PRELIMINARY TEST REPORT 10 KWt SOLAR ENERGY RECEIVER

Test Period, July 31, 1976—August 27, 1976

MASTER

October 1976

Work Performed Under Contract EY-76-C-02-2823

Sanders Associates, Incorporated
Nashua, New Hampshire

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

Division of Solar Energy

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

This report has been reproduced directly from the best available copy.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161

Price: Paper Copy \$4.00 (domestic)
\$6.50 (foreign)
Microfiche \$3.00 (domestic)
\$4.50 (foreign)

PRELIMINARY TEST REPORT
10Kwt SOLAR ENERGY RECEIVER

TEST PERIOD
JULY 31, 1976 - AUGUST 27, 1976

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

OCTOBER 1976

UNDER CONTRACT NUMBER: E(11-1)-2823
PREPARED FOR
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

SANDERS
ASSOCIATES, INC.

OFFENSIVE SYSTEMS DIVISION

NASHUA, NH 03060

MASTER
EB

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ABSTRACT

During August 1976, tests were conducted on the 10 Kwt Solar Energy Receiver. The preliminary results indicate that efficiencies above 85% were obtained with flux intensity variations of 3.5:1. Efficiencies were lower (~75%) when the variations in the incident flux distribution were approximately 10:1.

Test goal and achievements are:

PARAMETER	GOAL	ACHIEVED
INPUT POWER, KW	14.3	24.6
ΔT °F	550	864
T_{IN} °F	1150	945
T_{OUT} °F	1700	1768
ΔP INCH H_2O	2	0.1-0.3
η	0.7	0.85

TABLE OF CONTENTS

<u>Paragraph</u>	<u>Title</u>	<u>Page</u>
	SECTION 1	
	INTRODUCTION	
1.1	Background	1
1.2	Objectives	1
	SECTION 2	
	EXPERIMENT	
2.1	Receiver Design	2
2.2	White Sands Facility	2
2.3	Test Apparatus and Instrumentation	4
2.4	Test Procedure	7
	SECTION 3	
	RESULTS	
3.1	Method of Data Reduction	11
3.2	Results	14
3.3	Correlation with Computer Model	15
3.4	Infrared Scanner Results	16
3.5	Window Temperatures	22
3.6	Erosion Particle Measurement	22
3.7	Discussion and Conclusions	25

LIST OF ILLUSTRATIONS

<u>Figure</u>	<u>Title</u>	<u>Page</u>
1	White Sands Solar Furnace	3
2	Instrumentation Layout	5
3	The Equipment Installed at the White Sands Solar Furnace	6
4	Isoflux Map at Honeycomb Surface (Window at Focal Point)	8
5	Isoflux Map at Honeycomb Surface with Window 4-1/4" Aft of the Focal Plane	9
6	Input Solar Power versus Attenuator Transmission	10
7	System Thermal Transient Response	13
8	Efficiency versus Inlet Temperature	14
9	Temperatures Increase versus Input Power	17
10	Temperature Increase versus Input Power	18
11	Infrared Imaging Camera Experimental Arrangement	19
12	Scanner Calibration at 2.8 μ	20
13	Isotherms on the Silicon Carbide View through Receiver Window (Only the Central 5" Diameter Section is Scanned)	21
14	Thermal Scans of the Solar Energy Receiver, View of the Silicon Carbide Taken through the Window (Only the Central 5" Diameter Section is Scanned)	23, 24
15	Output Power versus Input Power - Unpressurized	26
16	Output Power versus Input Power - Pressurized	27

SECTION 1 INTRODUCTION

1.1 BACKGROUND

Under contract to the Energy Research and Development Administration (ERDA), Sanders Associates is developing a solar receiver/heat exchanger unit for use in advanced solar powered electric generation plants. The function of the receiver is to absorb the concentrated solar energy focused on it by a large mirror field and to transfer this energy to an air stream, heating the stream to temperatures suitable for efficient operation of air-turbine (Brayton cycle) powered generators. This report presents the preliminary results of the test program during which the first reduced power (10 Kwt) model of such a receiver was tested at the solar test facility, White Sands, New Mexico.

1.2 OBJECTIVES

The objectives of the test programs were to:

- a. Measure the efficiency of the receiver in the collection and transfer of solar energy.
- b. Develop the scaling factors from which high-power receivers can be designed.
- c. Determine the aerodynamic performance of the internal air-flow system.
- d. Demonstrate the ability of the structure to withstand combined thermal/pressure stresses. Prove window survivability and pressure seal integrity.

SECTION 2 EXPERIMENT

2.1 RECEIVER DESIGN

a. Description. The receiver unit is constructed of temperature-resisting steel alloys and high-temperature insulation. Solar energy entering through a quartz window on one end impinges on an internal ceramic honeycomb absorber. A series of external radiation shields prevents "spill" solar energy from striking the metal housing. Heated, compressed air, simulating the conditions appropriate to the Brayton cycle turbine, is supplied to the receiver where it is further heated while flowing through the honeycomb absorber. This air is exhausted from the unit through a restriction which maintains the internal pressure of the unit at the required level.

b. Operation Parameters. Design operating parameters of the receiver are as follows:

Input power	15KW (thermal, input)
Airflow Rate	.07 lb/sec
Input Air Temperature	1150°F
Output Air Temperature	1700°F
Internal Pressure	45 psig

2.2 WHITE SANDS FACILITY

The largest solar furnace currently operating in the United States is the U.S. Army White Sands Solar Furnace shown in Figure 1. This facility was designed to provide a high radiant flux to simulate the thermal output of nuclear weapons for testing military equipment. Originally designed for 35 KW the system is currently capable of delivering approximately 27 KW of radiant energy.

Figure 1. White Sands Solar Furnace.

2.3 TEST APPARATUS AND INSTRUMENTATION

The system under test consists of the receiver unit, the air heater unit, control and instrument panel, and a power distribution box. The functional inter-relationship of the items is indicated in Figure 2.

Figure 3 presents a photograph of the equipment installed at the White Sands solar furnace.*

a. Airflow Rate (lbs/sec). Airflow rate through the system was measured by the flow meter, F. The weight flow of air, $\dot{m}$, (lbs/sec) is related to the indicated SCFM reading (F), the input pressure (P_1) psia, and temperature (T_{20})^{°R}, by the equation: $\dot{m} = .00772F \sqrt{\frac{P_1}{T_{20}}}$.

The factor .00772 accounts for the calibration of the meter.

b. Temperature, °F. Temperature measurements were made using chromel-alumel exposed junction thermocouples. The individual junctions were read out on a 20-position digital pyrometer matched to the thermocouple characteristics. Exposed junctions were shielded from the effects of direct radiant heating.

c. Air Outlet Temperature. Two methods of obtaining the temperature of the air after it had been heated by the solar power were provided. The first consisted of a thermocouple (T.C.#4) located on the centerline of the receiver outlet where it would be exposed to a well mixed flow. Possible errors due to radiation losses were minimized by interposing a thin wall, stainless-steel honeycomb between the thermocouple junction and the receiver wall. A second measure was obtained from a 7-thermocouple rake located on the horizontal centerline 3 inches downstream of the matrix.

* Photos courtesy U.S. Army Photography Unit, White Sands Missile Range.

Figure 2. Instrumentation Layout.

Figure 3. The Equipment Installed at the White Sands Solar Furnace.

2.4 TEST PROCEDURE

a. Calibration. The first series of tests, conducted on 8/5/76 and 8/6/76, were calibration tests to determine the amount of radiant flux impinging on the window and the matrix in subsequent receiver runs. This was accomplished by scanning the flux distribution in the appropriate vertical plane and using these data to construct maps of flux contours such as shown in Figure 4 and 5. Based on these maps, the relation between total solar power as a function of direct solar flux and attenuator settings is shown in Figure 6, which gives the incident power in BTU/sec for the matrix at two different receiver positions.

In addition to the radiant input calibrations discussed above, it was also necessary to develop a calibration method to account for energy losses from the receiver due to conduction through the walls to ambient. This correction is required to isolate the effect of the honeycomb and permit correlation of scaling parameters with theoretical estimates. Furthermore, the small size of the test unit precluded the use of the same insulation techniques which would be used in full scale units and resulted in much greater percentage of heat losses. The heat loss calibrations consisted of a number of sun-off runs during which the input air temperature, flow rate and pressure were varied. Outlet air temperatures (which were lower than the input temperature due to heat loss) were recorded and from these, graphs of temperature drop as a function of input conditions were developed. This temperature correction ranged from 40°F to 100°F , being typically 70°F at design conditions.

b. Testing. The most effective test procedure, which evolved after a few days of operating experience, began by stabilizing the internal temperature of the receiver at the test operating temperature. This required at least 1 hour, with input air temperature and flow rate at approximately 900°F and .095 lb/sec during which periodic temperature readings were made. Stability was assumed when the output

MEASUREMENT MADE BY
SANDERS USING WHITE
SANDS FACILITY CALORIMETER

NOTE THE 10:1 FLUX
VARIATION

Figure 4. Isoflux Map at Honeycomb Surface (Window at Focal Plane).

Figure 5. Isoflux Map at Honeycomb Surface with Window $\frac{1}{4}$ " Aft of the Focal Plane.

Figure 6. Input Solar Power vs Attenuator Transmission.

temperature did not vary by more than $2-3^{\circ}\text{F}$ over a 5 minute period.

When stability was reached the heliostat was brought into automatic tracking with the attenuators closed, and the water cooled shutter raised in front of the receiver. Correct alignment would be visually verified by slightly opening the attenuators and observing the position of the concentrated flux on the shutter. The attenuator would then be opened to the first test point, usually the lowest setting of interest, the shutter would be lowered and the solar flux would enter the receiver. While the receiver was reaching a new equilibrium point, input conditions (temperature and flow rate) were maintained constant. Solar input during the test was monitored by recording both the output of a total reading pyranometer and a manually positioned pyrheliometer, the later being used to obtain the direct flux vector required to estimate the input energy. Periodic readings of the diffuse solar component and sun elevation angle were also manually recorded.

A period of approximately 20-30 minutes was required to reach the sun-on equilibrium point, during which time the thermocouple temperatures, air flow parameters, solar inputs and heater performance were periodically recorded. After equilibrium was reached and the final data set recorded the attenuator would be further opened increasing the solar energy into the receiver and the process would be repeated.

SECTION 3

RESULTS

3.1 METHOD OF DATA REDUCTION

The basic performance features of interest are the obtained temperature increase, ΔT , the heat exchanger efficiency, η , and the pressure drop across the honeycomb ΔP_2 .

The temperature increase of the air due to the input solar radiation was obtained by the relationship:

$$\Delta T = T_{out} - T_{in} + \Delta T_L$$

Where

T_{out} = Outlet air temperature, obtained either by the average of the seven rake temperatures or from the exit center-line thermocouple #4.

T_{in} = Inlet air temperature, obtained by averaging the upper and lower supply pipe inlet temperature; T.C. #2 and T.C. #3.

ΔT_L = Wall heat loss correction factor, illustrated in Figure 7.

The receiver efficiency is defined on an incremental basis as:

$$\eta = \frac{\text{energy added to airstream}}{\text{solar power input}}$$

$$\eta = \frac{\dot{m} C_p \Delta T}{\dot{Q}_{in}}$$

where $\dot{m}$ = weight flow rate (lb/hr) and $\dot{Q}_{in}$ = solar power incident on the matrix surface (approximately 90% of the energy incident on the window impinges on the matrix). It is obtained as determined by calibration from Figure 6, or from the formulas below:

$$\dot{Q}_{in} = \dot{Q}_o \frac{I T}{I_o T_o}$$

$$= 21.69 IT \text{ (for runs in the forward position) (BTU/sec)}$$

$$= 16.29 IT \text{ (for runs in the aft position) (BTU/sec)}$$

(where the subscript o refers to calibration conditions, I to direct solar flux, T, to attenuator transmission. Of course, units must be kept consistent).

Figure 7. System Thermal Transient Response

3.2 RESULTS

a. Forward versus Aft. This variable refers to the position of the receiver with respect to the focal plane of the solar furnace. The designation FORWARD (FWD) denotes the placement of the receiver so that the window (or aperture) is at the focal plane, while the designation AFT places the window 4 1/2" behind the focal plane. This position variable was unanticipated; the initial test plan considered only one position, the forward location. However, tests at the aft location were added when the results of the flux calibration test disclosed larger than expected variations in flux intensity over the matrix surface.

Figure 8 illustrates the effect of air inlet temperature on efficiency. As expected, efficiencies decrease with increasing inlet temperatures.

Figure 8. Efficiency versus Inlet Temperature.

The increase in efficiency obtained in the AFT location is attributed to the more uniform flux distribution at that location (Figure 5 shows a 3.5:1 variation over the matrix in the AFT position while a 10:1 variation exists over the surface in the forward location, as shown in Figure 4).

b. Pressurized vs. Unpressurized. Comparisons between pressurized and unpressurized runs with similar conditions are taken to show no notable difference. There is a tendency to better efficiencies in some of the pressurized data, but the increase does not exceed 5%, and could be related to inhomogeneous flux effects being moderated by pressure as much as to any direct contributions to efficiency.

3.3 CORRELATION WITH COMPUTER MODEL

A simplified single node heat balance was carried out with the intent of using it as a semi-empirical curve fit for the data, especially for outlet air temperature rise and efficiency purposes. For many data points, the fit has been good even when nominal solar flux values were used, with no special accounting in the model for the flux inhomogeneities in the real situation.

One use of this model in fitting the data is to show isolated points that are "out of line" with the main body of data in a particular run, in essence providing a counterpart of the averaging of single run data. Comparison with such semi-empirical curve fits can help identify "bad data points".

Figures 9 and 10 show some comparisons of data from various experimental runs with the model.

3.4 INFRARED SCANNER RESULTS

In order to obtain temperature information on the SiC matrix an infrared scanner was used to monitor the matrix temperature distribution during operation. The experimental setup is shown in Figure 11. The infrared scanner was placed directly in front of the receiver and aligned to look at the matrix through the quartz window. A 2.75 - 2.85 micron filter was placed in front of the scanner. Quartz has a high transmission at this wavelength allowing the scanner to view the ceramic matrix. In addition, the region 2.6-3.0 microns is a water absorption band in the atmosphere which highly attenuates the incoming solar energy. As a result, this experimental setup allows measurements of the matrix temperature during operation without interference problems due to reflected solar energy. The calibration curve for the scanner measured using an NBS traceable blackbody is shown in Figure 12. This calibration was made with the quartz window used in the White Sands tests in the optical path to account for reflection and absorption. Figure 13 illustrates the real time infrared images obtained using this system. The bright outline is an electronically controlled isotherm which can be adjusted to outline temperature contour of interest. As used in Figure 13, these allow a general view of the front surface temperature of the silicon carbide matrix. The hottest spot on the ceramic matrix is shown in Figure 13a. Figures 13b to 13f show progressively lower temperature regions. The information can also be displayed in a single line scan mode where each raster line of the image is viewed with

LARGE BORE HONEYCOMB - 70 HOLES/IN²
.09 LB/SEC

$T_{IN} = 900^{\circ}\text{F}$

PRESSURIZED

+ THEORY
● EXPERIMENT

FWD
8-12

+ THEORY
○ EXPERIMENT

AFT
8-20

09276-63

Figure 9. Temperature Increase vs Input Power.

Figure 10. Temperature Increase vs Input Power.

10286-17

Figure 11. Infrared Imaging Camera Experimental Arrangement.

Figure 12. Scanner Calibration at 2.8μ .

a

d

b

e

c

f

Figure 13. Isotherms on the Silicon Carbide. View through Receiver Window. (only the central 5" diameter section is scanned).

the amplitude representing the temperature (Figure 14). This is a particularly useful mode because it allows quantitative measurements of the matrix surface temperature. In Figure 14, the object is scanned from bottom to top, i.e., Figure 14a is a scan of the lowest position of the honeycomb and Figure 14p is the top of the honeycomb.

This information can be used to determine how efficiently the material is being used in a specific cavity design.

3.5 WINDOW TEMPERATURES

Measurements of the window surface temperature were made by a solar-blind radiometer. The results indicate a window surface temperature in the range of 575 to 850°F at design input power level. The large amount of scatter in the data is attributed to the variations in the cooling air stream which was directed across the front of the receiver to cool the radiation shield.

3.6 EROSION PARTICLE MEASUREMENT

Concern had been voiced regarding a possible turbine erosion problem caused by evolution of dust particles from the ceramic matrix. An attempt was made to determine the magnitude of particle evolution by trapping such particles in a fine mesh stainless steel screen placed in the receiver outlet ahead of the measurements section. Although numerous runs were made with screens in place, it was necessary to discontinue their use due to the high pressure drop introduced, and due to their tendency to break-up after prolonged exposure to the high temperature airflow. The two screens run appear visually to be free from such particles, but microscopic analysis has not been completed.

HORIZONTAL SCALE 1 CM = 2.5 INCHES

Figure 14. Thermal Scans of the Solar Energy Receiver, view of the Silicon Carbide taken through the window (only the central 5" diameter section is scanned)(sheet 1 of 2)

HORIZONTAL SCALE 1 CM = 2.5 INCHES

Figure 14. Thermal Scans of the Solar Energy Receiver, view of the Silicon Carbide taken through the window (only the central 5" diameter section is scanned)(sheet 2 of 2)

3.7 DISCUSSION AND CONCLUSIONS

Figure 15 summarizes the efficiencies obtained over a broad range of input flux levels for the unpressurized case. Efficiencies as high as 85% were realized for the pressurized receiver. These results are notable considering the range of experimental parameters including solar flux input, air inlet temperatures, and air flow rates. Of most interest is the importance of inhomogeneities in solar flux and/or airflow, which are taken to account for the very significant difference between data taken in the "forward" (10:1 flux variation) and "aft" (3.5:1 flux variation) locations of the receiver. (The former position locates the receiver aperture in the plane of best focus of the solar facility; the latter is 4 1/2 inches rearward.

CONCLUSIONS:

- a. Efficient solar receivers can be designed with air as a working medium for reasonable ranges of parameters such as solar flux levels, airflow rates, inlet air temperatures, flux homogeneity.
- b. The predicted low pressure drops for airflow through the honeycomb structures were confirmed at less than one inch of water.
- c. The value of solar-blind infrared scanning in providing receiver temperature measurements was demonstrated against a background of highly concentrated solar flux.

Figure 15. Output Power versus Input Power - Unpressurized

Figure 16. Output Power versus Input Power - Pressurized