422E+00
0.0000		.519E+00	.655E+00	.679E+00	.717E+00	.728E+00	.665E+00	.630E+00	.588E+00	.513E+00	.456E+00	.472E+00
-.2000		.458E+00	.598E+00	.673E+00	.735E+00	.735E+00	.708E+00	.661E+00	.571E+00	.480E+00	.464E+00	.470E+00
-.4000		.256E+00	.423E+00	.577E+00	.694E+00	.710E+00	.702E+00	.657E+00	.560E+00	.496E+00	.500E+00	.419E+00
-.6000		.762E-01	.198E+00	.368E+00	.512E+00	.609E+00	.650E+00	.603E+00	.528E+00	.538E+00	.512E+00	.314E+00
-.8000		.133E-01	.499E-01	.133E+00	.256E+00	.391E+00	.479E+00	.489E+00	.502E+00	.542E+00	.433E+00	.193E+00
-1.0000		.129E-02	.646E-02	.244E-01	.689E-01	.152E+00	.239E+00	.307E+00	.406E+00	.445E+00	.287E+00	.890E-01

TOWER COORDINATES OF TARGET POINTS 1, 11, 111, AND 121

.838E+02	.200E+02	.406E+01
.818E+02	.200E+02	.400E+01
.838E+02	.200E+02	.200E+01
.818E+02	.200E+02	.200E+01

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POWER MATRIX (INTEGRATIONS OF EACH SET OF 3 X 3 ARRAYS ABOVE)

.2985E+03	.8237E+03	.8880E+03	.6277E+03	.2348E+03
.7639E+03	.9680E+03	.1011E+04	.9607E+03	.6895E+03
.9937E+03	.1129E+04	.1077E+04	.9332E+03	.7544E+03
.6625E+03	.1052E+04	.1099E+04	.9003E+03	.7717E+03
.1186E+03	.4297E+03	.7292E+03	.7904E+03	.6425E+03

TOTAL POWER ON TARGET SURFACE IS .19355E+05 WATTS.

CHECK OF POWER MATRIX

.2996E+03	.8234E+03	.8882E+03	.6271E+03	.2355E+03
.7623E+03	.9698E+03	.1011E+04	.9605E+03	.6890E+03
.9936E+03	.1129E+04	.1078E+04	.9327E+03	.7556E+03
.6625E+03	.1051E+04	.1101E+04	.9001E+03	.7715E+03
.1191E+03	.4391E+03	.7266E+03	.7907E+03	.6420E+03

TOTAL POWER ON TARGET SURFACE IS .19355E+05 WATTS.

FACET AREA = 37.2 M**2
 REDUCED BY COS GIVES 29.7 M**2
 FURTHER REDUCED BY SHBL GIVES 29.7 M**2
 POWER INTERCEPTED BY MIRRORS = .2971E+05 WATTS.

OPTICAL QUESTIONS

Important optical differences occur with the use of a heliostat and reconcentrator or tracking paraboloid even for identical *average* flux concentrations, as noted below.

Paraboloid

The concentration level for a paraboloid is selected by defocusing sunlight on the sample area. The maximum concentration occurs at focus, and generally is approximately 10,000X. The area of the test section is correspondingly small. The variation of concentration over this area is also generally large because of mirror imperfections. When the concentration distribution is sampled out of focus, as when lower concentrations are to be used, the brightness fluctuations are worse. This effect is illustrated in Fig. 5.

In Fig. 5 the distribution for ± 2 units shows two effects. The central minimum is caused by the shadow of the test box itself. The fluctuations outside are due to random and systematic errors in the optical precision of the mirror surface.

The basic problem of a defocused paraboloid is concentration variations over the test area due to mirror errors. If the mirror were perfect, the variation would be close to zero except for the central shadow.

Focusing Heliostat-Reconcentrator

The use of a focusing heliostat with a reconcentrator to produce higher concentrations needed for sample tests is fundamentally different from that

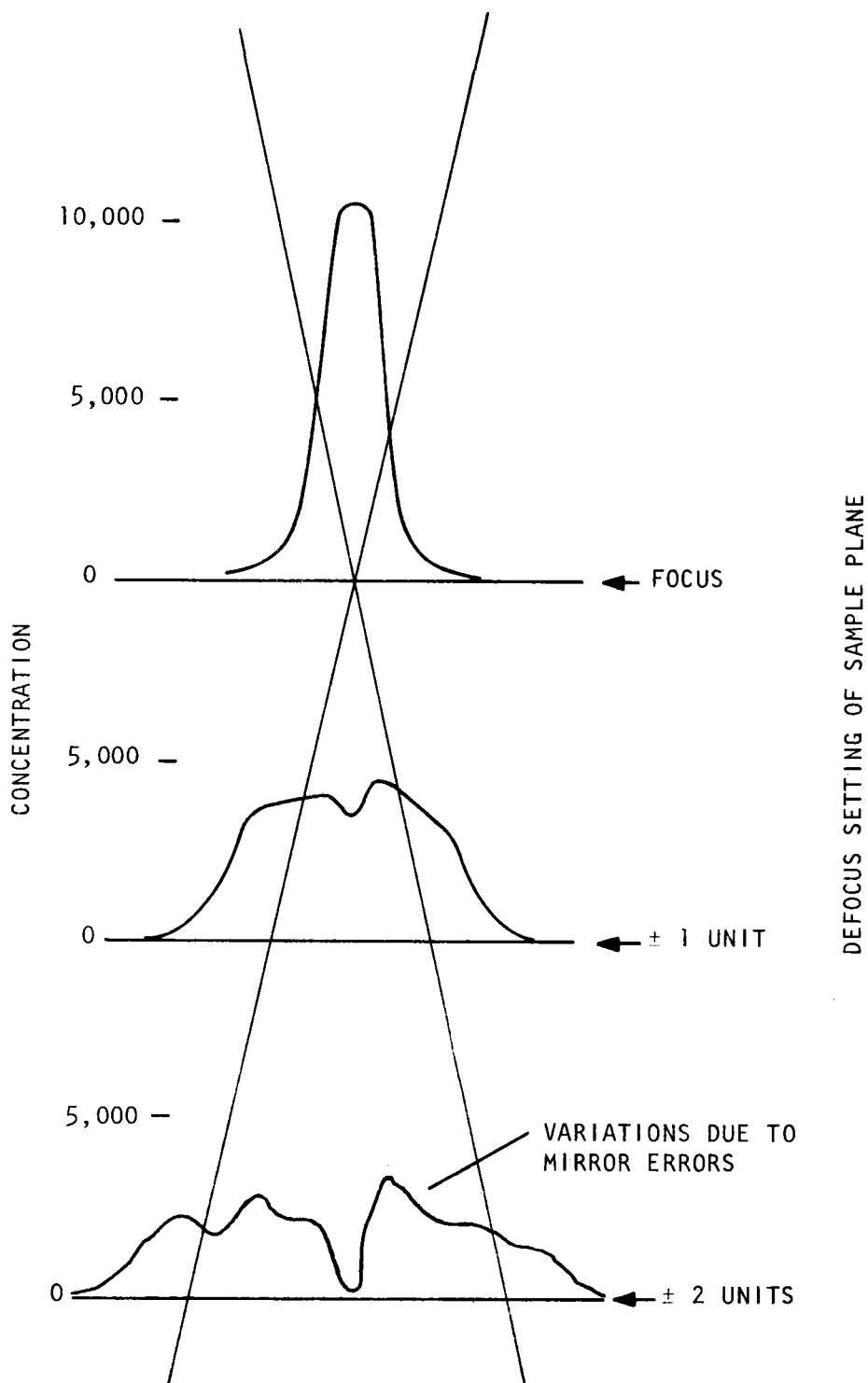


Fig. 5. Variation in flux concentration across a test area of a parabolic system as a function of defocus setting.

of the paraboloid. Significant differences occur in the behavior of the flux distribution.

The reconcentrator acts like a "field lens" in an optical system. A field lens forms an *image* of the first objective (the heliostat) at a focal plane, *not* an image of the sun. The heliostat images the sun (poorly) on the reconcentrator, and the reconcentrator reimages the heliostat.

The significance of this arrangement is that the intensity distribution in the "focal plane" is that of the sunlight on the heliostat, i.e., reasonably uniform except for gaps in the mirrors of the heliostats. The brightness distribution of sunlight arriving at the reconcentrator can be highly variable *without affecting* the distribution in the image plane of the reconcentrator.

As one goes out of focus of the reconcentrator the image spreads and lowers concentration. Since a reconcentrator mirror is much smaller than a tracking parabolic mirror, the mirror precision is generally much better. This means that the intensity distribution is more uniform, as illustrated in Fig. 6.

In Fig. 6 the gap between the mirrors of the Martin-Marietta heliostat at best focus of the reconcentrator would contribute to the two flux minima. As one proceeds out of focus these minima smooth out, but now the variation in input brightness to the reconcentrator mirror contributes to fluctuations. Since this input distribution changes with time of day because of optical astigmatism from the curved heliostats, the brightness distribution in the sample plan will vary with time.

Flux Scrambler

One can improve brightness uniformity in any fluctuating field by

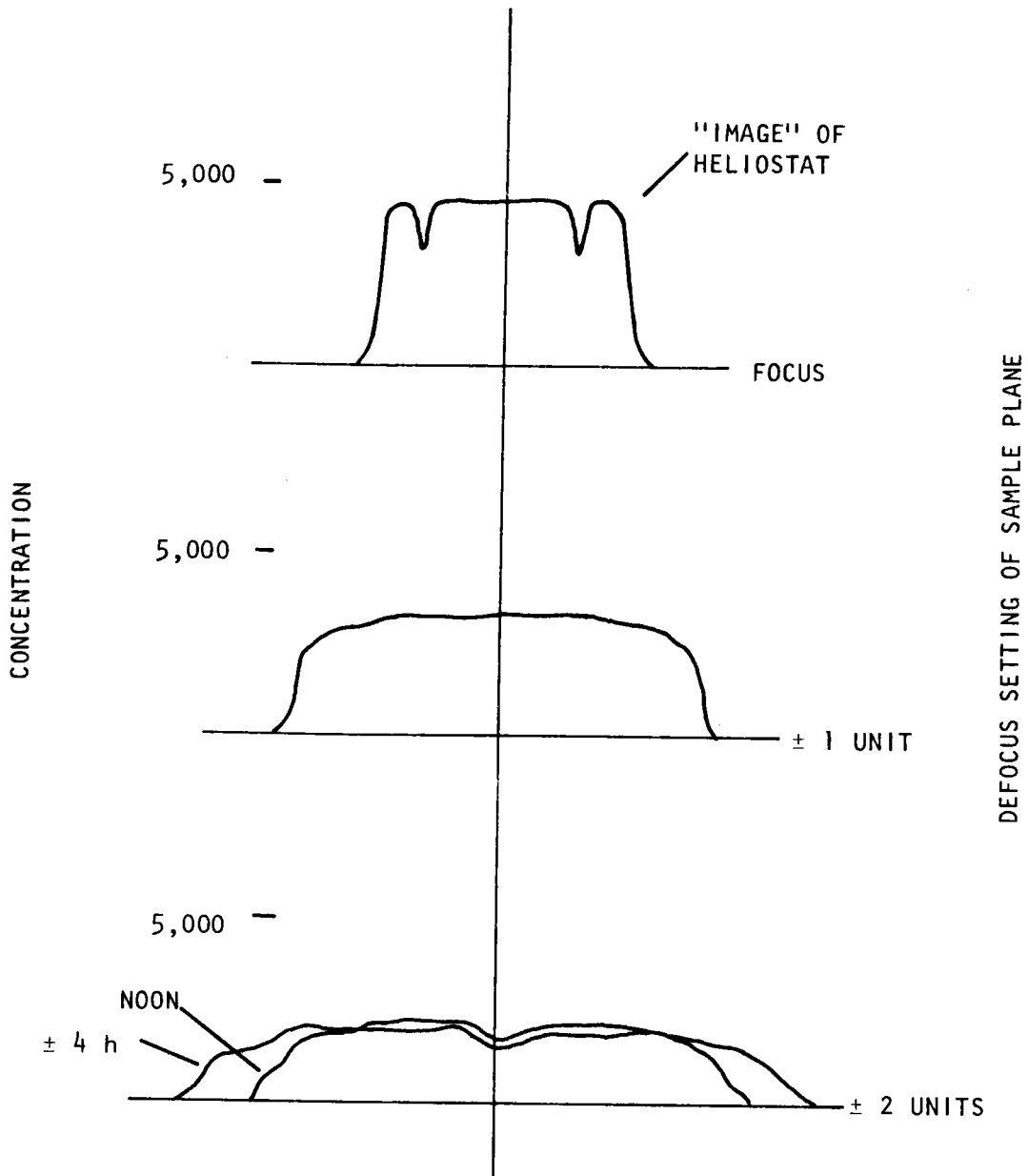


Fig. 6. Variation in flux concentration across the test area of a recon-
centrator system as a function of defocus.

placing a fine-ground transmitting plate a few inches ahead of the test section. A plate of fused silica would stand the thermal load and shocks and improve either the paraboloid or the reconcentrator system at small net loss to the test area.

The flux scrambler can also be useful in changing the concentration level and uniformity with the reconcentrator configuration, by placing the scrambler at various positions between the reconcentrator and test section, but near enough to the test section to avoid shadowing the reconcentrator mirror.

The effect of a central obscuration is eliminated if an off-axis reconcentrator is used.

SMALL RECONCENTRATOR MIRRORS

The ability to focus the heliostats means that one could use sub-diameter reconcentrator mirrors as small as 2.0 m in diameter. Sources of mirrors of moderate precision in this size are few. Searchlight mirrors are typically 55 to 60 inches in diameter. While easily available from military surplus depots, they would lose considerable energy at large sun angles because of spillover from the heliostat aberrations.

Manufacture of a specific mirror for this task would be expensive unless a simple method of manufacture were used. We have explored one option that has some interest for solar energy even beyond this project: explosive forming.

Explosive Forming of Mirrors

Explosive forming involves placing a flat sheet of material and a mold under water and detonating a small explosive charge to cause the sheet to be plastically deformed to the shape of the mold. This arrangement is schematically shown in Fig. 7.

The mirror sheet would be electropolished aluminum, heliarc welded to make a 2-m wide sheet (the reflectance is lost at this seam). The explosive force shapes the mirror and, we think, does not harm the surface polish. We plan some stretch experiments to measure the change in reflective properties as a function of the percentage of stretch. If these tests show promise, then this method offers an inexpensive way to make concentrator mirrors. The method has been successful in forming microwave paraboloids in this size range. These experiments have been done at the University of Arizona.

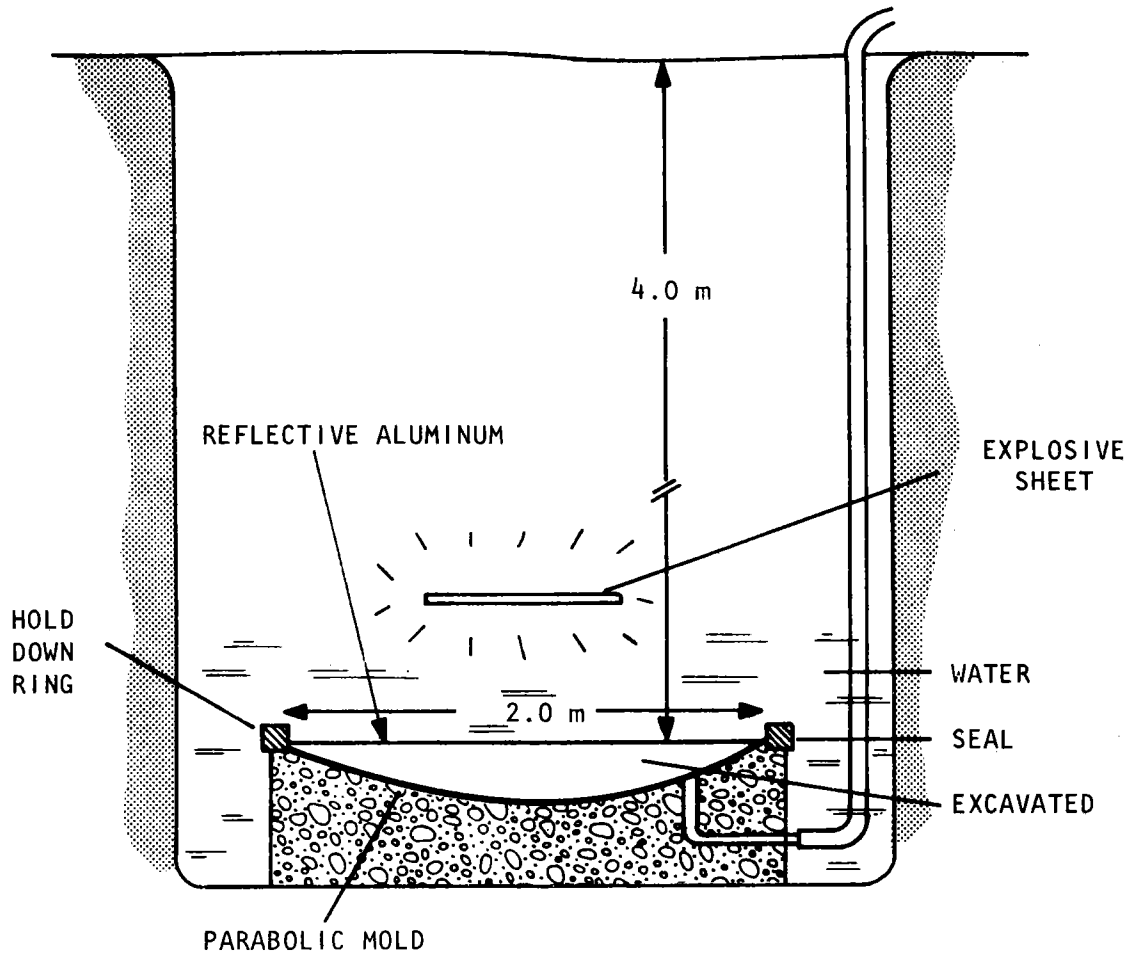


Fig. 7. Schematic arrangement for explosive forming of a parabolic mirror.

Diamond Turning of Mirrors

Diamond turning of an accurate parabolic surface has been done, but analysis of the costs shows it to be noncompetitive with the other options discussed in this report.

Searchlight Mirrors

Searchlight mirrors are either metal or second-surface glass and thus capable of handling the thermal load from a focusing heliostat. The test area, however, must be kept small to minimize light blockage. Several surplus searchlights are available to us from the Smithsonian Astrophysical Observatory gamma-ray project, but we do not recommend this option.

RECONCENTRATOR MIRROR HEATING

The best concentration for a heliostat focused at 0.000 hours (noon) for day 172 is approximately 3.2 W/cm^2 over a central area of $20 \times 20 \text{ cm}$. If the solar absorptance of the mirror is taken as 0.15 (0.85 reflectance), then a heat load of 0.48 W/cm^2 is injected into the mirror.

If we take an Omnium-G mirror for the flux reconcentrator, the above energy input can cause warping of the mirror due to thermal expansion of the aluminum relative to the foam plastic base. The foam is an insulator, so the heat loss to establish thermal equilibrium is from the front surface. The above input, coupled with an assumed emittance of the anodized aluminum of 0.60 yields heat losses as shown in Table IV.

Table IV. Reconcentrator Mirror Heat Losses

	T ($^{\circ}\text{C}$)		
	<u>127</u>	<u>227</u>	<u>327</u>
Radiative loss (W/cm^2)	0.087	0.213	0.442
Convective loss (W/cm^2)	<u>0.042</u>	<u>0.100</u>	<u>0.165</u>
Total (W/cm^2)	0.129	0.313	0.507

Ambient temperature = 27°C

In Fig. 8 we show the resultant heat loss from the mirror surface, noting that the equilibrium temperature is approximately 300°C above ambient. This temperature exceeds the service limit of polyurethane foams, and thus

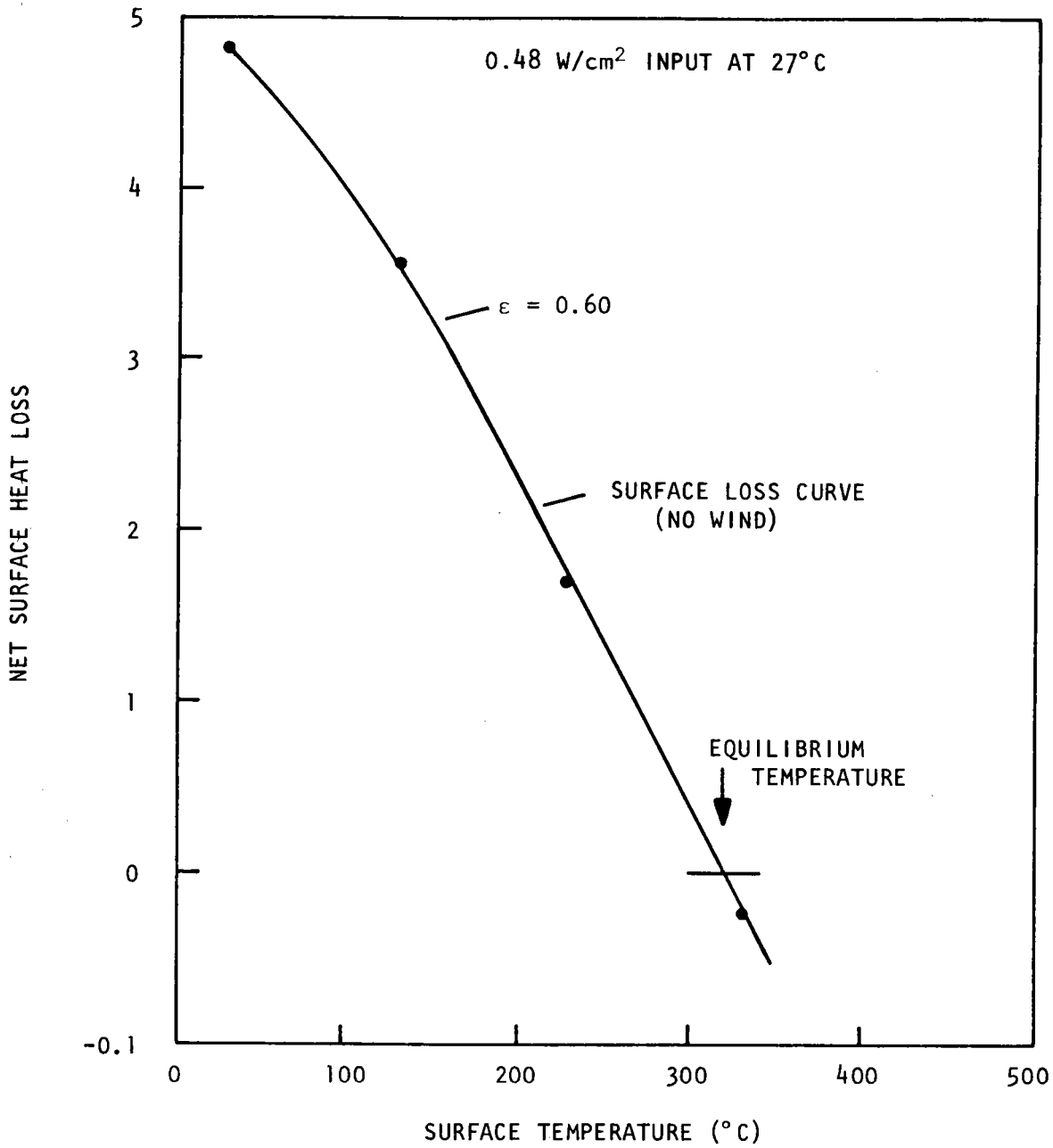


Fig. 8. Variation of heat loss from Omnium-G mirror surface for 32X input concentration under zero wind conditions.

the Omnium-G mirrors cannot be used in the focus of a heliostat. The manufacturer has no data on allowable input concentration, but thought it would be 3 to 5X.

The Omnium-G can be used if one defocuses the heliostat so that the full aperture (6.0 m) is filled. This option is attractive because of the relatively low cost of this paraboloid (\$29,000, Nov. 1978, FOB factory).

The high temperature caused by a 32X concentration on four sectors of the Omnium-G paraboloid (see Fig. 8) raises the question of using the full aperture and a much lower input concentration. Reducing the amount of focusing of a heliostat also reduces the amount of astigmatism when the sun is far off noon.

BEAM GEOMETRY

The geometry applicable to the full paraboloid aperture is shown in Fig. 9. The approximately 6 x 6 m beam from a plane heliostat is enlarged to about 8 x 8 m over the distance (62 m) from heliostat to paraboloid by errors in the flatness of the heliostat and finite angular size of the sun. There are several options at this point:

Case (1) Maintain 1X input, allow spillover loss.

Case (2) Reduce beam to fit circumscribed circle, no loss.

Case (3) Compromise between (1) and (2).

Case 1

In Case 1 there will be no heating problem of the paraboloid and the reconcentrator will be relatively uniformly illuminated, which will result in little warping of the parabolic surface. The loss of energy, outside the 6-m diameter mirror will be large, about 45%.

Case 2

The heliostat focuses the beam down to a 4.2-m square (approximate, due to cosine projection factor), and the beam fits into the 6-m diameter aperture. The flux concentration is 2.1X, causing a rise in mirror temperature of about 30°C, which is acceptable. The differential heating of portions illuminated and other portions not illuminated by the heliostat could cause warping of the parabolic petals, affecting intensity distribution in the focal plane.

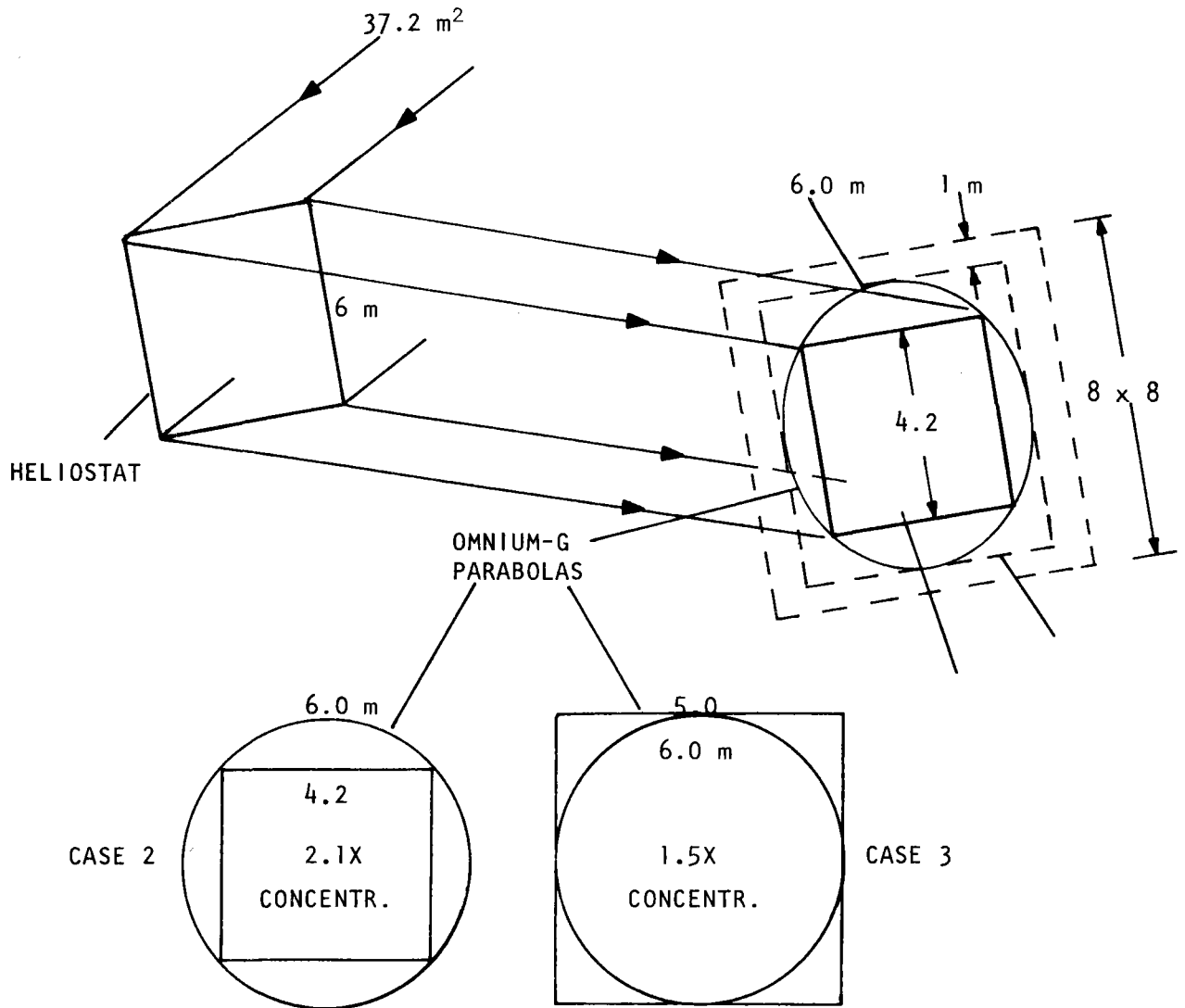


Fig. 9. Relative sizes of heliostat beam for illumination of an Omnium-G. Case 1: plane heliostat, 1.0X. Case 2: circumscribed circle, 2.1X. Case 3: compromise, 1.5X.

Case 3

A compromise focus (where the heliostat beam is made 5 to 5.5 m square) fills the paraboloid better, reduces the concentration to 1.5X, and reduces the possibility of significant warping.

In each of the above cases note that the heliostat beam never is an exact square owing to the tilt of the 6 x 6 heliostat with respect to the optical axis of the paraboloid. Nevertheless, the above options need to be considered.

STTF SITE BUILDING

The site facility using an Omnium-G fixed paraboloid is shown in Figs. 10 and 11. The building shown is a commercial Soule steel building 25 x 40 ft by 25 ft tall. Two sliding doors are located at one end, biparting, but still within the end profile of the building as far as wind is concerned.

The test area requires an access platform, shown as tilting to clear the incoming beam of the obscuration of the platform.

A cement slab floor is anticipated.

The building is rather large, but not much more expensive than a smaller custom-built structure such as would be used with the 2-m reconcentrator mirror system (Fig. 12). The additional floor space in the 1000 square foot enclosure will be most useful for locating monitoring equipment, experiment preparation, and storage. The building is also large enough to be useful to the STTF programs, being located adjacent to the heliostat field. If the materials test program is later moved to a commercial facility, this enclosure will be immediately useful.

The basic cost of the enclosure building is low, approximately 5 \$/ft² FOB factory. The actual cost, field installed, with all of the operational features one would like will be in the 25 to 30 \$/ft² range. The upper figure is shown in the attached project budget.

An additional 20-ft long module, attached to the end at the rear of the paraboloid, is worth considering as part of the original construction. It will provide a more generous working area for tests and test monitoring, that is out of the high brightness hazard area associated with a test section

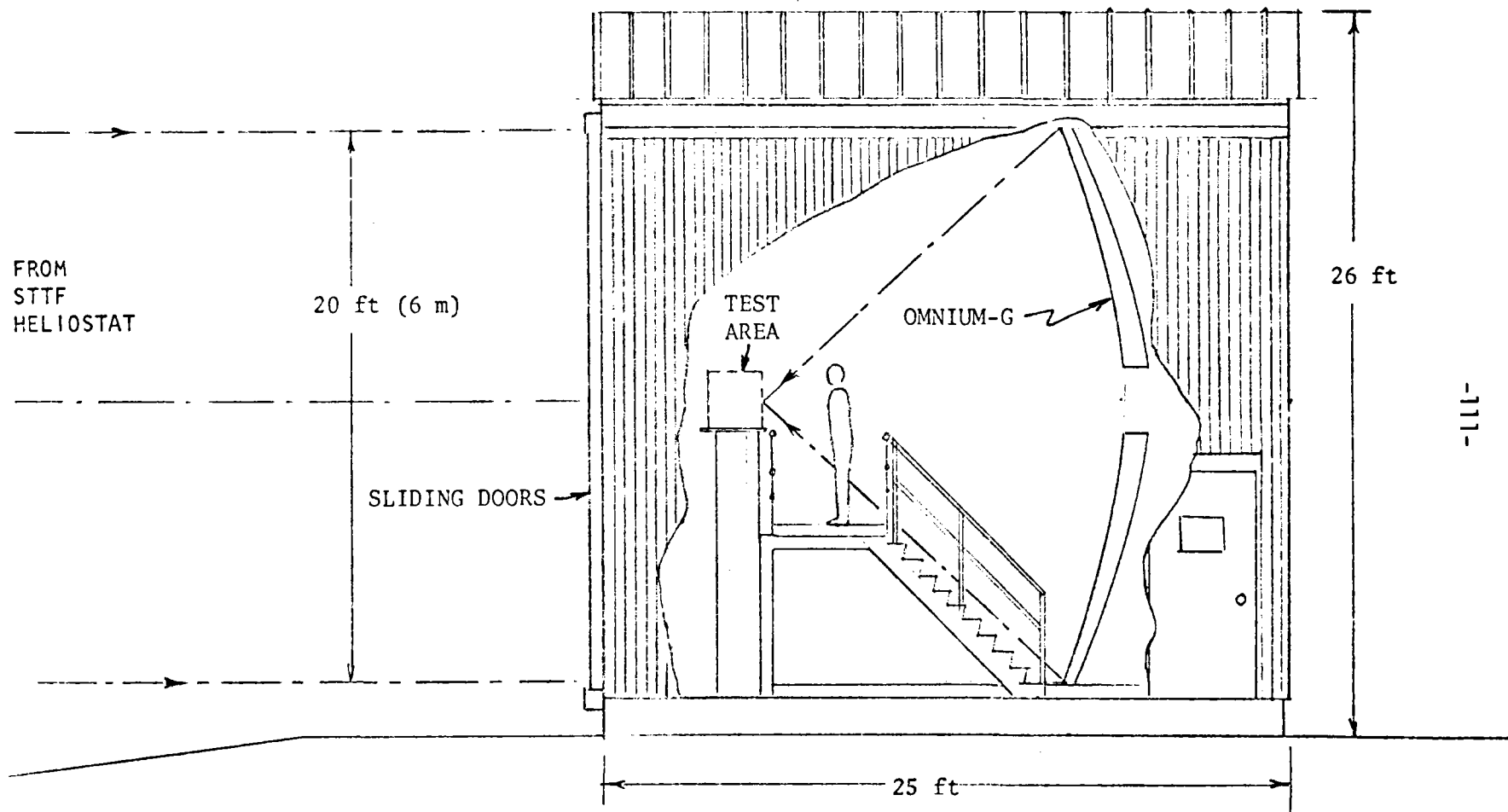


Fig. 10. North-south section through the recommended high temperature, high flux (HTHF) test building for the STTF, using an Omnium-G paraboloid.

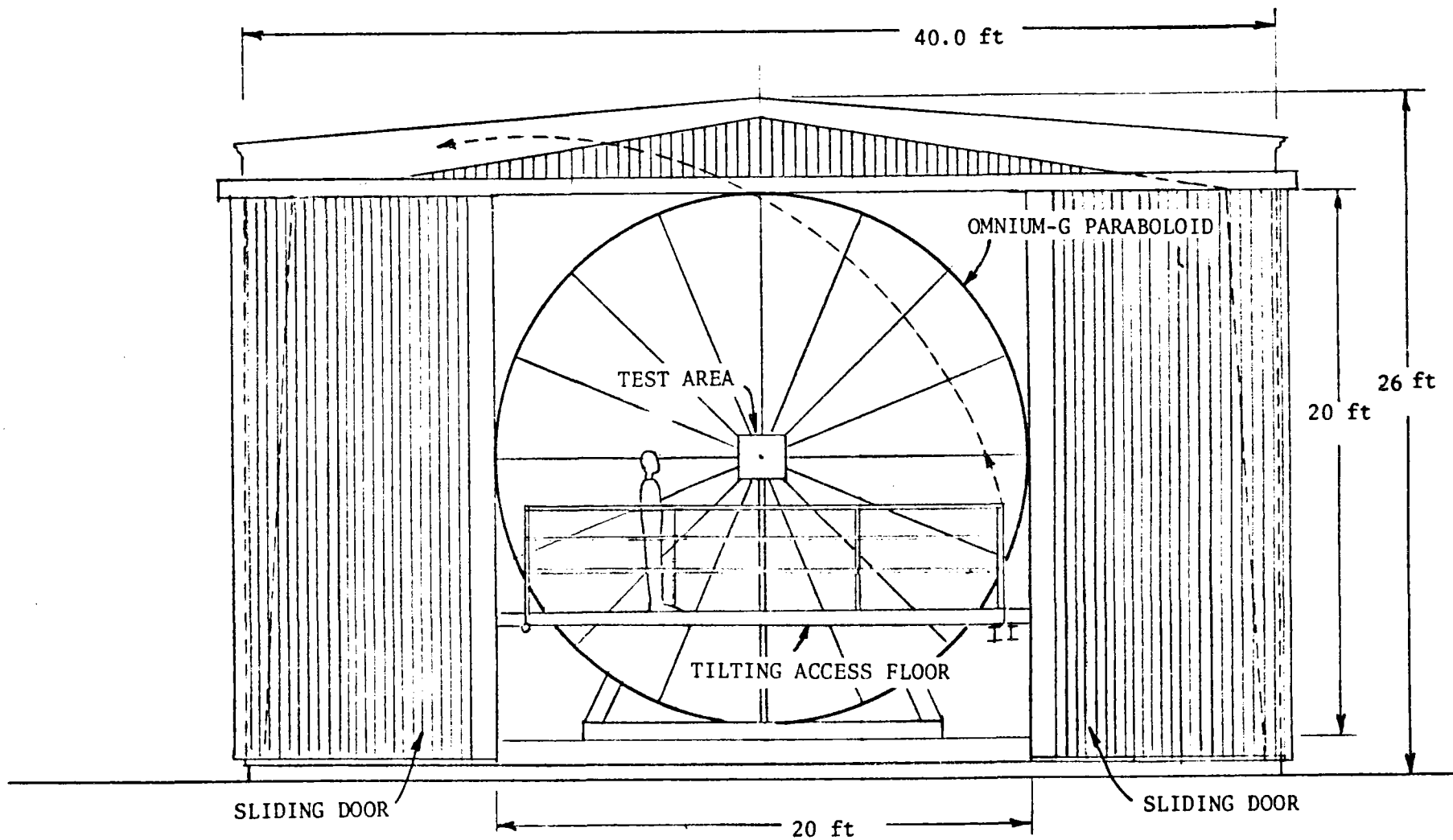


Fig. 11. East-west section through the recommended HTHF test building for the STTF, using an Omnim-G paraboloid.

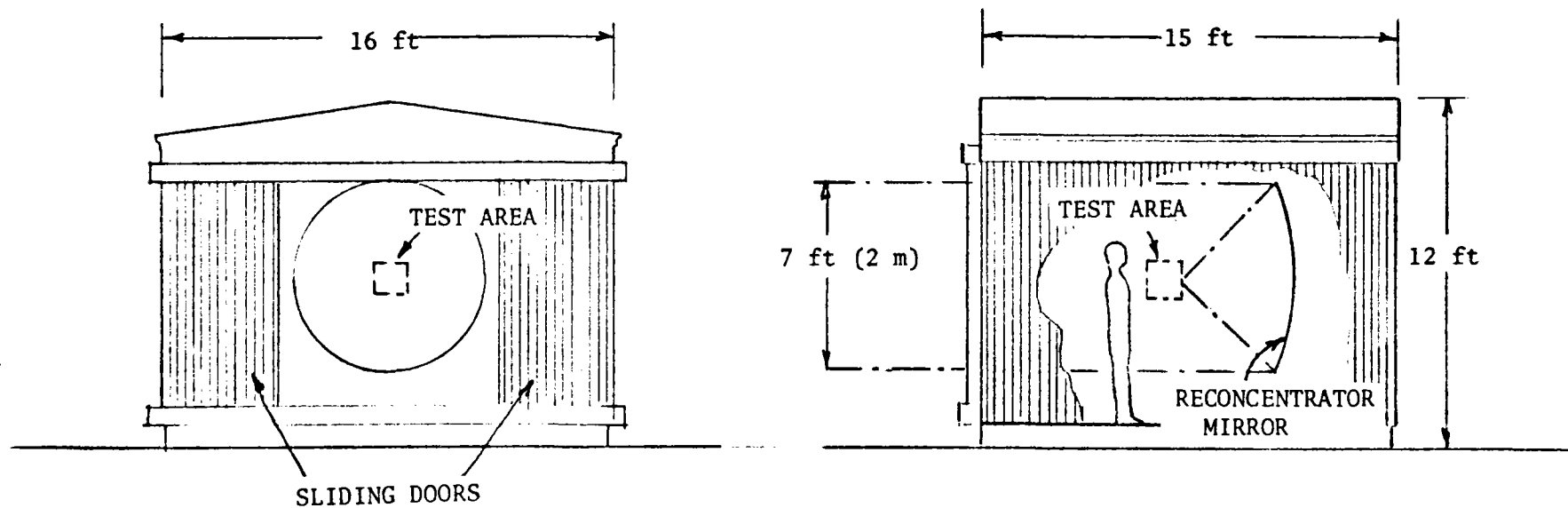


Fig. 12. Sections through a possible HTHF test building using a 2-m reconcentrator paraboloid.

is out of the high brightness hazard area associated with a test section that will probably be irradiated every clear day.

In Fig. 12 we show for comparison the size of a building required for a 2-m reconcentrator mirror. While the building is much smaller, it does not provide working space. Thus an auxiliary work area would be required, which would level the cost difference between the 6-m option. Note also the obvious restrictions in usable test space.

RECOMMENDATION

We recommend that a 6-m Omnium-G be used for the flux reconcentrator with the heliostat used with zero or minimal focusing. A test region concentration from a maximum of 500X to a minimum of 200X can thereby be supplied.

We recommend proceeding with the addition of this facility to the Sandia STTF and to use a single heliostat as much of the time as one can be spared.

We recommend that a focal plane test fixture be constructed to accommodate 25 x 25 and 50 x 50 test samples. This fixture is to be provided with water cooling to control sample temperatures and other features as detailed in this report.

COMMERCIAL TESTING FACILITY QUESTION

The question of whether or not long-term sample testing should be done by commercial testing laboratories, like DSET, Inc., New River, Arizona, has been raised. Short experiments or large-scale experiments clearly fall under the charter of federally supported facilities, but do long duration tests? Commercial labs have traditionally done much long-term testing of paints and materials, so the question is pertinent.

In discussions of this question with Gene Zerlaut of DSET a rather clear criterion seemed to emerge. The criterion is the level of business for a high flux facility in comparison to the capital investment involved. If the level of *assured* contract business at the inception of a new facility represents 50 to 75% of the cost of the facility, then the probability of continuing contract work makes the private investment a reasonable business risk.

The situation of high concentration testing is, however, quite different from the usual solar testing at DSET. A large collector still provides only a small test area. For example, a 10-m diameter collector could provide a test area at 1000X of only 32 cm (12 in.) diameter. If 2 x 2 in. samples are used, the total number accommodated would be 22 or about 55 1 x 1 in. samples (see Fig. 13). The cost of such a collector installed with monitoring equipment would be about \$100,000 each (\$180,000 if 10 were built).

If the irradiation occupied one year, the figure of 30% cost amortization per year would result in a per sample cost (for facilities only) of

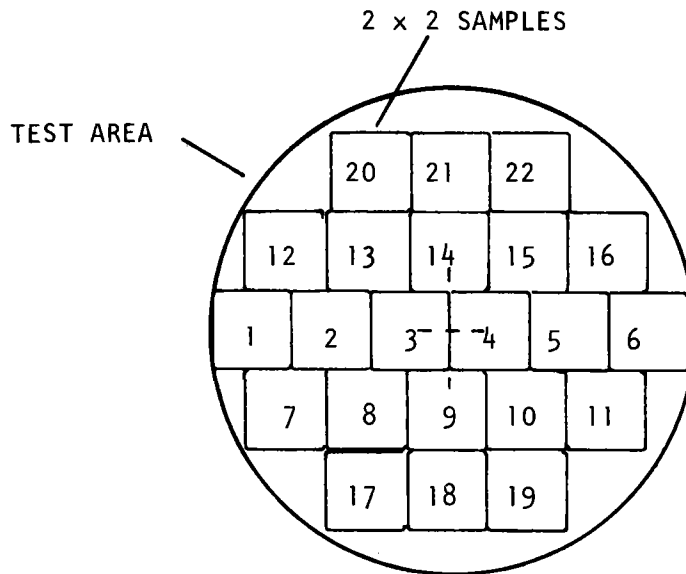


Fig. 13. Typical deployment of samples in a test region.

1500 \$/sample yr (2 x 2)

600 \$/sample yr (1 x 1)

This is a high cost per sample and would tend to limit critical experiments involving *slow degradation modes* to federal facilities where the burden of the facility cost is *not* borne by the particular experiment.

Experiments on high-flux, slow-failure mechanisms are apt to be of importance only for federal projects involving high temperature use systems for at least the next decade. When commercially attractive applications are developed, and where equipment manufacturers are interested in developing product superiority, then the need for a commercial testing facility will become apparent.

Commercial high temperature testing would probably be by means of a tracking paraboloid as the least expensive option. A heliostat/concentrator

is convenient when frequent access to the focal plane samples is necessary. Long-term testing, however, requires only infrequent access to the samples for testing of progress in the behavior of the samples.

The early use of a reconcentrator at Sandia then has value in seeing how a program of extended testing will develop, from short exposure tests to 1000 hour tests, for example. This early use, moreover, is necessary in order to assess the need for a commercial testing facility to take over this responsibility.

There probably will be few commercial customers. Most will be government laboratory and federally funded research groups. Thus there is little possibility for amortizing capital investment on a commercial volume.

An important aspect of whoever manages the long-term testing (federal lab or commercial test lab) is the support team, instrumentation, and calibration. At Sandia, for example, all of this is available, but national priorities for a major facility like the STTF can place routine materials testing at a low priority, with corresponding degradation in the degree of diligence on the part of persons involved with the materials test program. At a commercial lab like DSET testing is the main task and a high temperature test bed would have features that make it one of the top activities with a correspondingly high level of attention and care by the professional staff.

It is our recommendation that the need for high-flux, slow-failure mode tests be met for the decade of the 1980's through use of one of the federally sponsored solar test facilities. Within the scope of this recommendation we would include the construction of one or more high flux test concentrators at a commercial laboratory like DSET, with the full capital cost being the responsibility of the federal funding source.

TEST REGION GEOMETRY

Let us examine the test region geometry for the recommended case of a plane heliostat illuminating the Omnium-G paraboloid. The focal plane geometry is shown in Fig. 14.

There are two focal planes of interest, (1) the solar image focal plane at 400 cm from the vertex of the paraboloid and (2) the heliostat image focal plane at 420 cm. The image at (1) is a circle equal to the solar image diameter, blurred by mirror errors from *both* heliostat and paraboloid concentrating sunlight into a circle approximately 60 mm in diameter (solar image = 27 mm), where the average concentration is about 7,800X. Less paraboloid and heliostat reflectance loss this becomes 5,600X.

The image at (2) is about a 30 x 30 cm apparent shape of the heliostat, shown as a parallelogram in Fig. 15, blurred by the errors of the paraboloid *only*. The brightness is relatively uniform over the parallelogram, and about 225X, considering reflection losses.

Concentrations between 225 and 5600X can be obtained by placing the sample focal plane between (1) and (2), the image being a combination of the solar disc and the parallelogram, as indicated in Fig. 15b.

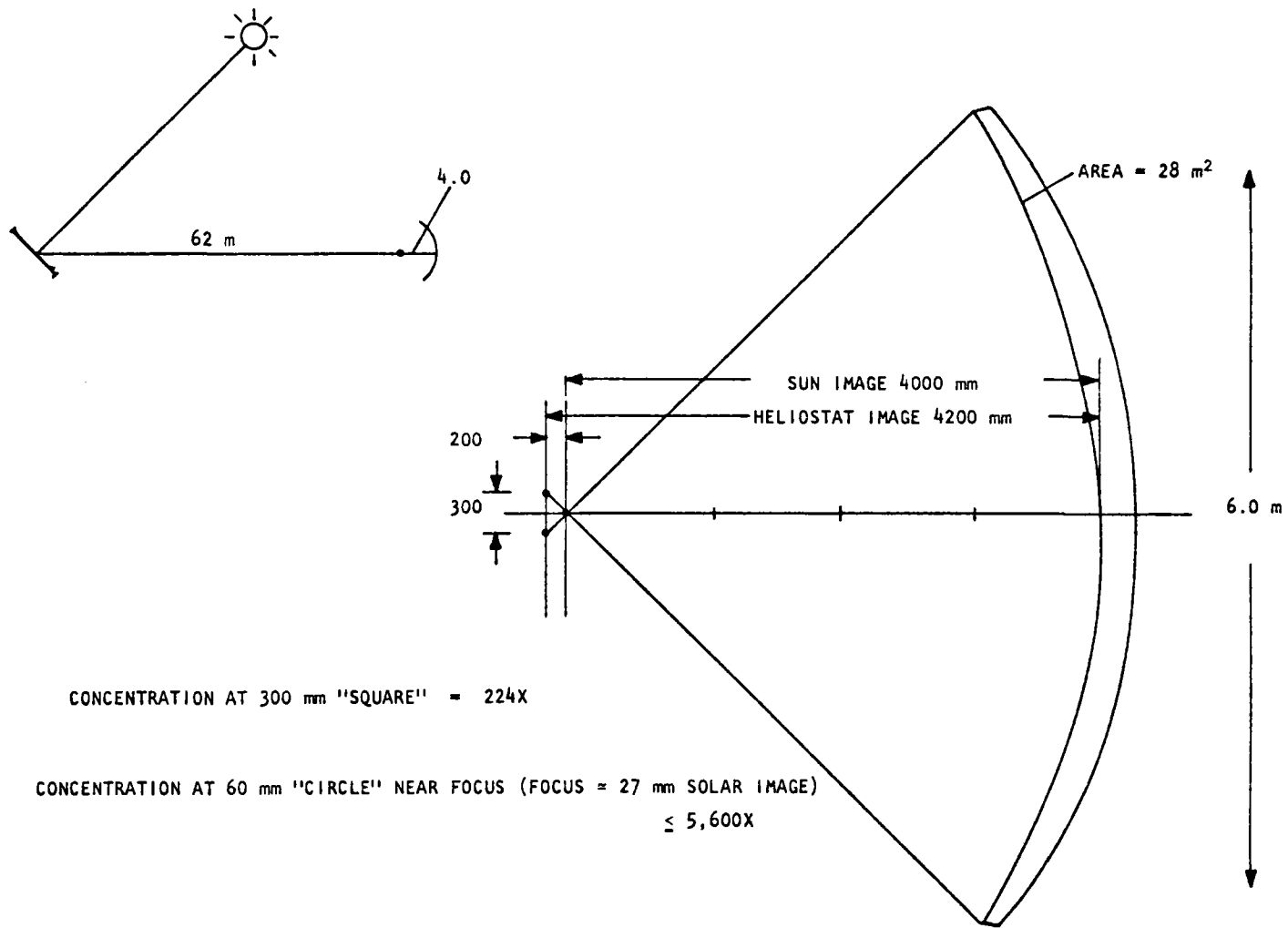


Fig. 14. Location of the image planes for a 6-m diameter Omnium-G paraboloid.

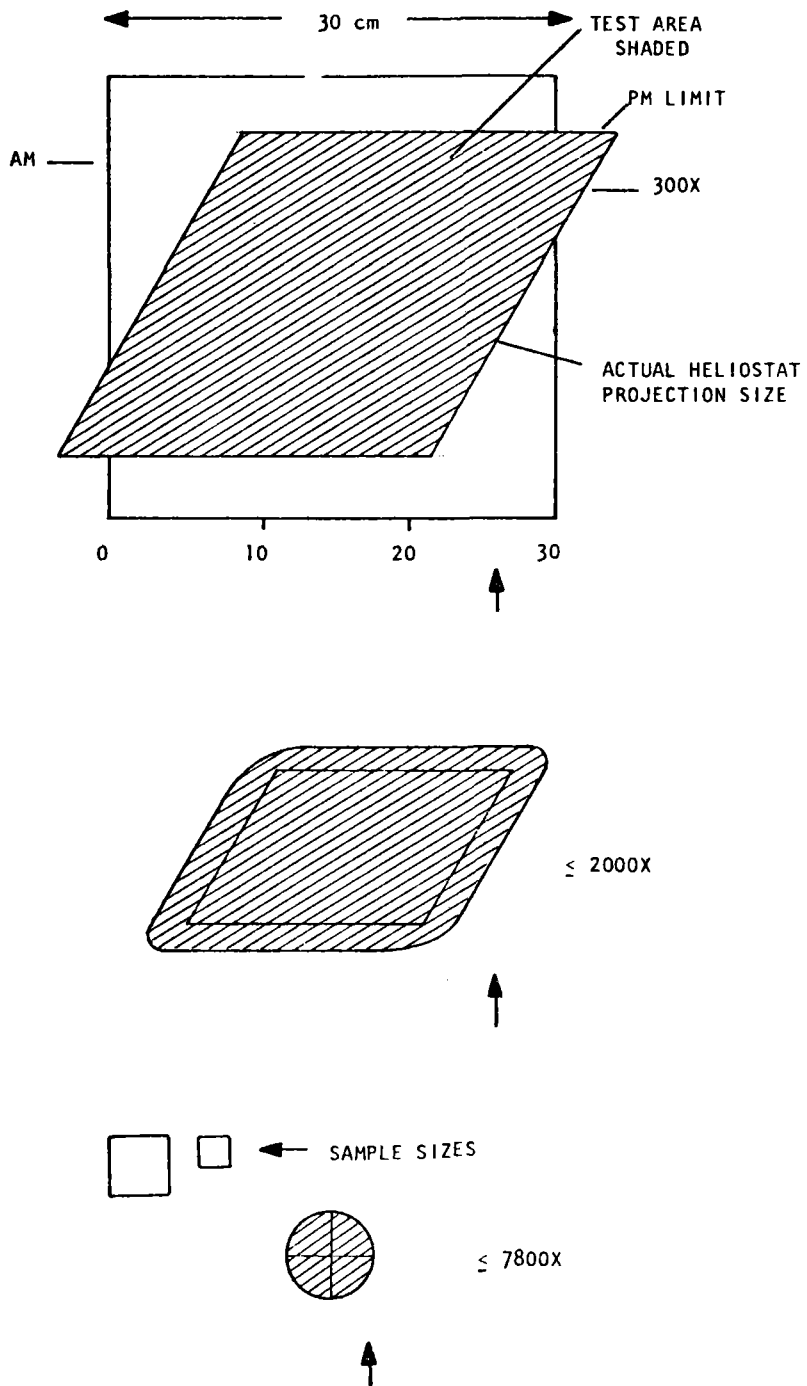


Fig. 15. Shape at heliostat image plane (top). The shaded area is that area illuminated from AM to PM limits. Shape at intermediate focal plane (center). Shape at solar image plane (bottom).

SAMPLE DEPLOYMENT

The typical sample size of 25 x 25 or 50 x 50 mm means that different numbers of samples can be accommodated at different concentrations. At the highest concentration one 50 x 50 array or four 25 x 25 arrays are the limit. At the heliostat image plane, 20 50 x 50 or 80 25 x 25 arrays can be accommodated.

It should be noted that the size of the test area is the same for either the 6-m plane heliostat combination or the 2-m focused heliostat (for equal flux concentrations. In practice, however, the test area can occupy a larger physical space in the former, allowing simpler and less expensive test fixtures, in the case of the 6-m input beam, simply from the standpoint of beam obscuration.

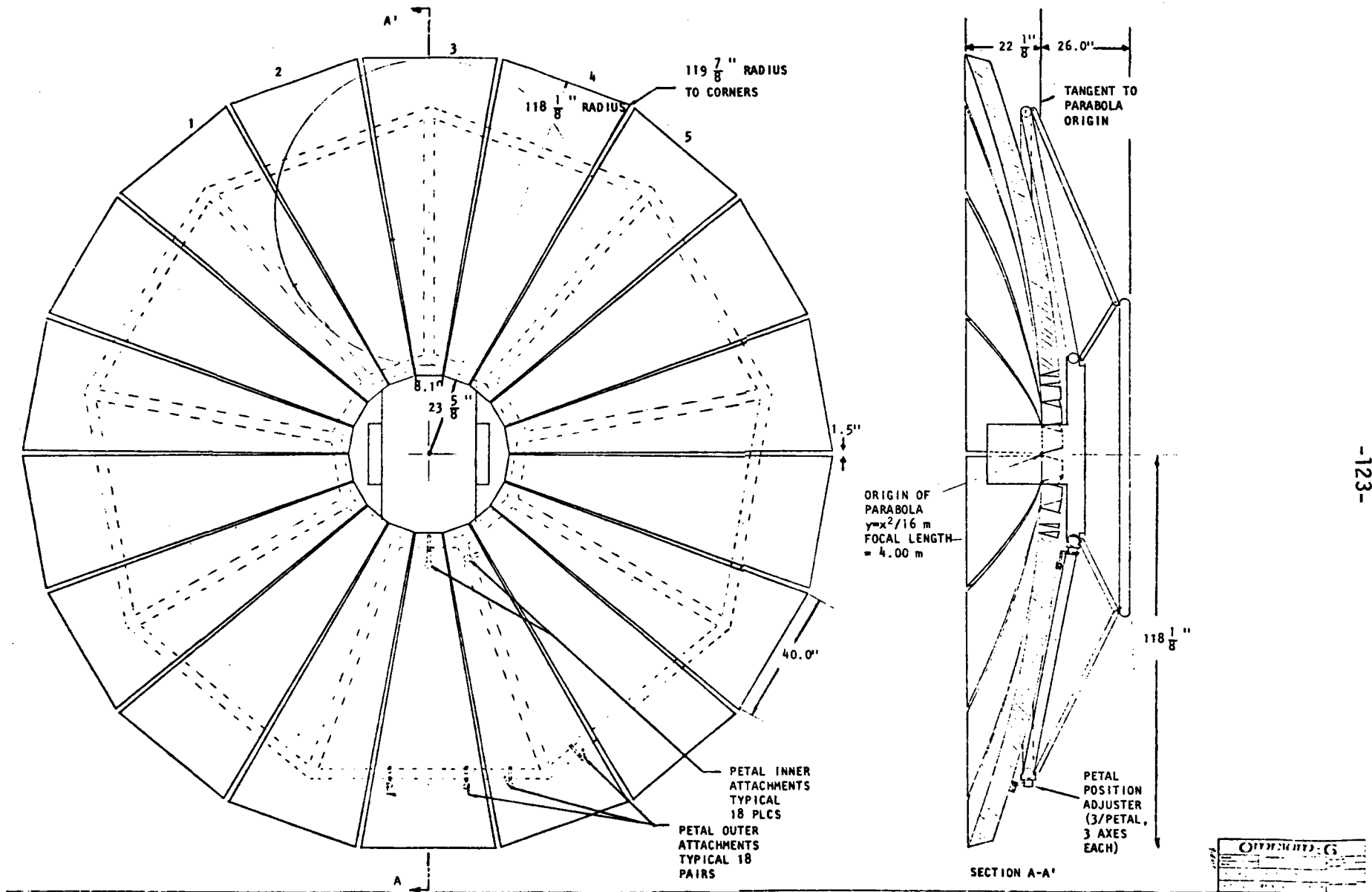
SAMPLE HOLDERS

The geometry of the sample holders depends in considerable degree on the experiments to be done. We (Meinel and Zito) have some experiments in which long exposures will be necessary to evaluate the temperature/time dependence of degradation of metal and composite surfaces. The design and construction time for the sample holder is less than that for the construction of the reconcentrator. Thus we propose closing the reconcentrator decision as recommended herein, and use funds still available in the present study contract for a no-cost extension to complete the sample holder design. Funding would be requested for construction of the sample holder at the next 6-month proposal date.

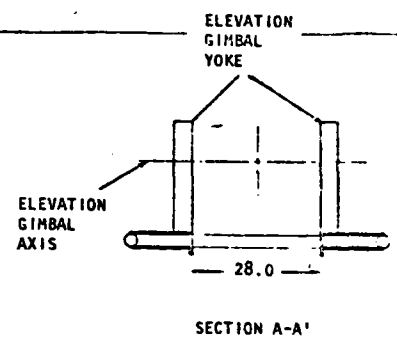
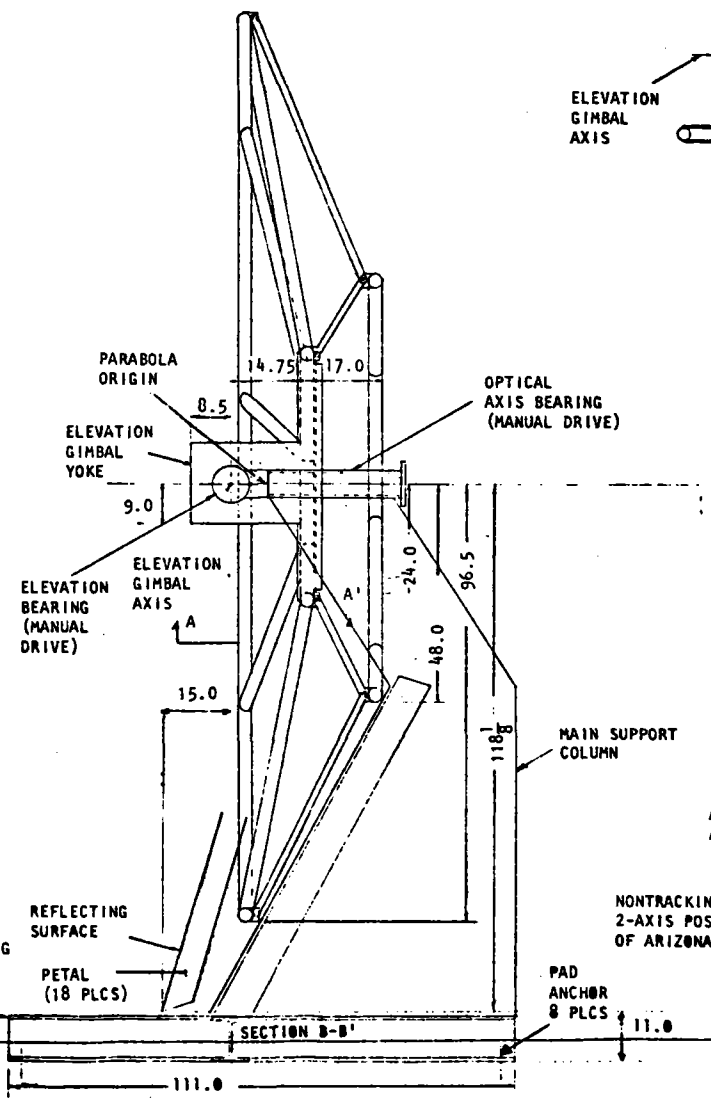
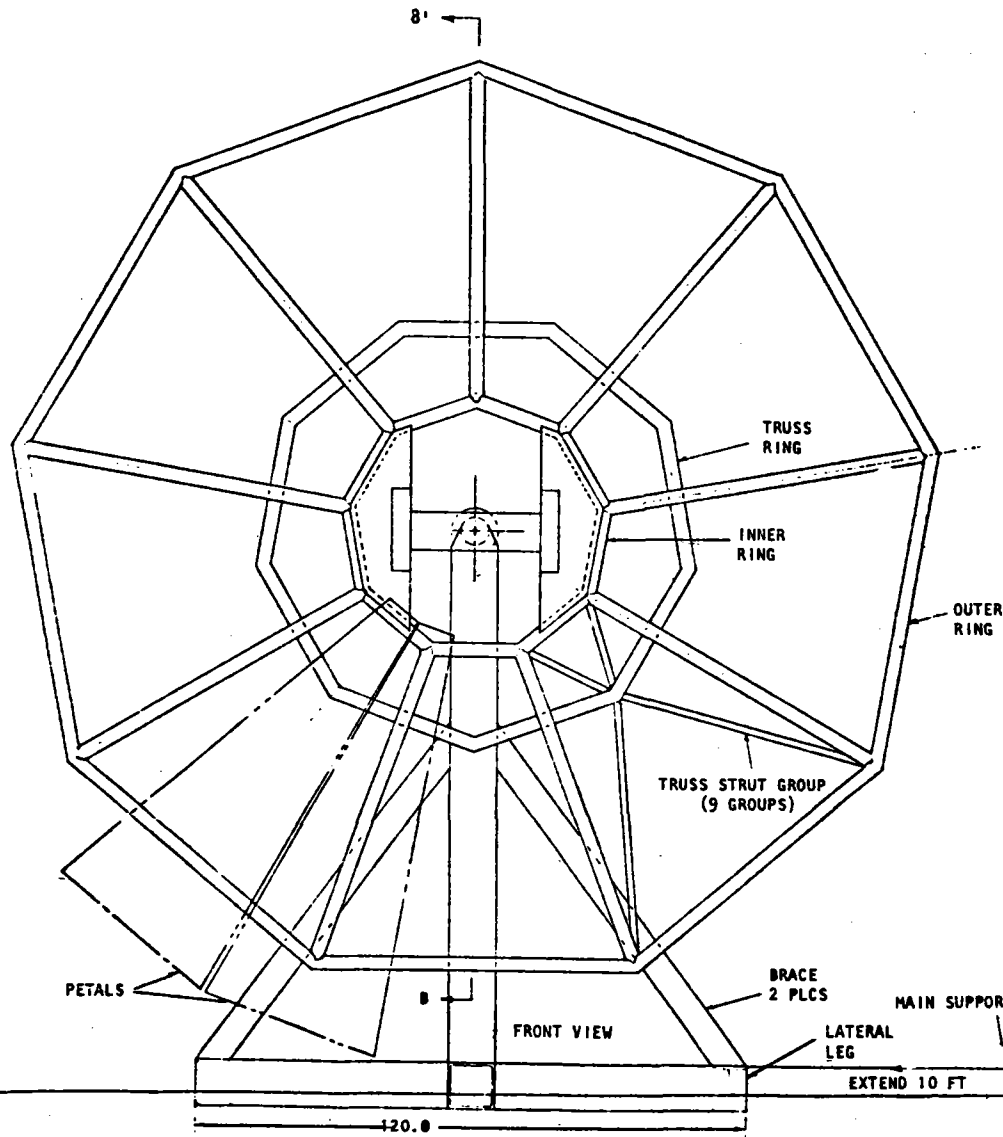
CONSTRUCTION BUDGET

The estimated costs associated with the construction of the recommended HTHF facility are given below.

(1) A & E	\$ 10,000
(2) Construction	
Omnium-G	30,000
Shipping	1,200
Foundation and services	4,000
Building 40 x 25	25,000
Site supervision	<u>3,000</u>
	\$ 73,200
(3) Instrumentation (as available at the STTF and to be determined)	
(4) Focal plane subsystem (to be determined)	



PETAL LAYOUT ON BACKUP STRUCTURE
 HTC-25 TRACKING CONCENTRATOR



ALL MAT'L IS ALUM
ALL DIMENSIONS IN INCHES

NONTRACKING CONCENTRATOR MOUNT
2-AXIS POSITIONABLE, FOR UNIV.
OF ARIZONA INSTALLATION

BACKUP STRUCTURE
MODEL HTC-25

SOLAR FLASH PYROLYSIS OF BIOMASS

Michael J. Antal, Jr.
Princeton University

Michel Rodot, Claude Royere, Andre Vialaron
CNRS, Odeillo, France

ABSTRACT

The use of solar heat for biomass gasification was analyzed recently in a major study for the President's Council on Environmental Quality (1). Three cases were considered: solar refiring a "conventional" biomass gasifier, solar flash pyrolysis, and a baseline case without a solar heat input. The solar refiring scenario displaced char combustion with solar heat, and did not appear to be economically competitive with the baseline case. However, direct use of the solar heat to achieve flash pyrolysis of the biomass appeared to be the most economical of the three alternatives.

Although this outcome surprised one of the authors (M. J. Antal), its rationale was clear. The "conventional" pyrolytic conversion process treated in the report produced a char residue. This residue represented a net loss from the gasification product slate, thereby degrading the process economics. It also proved to be a cheaper source of heat than that available from a solar tower. For these two reasons research at Princeton on biomass conversion has focused on the second alternative: solar flash pyrolysis of biomass, which produces a hydrocarbon rich synthesis gas with little or no char residue.

Pyrolysis of cellulose, the largest constituent of biomass, is characterized by two competitive reactions. The lower temperature, dehydration reaction leaves a char residue; whereas the higher temperature "unzipping" reaction forms only volatile matter (no char). High heating rates ($10000^{\circ}\text{K}/\text{sec}$) favor the "unzipping" reaction. It is known that no char residue is formed by pyrolysis when cellulose is exposed to modest ($\sim 100 \text{ w}/\text{cm}^2$) radiant fluxes (2). Lignin (about 25% of most biomass materials) is more difficult to gasify, but high heating rates are known to improve the gasification yields from materials high in lignin (3).

Because solar radiation has a characteristic temperature of almost 6000°K , it is capable of generating the very high heating rates required to achieve essentially total volatilization of the biomass by pyrolysis. The use of concentrated solar radiation to effect very high heating rates and thereby derive interesting chemical effects has been largely overlooked by previous workers. Experiments characterizing the effects of high radiant fluxes on biomass pyrolysis are scheduled to take place using the Odeillo solar furnace this summer. An entrained flow tubular reactor has been built at Princeton, and will be taken to France for the experiments. Large yields of olefins are anticipated. Results of the experiments will be described in future publications.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to the Solar Thermal Test Facilities Users Association and CNRS for their support of this research.

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DESTRUCTIVE TESTING OF THIN FILM MATERIALS IN AIR

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University of Arizona
Department of Physics

Destructive testing of thin film materials in air has been carried out. These tests set an upper limit to the temperature at which various selective surface stacks can be operated. This information will aid in the design of new high temperature photothermal stacks as well as high temperature microelectronic devices.

This presentation summarizes the completion of the first half of the thin film materials tests we have been conducting in the University of Arizona laboratories. These carefully controlled in-air tests on fused silica and soda-lime substrates clearly show the temperatures at which metal coatings about 1000 Å thick develop pinholes, agglomerations, cracks, peel disks, hillocks and other surface morphological changes within one hour. Pinholes appear first. The temperature required for pinhole formation in various metals is shown in Figure 1. It is seen that the algorithm

$$\frac{T_{PH}}{T_m} = .59 \left[1 - P \left(\frac{\theta - \theta_{ker}}{\theta} \right) \right]^2$$

supplies the correct film pinhole temperatures (T_{PH}). T_m is the bulk melting point of the metal film and $P = (N_{ox} - N_{film})/N_{ox}$ where N_{ox} , N_{film} are the electronegativities of oxygen and film metal, respectively. θ is the Debye temperature of atoms in the metal film and θ_{ker} is the Debye temperature of their "kernel" (II A atom of the same periodic row). This formula can also be justified on theoretical grounds by applying the two-dimensional melting theory of Kosterlitz, Thouless and Feynman to the mobile surface layer of metal film atoms. Some of this work has been described in previous Users Association conference proceedings*.

A thermal gradient was developed along our substrates and it can be seen (Figure 2) that the number of pinholes increases with increasing temperature until the pinholes blend together leaving islands of metal.

At this latter stage, the film is said to be agglomerated. Figure 3 shows a close-up of pinhole geometry with related "hillocks." The formation of these hillocks or mounds is easy to understand since metal removed from pinholes via surface diffusion must turn up somewhere else as a mound. Typically complete agglomeration occurs at temperatures about 30°C higher than the pinhole formation temperature.

Pinholes may develop into other destructive phenomena in metal films besides agglomeration. Figures 4 and 5 show a network of cracks in Cu and Cr films. These micrographs show cracks radiating from point defects. Branching of cracks may also occur. That is, a crack may nucleate on another crack defect. To test this hypothesis, a scratch was placed on a Cr coating and brought up to about 312°C. The result is shown in Figure 6. Cracks are clearly seen to radiate from the scratch thus explaining the branching phenomenon.

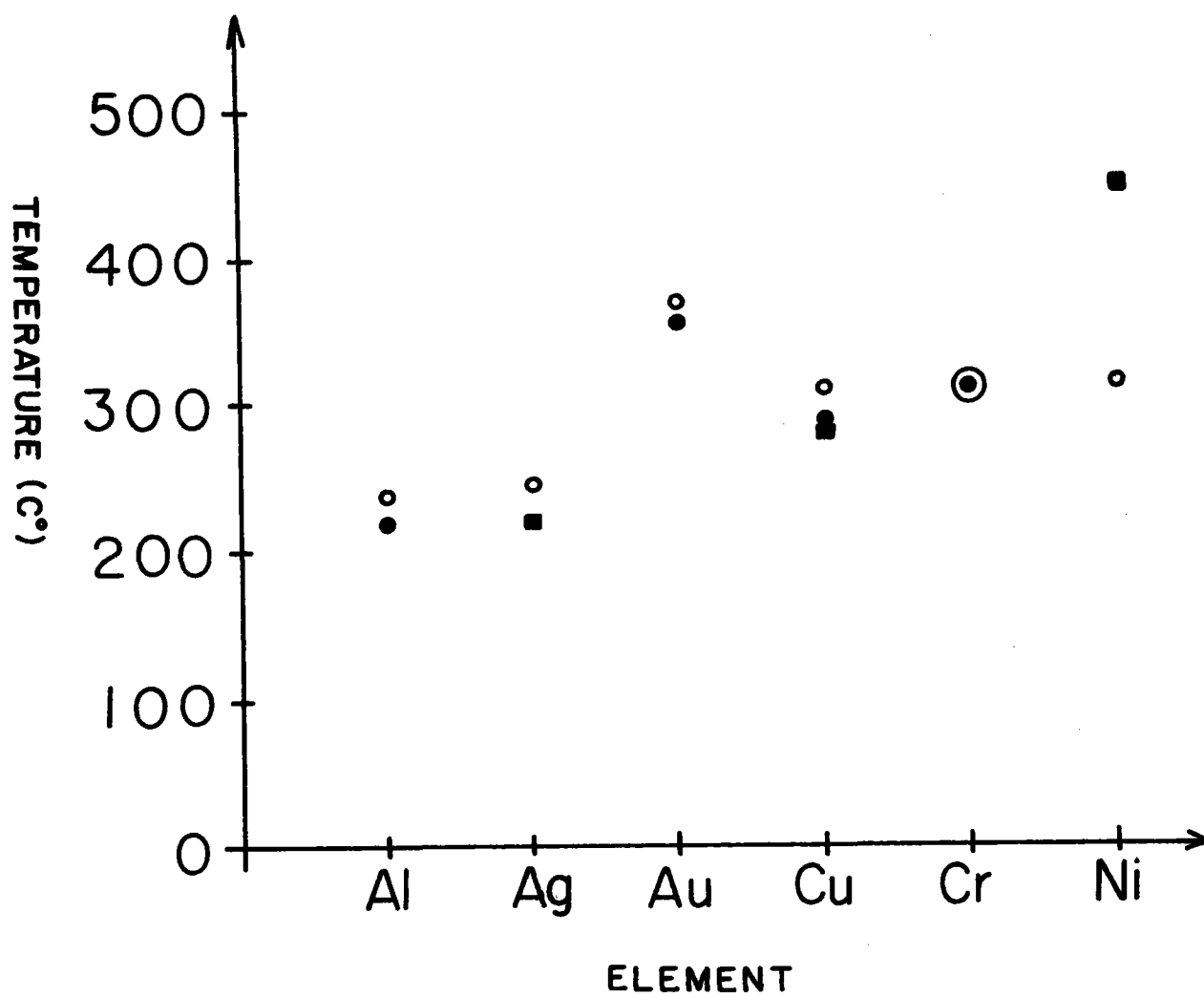
Peeling of metal films of the glass substrates usually starts as a collection of defects called a peel disk. One such disk appears to be developing Figure 2. A well-developed, large peel disk in an Al coating is shown in Figure 7. As of now, we have no well-developed theories to explain the onset and development of this phenomenon. However, our current thinking is that poor adhesion of metal to the substrate due to surface substrate defects is at least partially responsible. Further research in this area will be needed.

Finally, it should be noted that changing the substrate from soda-lime glass to fused silica generally results in only a 20°C lowering of the pinhole temperature in spite of the fact that the coefficient of

expansion for silica is about fifteen times smaller than for soda-lime glass. Thus, the pinhole temperature is principally an intrinsic property of the metal film with substrate-mediated effects being of second order importance.

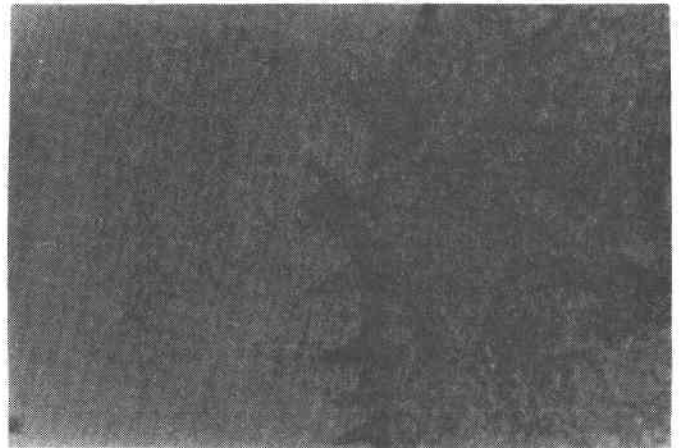
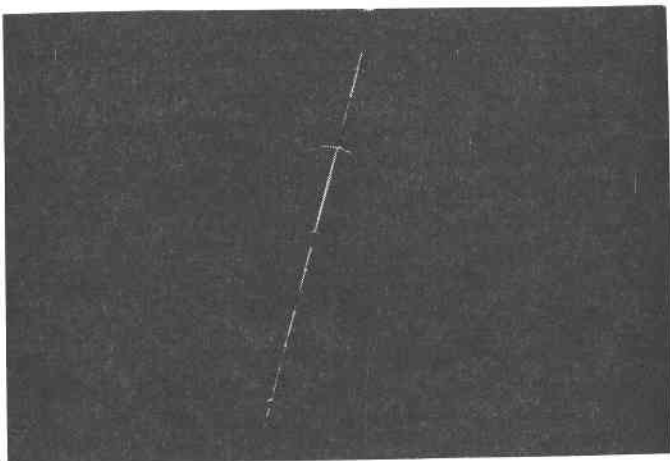
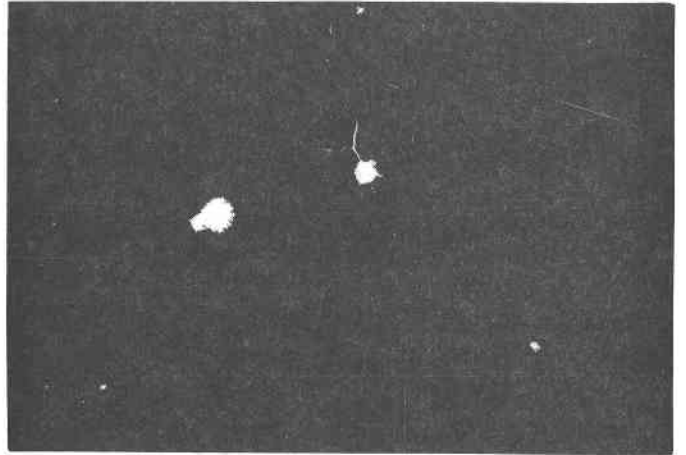
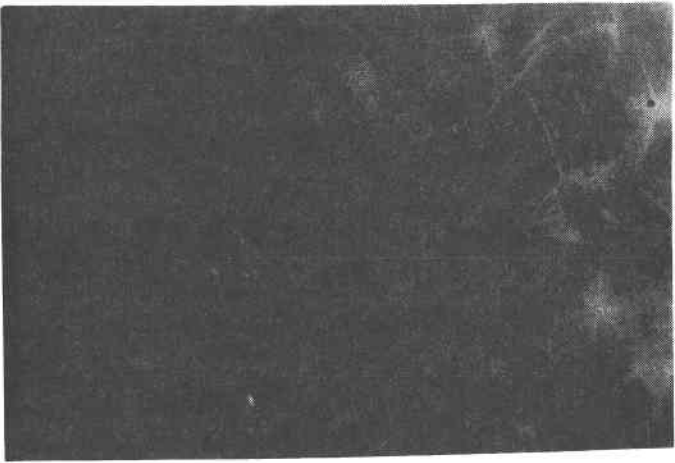
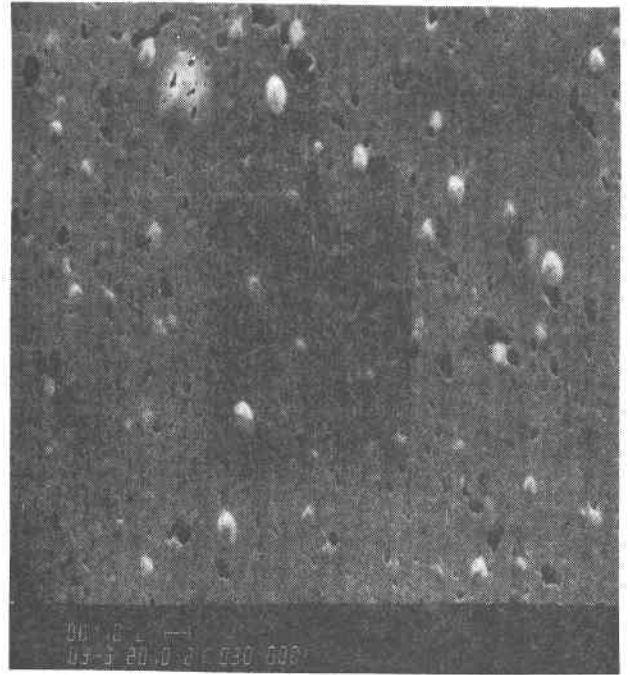
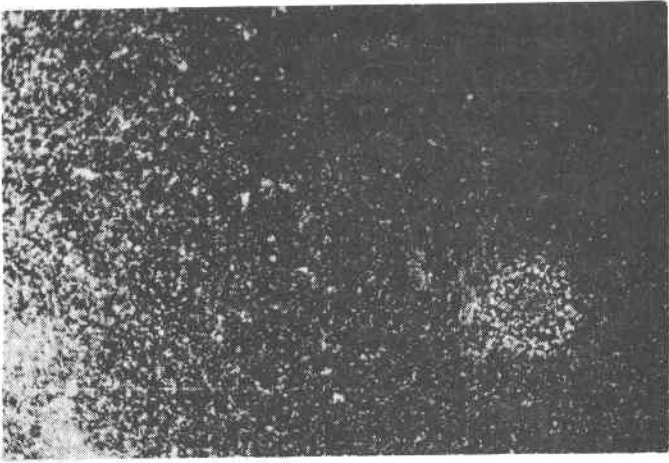
CAPTIONS

1. Temperatures resulting in pinhole formation after one hour of heating. Open circles mark theoretical predictions. Solid circles mark results on soda-lime substrates and solid squares mark results on fused silica substrates.
2. This transmission optical photograph taken in visible light at 125x shows numerous pinholes in an Au film (~ 1000 Å thick) on soda-lime glass. A thermal gradient was placed along the film. The hot end (left) shows complete break-up of the film into islands of metal (agglomeration); the cold end shows pinholes and a circular collection of defects, possibly developing into a "peel disk." The field of view is ~ 1 mm².
3. The scanning electron micrograph above shows numerous pinhole valleys (dark) and hillock mounds (bright) in a typical Au film (~ 1000 Å) on soda-lime glass after heat treatment. The magnification is 3×10^3 times and one micron is shown in the scale below the photo.
4. Cracks in Cu on soda-lime glass. Magnification is 125x in reflected visible light. Oxidized Cu film is dark, bare glass showing through pinholes looks bright. The field of view is ~ 1 mm².
5. Cracks in Cr (~ 1000 Å) on soda-lime glass. Magnification is 250x in transmitted light.
6. Cracks nucleating on a scratch in a Cr coating (~ 1000 Å) on soda-lime glass. Magnification is 250x in transmitted light.
7. A huge peel disk in a 1000 Å Al film on soda-lime glass. The magnification is 125x in reflected light. The field of view is ~ 1 mm².
- *. FOOTNOTE: Proceedings of the Solar High Temperature Industrial Processes Workshop, September 28-30, 1978, Atlanta, GA, SERI 10637-4, pp 362.



ELEMENT

FIGURE 1



THERMOCHEMICAL ENERGY TRANSPORT USING $\text{NH}_3 \rightleftharpoons 1/2 \text{N}_2 + 1-1/2 \text{H}_2$

P. O. Carden

Australian National University Program

Introduction: Work on the NH_3 system began in 1974. It is continuing in parallel with the development of inexpensive methods for manufacturing paraboloidal mirror collection. Ammonia was chosen primarily for its ease in experimentation (no side reactions) and because it had minimal environmental and corrosion problems. The entire concept from collection through to conversion to work is continually under review and research the effort at any particular time is channelled into the element which seem to be the most critical.

Accordingly we have given a lot of attention in the past to the following:

- ammonia dissociation experiments
- system thermodynamics
- synthesizer design and work recovery

For each of these areas work has proceeded or is proceeding until enough problems are solved to render it less critical than some other area.

A recent step upwards in funding has enabled us to hasten the process of determining the feasibility of the concept. We have engaged consultants from industry, in particular the chemical engineering and plant design industry, and we expect to have a good idea of the feasibility of our basic concept by July 1979.

Basic Concept: The scenario is a remote Australian mining township 15 - 20 years from now. Solar power level is 10MW_e . The township is supplied by a hybrid of conventional and solar power operation. It is anticipated that conventional power generation (using diesel engines) will improve in efficiency during the next 15 - 20 years by use of waste-heat driven steam turbines. Alternatively, steam turbines using a less expensive fuel oil than dieselene may displace diesels. In either case the steam turbine will constitute the common prime mover powered by both solar and conventional sources. The basic concept does not include substantial energy storage.

Dissociation Experiments: Approximately four experiments have been built and subjected to a series of tests. The first were simple tubes fitted with thermocouples, packed with catalyst granules, and attached to a counter-flow heat exchanger. The catalyst tubes were heated electrically. The last was quite sophisticated in its instrumentation but in many respects was the simplest to construct. It has been thoroughly studied and has been accurately modeled by a computer program. We have therefore been able to extrapolate the results for a series of specific receiver designs.

In general we have found that modest improvements in catalyst activity will allow economical receiver designs (of the order of \$10 per m^2 of collector aperture) provided reasonable catalyst lifetimes can be retained (of the order

of 10 years). Catalyst activity that we have measured relates to an easily obtainable commercial cracking catalyst which however is designed for a much lower pressure than our system pressure.

Thermodynamics: The recovery of work from thermochemical energy transport systems has been the subject of an extensive theoretical study (P. O. Carden and O. M. Williams, Energy Research Vol 2, 389-406 (1978)). In this study the efficiency is divided into two components: the energy storage efficiency and the work recovery efficiency. The energy storage efficiency relates the enthalpy difference between the two low temperature or ambient fluid streams to the input of solar energy. The work recovery efficiency relates the maximum possible work output to the enthalpy difference. The enthalpy difference is a measure of the energy actually flowing in the energy transport system so is therefore an appropriate intermediate quantity entering the definition of both efficiencies. A paper by O. M. Williams and P. O. Carden (also in Energy Research) addresses the specific question of the energy storage efficiency for the ammonia based system.

The most important finding of the study is that exothermic reactions should be run non-isothermally for maximum work recovery and that the ideal work recovery efficiency may be determined solely from the temperature profile of the catalyst bed (temperature vs reaction extent).

Future Plans: Assuming that the basic 10MW_e concept is shown to be feasible, future plans provide for the construction of a complete energy transport loop at the 5kW_{th} to 10kW_{th} level using an electrically heated dissociation. Several synthesizer concepts will be tested and work will continue on catalyst screening and testing (lifetime and cycling). Since the design of the receiver is intimately related to catalyst properties, it does not seem appropriate to finalize the receiver design at this stage although it must be emphasized that quite specific designs have been produced and analysed. A separate series of experiments related to receiver materials, absorptivity, connection losses etc., has been in progress and will continue.

TITLE: INTERFACING SOLAR HEAT SOURCES AND HYDROGEN PRODUCTION PROCESSES*

AUTHOR(S): Melvin G. Bowman

SUBMITTED TO: To be presented at the Solar High-Temperature Experiments Workshop, Albuquerque, NM May 3-4, 1979

Sponsored by the Solar Thermal Test Facilities Users Association

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INTERFACING SOLAR HEAT SOURCES AND HYDROGEN PRODUCTION PROCESSES

Melvin G. Bowman

INTRODUCTION

The high capital costs of solar concentrator systems offer sufficient justification for rather comprehensive programs to develop high efficiency processes for the utilization of solar heat. It is also desirable that such processes incorporate energy storage features. Since hydrogen fulfills the requirement for energy storage, is potentially valuable as a transportable fuel and is the "intermediate of choice" in the production of a wide variety of fuels and chemicals, a significant fraction of this program effort should be concerned with coupling hydrogen production processes to high temperature solar receiver systems. Since current processes and concepts were seldom developed specifically for current central receiver designs some mismatch is inevitable and it is obvious that liaison and cooperative efforts between facility operators/designers and process developers should be promoted.

In addition to this valuable effort, however, the obvious advantages of high efficiency essentially mandate support for a reasonable level of effort directed toward interfacing very high temperature solar receivers with high technology processes whose temperatures and heat requirements match the heat delivery characteristics of the solar furnace. With adequate liaison between facility developers and process developers one should expect that current limits of practicality will be elevated, not only for operating temperatures of practical solar systems and the matching hydrogen production processes, but also for the resultant efficiencies for heat utilization.

I. Electrochemical Methods for Hydrogen Production

The production of hydrogen by the electrolysis of water is well known. At the present time a great deal of R & D effort is being expended in efforts to make this process more efficient and less costly. Finally, efficiencies will be limited by efficiencies realized for power production. For high temperature heat sources, higher efficiencies for power production can be expected, but only if the conversion system matches the maximum temperature

and temperature range. Thus, topping cycles are being developed to couple with more conventional low temperature methods. The combined systems will be expensive, but higher efficiencies may justify extra costs.

One potentially promising concept now receiving significant attention is the high temperature electrolysis of H_2O by means of stabilized ZrO_2 (ref. 1) which is an oxygen ion conductor with fair conductivity for oxygen ions and adequately low conductivity for electrons at temperatures of the order of 1500 K. The advantages of this method derive not only from lower standard potentials, but also from much lower overvoltages. Since solar heat involves "clean" systems, one can conceive of a high technology process in which efficient high temperature, D.C. power production (e.g., MHD or Thermionic Diode Systems) is coupled with high temperature electrolysis of H_2O (or CO_2).

Thermionic diode systems are usually considered to be short lived. However, recent developments with thermionic emitters are quite promising (ref. 2,3,4). Continued research seems justified to develop efficient emitters that incorporate long life (low vaporization loss), resistance to thermal shock and, perhaps, low photon emissivity at operating temperatures. It is also clear that the overall concept could benefit from research to determine the factors that enhance ionic (also, electron) conduction through solids; H^+ as well as O^- .

II. Thermochemical Methods for Hydrogen Production

The possible advantages of thermochemical cycles for utilizing a primary heat source for the decomposition of water have been described several times in glowing terms. Perhaps as a result of this optimism, many papers have been published, and patents have been issued, for conceptual thermochemical cycles for the decomposition of water. Unfortunately, a large number of these cycles were ill conceived and thermochemically invalid. Furthermore, only a few of the cycles based on sound thermochemistry were tested in the laboratory prior to publication of the concept. As a result of this overoptimism and of poor examples, negative opinions of thermochemical cycles have been generated and engineering and economic analyses have been published that were designed to show that the thermochemical concept is impractical. Despite this semi-confusion good programs are being conducted and objective engineering evaluations have been attempted even though only preliminary data and process flow sheets were

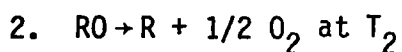
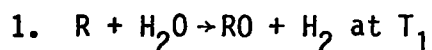
available. These evaluations have been useful not only for revealing weaknesses in specific processes (and thus suggesting improvements), but also for identifying process features that should be avoided in the development of thermochemical cycles. It is possible that one or more of the cycles now being developed will also prove to be practical. Additional development will be necessary before realistic evaluations can be made. Nevertheless, it is still true that no cycle that closely approximates the thermochemical criteria for maximum efficiency has yet been identified and adequately demonstrated in the laboratory.

II-A. Thermochemical Criteria for "Ideal" Cycles

One of the advantages cited by advocates of thermochemical cycles for water decomposition is the fact that (in contrast to electrical power production) a "topping cycle" is not required for the efficient utilization of heat from high temperature heat sources. The statement can be true, but it should include the qualifying phrase "if the reaction temperatures and heat requirements of the cycle match the maximum temperature and heat delivery characteristics of the heat source."

One method for defining thermodynamic criteria for efficient cycles, in terms of "ideal" enthalpies and entropies has been presented several times beginning in 1974 (ref. 5). It is presented again here as background for a consideration of problems of interfacing thermochemical water splitting cycles with solar heat sources.

Consider a two-step (single temperature cycle) process in which a reactant (R) reduces water at a low temperature (T_1) to evolve hydrogen and form the compound RO (R may also be an oxide), followed by thermal decomposition of RO at high temperature (T_2) with the evolution of oxygen. The reactions can be written as:



If an ideal cycle is considered to be one in which $\Delta G^0 = 0$ for all reactions, and if one utilizes the approximation

$$\Delta G_T^0 = \Delta H_{298}^0 - T \Delta S_{298}^0$$

"ideal" values for entropies and heats of formation (from R + 1/2 O₂) of the compound RO are approximately defined by the expressions:

$$\text{"Ideal" } \Delta S_F^0 = \frac{\Delta G_F^0 (H_2O) : \text{ at } T_1}{(T_2 - T_1)}$$

$$\text{"Ideal" } \Delta H_F^0 = \Delta S^0 \times T_2$$

where $\Delta G_F^0 (H_2O)$ is the free energy of formation of water at T_1 (the low temperature). To illustrate, if we assume $T_1 = 400$ K (where $\Delta G_F^0 (H_2O) = 224$ kJ), and assume different temperatures for T_2 , the corresponding parameters computed for RO are those given in Table I.

TABLE I

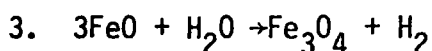
T_2	$-\Delta S_F^0 (RO)$	$-\Delta H_F^0 (RO)$
1200	280	336
1500	204	306
2000	140	280
2500	107	268

Since entropies of formation of oxides (per oxygen atom) are characteristically near -100 J/K, it is clear that very high temperatures will be required for two-step oxide cycles. This observation is the basis for published statements that two-step cycles are not feasible. Actually, two-step cycles are possible, in principle, even for relatively low maximum temperatures if one can identify usable reactions with the necessary large entropy changes.

II-b. Oxide Cycles

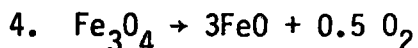
In considering the problems of interfacing solar heat sources with thermochemical "water splitting" cycles, only modest optimism is required to assume that operating temperatures well above 2000 K may eventually become practicable. A solar furnace has a second important attribute: Heat can be delivered at a constant temperature near the temperature maximum (in contrast to a gas cooled reactor, for example). Therefore, cycles involving the high temperature decomposition of a solid (e.g. reaction 2 above) are entirely feasible.

A two-step iron oxide cycle for water decomposition has been proposed several times. The high temperature decomposition has also been studied by Tofighi, et.al., with the solar furnace at Odeillo. The cycle may be described by the following reactions.



$$\Delta H_{(298)}^{\circ}: \text{ with } \text{H}_2\text{O}(\ell) = -19 \text{ kJ}, \Delta S^{\circ} = +24 \text{ J/K}$$

$$\text{ with } \text{H}_2\text{O}(\text{g}) = -63 \text{ kJ}, \Delta S^{\circ} = -95 \text{ J/K}$$



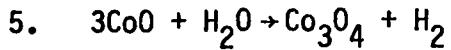
$$\Delta H_{298}^{\circ} = +305 \text{ kJ}, \Delta S^{\circ} = +139 \text{ J/K}$$

Decomposes to $\text{FeO}_{(1+x)}$ liquid at $\sim 2150 \text{ K}$

ΔG° is negative for reaction 3 up to a relatively high temperature and is significantly negative at the reaction temperature. (This is necessary. Low temperature reactions with $\Delta G^{\circ} = 0$ cannot be expected to occur at reasonable rate). The reaction is a known reaction. It is of interest to note that reaction 4 (if written as a solid-solid decomposition reaction), exhibits one of the largest entropy changes known for this type of reaction. At first glance the cycle seems promising, but as one should expect (and as Tofighi, et. al., found), Fe_3O_4 melts before it decomposes and oxygen evolution is over a relatively narrow liquid homogeneity range.

It is unfortunate, perhaps, that Fe_3O_4 melts before it decomposes since suitable substitutes for Fe_3O_4 in this type of cycle have not been identified.

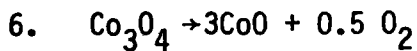
For some systems, the high temperature oxygen evolution step seems feasible but the low temperature reaction with H₂O will not occur. One interesting potential cycle of this type can be represented by the following equations:



ΔH° : For H₂O(l) = +98 kJ, ΔS° = +5 J/K

For H₂O(g) = +54 kJ, ΔS° = -114 J/K

For hybrid: E° = -0.50 V

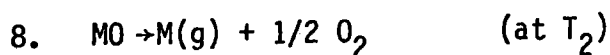
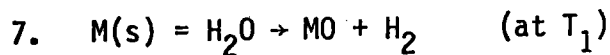


ΔH°_{298} = +188 kJ, ΔS° = +158 J/K

Td reported: ~1175-1225 K

The E° value listed for a possible hybrid cycle does not imply that credible electrode reactions have been identified. It is given as the minimum energy to be contributed by additional chemical reaction steps or by a hybrid step. Reaction 6 exhibits a large entropy change and a reasonable decomposition temperature. It should be emphasized, however, that this reaction does not interface well with a gas-cooled reactor as a heat source since it would be an isothermal reaction near the maximum credible HTGR temperature.

A second type of two-step, oxide cycle includes a solid decomposition reaction to form two gaseous products rather than a condensed phase and gaseous oxygen. The concept can be illustrated by the following equations (where M is a metal),



Typical ΔS° ~200 -210 J/K

If the typical ΔS° for reactions represented by equation 8 is compared with values listed in Table I, a temperature difference of ~1100^o is implied for this cycle. However the high temperature endothermic heat requirement

(and the value implied for $\Delta S \times T_2$) includes the sum of the heat of sublimation of the metal plus $-\Delta H_f^0$ (MO). Since entropies of vaporization for metals are fairly similar, the ideal metal for this type of cycle would be one with a low boiling point (to minimize heat of vaporization) that would just reduce water at low temperature. Cadmium and zinc are two candidates frequently mentioned for this type of cycle. Neither is an ideal candidate although both have relatively low boiling points. Published boiling points and oxide decomposition temperatures are as follows:

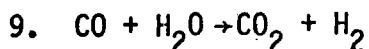
CdO: $T_d = \sim 1750 - 1800K$, BP (Cd) = 1038 K

ZnO: $T_d = \sim 2300 K$, BP (Zn) = 1180 K

From published thermochemical data, reaction 7 with Cd should not be expected and, in fact, does not occur. However, in 1976, Pangborn of IGT described an electrochemical method for promoting the reaction (ref. 7). The proposed cycle was not developed into an actual process since projected gas cooled reactors (the "target" heat sources at that time) were not suitable for the high temperature isothermal step, even for the lower CdO decomposition temperatures sometimes reported.

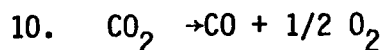
In contrast to the Cd cycle, reaction 7 with Zn is very exothermic. This difference is reflected in the much higher oxide decomposition temperatures. Since back reaction between oxygen and gaseous metal atoms must be minimal, the high decomposition temperature for ZnO implies a very difficult cycle even if the high temperature isothermal heat source is available. Therefore, despite the awkward electrochemical step, the IGT hybrid cycle is probably the best candidate at this time for this type of cycle.

A third type of two-step oxide cycle is represented by "The LASL CO₂ Cycle." The reactions are as follows:



ΔH_{298}^0 : For $H_2O(l) = +2.8$ kJ. $\Delta S^0 = +76.9$ J/K

For $H_2O(g) = -41.2$ kJ, $\Delta S^0 = -42.0$



$$\Delta H_{298}^{\circ} = +283 \text{ kJ}, \Delta S^{\circ} = + 86.4 \text{ J/K}$$

The ΔS° for reaction 10 is smaller than the characteristic value for solid oxide decompositions. Also, ΔG° for reaction 9 remains negative up to a fairly high temperature. Therefore, ΔG° for reaction 10 remains positive up to a temperature of ~3340 K. However, since the decomposition involves a gaseous reactant and two gaseous products, the reaction is not isothermal and is characterized by a shifting equilibrium over a wide temperature range. Thus, at equilibrium and 1 atm. pressure, CO_2 should be 44% dissociated at 3000 K. At 2400 K, the dissociation should be 9% at 1 atm. pressure and 14% at 0.25 atm. pressure.

Since the beginning of our program, we have considered The LASL CO_2 cycle to be the most promising candidate for use at very high temperatures. However, we have not studied the cycle in any detail because of four obvious problems.

- (1) It has been difficult to believe in the availability of heat at the required high temperatures.
- (2) It is not certain that materials will be available to contain (and transfer heat to) the gases at required temperatures.
- (3) It is clear that the back reaction of CO plus O_2 can be a prohibitive problem if reaction rates are too rapid since heat must be extracted from the product gases for an efficient process.
- (4) The problem of separating the CO_2 -CO- O_2 gas mixture may be difficult and may require significant amounts of work energy.

At the present time, perhaps it is not too optimistic to project that practical, very high temperature heat sources can be developed. If this becomes reality, the other problems cited can be regarded as challenging research problems rather than obstacles to practicality. Consequently, we are engaged in a program to study and develop the cycle.

Oxide-Sulfate Cycles. It is apparent from Table I that two-step cycles should be possible at lower temperatures if reactions with sufficiently large entropy changes can be found. Since ΔS° values for decomposition reactions increase with the number of gaseous molecules evolved, our early studies were directed

toward oxide-sulfate cycles. The concept can be illustrated by the following equations:

11. $MO + SO_2 \rightarrow MSO_3$ (low temp.)
12. $MSO_3 + H_2O \rightarrow MSO_4 + H_2$ (low temp.)
13. $MSO_4 \rightarrow MO + SO_2 + 0.5 O_2$ (high temp.)

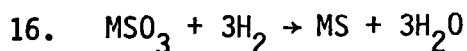
Typical ΔS^0 ~275-290 J/K

Fits ΔT of 800^0 for two-step H_2O decomposition

As indicated, the typical ΔS^0 for the decomposition of a sulfate to an oxide plus sulfur dioxide and oxygen is sufficiently large for a two-step cycle with a temperature difference of 800^0 between low temperature and high temperature reactions. Thus the concept seems attractive for a sulfate with the appropriate ΔH^0_f . However, it should be emphasized that equations 11 and 12 do not represent thermochemical equilibrium for sulfite systems. For equilibrium at low temperature, the sulfite should undergo one of the following reactions,

14. $MO + SO_2 \rightarrow 0.75 MSO_4 + 0.25 MS$
15. $MO + 1.5 SO_2 \rightarrow MSO_4 + 0.5 S$

depending on the relative stability of oxide versus sulfide and on the temperature as well as the SO_2 pressure. In our program, we attempted to carry out reactions represented by equations 14 and 15 with partial success in only a few cases. For most systems, however, sulfites form in accordance with equation 11 and simply decompose when the temperature is elevated. Consequently, we were encouraged to test reactions represented by equation 12 for hydrogen production. We were aware that hydrogen, if formed, could reduce the sulfite reactant according to the equation:

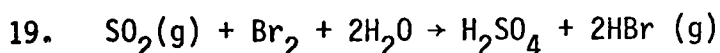
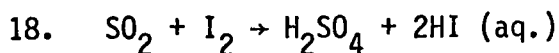
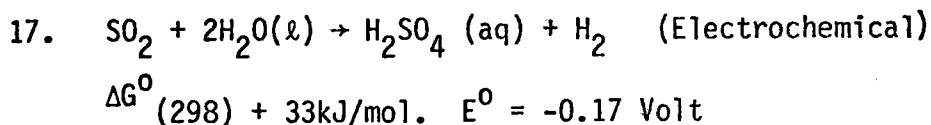


However, this seems to be a relatively complex, multi-step reaction and we assumed it might not occur. It should be noted that the difference in stability between solid sulfite and solid sulfate is sufficiently large for reaction 12 only for the most stable sulfates ($CaSO_4$, $BaSO_4$ -----). However, where the free

energy of solution of the sulfate is more negative than that of the sulfite, reactions to form aqueous sulfates might be expected.

We have attempted to promote reaction 12 in many different sulfate systems representing a wide range of stability. Our results have never included significant hydrogen yields.

In a parallel program, we also studied cycles based on the formation and decomposition of sulfuric acid. These studies will not be described here. It is relevant to note that three different sulfuric acid systems have been incorporated into closed-circuit systems on a laboratory model scale. The formation reactions may be described by the following equations.

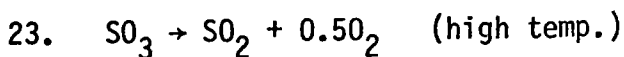
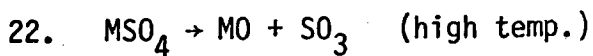
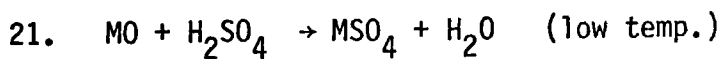
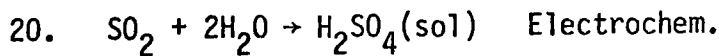


A cycle based on reaction 17 is under development by the Westinghouse Co. (ref. 8). The General Atomic Co. "Prime" cycle is based on reaction 18 (ref. 9). The Euratom Laboratory at Ispra, Italy is developing a hybrid cycle involving an electrolysis step for the decomposition of the HBr produced in reaction 19. (ref. 10). All of the cycles include relatively inefficient methods for achieving hydrogen evolution. They all involve the formation of sulfuric acid solutions (rather than $\text{H}_2\text{SO}_4(\ell)$) and require solution drying operations.

The overall decomposition of $\text{H}_2\text{SO}_4(\ell)$ includes an evaporation step to form $\text{H}_2\text{SO}_4(\text{g})$, a decomposition step to form $\text{H}_2\text{O}(\text{g})$ and $\text{SO}_3(\text{g})$ and the decomposition of $\text{SO}_3(\text{g})$ to form $\text{SO}_2(\text{g})$ and $0.5 \text{ O}_2(\text{g})$. Since the homogeneous decomposition reactions occur over significant ranges of temperature, the overall process requires heat over a wide temperature range. Therefore, it is compatible with the heat delivery characteristics of high-temperature, gas-cooled reactors. Indeed, the processes have been developed for this type of heat source. However, it should be apparent that if sulfuric acid systems are coupled to solar heat sources, the advantages of such heat sources (higher temperature and efficient heat delivery to isothermal processes near maximum temperature) will be compromised.

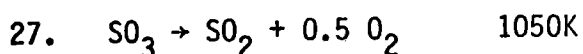
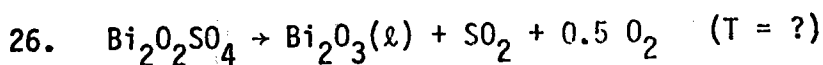
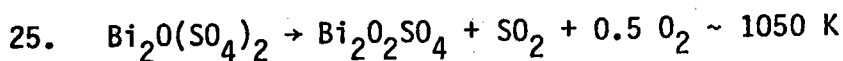
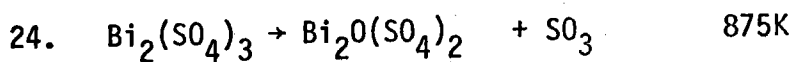
Hybrid Sulfuric Acid-Metal Sulfate Cycles

If sulfuric acid, formed by any of the reactions given above, is reacted with a metal oxide to form a metal sulfate, in principle the sulfuric acid concentration step can be eliminated and corrosion problems can be minimized since the sulfuric acid vaporization step is avoided and the final decomposition involves only the solid and dry gases. The application of the concept to the hybrid sulfuric acid system is described by the following equations.



For highest efficiencies, the metal sulfate should be insoluble, should not form a hydrate and should not require excessive heat for its decomposition (i.e., should decompose near the SO_3 decomposition temperature). Since the overall decomposition would be essentially an isothermal step, it would not interface well with an HTGR heat source, but could interface with heat from the blanket of a Fusion Reactor and, of course, would be suitable for a solar heat source.

One potential solid sulfate system being studied at LASL involves the formation and decomposition of bismuth oxysulfate. The overall decomposition of bismuth sulfate can be described as follows:



The temperatures listed for reactions 24 and 25 are for total dissociation pressures of about one atmosphere. The temperature listed for reaction 27 is the computed temperature for $\Delta G^0 = 0$. In an actual system, somewhat higher temperatures will be used. Our current concept involves the formation of $\text{Bi}_2\text{O}(\text{SO}_4)_2$ from $\text{Bi}_2\text{O}_2\text{SO}_4$ and dilute sulfuric acid (0.5 molar) and the decomposition of $\text{Bi}_2\text{O}(\text{SO}_4)_2$ as the high-temperature isothermal step. In principle, the low concentration required for the sulfuric acid should permit a lower voltage for the electrochemical step. However, this has not yet been demonstrated. The advantage of eliminating the sulfuric-acid drying step is somewhat minimized by the fact that solution adsorbed on the $\text{Bi}_2\text{O}(\text{SO}_4)_2$ precipitate must be removed in a drying step before the high temperature decomposition. Nevertheless, solid sulfate cycles, rather than sulfuric acid cycles, appear to be advantageous for interfacing with solar heat sources.

Characteristics of other solid sulfates are being studied and it seems probable that a cycle better than the bismuth sulfate system can be developed.

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A SUMMARY OF
EPRI/BOEING SOLAR RECEIVER TESTS
AT CRTF

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J. R. Gintz

Boeing Engineering and Construction Company

The EPRI/Boeing Bench Model Solar Receiver, shown with the back removed on Figure 1, was designed for tests in the Central Receiver Test Facility at Sandia Labs, Albuquerque, New Mexico. Figure 2 indicates pictorially the instrumentation and control systems on each of the eight (8) panels. Solar tests were conducted at CRTF during late 1978 and through March of 1979. The test site activities during this period are shown in Figure 3. During this time the receiver was routinely operated at solar power inputs of one megawatt and air outlet temperatures of 816°C. The main goals of the testing program have been realized. These were:

- o Verify design of gas-in-tube heat exchangers;
- o Operate "Inconel 617" heat exchangers at more than 930°C;
- o Verify automatic gas outlet temperature control;
- o Verify reflective re-distribution of solar input;
- o Verify analysis of radiant thermal and solar heat losses;
- o Obtain operating experience with central receiver solar thermal system.

A series of checkout (CO) and system verification tests (SV) were jointly planned and conducted by the CRTF operations staff and BEC test personnel. These tests provided an opportunity to: a) check out the experiment controls and instrumentation; b) conduct facility checkout and calibration, and; c) resolve all data system and operational interface problems prior to initiation of high temperature tests. The test conditions and general objectives are shown in Table 1. The heliostat targeting testing (SV-2 through SV-4) were conducted utilizing the Real Time Aperture Flux measuring device (RTAF) supported by additional calorimeter data from a cross mounted in the aperture plane. This data permitted development of the necessary

transfer functions to be applied to RTAF data during the regular test runs.

Several test series were conducted to measure controlled parametric data to permit assessment of the thermal performance characteristics of the receiver. In addition, several "demonstration" test series were done to determine operational flexibility of gas cooled solar receivers. The general objectives and test conditions for those tests are summarized in Table 2.

Unexpected results of the test program were:

- o Receiver hot wall insulation designed for 450 suns deteriorated at much lower flux, failed at less than design flux;
- o Convective heat transfer is significant, even in this one megawatt receiver.

The job of analyzing BMSR test results is just beginning. While not conclusive, a free convection mechanism, sketchily derived by observations of tests and a bare minimum of in-cavity air flow data, can be postulated which resolves the only major differences between pre-test analyses and results.

The BMSR utilizes a solar reflective cavity design to redistribute the highly non-symmetrical solar input from the "North Quadrant" collector field at CRTF. Upon entering the receiver aperture, all the solar flux is first incident on a bare insulation wall. This is the conical back portion of the receiver on Figure 2. It is all reflected or reradiated diffusely from this wall before heating the heat exchangers. Two important design goals are accomplished by this reflective/reradiative design.

- o Incident solar heat flux is reduced from about 400 suns at the back wall to about 150 suns at the heat exchangers. This allows use of the metal gas-in-tube heat exchangers at gas temperatures up to 816°C.
- o Insertion of a diffuse radiant mechanism in the solar heating process results in the heat exchangers being nearly equally heated in spite of large variations in the spatial distribution of receiver solar input with time of day.

Tests confirmed the accomplishment of these design goals. The receiver was operated at equal solar input to compare its individual panel heat loads with "uniform" and "east side only" heliostat field configurations. These tests showed that heat loads on individual heat exchangers were not significantly changed by these large changes in solar input distributions. Nevertheless, the heat loads on the eight heat exchangers in the receiver were significantly and unexpectedly different from one another. Intentional changes in the solar input distribution from the heliostat field did not significantly alter this distribution of heat loads.

Compared with pre-test thermal analysis, the experimental data show:

- o Reduced load on lower heat exchangers (4, 5, 6);
- o Increased load on upper heat exchangers (8, 1, 2);
- o An unexpected additional receiver heat loss of about 65 kW, at 950 kW solar input.

These differences are tentatively attributed to a very significant free convection mechanism at work in the cavity.

The authors wish to acknowledge the significant contribution made by the entire CRTF staff to the success of this program. Their personal dedication and technical competence made the start up of a complex new facility go relatively smoothly. In addition, their advice and assistance in the startup and checkout of the experiment instrumentation and control system were invaluable.

TABLE 1: CHECKOUT AND SYSTEM VERIFICATION

TEST	SOLAR INPUT (KW)	OUTLET TEMP. (°F)	FEATURES
CO-1	-0-	AMBIENT	CHECKOUT DAS AND BMSR CONTROLS
CO-2	-0-	AMBIENT	CHECKOUT RTAF
SV-1 (3)	-0- 30 TO 600	AMBIENT	VERIFY AIR FLOW AND CONTROLS
SV-2 (4)		UP TO 700	SINGLE HELIOSTAT TARGETING
SV-3 (9)			TARGETING GROUPS OF HELIOSTATS
SV-4 (18)			

() Indicates no. of runs during test sequence

TABLE 2: SUMMARY OF SOLAR TESTS

TEST	SOLAR INPUT (KW)	OUTLET TEMP. (°F)	FEATURES
EB-1	650	1150	HEAT BALANCE AT QUASI-EQUILIBRIUM CONDITIONS
EB-2	640	1300	
EB-3	710	1490	
EB-4 (3)	620 TO 700	1155	
EB-5	800	1300	
EB-6	840	1500	
EB-7 (2)	830 TO 980	1147	
EB-8 (3)	910 TO 1030	1298	
EB-9 (3)	970 TO 1100	1500	
NI-1	775	1140	TRANSITION FROM UNIFORM INPUT TO EAST SIDE HELIOSTATS ONLY
NI-2	840	1280	
TH-2	1050	1300	SOLAR INPUT TRANSIENTS
TH-4	1000	1480	
RF-2	830	1300	RESTRICTED FLOW THROUGH PANEL NO. 3, OBSERVE EFFECTS
RF-3	1000	1480	
CS-2 AND 3	1000	1300 & 1500	SIMULATED PILOT PLANT STARTUPS AND SHUTDOWNS
EC-1,2,3	750 TO 1000	1150 TO 1500	
SF-2	950 TO 1100	1480	FULL DAY SOLAR LOAD FOLLOWING

() Indicates repeats of test

Figure 1. BMSR During Functional Test

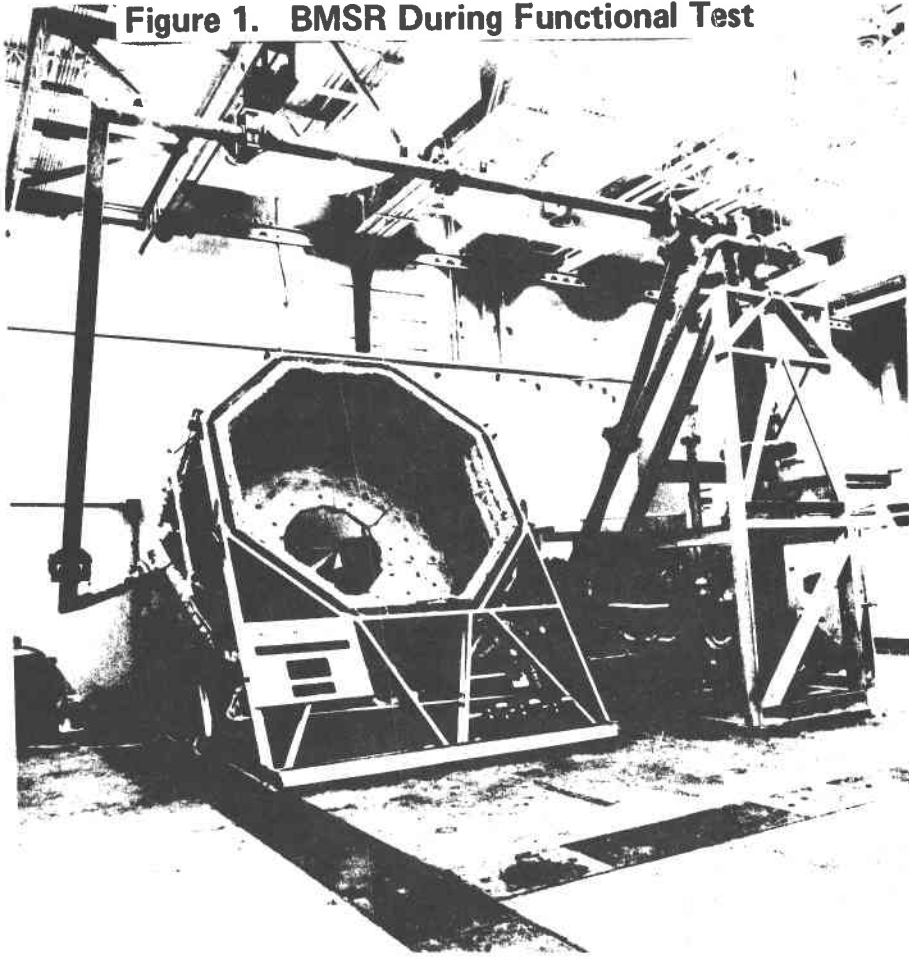


Figure 2. BMSR Instrumentation Schematic

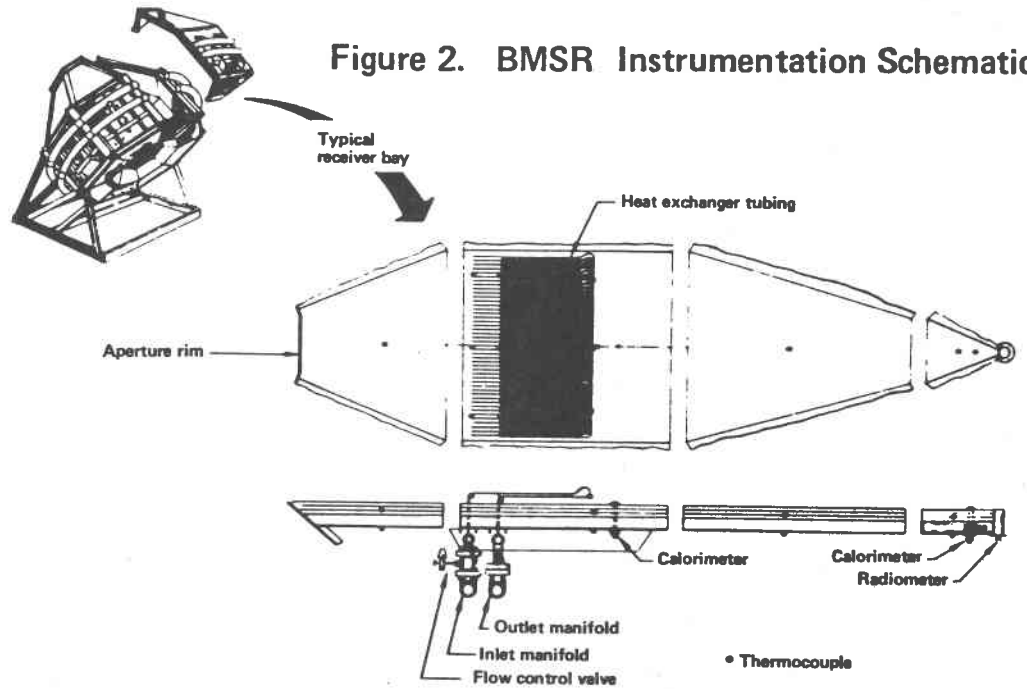


Figure 3. Test Site Activities—Solar Testing Calendar

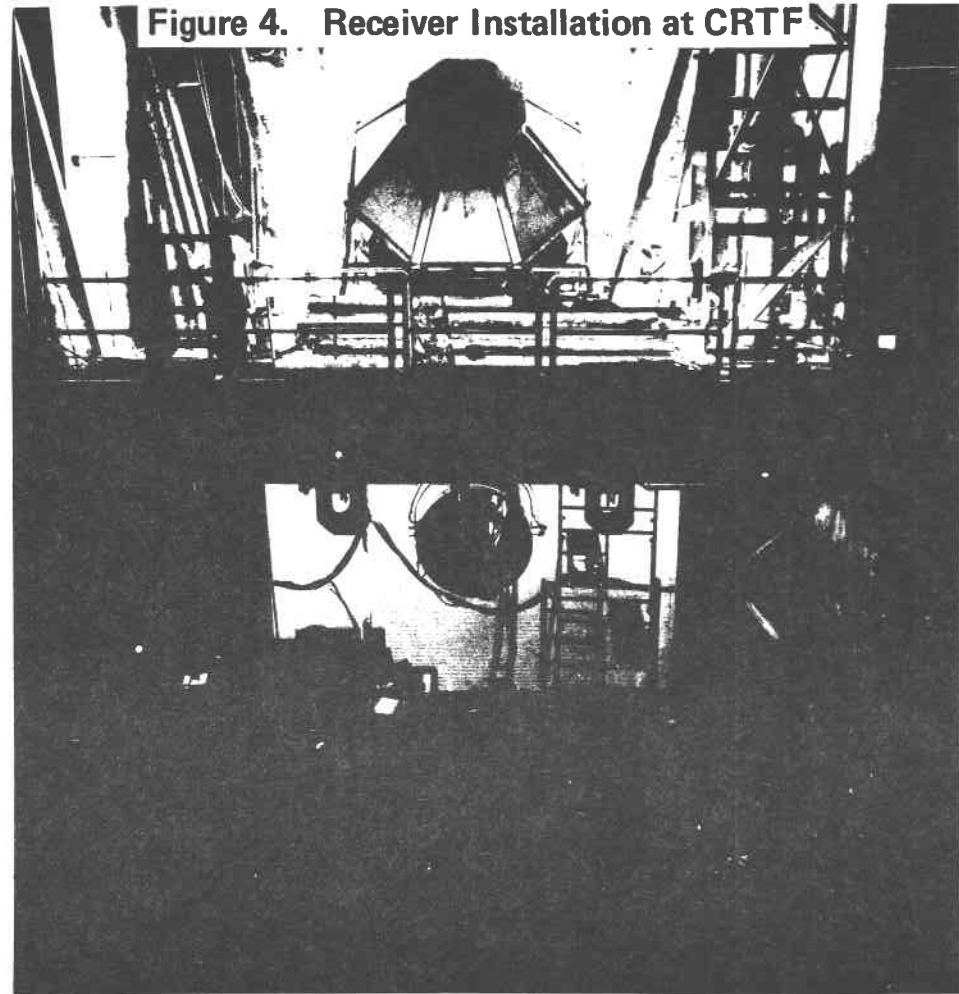
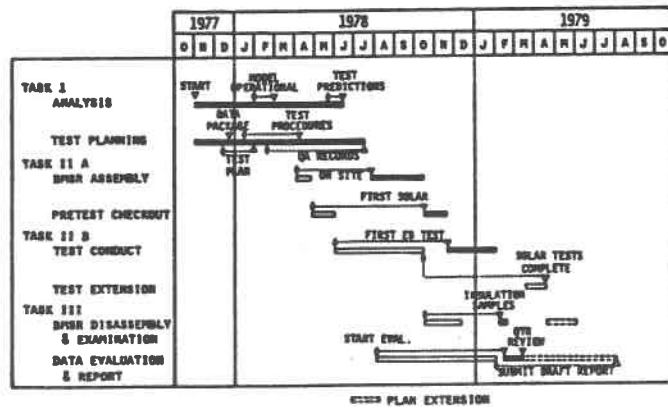


Figure 4. Receiver Installation at CRTF

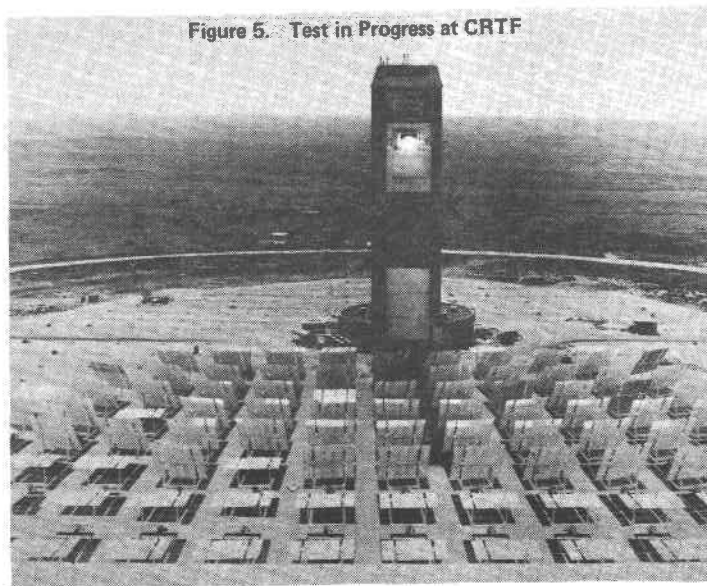


Figure 5. Test in Progress at CRTF

ONE-QUARTER MW_t AIR CYCLE RECEIVER

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INTRODUCTION

Sanders has recently tested a 1/4MW_t Air Cycle Solar Receiver at the Georgia Institute of Technology, Advanced Components Test Facility. The receiver was designed to deliver air at 2000^oF. The receiver operates at ambient pressure and does not require a window to seal the aperture. By using a novel ceramic matrix for solar energy absorption and heat transfer, the receiver can provide high efficiency solar energy collection with very low pressure drops. An additional feature is a compliant ceramic support system which minimizes the thermal stresses.

Design Objective

Before beginning the receiver tests, the flux distribution near the focal zone was mapped by G.I.T. personnel. As part of the test series, additional measurements were made using both the G.I.T. flux scanner and a flux scanner built by Sanders to map the flux distribution on the receiver surfaces. The flux scans indicated a mirror aiming and tracking error, $\sigma = 11.8\text{mr}$ for the facility. Sigma has a large impact on the amount of energy which can be directed into a receiver. The Sanders receiver is designed for a field pointing dispersion of $\sigma = 6.6$ milliradians. The receiver aperture diameter has been reduced to 20 inches by using a terminal concentrator to redirect the outer rays into the aperture. The increase in σ from 6.6mr to 11.8mr results in a reduction in the solar energy, which can be directed into the receiver, from 316KW to 190KW.

Test Results

Based on this evaluation of the facility a limited test plan aimed at providing a shakedown of both the Sanders receiver and the G.I.T. facility was followed. The objectives of the revised test plan were:

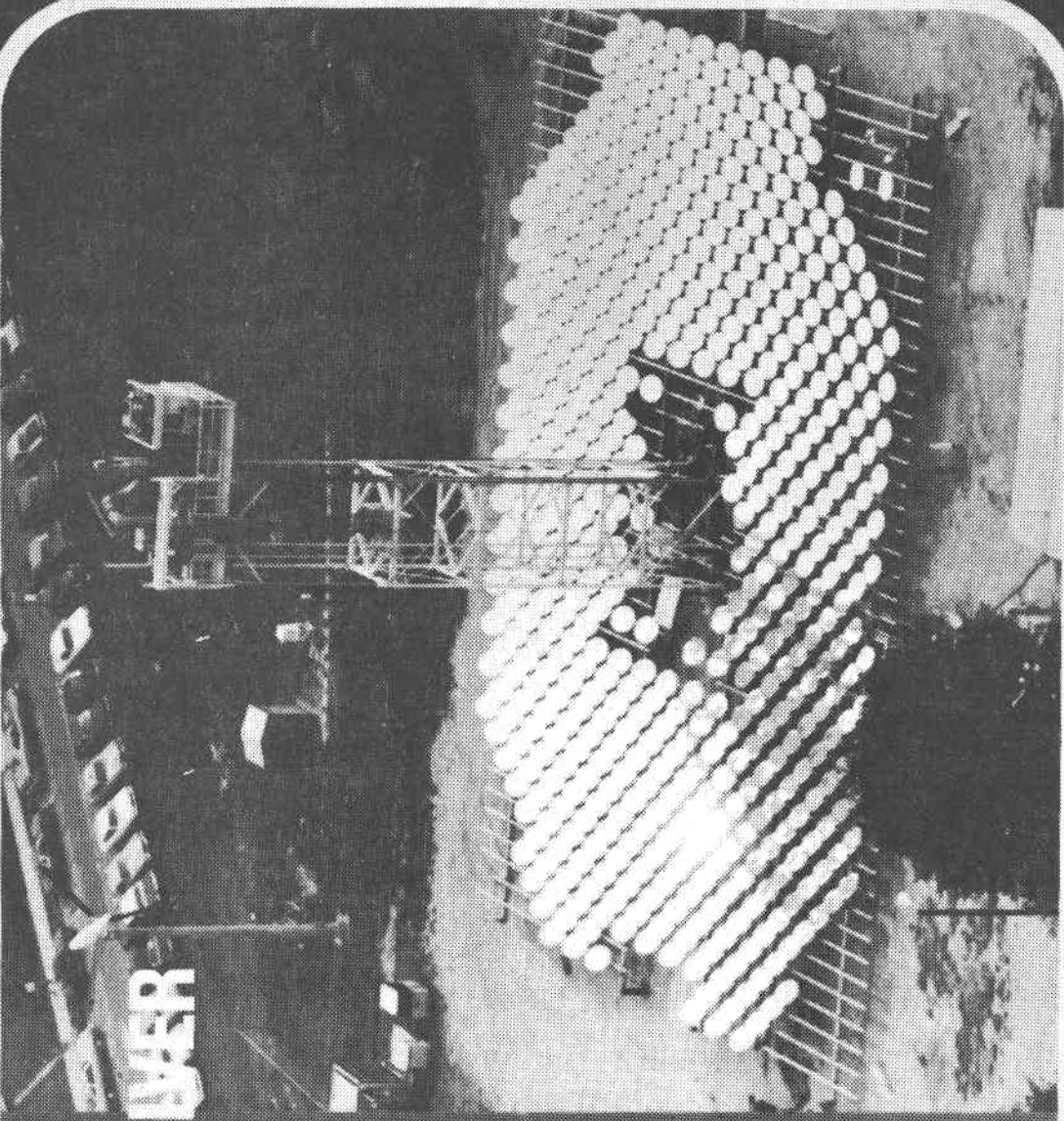
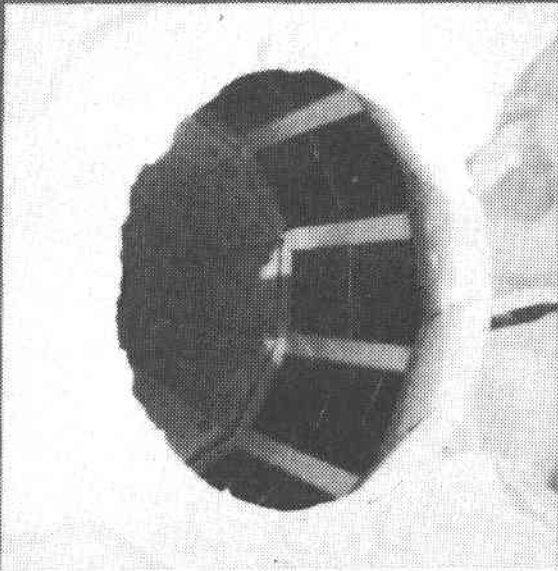
1. Operate at reduced flow to obtain design temperature.
2. Operate at design mass flow. Determine operating temperature and power delivered to the airstream.
3. Make a measurement of the convective losses.

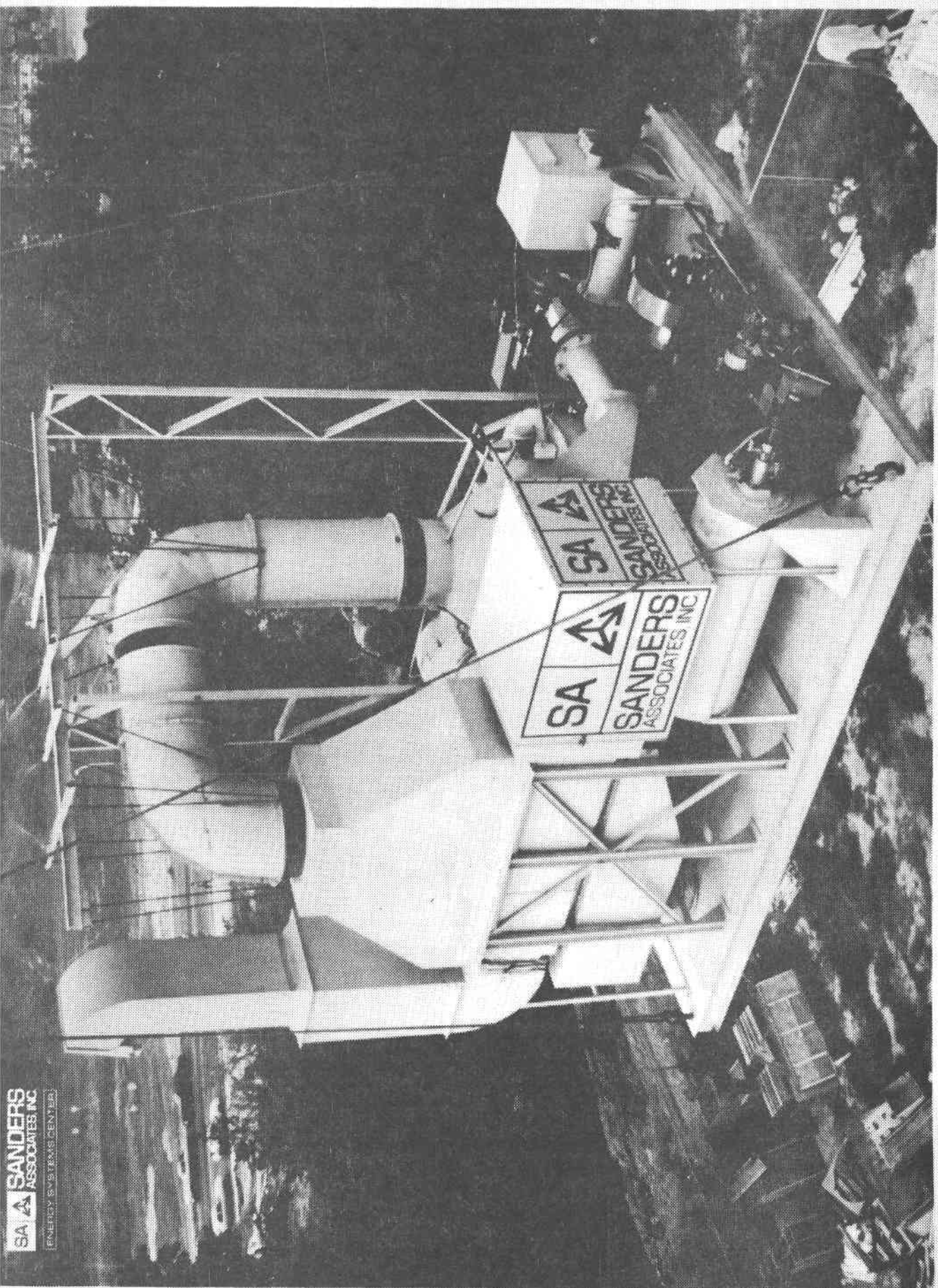
Now that the objectives of the revised test plan have been accomplished, the receiver will be stored while modifications are made to the solar facility to bring the sigma up to the design value - 6.6mr. At that time the receiver will be tested at full power to measure its efficiency and the response to the high flux values.

The objectives of the first test series have been successfully accomplished:

1. Output air temperatures of 1955⁰F were maintained with honeycomb temperatures of ~2200⁰F for reduced flow with an average insolation of ~900 w/M². No visible changes in the receiver interior were noticeable after thermal cycling.
2. Output air temperatures of ~1530⁰F were obtained for design mass flow with approximately 100KW delivered to the air. Insolation for this test was ~805 w/M².
3. Several hot convective loss runs were conducted using excess nitrogen as the trace gas and oxygen concentration as the measured variable. Maximum wind velocities of 8 fps produced heat loss determinations, that confirmed the Wolfeboro Railroad test, i.e., ~1/2% of design thermal input.

SOLAR RECEIVER





SA SANDERS ASSOCIATES, INC
ENERGY SYSTEMS CENTER

SUMMARY OF PANEL DISCUSSIONS

Chairman: Frank Smith

SMITH: Gentlemen, next we'll have a 10-minute report of each panel chairman and a then a 10-minute discussion period.

Central Receivers - John L. Russell

RUSSELL (Georgia Tech): The members of our panel were Aden and Marjorie Meinel, Jim Schreyer, Bill Thayer, Jeff Smith, Claude Royere, Ted Nussdorfer, John Gintz, Phil Jarvinen and myself.

The subjects we covered were the various technical aspects of building the receiver at the middle of the collector field or at the focal point of the concentrated light, windows, secondary concentrators, and insulating materials.

Several points came up on the window discussion. One is that aerodynamic windows, if they are going to support an atmosphere of pressure, require supersonic velocity with layers of air an inch or so thick and won't work for holes more than a foot in diameter. Quartz windows seem to work fairly well where they've been used. The technology for making very large quartz windows seems to be moving along. They are planning to build a 400-inch telescope in much the same way as making a window, by spreading a boule of quartz to about 400 inches, which would be a good sized window. However, the cost would be about a million dollars. In addition, a window has to be actively cooled and kept clean. If rotary kilns are used, they tend to splatter and if enough material splatters on the inside of the window, it doesn't work well. If a fluidized bed or some kind of column of material is being heated from the side, one big worry is that the inside of the mirror will be abraded and its optical transmission affected. It was pointed out that laser experience with similar geometry heating corrosive gasses frosts the inside of the quartz tube but does not seem to influence the transmission enough to measure. Maybe that problem is not as insurmountable as it seems. The problem of seals was also raised, but seemed to have engineering solutions. If the window can be kept below about 400°, a heat mirror can be considered; something that transmits 85% of the light but reflects 70% of the IR from a 1000°C blackbody. This sort of work is being done at MIT. If a receiver can be designed so the temperature is increasing as the light goes into the system, some low-temperature heat can be utilized. Then the radiated heat is not necessarily lost but merely absorbed in colder systems and utilized. The Francia receiver at Georgia Tech utilizes that principle. General Electric infrared transmitting quartz would probably have to be used because if ordinary UV grade quartz is used, it solarizes. It contains OH and at high temperatures it tends to cloud the surface.

Our panel concluded that secondary concentrators are of marginal value in general, but, in specific cases, might be worth from several percent to as much as a factor of two in concentration. This is, Winston-type concentrators or beam trimmers, terminal concentrators, etc.

A lot of discussion went into insulation materials, particularly regarding the problem of spreading the beam inside a cavity or stopping or trimming the beam before it goes into the cavity. For instance, the Boeing beam shuffler, or light spreader, in the back where the insulation fell off, may be a general problem because of the cycling and the very high temperatures of exposure to the atmosphere.

The general conclusion was that, considering things like aluminum oxides, zirconium oxides, sintered silica bricks, etc., high-temperature insulation will be a high maintenance item for a long-lived facility and requires some consideration. Of course, the reason is because of trying to avoid the extreme thermal stress that involves heat exchanges when more light is put on one side than the other.

Finally, the Meinels brought up the question of applicability of intermediate- and small-sized facilities. It was pointed out by the French representative that the philosophy in France is to have 1-kW, 50-kW and 1-MW facilities because it's too far from 1 kW to 1 MW. They are all used to doing more individual experiments on smaller facilities before working up to significant experiments on big facilities. We can perhaps learn from that.

SMITH: I would like Tom Brown to tell us about what I believe is the only vertical-axis solar facility available in the US today.

BROWN: We do have on the Georgia Tech campus a vertical-axis searchlight facility. We also have a horizontal-axis facility. It is outside on the south wall of about a three- or four-story building at about the three-story level, overhanging a window.

We also have another searchlight similar to this, a 60-inch version which is not nearly as sophisticated as the CNRS facility but does provide approximately 1-kW downward-concentrated beam similar to some of Coutures' furnaces. If anyone is interested in using it, I can put him in touch with the fellow who manages the facility.

ROYERE: I think our lab at Odeillo would agree to give any information needed to anyone who would like to build such a facility. We have already given such information to Germany. We have been building this kind of facility for 30 years and have the information available.

BROWN: As Claude has just said, this particular heliostat and the support structure is essentially a carbon copy of the type of heliostat they have at Odeillo, and we're grateful to be able to transfer that kind of information.

High-Temperature Chemical Processes - Paul Gilles

GILLES (University of Kansas): Jean-Pierre Coutures was the chairman, and Bob Skaggs helped considerably in the reporting. The facility operator was Richard Hays.

Jean-Pierre Coutures began by describing the advantages of solar heating for high-temperature chemical purposes. We need not have a crucible and so we need not introduce any foreign material. Any atmosphere, particularly oxygen, is appropriate. No other electric or magnetic field is involved. On-line gas analysis is relatively easy to accomplish and mass spectrometry can be used relatively easily.

But there are problems. First, the matter of measuring temperature, and there are four sub-problems: 1) the reflection from the surface of the sample; 2) the emissivity of the sample; 3) dust which may get in the way, and 4) vapor that arises from the sample which may coat the window. Coating of the window not only disturbs the temperature measurement but also cuts down the flux the sample receives.

The second major problem is the homogeneity in the temperature across the sample. Thermal shock can be a problem in some circumstances. Gases may corrode part of the equipment and, finally, the matter of temperature control is a source of concern. Some of these problems have solutions; some do not.

Here are those that have solutions. How can the reflectivity of the sample be handled in order to make a good temperature measurement? Suggestion is that one work in the infrared region of the spectrum where sunlight does not arrive at the sample, which is the so-called solar blind reading. Infrared pyrometers are available and are used.

Emissivity is more of a problem. There are two ways of handling the unknown emissivity of a sample. One or both involve, in effect, measuring emissivity. The first one is a new scheme being developed by Jean-Pierre Coutures. The hope in France is that a two-color infrared optical pyrometer can be built. The design is in concept. All that is lacking is the money, and a proposal has been submitted to the appropriate French authority for an amount that will enable them to do it in an appropriate time span. The second way is a scheme that has been proposed by Jean-Pierre and others involving four or five independent measurements for establishing four or five unknowns. That endeavor involves using a laser and the sun separately and together in the visible region with an ordinary optical pyrometer.

Another way of measuring temperature is to use a thermocouple. But if one does, he must be very careful. We had a textbook discussion on some of the problems associated with thermocouples. Temperature homogeneity is a serious problem and the best suggestion we heard from Jean-Pierre was that one can work out of a focal plane. Thermal shock can be mitigated somewhat if the heating is accomplished slowly.

As far as temperature control is concerned, one can use attenuators and one can alter the position of the sample to some extent, but it could obscure the sun. Maintaining a constant temperature will always be a problem. One question then discussed was: How important is temperature control? The conclusion reached was that it depends solely on the experiment. For chemical production, temperature control normally is much less important than it would be for the study of thermodynamic or kinetic properties.

We then had a discussion of crucible materials, such as graphite, that might be used for high-temperature chemical purposes. We also had a discussion about quartz and Pyrex windows, but did not raise the matter of OH quartz.

Several people then presented their projects. I talked about the thermodynamics of metal-rich oxygen alloys. Bob Skaggs talked about processing MoS_2 in the future at White Sands. Tom Whaley talked about a possible use of solar energy in the production of zinc oxide from scrapped dye casts for use in tests. Duncan talked about a plan to get calcium carbide from calcium oxide. And Clements talked about heat transfer and flux measurements.

Coutures' closing comments were that many preliminary experiments could be done in ordinary laboratory ovens and we should, before we move to a solar facility, consider the possibility of doing initial experiments at home. His second comment was that the US needs laboratory-sized solar furnaces.

Chemical Transmission Panel - Al Hildebrandt and Talbot Chubb

CHUBB (Naval Research Lab): The Chemical Conversion and Transmission group began by raising the question of future test and general development plans. We started with Peter Carden's work in ammonia, which is certainly the program that is furthest along. He said their next objective is to build a complete full loop, including dissociator and synthesizer, working in the lab at a level of about 5 kW using electrical heat. Their receiver work is going on in parallel but the emphasis is not on interfacing the ammonia dissociation with the receiver at this time.

In addition, they have an analytical program, which is directed toward designing and showing the feasibility and competitiveness of building a power system that would provide 10 MW of electricity to a remote Australian community. This program is trying to show that the thermochemical ammonia process is economically competitive with other possible methods of providing power. The system is designed to be a hybrid in which solar would provide the power during the daytime and other systems would provide the power during the nighttime. The viability of the ammonia effort in Australia is really dependent upon some evidence that there is a reasonable probability that the thermochemical system will be competitive. The studies which have been done so far indicate that there won't be any difficulty in demonstrating that.

The other part of the hybrid system would be fairly sophisticated, using the waste heat from a diesel engine to generate steam or, alternatively, a small steam turbine system. What they have to compete against is use of other relatively efficient small systems being used for total power for the community.

There were questions raised about temperature cycling of chemical systems. In general, industrial systems like gas reforming, cycle infrequently. It is recognized that diurnal or more frequent temperature cycling in solar thermal receivers needs to be investigated. There is a general feeling that the problems can be overcome. One worries about powdering of the catalyst due to expansion and contraction which cracks catalytic drains as in a vise. In some systems where nickel is used, and in steam methane for example, one worries about carbonyl formation.

Another discussion involved whether there are any other systems people are interested in or working on the ammonia concept. Peter Carden said he is going to visit Germany where Hans Teigers is investigating the possibilities of ammonia as one of the thermochemical cycles.

Lloyd Wartes, who is involved in manufacturing gypsum board in Wyoming is faced with very serious problems due to the increased price of natural gas. The very economic existence of this technology is really threatened by the rising price of fuel, and he was asking us whether help would be provided in this area. In their case, the need is for different heats in different parts of the 600-foot long kilns, higher in the front and lower in the back, and it's a 24-hour-a-day operation.

This led to a discussion of a moderate-temperature thermochemical system that Terry Lenz has been examining theoretically. This is a pure liquid system based upon Diels-Alder chemistry. Terry feels the chemistry is particularly clean because there is not much likelihood of side reactions. Also, it has good heat-of-reaction per gram of molecular weight with large enough value in change of enthalpy so that there's not too much difference between where you do the dissociation and the recombination. Although this is a liquid-liquid system, it still uses a catalyst on a solid substrate to promote the chemical reaction both at the endothermic high temperature and exothermic, low-temperature, ends of the system. It does have the possibility of fairly efficient volumetric storage. In general, for higher temperature systems in the relatively near-term, Lenz, Carden, Hildebrandt and I agree that early applications in this reversible chemical cycle approach are largely in the conversion and transport area. The emphasis should not be on storage at this time.

We discussed interactions between the facility operators and users and decided that users and operators really need to communicate at an early stage to tell the potential users to state what they need and to ask the operators if they can provide what is needed. In many cases they can because some of the facilities are part of a much larger group where equipment is available. Some may not be directly tied to the facility but can be borrowed to support a particular experiment. Advice to users planning to install equipment in the control area is that they go to the facilities early to see what space is available, and how their control equipment might be configured so it would fit into that space. In their own lab they should configure their control equipment for planned tests in the same general form as the facility so they will be familiar with it before it goes into the solar facility.

Again, talking to the people who are interested in developing thermochemical receivers, Terry Lenz is going to do electrical testing in the lab for his ammonia system. The flexibility of electrical testing permits easy cycling and efficient use of his people. However, he is still directed toward solar testing and most likely his first test will be done on the Omnium G receiver at SERI. Al Hildebrandt has aspirations about doing a receiver design and lab testing with Richardson at Houston. Very likely not too far down stream, they will do some tests on their Omnium G system although the Omnium G at Houston is currently being used in the generation of steam.

Regarding our (NRL) interest in SO_3 , CO_2 , and methane in conjunction with New Mexico State University, we are again talking about doing a lab test program with electrical heating, leading to demonstration testing at the White

Sands Solar Furnace as early as possible. In general, it was pointed out there really are three types of testing in the development of these systems: 1) simple testing in a laboratory furnace, frequently with a straight tube in a furnace where the heat flow is fairly symmetrical; 2) electrical testing, where heat is applied to the receiver to test the asymmetric heat transfer in the receiver when it is used as a cavity receiver on a solar furnace; and last, solar furnace testing.

I think, in general, the small group discussions were very helpful in benefiting communications between different people who approach their particular thermochemical problem from different reference points. For example, there is the work in ammonia which is very high pressure and involves incomplete conversion of synthesis, and a separation system where liquid ammonia is removed and the gasses which have not been synthesized are recycled through the synthesizer. This recirculation of the gasses through the synthesizer is basically nothing but recirculation. It doesn't really involve any significant gas compression or any significant energy use. Also, thinking in terms of the temperature at which heat is delivered by the synthesizers, the Carden approach is to build the synthesizer and a thermo-type of arrangement where some heat can be produced at quite high temperatures on top of the synthesizer, and the last of the heat at relatively low temperatures at the bottom of the synthesizer. This thermo-type of property is used in heating, and the super-heating steam is used for other purposes. It was an interesting concept with which some of us had not been very familiar.

Another Carden concept is the use of relatively low temperature steam as part of the total energy usage of the system. The ammonia, which is condensed and fed out as a liquid to the distributed receivers, is used as a source of 100-200°C steam.

These recirculation systems do involve increased heat exchanger problems as compared to a system in which all the synthesis is done in serial steps. It is not a big problem; the heat exchanger has to be only three times or so larger than if it were a one-step situation.

Another conclusion of our discussion was that there is a difference in designing receivers for small systems because of the difference in area-to-volume ratios and maybe there should be receiver studies done now on both large and small thermochemical receivers.

COMMENT: You mentioned that you and Hildebrandt and others agreed that these thermochemical reactions are more useful right now to transmit energy than to store it. I think storage is as important as transmitting the energy, if not more so.

CHUBB: In long-term storage, the thermochemical systems are really going to come into their own. In short-term storage, they do have to compete against sensible heat and phase-tanks storage systems. I think there have been some studies that indicated that short-term chemical storage systems did not really have much of an advantage.

COMMENT: I have the feeling that the systems you described, like sensible heat and so on, don't reach very high temperatures, while a chemical reaction would. Is that correct?

COMMENT: The chemical reaction might reach a high temperature, but the end-use is at a lower temperature. For instance, the ammonia, methane, water, methane - CO₂ and SO₃ all may require relatively high temperature inputs but their output is at maybe 450° or 500°C.

COMMENT: The storage economics were dominated by the short-term diurnal and two- or three-day storm-type losses.

COMMENT: It seems there could be higher energy temperature storage with sensible heat with some chemicals. Why wouldn't chemicals compete in all of them?

COMMENT: For a chemical system typically, power-related costs are higher while the energy-related costs are lower. So the value of a chemical system is in storing energy for longer periods of time. But for shorter periods the high power-related cost makes it simply noncompetitive with thermal, sensible, or latent heat storage.

HILDEBRANDT: Lenz mentioned the liquid-liquid system, that is, the catalytic system that would have a higher energy density storage. That's an attractive one but in the talking stages only.

The AHS system that Wentworth has been working on is a bit downstream. Sandia Livermore puts it in their general program downstream and I don't know that they will continue it, because the storage system they want requires very high efficiency in the conversion cycle and low cost for the chemical apparatus on top of the tower. Some of the systems are fairly complicated that get away from the catalytic system; the cost on the tower is also rather complicated. The efficiency of some of those chemical cycles, if you really go to storing a liquid, tends to drop as you go through the entire operation.

I believe in the long-term that a liquid-liquid system or a liquid storage is going to be very attractive. But at this time I believe sensible heat storage probably would be better for short-term.

COMMENT: Carden pointed out that over the longer period of time, the storage of high-pressure gasses which come out of, say, the ammonia system, do lend themselves to storage in natural reservoirs in the ground at, 3,000-6,000 feet where ammonia or natural gas is stored. That will in time become an important aspect of the situation. It's a way off because the capital cost of building the chemical system to provide a very high-powered output is not competitive right away with the sensible and latent systems. I think that's a bonus we're going to get. But maybe we're not going to get it until we at least complete the conversion transport aspects.

SMITH: Did you touch very much on the interface problem between facilities and users in getting experiments designed and run?

CHUBB: The biggest interface problem is getting communications started at an early enough stage so people could work out their problems.

Hydrogen, Pyrolysis, and Coal Gasification - Melvin Bowman

BOWMAN (Los Alamos Scientific Lab): We gave each panel member the opportunity to talk about an experiment he might like to do and the problems he would have in doing it, whether he planned to submit a proposal or not, in the areas of pyrolysis, coal gasification and hydrogen production. There were some experiments they would like to do that also relate to central receiver design.

The overriding similarity for most of the proposals was the desire to put solar heat into solids for rapid heating, for pyrolysis of both coal and biomass, for high-temperature (essentially isothermal) decompositions of solids, for thermochemical hydrogen processes and, of course, to put solar heat directly into solids for the reactions between the solids and the gasses that go into coal gasification processes. Most people feel that the advantages of solar energy for these uses relates to the fact that very rapid heating excursions are possible for the pyrolysis steps, that higher temperatures are directly available for the high-temperature decomposition steps, and that heat can be transferred directly to solids rather than through a heat exchanger or through a circulating gas. I think these are valid expectations.

In addition to the experiments that are in the area of heat into solids, there is the problem of windows. We discussed windows and I told the group that they'd never make a window work, but one day I hope they will make me eat my words so that I can use a window.

Several things were discussed regarding the design of central receiver window reactors for coal gasification. First, the transfer of heat through a ceramic heat exchanger. Second was the transfer of solar energy to a fluidized bed system in order to transfer heat to the processes. Third was a window design having heat come in horizontally, or from the side through a window, into a mesh that would contain a solid and intervening gas to keep it clear. All of these are worthy of some examination because they are going to be the key areas. The types of experiments, as I've said, are aimed at the rapid heating of particles.

The experiments themselves will require some rather sophisticated support. One would like to have on-line gas analysis for all of these processes. Also there is a need for mass spectrometry, infrared spectrometry, and very-quick-turn-around gas chromatography. There was discussion about whether facilities should have these kinds of backup equipment available. The facility operators said they cannot have the trained personnel on hand at all times to operate these types of equipment. John Holmes (Sandia CRTF) offered to explore the possibility that people could call on Sandia for support in this area because they do have these capabilities very close to the experiment. It is possible that the Users Association could list the equipment available at the facilities for potential users. Possibly some type of blanket agreement could be negotiated by the Users Association, with agreement by Sandia, so these things could be used by experimenters. At other sites, the possibility of using facilities at universities and so forth could be explored.

Small units in various laboratories would be advantageous so experiments could be well prepared for the big facilities. It was suggested that trailers could carry small furnaces to be available to different laboratories.

We also discussed at length the need for a vertical solar heat source so that a solid could be heated from above.

Steve O'Kelley said many proposals suffer from the proposers not being as specific as they should be about which facility they plan to use; what they plan to do; or the equipment and supporting activities they need. This led to some discussion about how well prepared one must be before going to a solar furnace. It was suggested that one should be able sometimes to run "Gee Whiz Experiments," to see what would happen without really having the answer in advance.

ANTAL: I'd like to amplify the question of gas analysis. Gas analysis is critical to these types of experiments and is absolutely nontrivial. The sorts of gas analysis that we do at Princeton has been the subject of articles in such journals as Analytic Chemistry. In our case, we hired an individual who had 15 years of experience in running the Cities Service Research Laboratories Gas Analysis Lab, which is a large facility. Somehow, this sort of sophistication needs to be provided to experimenters like ourselves, whether it is done by bringing our own lab to the facility, the facility maintaining a lab, or there being a contractual relationship between the facility and a local lab such as must be accomplished internally at Sandia. It is a question which needs to be examined. But there is an absolute need for sophisticated gas analysis.

Another point is simply that there is a perceived need for many more small-scale solar furnaces. There just aren't enough, as Coutures pointed out, also. Chemical experiments generally begin with grams of material in a 5-MW furnace. I think a real effort should be made to spread some small solar furnaces around to the field.

The last point I want to bring up has to do with whether there is a likelihood of photolytic effects in solid reactions using solar energy. I think the only conclusion reached was that each individual who had thought about it was sure his own conclusion was correct.

HILDEBRANDT: I'd like to raise a question about the small solar facilities. I think having the solar spectrum available can be an advantage for testing receiver materials and external components. But there are also some advantages to using an electrical system. I think Terry Lenz was talking about using an electrical infrared system to illuminate the cavity. What are the pluses and minuses of getting the chemistry experiment started using the solar facility directly?

COMMENT: I think it depends on what you're doing. In the case of ammonia, which is a new concept in itself, the critical elements within that concept are of importance, not the interface between the solar and the dissociator. That's why we chose to experiment with an electrical heater to begin with. Until the whole concept is going, there seems to be no point in developing the solar interface. With some other experiments, such as metallurgical, where the metallurgy is well known and the problem is their interface, it seems sensible to do solar experiments with the receiver. I don't think you can generalize.

ANTAL: I think you are right. We at Princeton and others I know have fabricated focusing optics and light sources that can provide relatively high fluxes. However, the solar spectrum has certain unique characteristics with which we are

all familiar, and the question of photolytic effects exists. It is important to have a solar furnace available to study them.

HILDEBRANDT: What is a good size?

COMMENT: It doesn't have to be large; I think something beyond the Omnium G.

COMMENT: A few people here got involved in receiver concepts and designs with the small furnaces product concept. One of the big questions we have is the coupling between the solar spectrum and the receiver itself. It frightens me sometimes to look at the extremely large-scale attempts, such as what we looked at yesterday, when we don't understand the small-scale phenomena yet.

HILDEBRANDT: You're talking specifically about using the solar spectrum and getting it to the size of a receiver.

COMMENT: Before building a 30-meter receiver, build a 2 x 2-inch receiver and see if some of the micro-scales work.

COMMENT: When the nuclear industry was developing, there was a perceived need for many people to have experience with nuclear reactors and there was a proliferation of reactors all over the country. Many universities have their own nuclear reactors, which are much more expensive than solar furnaces. The country needs people trained in solar furnace technology just as much as we needed the nuclear technology. I think there's a real rationale for getting some solar furnaces spread around.

COUTURES: At Odeillo we have eight vertical-axis solar furnaces. We also have two 2-meter parabolas. The focal length is 85 cm, the focal spot is 80 cm, and the flux is around 16. We have two 1.6-meter parabolas.

COMMENT: One of the nice things is the extensive laboratory space immediately accessible to the beam.

SMITH: If any of you have a science building being planned or under construction, you might want to consider a vertical solar furnace with a heliostat on the ground. I, for one, am convinced we do need some smaller facilities--especially a vertical beam one. Where, how many, and who will run them are open questions. This may be one of the items to put on the list of recommendations which we hope to prepare for SERI or DOE in order to make the most progress in this area.

Facility Operators Panel - Richard Hays

HAYS (White Sands Missile Range): Three areas were covered: instrumentation, experimenter-facility interface, and safety. I'll address the experimenter-facility interface first. It is quite evident that the experimenters and the facility people need to get together very early in the planning of their experiments. Possibly the Users Association could provide a limited amount of funding for visits to facilities or it could be included in your proposals. It

is apparent there must be a definition of experimenter and facility operator responsibilities. Georgia Tech has such a document, called a "Definition of Agreement."

The next area covered was instrumentation. Our meeting was at Sandia. Larryl Matthews discussed their real-time aperture flux system, which has worked very well. Larryl also discussed his development of the photon counter and calorimeter heat flux measuring device. It looks very promising for rapid calorimetry measurements. Our panel also discussed spectral measurements. We have done minimal work in this area, but feel it will be developing in the future. Another discussion was on deterioration of heat flow calorimeters. Experience at Sandia, Odeillo, and White Sands shows that they hold up very well. At White Sands, we send them back for calibration about every six months. That is about the time when a particular unit, like High-Cal, goes from an absorptivity of .89 to .81, which is not a great percentage change.

Another subject discussed was safety. Solar work is very dangerous to people who are unfamiliar with it, and some burn accidents have occurred. If we get several of the proposed small facilities at various locations, we need to educate those controlling and operating them so we don't have more burn accidents. We discussed a written Safe Operating Procedure. We have obtained copies of the Sandia SOP for the other operators. When we again get together to exchange information, maybe we can come up with some comments and solutions for safety problems.

WSSF and the French facility require the wearing of welders' goggles. I received a report from the Surgeon General which indicates there is some long-term eye damage from viewing highly intense solar radiation. I will pass that report on to all the operators. We must stress that experimenters not view their experiment in operation unless absolutely necessary. If so, do it in a minimal amount of time or view it remotely through a TV camera. This is very important. Sandia provides safety glasses for their visitors consisting of three layers of aluminized mylar with pipe cleaner ear pieces, which minimizes the liability problem.

COMMENT: Those of you who are thinking about designing a facility using a searchlight mirror or something similar should give serious consideration to providing a safety barrier to keep people out of the beam.

COMMENT: The facility operators should develop Standard Operating Procedures and Safety manuals, and users should have them along with the experiments manuals.

HAYS: There is no common base for determining facility operating cost. A possible solution might be to have a standard test defined and costed by each facility.

QUESTION: SERI now has a six-meter solar furnace. Are they interested in seeing that used by outside experimenters?

BIM GUPTA (SERI): The six-meter unit is an Omnium G dish. Its primary purpose at SERI is to examine its thermal, optical and electrical performances in the system. At this time, we were not setting it up as an operating facility, as some of the other facilities are, for the Users Association. As time goes

on, we are expecting to have available at SERI a new high-temperature R&D facility primarily for conducting in-house efforts at SERI. It will take some time, of course, but I can foresee that new facility becoming available for other people to utilize as an experimental facility.

QUESTION: Can you say more about the "new facility"?

GUPTA: It's not a new one. I would call it an extension of those Omnium G dishes, which mean it would have a much broader capability for performing high-temperature experiments.

QUESTION: It's not a different type of dish then, or mirrors?

GUPTA: It may be a different type of dish or it may be an extension of that to include other than the dish also. That is also something we are looking at to decide what it should include to make it a capable high-temperature R&D experimental facility.

QUESTION: In your new building, are you planning anything at all such as a vertical beam going up into the laboratory like they have at Odeillo? If you aren't, is it too late to consider it?

GUPTA: I don't believe that something like that is being considered for the permanent facility. Even if we did consider it, I'm not sure whether it would be accepted as part of the laboratory to perform the high-temperature work as it is so close to the office space. We may have available, at some point in the future, such an experimental facility. I don't think it's too late to be considering such a thing if the need for it exists.

HILDEBRANDT: The parabola at Odeillo is in the office space, and you can't get closer than that.

GUPTA: SERI, as an institution, has a different feeling regarding office space and, from that perspective, I don't think it will be as close to the office complex.

ZENTY: Regarding your earlier request for suggestions for your Association, I have two items. I suggest you accept proposals to design specifically the limits of different types of window materials as a separate program. The other suggestion is regarding the photolytic effect, whether it is an important factor or whether it exists. One of the principal factors that distinguishes solar experiments from all others, besides the ability to deliver energy at a high-flux rate, is the possibility of the photolytic effect. If it does exist, you have a tremendous selling point and I think it would strengthen the Association's position.

SMITH: We will go through our transcript and see what recommendations have come out of it. I think there will be several. If anyone has any after-thoughts or postmortem notes that you would like to send us, we would be very receptive to hearing from you, including especially any suggestions for improving this kind of meeting.

I feel this meeting was very successful in that we have learned a great deal from you who have attended--particularly from people from France who have many years of solar experience. If we are not serving your purposes or if you could see where we could do it better, we would like to know about it. Let me say again that I tremendously appreciate your participation in this workshop.

HILDEBRANDT: I'd like to add to that my thanks for your coming, and also to the Executive Committee members for taking time off from a very busy schedule. I would also like to thank Frank and especially Marylee and Win for the coordination and the arrangements for the meeting. Thank you.

AGENDA

FACILITY OPERATORS AND EXPERIMENTERS WORKSHOP

May 3-4, 1979
Albuquerque, NM

Thursday, May 3

Opening Remarks

Operators' Review of solar Facilities Status, Improvements,
Current Projects, Schedules, Etc.

Georgia Tech ACTF - Tom Brown
White Sands Solar Furnace - Richard Hays
Odeillo Laboratory-Scale Solar Furnace - Jean-Pierre Coutures
Odeillo 1-MW Solar Furnace - Claude Royere
Sandia CRTF - John Holmes

Review of Completed UA-Funded Projects

Molybdenum Ore Processing - Skaggs, LASL
High-Temperature Solar Absorbing Coatings - Schreyer, ORNL
Degradation of Black Chrome - Smith, U of Houston
Solar Ammonia Dissociation - Lenz, Colorado State U
Solar Reconcentrator - Meinel, U of Arizona
Solar Flash Pyrolysis of Biomass - Antal, Princeton U
Destructive Testing of Thin Film Materials - Zito, U of Arizona

Associated Projects

Thermochemical Energy Transport Using $\text{NH}_3 \rightleftharpoons 1/2 \text{N}_2 + 1-1/2 \text{H}_2$ -
P. O. Carden, Australian National University

Interfacing Solar Heat Sources and Hydrogen Production Processes -
Melvin Bowman, LASL

EPRI/Boeing Receiver Test at Sandia - John Gintz, Boeing

Sanders Associates Receiver Test at GA Tech - Ted Nussdorfer, Sanders

Concurrent Panel Discussions of High-Temperature Solar Experiment
Design and Testing

Hydrogen, Pyrolysis and Coal Gasification
Chemical Conversion and Transmission
Central Receivers, Windows, Materials
Chemical High-Temperature Processes

Friday, May 4

Continuation of Panel Discussions

Reports of Panel Chairmen: Definition of Needs for Future Experiments

Summary Discussion

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Albuquerque, NM, May 3-4, 1979

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