AN INTENSITY AND UNIFORMITY MONITOR
FOR SOLAR SIMULATORS

ARO, Inc.

June 1966

Distribution of this document is unlimited.
NOTICES

When U. S. Government drawings specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise, or in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Qualified users may obtain copies of this report from the Defense Documentation Center.

References to named commercial products in this report are not to be considered in any sense as an endorsement of the product by the United States Air Force or the Government.
AN INTENSITY AND UNIFORMITY MONITOR
FOR SOLAR SIMULATORS

ARO, Inc.

Distribution of this document is unlimited.
FOREWORD

The research reported herein was sponsored by Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Program Element 61445014, Project 8951, Task 895104.

The results of the research were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, under Contract AF 40(600)-1200. The work was performed under ARO Project No. SW2407, and the manuscript was submitted for publication on March 23, 1966.

In addition to the authors shown on the cover, R. C. Birkebak of Georgia Institute of Technology is an author of this report.

This technical report has been reviewed and is approved.

Terry L. Hershey
Captain, USAF
Aerospace Sciences Division
DCS/Research

Donald R. Eastman, Jr.
DCS/Research
ABSTRACT

An experimental study of a portable intensity and uniformity monitor for solar simulators is presented. The monitor is a modified integrating sphere coated with MgO and utilizes a thermopile as the detector. The radiation wavelengths used in evaluating the monitor were generated by a carbon arc solar simulator. These data were obtained as a function of time, intensity, temperature, and uniformity. The theory and operation of the monitor employed in these experiments are discussed. A modification of this monitor for use as a reflectometer is also presented.
CONTENTS

ABSTRACT ................................................... iii
 NOMENCLATURE ............................................ v
 I. INTRODUCTION .......................................... 1
 II. INTENSITY AND UNIFORMITY MONITOR ................. 2
     2.1 Theory .............................................. 2
     2.2 Prototype Monitors .................................. 3
     2.3 Monitor with Variable Aperture ..................... 5
 III. PORTABLE REFLECTOMETER ............................ 5
 IV. CONCLUDING REMARKS ................................ 6
 REFERENCES .................................................. 7

ILLUSTRATIONS

Figure

1. Prototype Intensity Monitor Diagram .................. 9
2. Experimental Verification of Monitor Theory .......... 10
3. Radiation Intensity and Uniformity Monitor .......... 11
4. Schematic of 8-in.-diam Monitor ...................... 12
5. Calibration of 8-in.-diam Monitor ..................... 13
6. Monitor Output Variation with Time .................. 14
7. Monitor Temperature Variation with Time ............ 15
8. Monitor with Variable Aperture ........................ 16
9. Intensity Distribution ................................... 17
10. Portable Reflectometer ................................. 18

NOMENCLATURE

\( A_d \) Detector surface area, \( cm^2 \)
\( A_e \) Aperture surface area, \( cm^2 \)
\( A_s \) Interior surface area of a sphere, \( cm^2 \)
\( A_t \) Interior surface area of a truncated sphere, \( cm^2 \)
$A_V$  Vehicle surface area, cm$^2$

$I_0$  Radiation intensity, w/cm$^2$

$I_w$  Relative intensity, $I_0$/Total $I_0$

$k$  Detector response constant, mv/w

$r$  Radius of aperture, cm

$V_1$  Detector response from the first reflection, mv

$V_2$  Detector response from the second reflection, mv

$V_3$  Detector response from the third reflection, mv

$V_4$  Detector response from the fourth reflection, mv

$V_i$  Detector response from $i$ reflectance, mv

$V_T$  Detector response from the total reflection, mv

$\alpha$  Slope of $V_T$ versus $I_0$

$\rho_V$  Vehicle surface reflectance

$\rho_w$  Wall reflectance

$\phi$  Position of the detector, deg
SECTION I
INTRODUCTION

Precise data on the thermal performance of a vehicle cannot be obtained in ground test facilities without accurate simulation of the major energy sources encountered in space. Since the sun is the main energy source in space, its simulation in space chambers is of prime interest (Refs. 1 through 4). The four major parameters which describe the performance of any solar simulator are (1) radiation intensity, (2) flux uniformity, (3) collimation angle, and (4) spectral distribution. The collimation angle is primarily a mechanical parameter in that it remains essentially constant after system installation is completed. However, the other three parameters are subject to change because of contamination or degradation of the optical characteristics of the system. For example, a lens or mirror system may become contaminated by the backstreaming from an oil diffusion pump or by outgassing from a surface. This could change the optical characteristics of the transfer system and introduce uncertainties in the spectral and intensity parameters. Therefore, these parameters should be monitored to ensure the validity of the test results.

The intensity of the radiation is normally measured with a calibrated thermopile. This system has several advantages over other measuring devices in that it is relatively portable, rugged, and requires only a simple readout system. The main disadvantages of this device are the potential sources of error that arise from the difference between conditions that may exist during calibration and actual tests such as: (1) temperature stability of the heat sink during irradiation, (2) "tare"* resulting from the unavoidable excess field of view and tare stability, and (3) energy losses caused by protective window (low-level calibration and high-intensity use).

Calorimetric techniques have also been used for measuring the total incident energy. These systems suffer from the same general problems associated with thermopiles. They also require precise metering of coolant flow during operation, and this results in another source of error.

The uniformity of the flux density may be measured with thermopiles or calorimeters. However, several difficulties also arise with these measurements. The coolant system required for these instruments complicates the scanning operation, and because of their slow response time, 20 to 30 min is required to survey a 6-ft line of a system. Solar cells or photovoltaic cells have rapid and linear response. These devices are used for

*t"tare" is the stray radiation striking the detector.
flux uniformity measurements. The main disadvantage is that they are normally quite small and the time required to map the uniformity of large solar simulators is much too great.

This report describes an intensity and uniformity monitor which eliminates or minimizes the potential sources of error previously described. The system does not require a coolant and will monitor a large area. The monitor is based on the principle of the integrating sphere in that the detector is irradiated by multiple reflections from the sphere wall. A discussion is given on the modification of the integrating sphere theory to correct for the large aperture. The effects of variable aperture, sphere size, and wall temperature variations are also discussed. The use of this system as a portable reflectometer for monitoring changes in vehicle surface reflectance and a discussion of tare stability are presented.

SECTION II
INTENSITY AND UNIFORMITY MONITOR

2.1 THEORY

The classical integrating sphere (Refs. 5 and 6) can be modified and used as an intensity monitor for a solar simulator (Ref. 7). Classical theory assumes that the interior wall of the sphere is uniformly irradiated by reflected radiation and that the wall is a perfectly diffuse reflector.

Consider a sphere (Fig. 1) of interior surface area $A_s$ which has an aperture of radius $r$. The aperture cuts off an area $A_e$ such that

$$A_s = A_t + A_e$$

where $A_t$ is the interior surface area of the truncated sphere. Then the detector response can be formulated as follows.

Let collimated radiation of intensity $I_0$ enter the aperture and illuminate the sphere. Then the area illuminated by the direct radiation is $A_e$, and the total energy is $I_0 A_e$. The radiation reflected from a unit area would be $\rho_w I_0$ and the total radiation reflected would be $A_e \rho_w I_0$. Since this radiation is reflected diffusely, the irradiance on any unit area of sphere wall would be $(A_e \rho_w I_0)/A_s$, and the detector response from the first reflection, $V_1$, is

$$V_1 = (k A_d \rho_w I_0 A_e)/A_s$$

where $k$ is the detector response constant, $A_d$ the detector area, and $\rho_w$
the wall reflectance. This assumes that the detector is not irradiated directly but only from reflected radiation.

Since \((A_e \rho_w I_o)/A_s\) radiation strikes each unit area of the sphere from the first reflection, the radiation reflected by each unit area would be \((A_e \rho_w^2 I_o)/A_s\). Thus, from second reflections, the detector response is

\[ V_2 = \frac{(kA_d A_t A_e \rho_w^2 I_o)}{A_s^2} \]  

(3)

where \(A_t\) is the number of unit areas reflecting to the detector, assuming that \(A_d\) is smaller than \(A_t\). Similarly, the detector response for the third reflection is

\[ V_3 = \frac{(kA_d A_t^2 A_e \rho_w^3 I_o)}{A_s^4} \]  

(4)

and the fourth reflection is

\[ V_4 = \frac{(kA_d A_t^3 A_e \rho_w^4 I_o)}{A_s^6} \]  

(5)

Then the detector response for all reflections would be

\[ V_T = \sum_{i=1}^{n} V_i = \frac{kA_d A_e \rho_w I_o}{A_s} \left[ 1 + \frac{\rho_w A_t}{A_s} + \left( \frac{\rho_w A_t}{A_s} \right)^2 + \left( \frac{\rho_w A_t}{A_s} \right)^3 + \ldots \right] \]  

(6)

or in closed form

\[ V_T = \frac{kA_d A_e \rho_w I_o}{A_s} \left( \frac{1}{1 - \frac{\rho_w A_t}{A_s}} \right) \]  

(7)

which upon rearrangement becomes

\[ V_T = kA_d \rho_w I_o \left( \frac{A_e}{A_s - \rho_w A_t} \right) \]  

(8)

Thus

\[ V_T = \alpha I_o \]  

(9)

for any given system and a plot of \(V_T\) versus \(I_o\) would give a straight line through the origin with a slope of \(\alpha\). This implies that a single calibration point will define the calibration curve for the system.

2.2 PROTOTYPE MONITORS

A monitor based on the integrating sphere technique was fabricated from a 3.5-in.-diam stainless steel sphere (Fig. 1). The entrance aperture was 1 in. in diameter and was equipped with a 6-in.-long, 1-in.-diam collimating tube. The interior of the collimating tube was coated with acetylene black, and the interior of the sphere was smoked with magnesium.
oxide (MgO). The MgO surface meets the requirement for a diffuse reflecting wall (Ref. 8). Using the sun as a source of parallel light, the wall irradiance was measured as a function of position as determined by the angle $\phi$ (Fig. 1). This was accomplished by attaching calibrated solar cells to a rotating arm of appropriate curvature for mapping the wall irradiance. These experiments were repeated with MgO-coated spheres of 4, 6, and 8-in. diameters, all with a 1-in.-diam aperture. No change in wall irradiance was observed for any of the spheres. This indicates that the requirement ($\pm 2$ percent) for uniform wall irradiance is met by such systems for $A_s/A_e$ ratios from 50 to 256.

The rotating arm was replaced by a calibrated solar cell detector and a measurement of the wall irradiance was determined from the detector output. The energy source used in these experiments was a tungsten-iodine lamp, and the same detector was used for the different size spheres. These data (Fig. 2) were also obtained for the spheres with 2- and 3-in.-diam apertures. The solid line represents the detector output as calculated from Eq. (8). The data for the different diameter spheres and aperture sizes are represented by the designated symbols. These experiments show very good agreement between the theory and experimental data.

Based on the results obtained with the prototypes, an 8-in.-diam monitor with a 0.1-ft$^2$ aperture was fabricated (Fig. 3). Because of the temperature variations between the detector and its surroundings caused by radiation absorption, the exterior sphere surface was shielded by a reflector (Fig. 4). The aperture in the sphere was covered by a quartz plate to minimize convection losses. This system was calibrated using two sources, the sun and a carbon arc. The sensitivity of the system was 0.060 and 0.0585 mv/mw when the sun and the carbon arc, respectively, were employed. The carbon arc data are shown in Fig. 5 as a function of irradiance. Data are shown by symbols, and the solid line was calculated from Eq. (8). The constants in Eq. (8) were obtained from the data point corresponding to the detector output of 7 mv. The data for this sphere also agree very closely with theory. Figure 6 shows the variation of detector output with time. The dotted line represents the average output over a 12-min period. The 4-sec rotation of the carbon rod in the arc source can be observed in the detector output.

Three thermocouples, the locations of which are shown in Fig. 4, were used to monitor the temperature variations on the sphere during irradiation. These data are shown in Fig. 7. The slow steady rise in the thermopile base temperature as indicated in the figure would cause uncertainties in the detector output. The thermopile used here was not
temperature controlled; however, the uncertainties could have been mini-
mized by using the coolant system.* If a thermopile detector such as
described by Frazine (Ref. 9) were used, no coolant lines would be required,
and the system would be more readily portable.

A monitor with a small aperture, i.e., 1/2-in. diameter, could be
equipped with a filter wheel, and spectral distribution measurements could
be obtained. The equations previously derived would not be altered, but
care would have to be taken to incorporate the appropriate transmittance
and sensitivity factors of the filters and detector to ensure accuracy.

2.3 MONITOR WITH VARIABLE APERTURE

A monitor with a variable entrance aperture would be more versatile
than one with a large fixed aperture. It could not only obtain an integrated
intensity over a large area but could also measure the distribution of
intensity over this large area. If the system were a truncated sphere with
a flat plate, which contained the variable aperture (Fig. 8), the irradiance
within the sphere would not be uniform (Ref. 10). This is because the dif-
fuse reflections from the flat plate, A (Fig. 8), would not uniformly irradiate
the sphere walls. The intensity distributions for 1-, 2-, and 3-in.-diam
apertures in a 5-in.-radius sphere, truncated with a 4-in. plate are shown
in Fig. 9. The data points for values of $\phi$ less than 57 deg represent the
intensity on the flat plate; those for $\phi$ larger than 57 deg show the intensity
distribution on the walls of the truncated sphere. Similar calculations
have also been obtained for 1.5-, 3-, 4-, 6-, and 7-in. radii. Equation
(8), previously derived, cannot be applied to this type of system because
the flat plate voids the assumption of uniform irradiance. However, any
particular system could be calibrated.

SECTION III
PORTABLE REFLECTOMETER

If the reflectance characteristics of the surface of a test vehicle
change because of contamination during a thermal balance test, test data
may be lost unless the reflectance change could be monitored. The uni-
formity monitor previously described could be used for this purpose with
a few minor changes. The changes would consist of placing another aper-
ture opposite the source aperture such as shown in Fig. 10. The sample

*No data were taken with the cooling system operating (Fig. 3).
at A would be irradiated by the solar simulator through aperture B and the reflectance of the vehicle surface could be monitored. This would not be an absolute measurement since a standard would not be used, but relative changes in reflectance could be obtained by using a calibration curve. The reflectometer data would allow appropriate corrections to be made to the thermal balance data. However, large changes in the specular component of the reflectance of the vehicle surface could give misleading results. This would result from the reflectance becoming more diffuse, and the detector output would indicate an erroneous increase in reflectance. With proper calibration and experimental technique, the system could yield useful data on surface conditions and changes. This method could be made to yield absolute reflectance measurements by placing a known light source at B such as shown as an alternate source in Fig. 10. Then, following the standard integrating sphere procedures for reflectance measurements (Refs. 5 and 6), absolute values of total reflectance can be obtained.

Equation (8) may be modified to correct for the change in reflectance of the sample area. That is,

$$V_T = \frac{kA_d l_0 \rho_v A_v}{A_s - \left[\rho_w (A_t - A_v) + \rho_v A_v\right]}$$

(10)

where $\rho_v$ is the reflectance of the vehicle surface of area $A_v$.

SECTION IV
CONCLUDING REMARKS

It has been shown that a simple and accurate radiation intensity and uniformity monitor for large areas can be built and operated. The cost is considerably less than present models in use.

The system requires a minimum of hard line connections and no coolant, which simplifies installation. Calibration of the device can be made in situ, thus, minimizing the errors arising from remote calibration and transfer.

The monitor, with minor modifications, could be used as a portable reflectometer which could supply important data in heat balance and thermal testing.
REFERENCES


Collimator

Acetylene Black Walls

$A_e$

$A_t$

Rotating Arm

$r$

Detectors

$\phi$

Fig. 1 Prototype Intensity Monitor Diagram
The number above each data point indicates the aperture diameter in inches.

Fig. 2 Experimental Verification of Monitor Theory
a. Front View

b. Side View

Fig. 3 Radiation Intensity and Uniformity Monitor
Fig. 4 Schematic of 8-in.-diam Monitor
Fig. 5 Calibration of 8-in.-diam Monitor

Sensitivity = 0.0585 mv/mw/cm²
Fig. 6 Monitor Output Variation with Time
<table>
<thead>
<tr>
<th>Sym</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>○</td>
<td>Faceplate, TC₁</td>
</tr>
<tr>
<td>□</td>
<td>Back of Sphere, TC₂</td>
</tr>
<tr>
<td>△</td>
<td>Thermopile Base, TC₃</td>
</tr>
</tbody>
</table>

Fig. 7 Monitor Temperature Variation with Time
Fig. 8 Monitor with Variable Aperture
Fig. 9 Intensity Distribution
Fig. 10 Portable Reflectometer
An experimental study of a portable intensity and uniformity monitor for solar simulators is presented. The monitor is a modified integrating sphere coated with MgO and utilizes a thermopile as the detector. The radiation wavelengths used in evaluating the monitor were generated by a carbon arc solar simulator. These data were obtained as a function of time, intensity, temperature, and uniformity. The theory and operation of the monitor employed in these experiments are discussed. A modification of this monitor for use as a reflectometer is also presented. (U)
solar simulators
intensity measurements
uniformity measurements
optical measurements
integrating sphere

reflectometer

temperature measurements

14.

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization (corporate author) issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b. 8c. & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers (either by the originator or by the sponsor), also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through DDC."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through DDC."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through DDC."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as (TS), (S), (G), or (U).

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.