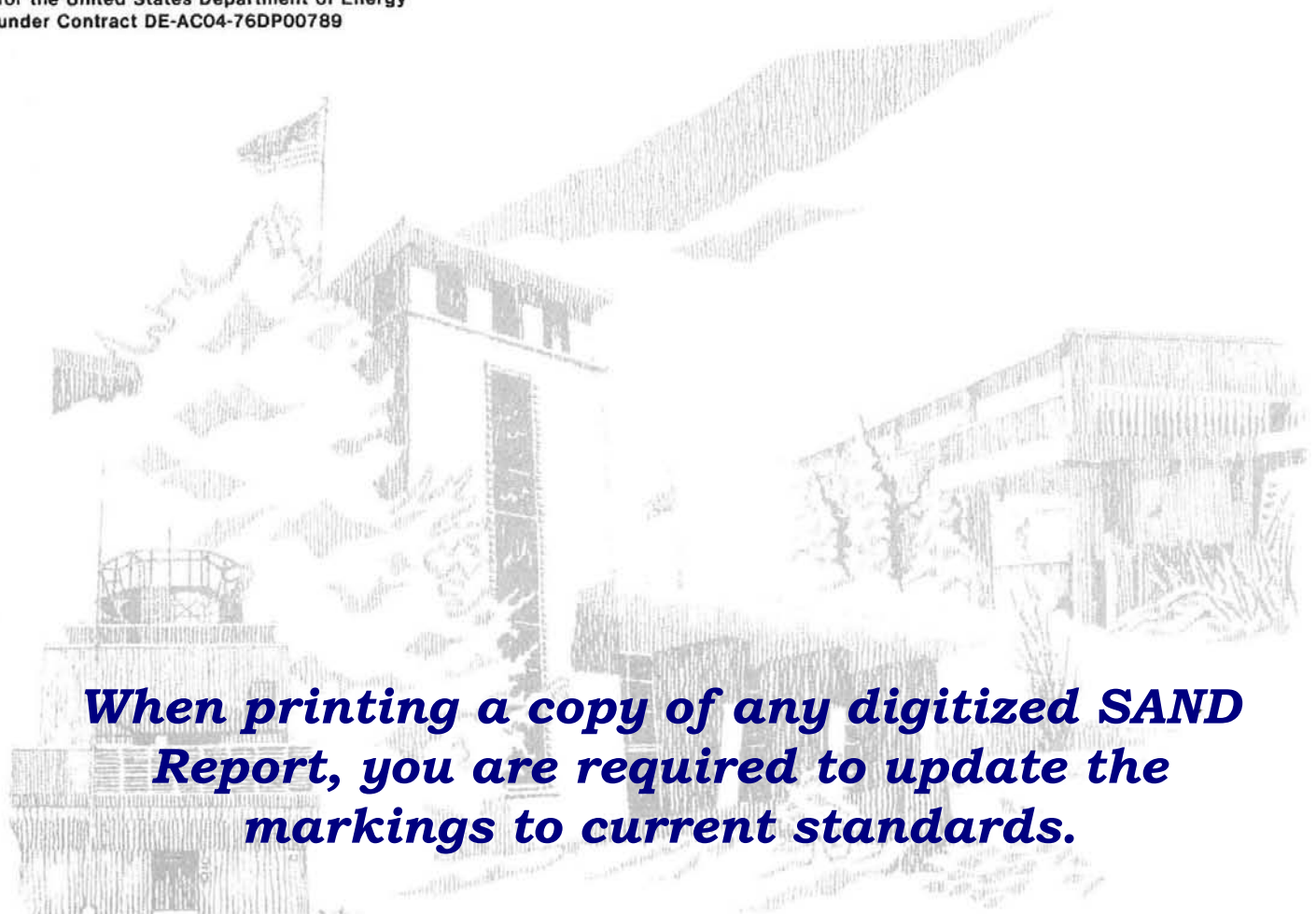


# Accelerated Aging of Aluminized Acrylic Solar Mirror Materials

A. R. Mahoney, R. B. Pettit, G. S. Kinoshita

Prepared by  
Sandia National Laboratories  
Albuquerque, New Mexico 87185 and Livermore, California 94550  
for the United States Department of Energy  
under Contract DE-AC04-76DP00789



***When printing a copy of any digitized SAND  
Report, you are required to update the  
markings to current standards.***

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

**NOTICE:** 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, 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. 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, any agency thereof or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof or any of their contractors or subcontractors.

Printed in the United States of America  
Available from  
National Technical Information Service  
U.S. Department of Commerce  
5285 Port Royal Road  
Springfield, VA 22161

NTIS price codes  
Printed copy: A02  
Microfiche copy: A01

SAND84-0532  
Unlimited Distribution UC-62  
PRINTED: October 1984

Accelerated Aging of Aluminized Acrylic  
Solar Mirror Materials\*

A. R. Mahoney, R. B. Pettit and G. S. Kinoshita  
Sandia National Laboratories  
P. O. Box 5800  
Albuquerque, NM 87185

ABSTRACT

The accelerated aging characteristics of an aluminized acrylic reflector material (3M Company ECP-244) were studied when bonded to either an aluminum or acrylic painted steel substrate. The aging consisted of temperature/humidity cycling between extremes of 54° to -29°C. After 255 days of environmental chamber exposure, the solar averaged specular reflectance values for both types of samples indicated no degradation, within experimental errors. Therefore, the acrylic painted steel substrate appears to be a suitable substitute for a sheet aluminum substrate.

## Introduction

Concentrating solar collectors, that utilize mirrors to redirect sunlight onto a receiver surface, require mirrors that are formed into a curved shape.<sup>1</sup> Potential mirror materials for these applications can be divided into three categories:<sup>2</sup> (1) silvered glass; (2) roll polished aluminum; and (3) metallized plastic films. Of the metallized plastic films, an aluminized acrylic film manufactured by the Energy Control Products (ECP) Division of 3M Company, has often been used in these collectors.<sup>1,3</sup> This material consists of a 0.1 mm thick acrylic film which is laminated to a substrate using a pressure sensitive adhesive supplied with the film (see Fig. 1). The typical substrate chosen in past designs was a sheet aluminum material.<sup>3</sup> Replacing the aluminum substrate with a steel sheet would reduce the cost of the mirror and thereby the collector cost. However, the steel surface requires protection from the outdoor environment. Thus, a compatible approach for film attachment to a protected steel substrate was studied.

Past research at this laboratory on film/steel laminates resulted in less than satisfactory solutions for producing an effective solar mirror. Films laminated to galvanized steel produced mirror surfaces with print-through images of the surface irregularities which reduced the specularity of the reflected beam.<sup>2</sup> Epoxy coated steel substrate produced laminates which debonded at the adhesive/epoxy interface when thermally cycled. Therefore, to provide a surface that was more compatible with the acrylic adhesive supplied on the film, an acrylic paint was suggested as an alternative to the epoxy. Several 30-cm square samples of the aluminized acrylic film (designated ECP-244<sup>4</sup>) laminated to acrylic painted steel were fabricated. These samples, together with samples of ECP-244 laminated to aluminum sheets, were evaluated for optical properties both before and after exposure to temperature/humidity cycling.

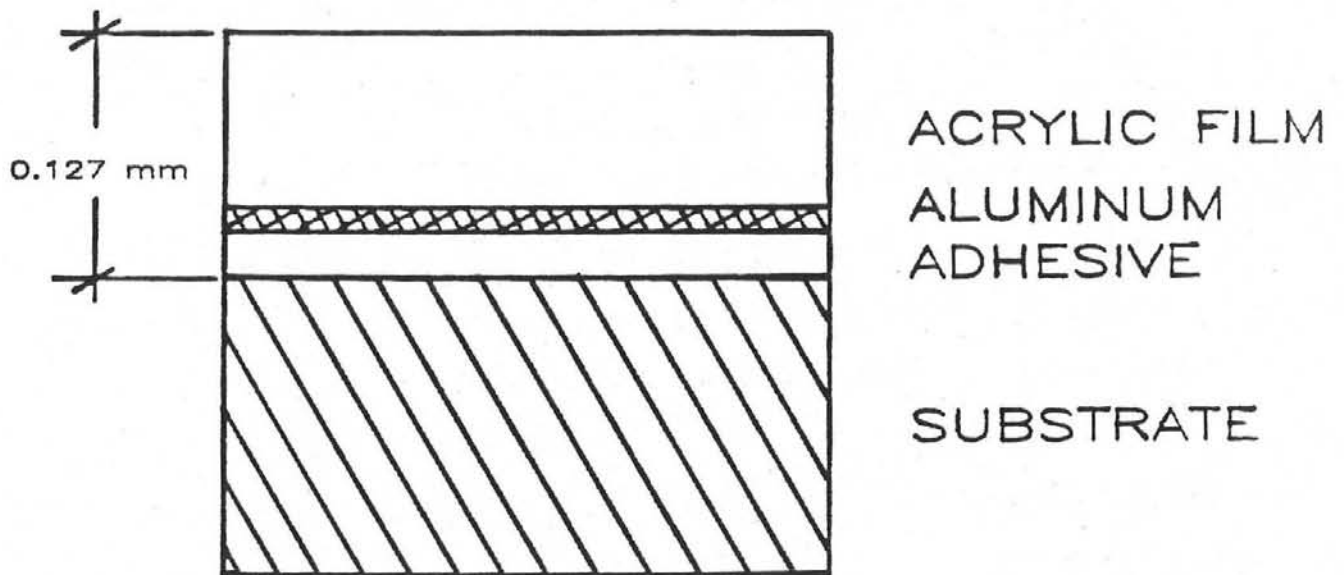


FIG. 1. Schematic diagram of the reflector sample showing the acrylic film, evaporated aluminum film, adhesive and substrate.

## Optical Measurement Techniques

The optical properties of each sample were characterized using both hemispherical and specular reflectance measurement techniques. The normal-hemispherical reflectance  $R(\lambda; 2\pi)$  was determined for wavelengths,  $\lambda$ , from 270 nm to 2400 nm using a Beckman<sup>4</sup> Model 5270 spectrophotometer equipped with an integrating sphere accessory.<sup>5</sup> With this accessory, all radiation reflected into a hemisphere (solid angle =  $2\pi$  rad.) was measured. Data were referenced to an aluminized mirror standard that had been calibrated by The National Bureau of Standards (NBS) to within  $\pm 0.005$  reflectance units (1.00 reflectance units equals 100% reflectance) over the same wavelength range.<sup>6</sup>

In addition, the normal, diffuse reflectance,  $R(\lambda; D)$ , was measured over the same wavelength range, also using the integrating sphere accessory. For this measurement, a plug in the sphere wall opposite the sample location (see Fig. 2) was removed so that the specularly reflected beam from the sample exited the sphere and was not measured. In this way, only the scattered (diffusely) reflected radiation was measured. For our sphere, the angular size of the diffuse port in the sphere wall, as seen by the sample, was approximately 135 mrad ( $7.7^\circ$ ). Thus,  $D$  above denotes a solid angle that includes a hemisphere except for a small cone centered around the specular direction with a full width of 135 mrad. The diffuse reflectance properties were used to determine the wavelength dependence of any scattered radiation across the solar spectrum (see discussion below and Ref. 7) so that the solar averaged specular reflectance could be determined.

Finally, the specular reflectance,  $R_{D-S}$  (660; S) was determined using a Devices and Services<sup>4</sup> (D&S) portable specular reflectometer, Model 15R.<sup>8</sup> For this measurement, the collection aperture on the instrument was set to 46 mrad ( $2.6^\circ$ ) and thus  $S$  above denotes a cone centered around the specular

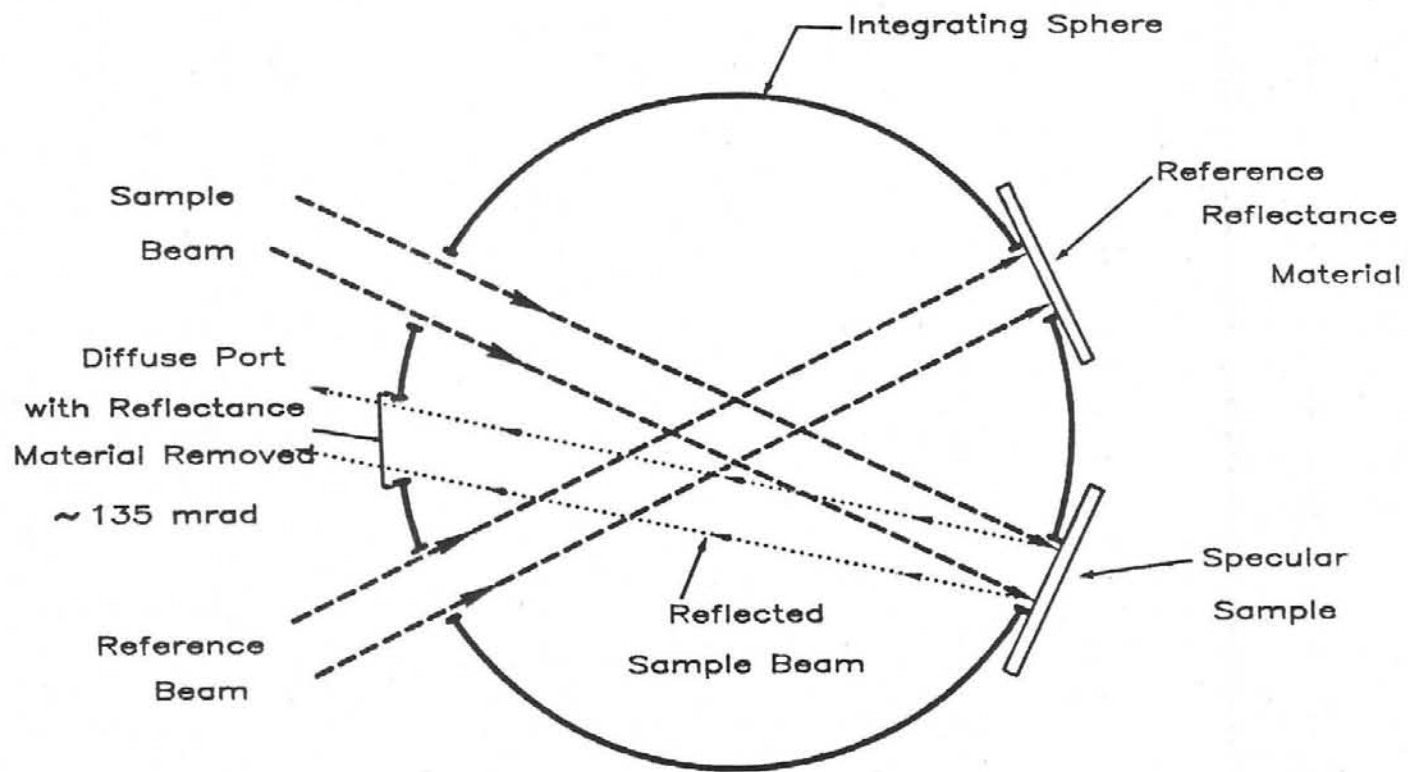


FIG. 2. Diagram of an integrating sphere reflectance accessory showing the sample and reference beams and the location of the diffuse reflectance port.

direction with a full width of 135 mrad. In this instrument, the specular reflectance was determined at a wavelength of 660 nm (band width of ~30nm), while the size of the beam incident on the mirror was ~1 cm diameter. The  $R_{D-S}$  (660; S) value reported here for each sample represents an average of at least 10 readings randomly obtained over the sample surface. Reflectance data obtained using this instrument have been found to be as accurate as the standard used for calibration; thus the 660 nm specular reflectance values are also accurate to  $\pm 0.005$  reflectance units.

#### Data Analysis Procedure

Both the hemispherical and diffuse reflectance data were averaged over a solar energy spectral distribution in order to determine a solar averaged hemispherical reflectance [ $R_s(2\pi)$ ] and a solar averaged diffuse reflectance [ $R_s(D)$ ]. The solar spectral distribution chosen was obtained from Thekaekara<sup>9</sup> for an air mass 1.5 condition (AM1.5).

As noted above, the D&S portable specular reflectometer only determines the specular reflectance properties in a narrow wavelength interval centered at 660 nm. Therefore, a procedure was developed so that the solar averaged specular reflectance could be estimated. This procedure is discussed in detail in Ref. 7.

Using the three measured quantities [ $R(\lambda; 2\pi)$ ,  $R(\lambda; D)$  and  $R_{D-S}$  (660; S)] the solar averaged specular reflectance,  $R_s(S)$ , could be determined. First the  $R_{D-S}$  (660; S) value was compared to the hemispherical reflectance measured at 660 nm  $R(660; 2\pi)$ . The difference

$$\Delta R(660) = R(660; 2\pi) - R_{D-S} (660; S) \quad (1)$$

gave a measurement of the amount of scattered reflected radiation at 660 nm. If  $\Delta R(660)$  was less than the estimated measurement error (0.005), then the



hemispherical and specular reflectance values could be considered as essentially equal. Experience has indicated that in this case the hemispherical and specular reflectance values are equal at all wavelengths and that  $R_S(S) = R_S(2\pi)$ .

On the other hand, if  $\Delta R(660) > 0.005$ , it was necessary to determine a solar average value for  $\Delta R$ . Previous measurements have shown that the wavelength dependence of  $\Delta R$  is the same as the wavelength dependence of  $R(\lambda; D)$  the diffuse reflectance.<sup>10</sup> Therefore, the solar average value is given by

$$\Delta R_S = \frac{R_S(D)}{R(660; D)} \cdot \Delta R(660) \quad (2)$$

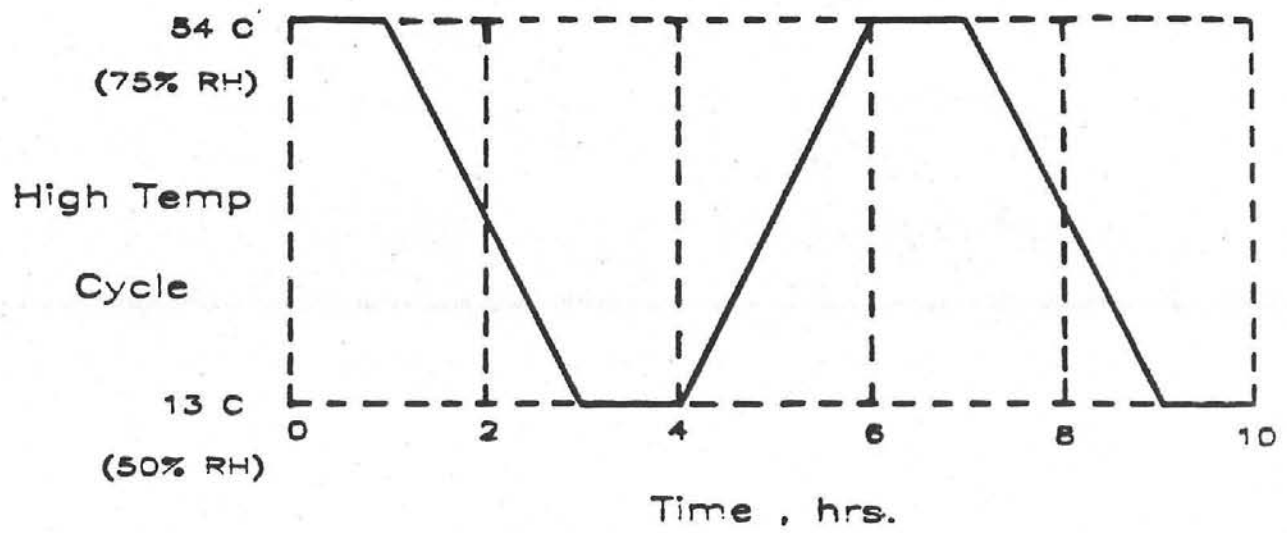
Here  $R(660; D)$  is the diffuse reflectance measured at 660 nm. Using this value, the solar averaged specular reflectance was given by

$$R_S(S) = R_S(2\pi) - \Delta R_S \quad (3)$$

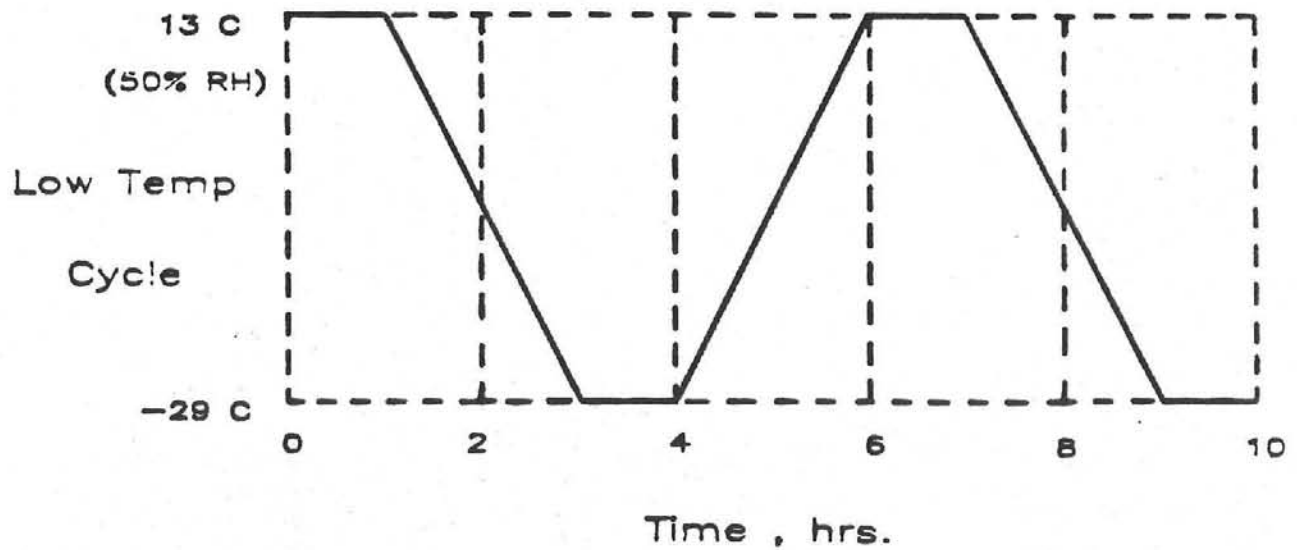
#### Environmental Chamber Exposure

The environmental chamber conditions chosen for testing the laminated mirror samples combined accelerated temperature cycling with high humidity conditions. The temperature cycling was divided into two separate tests, as diagrammed in Figure 3. Each cycle lasted 6 hours and thus was repeated 4 times each 24 hour period. Testing alternated on weekly intervals between the high and low temperature cycles. Relative humidity varied with temperature: at 54°C the relative humidity was ~75% and decreased to ~5% just before freezing.

Previous temperature/humidity cycling carried out at Sandia in support of the solar program used a single 8-hour cycle as shown in Fig. 4.<sup>11</sup> This cycle was used to accelerate damage in parabolic trough mechanical structures



(a)



(b)

FIG. 3. Thermal cycling conditions for the (a) high temperature and (b) low temperature cycles.

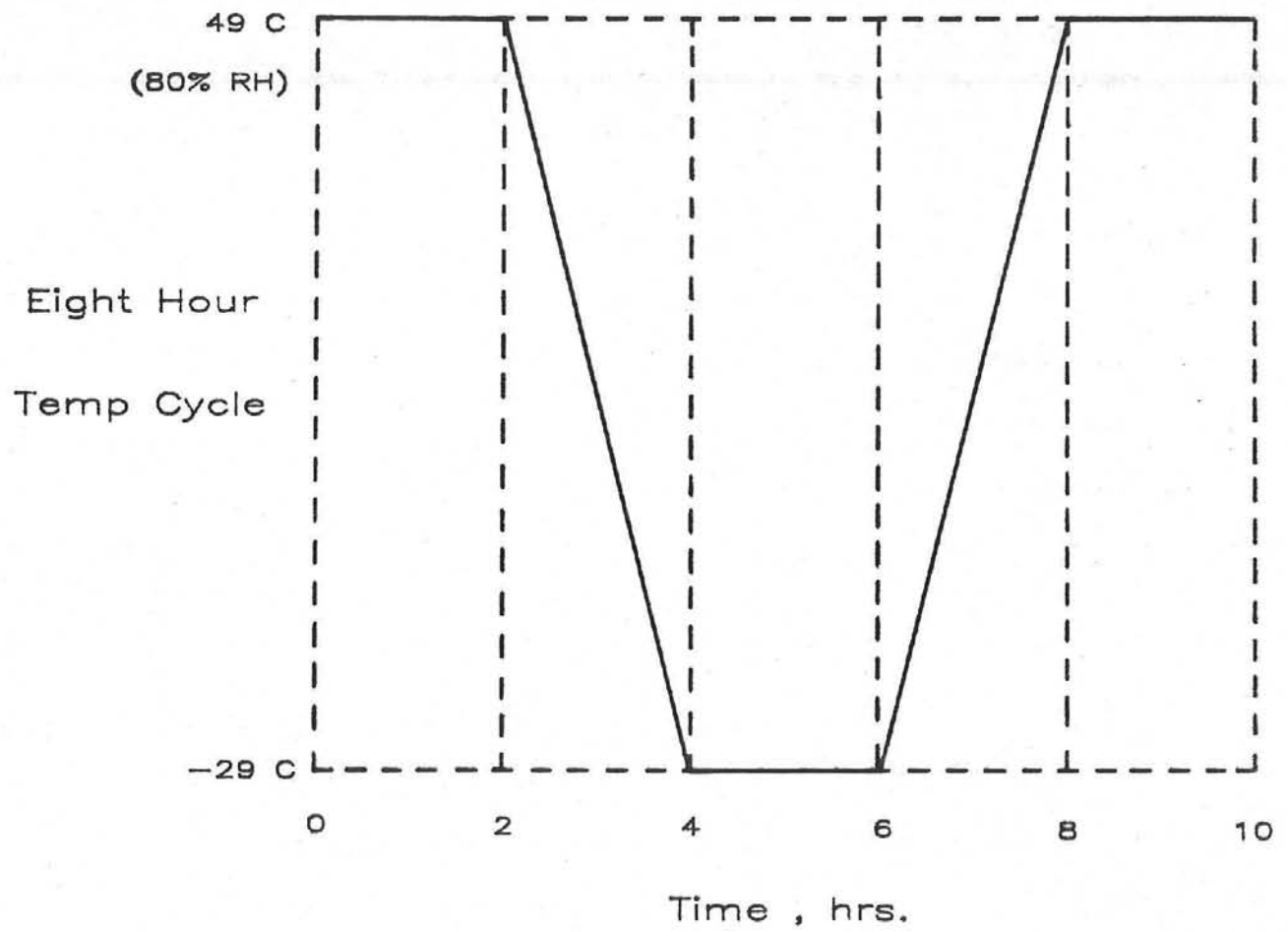


FIG. 4. Thermal cycling conditions previously used at Sandia for solar collector testing.

due to moisture and thermal gradients, as well as freeze/thaw mechanical stress/strain damage. It is now felt that the high and low temperature cycles used here more closely simulate actual summer/winter cycling conditions.

Three 30-cm square reflector panels were prepared, two samples were ECP-244 laminated to acrylic painted steel and the third was a control sample of ECP-244 laminated to aluminum. Samples were exposed in the environmental chamber and were removed after 26, 216 and 255 days for optical property measurements.

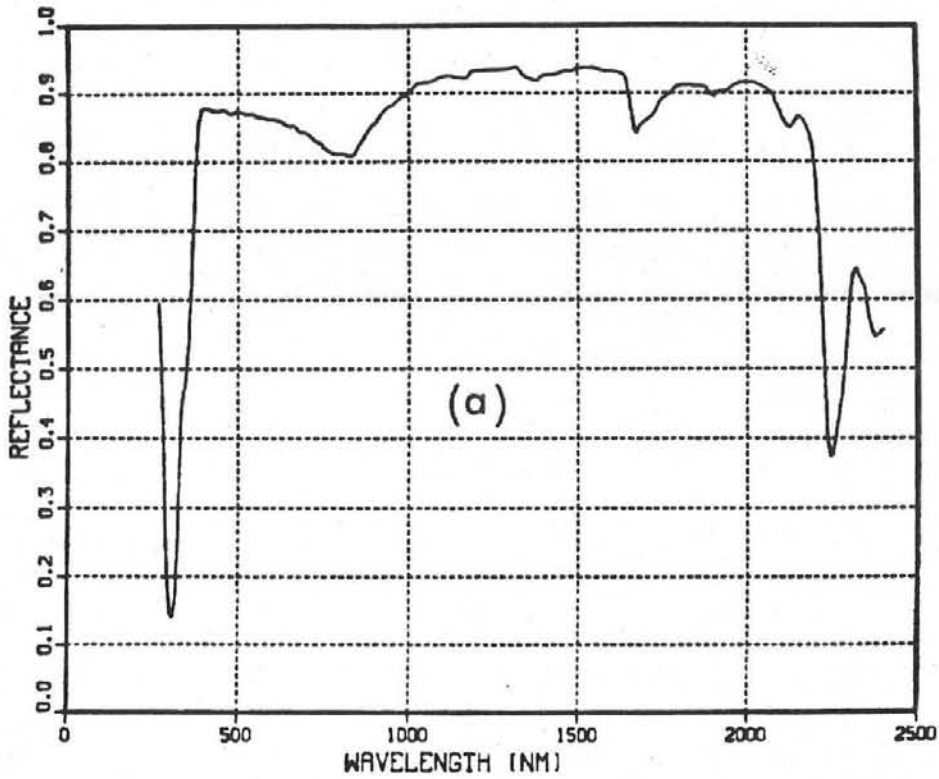
During the test chamber exposure, deposits accumulated on the reflector surface that caused a measurable decrease in the specular reflectance. Therefore, measurements were obtained for the samples both as-received and after cleaning. The cleaning procedure consisted of applying a mild detergent and de-ionized water solution to the mirror and wiping lightly with a soft towel. The surface was then rinsed with de-ionized water and allowed to air dry.

### Results and Discussions

The hemispherical and diffuse reflectance properties of a typical sample are shown in Figure 5 as a function of wavelength. For this sample, the solar averaged values were  $R_S(2\pi) = 0.853$  and  $R_S(D) = 0.019$ . The strong absorption bands at 300 nm, 1700 nm and 2250 nm are due to the acrylic film, while the broad reflectance minimum near 800 nm is due to an interband transition in aluminum. The solar averaged hemispherical reflectance value of 0.85 for this material is close to be theoretical maximum of 0.88 predicted for these materials.<sup>2</sup>

The important reflectance properties of the three samples are listed in Table I both as-received and after the environmental chamber exposure. The important results are summarized below:

HEMISPHERICAL REFLECTANCE OF ECP-244 ON ACRYLIC PAINTED STEEL



DIFFUSE REFLECTANCE OF ECP-244 ON ACRYLIC PAINTED STEEL

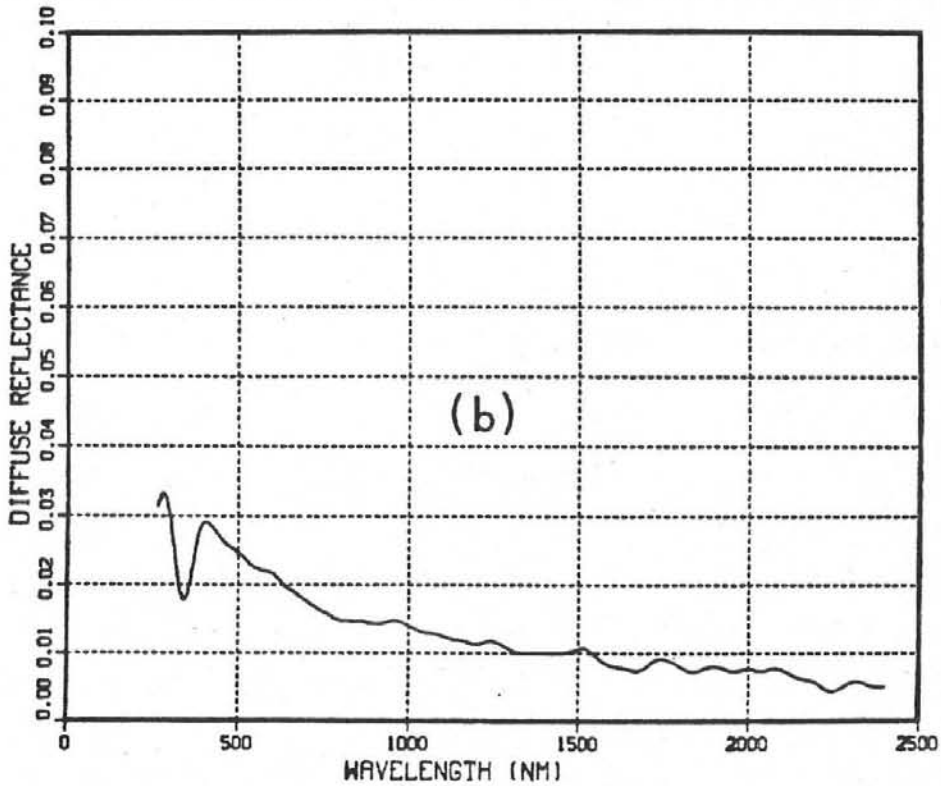


FIG. 5. Typical (a) hemispherical and (b) diffuse reflectance

TABLE. Summary of Optical Properties of ECP-244 Before and After Environmental Chamber Exposure

Sample	Condition	$R_g(2\pi)$ AM1.5	$R_g(D)$ AM1.5	$R_{D-S}$ (660;S)	$R(660; 2\pi)$	$\Delta R_g$ AM1.5	$R_g(S)$ AM1.5
#1 Acrylic Painted Steel	As-Rec	0.853	-	0.828	0.848	0.020	0.833
	26 d	0.851	-	0.833	0.847	0.014	0.837
	216 d/As-Rec 216 d/Cleaned	0.850 0.857	0.019 0.010	0.813 0.836	0.846 0.852	0.033 0.016	0.817 0.841
	255 d/As-Rec 300 d/Cleaned	0.852 0.852	0.006 0.012	0.832 0.837	0.849 0.847	0.017 0.009	0.835 0.843
#2 Acrylic Painted Steel	AS-REC	0.857	-	0.818	0.852	0.034	0.823
	26 d	0.854	-	0.830	0.849	0.019	0.835
	216 d/As-Rec 216 d/Clean	0.844 0.856	0.043 0.017	0.792 0.834	0.840 0.853	0.044 0.016	0.800 0.840
	255 d/As-Rec 300 d/Clean	0.848 0.850	0.019 0.020	0.832 0.836	0.845 0.844	0.013 0.008	0.835 0.842
#3 Rolled Aluminum	AS-REC	0.860	-	0.834	0.854	0.020	0.840
	26 d	0.857	-	0.835	0.852	0.017	0.840
	216 d/As-Rec 216 d/Clean	0.844 0.854	0.023 0.016	0.800 0.831	0.837 0.849	0.034 0.016	0.810 0.838
	255 d/As-Rec 255 d/Clean	0.846 0.849	0.019 0.020	0.814 0.820	0.840 0.841	0.023 0.018	0.823 0.831

(1) The solar averaged hemispherical reflectance values for all samples remained essentially constant throughout the exposure period. The average value of all samples after cleaning was  $0.853 \pm 0.003$ . After cleaning,  $R_g(2\pi)$  increased slightly, particularly after the 216 day exposure period; on the average the improvement was only 0.006 reflectance units.

(2) The solar averaged diffuse reflectance after cleaning also remained unchanged throughout the exposure, and was typically less than 0.020 reflectance units. The  $R_g(D)$  value was also approximately equal to the diffuse reflectance value at 660 nm. This means that changes in the D&S specular reflectance values accurately tracked changes in the solar averaged specular reflectance (i.e. from equation (2)  $\Delta R_g = \Delta R(660)$ ).

(3) The specular reflectance values measured with the D&S specular reflectometer actually increased after the 26 day exposure period as compared to the as-received condition. This increase was particularly evident for sample #2 (an increase of 0.012 reflectance units). Because the specular reflectance values for all three samples were approximately equal after the 26 day exposure period (0.837, 0.835, 0.840) while the  $R_g(2\pi)$  values remained unchanged, it is believed that the samples were cleaned during the initial chamber exposure as a result of humidity condensation. Therefore, it is recommended that, in future tests, all samples should be cleaned prior to their initial measurements and environmental chamber exposure.

(4) After cleaning the samples, the specular reflectance at 660 nm increased while the diffuse reflectance decreased. Thus, after 216 days of exposure,  $R_{D-S}(660; S)$  increased 0.023, 0.042 and 0.031 reflectance units for samples #1, #2 and #3, respectively, while  $R_g(D)$  decreased 0.009, 0.026 and 0.007 reflectance units. Therefore, surface contamination occurred during the chamber exposure, and it must be removed in order to adequately assess the effects of the exposure on the specular reflectance properties.

(5) The solar averaged specular reflectance values [ $R_s(S)$ ] after cleaning averaged  $0.840 \pm 0.003$  reflectance units through the exposure period, except for sample #3 which decreased to 0.831 after 255 days. Thus, the environmental chamber exposure did not alter the specular reflectance properties of the acrylic painted steel samples. While the decrease in specular reflectance for sample #3 to 0.831 is within experimental errors, the solar averaged hemispherical reflectance value for this sample did not change. The decrease in specular reflectance for sample #3 may be related to a change in the surface texture as discussed below.

(6) Finally, note that the solar averaged specular reflectance value of 0.840 is  $\sim 0.013$  reflectance units below the solar averaged hemispherical reflectance of 0.853. Thus, there was a small but measurable scattering of the reflected beam even for new samples, although the amount of scattering is close to our estimated experimental errors.

#### Surface Appearance

Visual examination of the samples before and after exposure revealed no apparent adhesion problems (peeling, checking, bubbling, etc.). Surface imperfections initially observed, before exposure, showed no indication of growth after exposure. Closer examination of the aluminum substrate sample #3, using dark field techniques, revealed a cloudy appearance due to scattering of light which originated between the outer acrylic film and the aluminum layer. The cloudiness of this sample correlates with the slight decrease in solar averaged specular reflectance value after 255 days exposure. However, there were still some areas that appeared more specular than the surrounding cloudy regions. These areas, illustrated in Figure 6, appeared as either narrow bands ( $\sim 6$  mm maximum width) or irregularly shaped splotches. The more



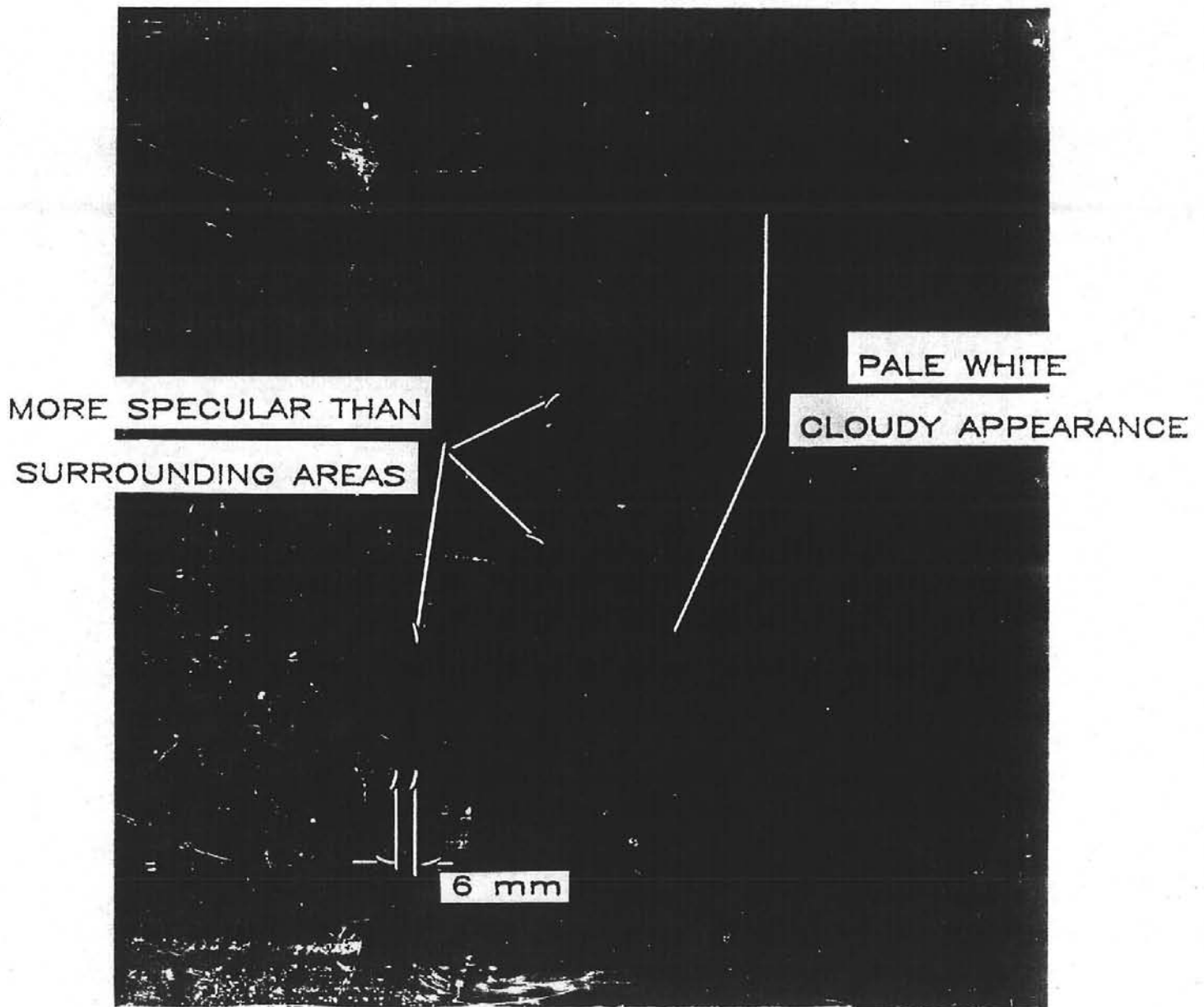


FIG. 6. Photographs of the ECP-244 reflector bonded to aluminum sheet after 300 days of environmental chamber exposure. Dark field techniques were used to highlight the mottled areas.

specular areas covered only ~25% of the sample surface. The fact that the more specular regions were all orientated in the same direction may indicate a processing problem during the lamination procedure.

Similar, but a much less noticeable, cloudy appearance was observed on the acrylic painted steel samples. In addition, the more specular areas only covered a small area of one side of each sample.

### Conclusions

1. The solar averaged specular reflectance values for an angular aperture of 46 mrad, after the 255 days environmental chamber exposure, varied 0.80 to 0.81. After cleaning, the values increased to an average of 0.840.
2. No degradation in the solar averaged specular reflectance was observed for either the acrylic painted steel reflector samples or the aluminum control sample under the testing conditions used, within experimental errors. Thus, the acrylic painted steel substrate appears to be a suitable substitute for an aluminum substrate.
3. No adhesion problems were apparent after the environmental chamber exposure. Mottled areas, which appeared to be under the protective acrylic film, were observed on all samples but were more pronounced on the aluminum substrate sample. The cause for these defects is unresolved at this time, but appear to have little effect upon the measured optical properties.

### References

1. See Proceedings of the Distributed Solar Collector Summary Conference - Technology and Applications, Sandia National Labs Report SAND83-0137 (March 1, 1983).\*

2. R. B. Pettit and E. P. Roth, "Solar Mirror Materials: Their Properties and Uses in Solar Concentrating Collectors", Chapter 5 in Solar Materials Science, Edited by L. E. Murr Academic Press (1980).
3. J. A. Leonard and R. W. Hunke, "The Shenandoah Solar Total Energy Project", Sandia National Labs Report SAND80-2560 (Dec., 1982).\*
4. B. A. Benson, "Acrylic Solar Energy Reflecting Film - 3M Brand ECP-244 (Formerly FEK-244)", in proceedings, pp. 501-505.
5. Identification of commercial equipment is included in order to adequately specify the experimental procedure. This does not imply endorsement by Sandia National Laboratories nor that the equipment identified is necessarily the best available for the purpose.
6. National Bureau of Standards Specular Reflectance Standards SRM 2023, Office of Reference Materials, Washington DC 20234.
7. R. B. Pettit, "Characterizing Solar Mirror Materials Using Portable Reflectometers", Sandia National Labs Report SAND82-1714 (Sept., 1982).\*
8. R. B. Pettit, J. M. Freese and A. R. Mahoney, "The Development of a Portable Specular Reflectometer for Monitoring Solar Mirror Material", SPIE Conference Optical Coatings for Energy Efficiency and Solar Applications, Aug. 23-24, 1983 (San Diego, CA). Paper 428-11.
9. M. A. Lind, R. B. Pettit and K. D. Masterson, Solar Energy Engineering 102, 34 (1980).
10. R. B. Pettit and J. M. Freese, Solar Energy Materials 3, 1 (1980).
11. R. B. Pettit and B. L. Butler, Proceedings ERDA Concentrating Solar Collector Conference, pp. 6-31 to 6-40. Georgia Institute of Tech, Atlanta, GA (Sept. 26-28, 1977).\*

---

\*Available from: National Technical Information Services  
 U. S. Dept. of Commerce  
 5285 Port Royal Road  
 Springfield, VA 22161

Distribution:  
Unlimited UC-62

AAI Corporation  
P. O. Box 6767  
Baltimore, Maryland 21204  
Attn: G. Ronald Christ  
Harold Wilkening

Burton A. Benson  
Energy Control Products Div.  
3M Company  
3M Center - Bldg. 209-2N  
St. Paul, Minnesota 55101

Devices and Services  
10,911 Dennis Road, Suite 405  
Dallas, TX 75229  
Attn: Charles Moore

Ford Aerospace and Communication  
Corporation  
Western Development Laboratory  
Division  
3939 Fabian Way  
Palo Alto, California 94304  
Attn: John Nitchey

Richard A. Hays  
White Sands Solar Furnace  
WSMR, STEWS-TE-AN  
White Sands, New Mexico 88002

Mr. E. W. Hoffman  
Solar Systems Industries, Ltd.  
No. 2-11771 Horseshoe Way  
Richmond B.C. V7A 4S5  
CANADA

Jacques L. Hull  
Acurex Corporation  
485 Clyde Avenue, MS 8-8800  
Mountain View, California 94042

Joe A. Hutchison  
Solar Kinetics, Inc.  
3300 Century Circle  
Dallas, Texas 75060

Paul Schissel  
SERI  
1617 Cole Blvd.  
Golden, Colorado 80401

Stan Moore  
LASL, Group Q-11  
P. O. Box 1663, MS-571  
Los Alamos, New Mexico 87545

George D. Rohades  
Lockeed  
Department 6263  
Building 104  
Sunnyvale, California 94086

1800 R. L. Schwoebel  
Attn: 1810 R. G. Kepler  
1830 M. J. Davis  
1840 R. J. Eagan  
1820 R. E. Whan  
Attn: 1821 N. E. Brown  
1822 K. H. Eckelmeyer  
1823 J. A. Borders

1824 J. N. Sweet  
1824 E. P. Roth  
1824 R. B. Pettit (4)  
1824 A. R. Mahoney  
3141 C. M. Ostrander (5)  
3151 W. L. Garner (3)  
3154 C. Dalin (25)  
for DOE/TIC  
5164 G. S. Kinoshita  
6222 J. V. Otts  
6224 E. C. Boes  
6227 J. A. Leonard (5)  
6227 R. L. Champion  
6227 R. L. Alvis  
8310 R. W. Rohde  
8424 M. A. Pound  
8450 J. B. Wright