FINAL REPORT

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PROTECTIVE COATINGS FOR
FRONT SURFACE REFLECTORS

PHASE I

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ABSTRACT

Silicone resins were evaluated as protective coatings for front surface aluminum and silver reflectors.

The solar weighted hemispherical reflectances and specular reflectances of float glass squares metallized with silver and aluminum and protected with silicone coatings were measured.

The float glass squares metallized with silver and aluminum were highly reflective. The total reflectances of the silver samples were 5-7% higher than the aluminized samples. The resin coated aluminum samples were much more specular than the silver samples. Coupling agents used to improve the adhesion of the protective silicone resin coating to the silver surface adversely affected the specularities.

The reflectances of the aluminized squares were remeasured after 500 hours exposure in an Atlas Filtered Weatherometer®. Some of the aluminized float glass squares protected with thin silicone resin coatings lost their good specularity after 500 hours exposure, however, some coatings were unaffected by this exposure.

Front surface aluminum reflectors can be protected with silicone resin coatings.

Work is now in progress to determine the durability of such protective coatings on silver and aluminum during exposure to harsh conditions including: sulfur dioxide, high humidity, salt spray and natural outdoor weathering. This work is funded by the Department of Energy and is monitored through the Materials Branch of the Solar Energy Research Institute in Golden, CO.

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I INTRODUCTION

Most power systems which use the sun as the energy source require concentration of the solar energy to achieve practical, usable fluxes. One of the most practical means of achieving this concentration is by focusing the solar rays with specularly reflective surfaces.

Conventional second surface glass mirrors are inefficient because a large portion of the incident radiation is absorbed by the glass. In addition these conventional mirrors degrade when used outdoors in weathering environments. Sheet metal reflectors such as anodized aluminum have lower reflectivity than conventional second surface silver mirrors and would require a protective coating to prevent loss of reflectance in harsh weathering environments.

The reflectors which are available in commercial quantities are fabricated using wet chemical techniques to deposit a reflective silver layer on the back or second surface of glass. This silver layer is usually protected with a layer of copper which is then painted. Reflectors of this type have been used in heliostats with marginal success. The reflectivity diminishes with time due to the weathering and degradation of the reflective silver surface.

Front or first surface reflectors have not been developed or used in current large scale applications because the increase in specular reflectance over conventional second surface reflectors made possible by such reflectors was not of significant value.

The potential of concentrating solar energy by using reflectors with relatively large surface areas has stimulated an interest in developing reflectors with high specular reflectance. There is a direct correlation between an increase in the specular reflectance and a decrease in the area of reflective surface needed to provide an

equivalent amount of energy at a target. This reduction in surface area means cost savings in terms of the amount of reflective surface needed and also reductions in the space required for the reflector field along with the accompanying aiming and maintenance costs.

The thin protective coating on a first surface reflector absorbs less energy than the glass cover of a back or second surface reflector. This permits more energy per unit area of incident solar radiation to be reflected and concentrated on a selected target. In order for this front surface reflector to be practical the protective coating must be durable, dirt resistant and transparent. In addition, the protective coating must have good adhesion to the reflective metal surface to provide protection from corrosion in weathering environments.

Silicone resins have the properties which are required for the protection of front surface reflectors. As a family of polymeric materials, silicones are known for their inertness and durability in high temperature and outdoor weathering environments. Most silicone resins and polymers can be formulated to provide a range of properties from very hard abrasion resistant coatings to relatively soft, stress-relieving elastomers.

This work is designed to evaluate a number of silicone resins which represent a range of physical properties and chemical compositions to determine the best candidate for use as protective coatings for first surface reflectors.

II RESULTS AND DISCUSSION

This investigation was divided into six separate identifiable tasks:

1. Identification and Characterization of Candidate Silicone Resins.
2. Measurement of Optical Properties of Cured Resin Films.
3. Measurement of the Resistance of Cured Resin Films to Dirt Pickup.

4. Measurement of Spectral and Specular Reflectance of Silicone Resin Coated Aluminized Float Glass Squares.
5. Changes in Specular Reflectance Caused by Exposure to UV Radiation.
6. Spectral and Specular Reflectance of Silicone Resin Coated Silvered Float Glass Squares.

Resin Identification and Characterization

Thirteen silicone resins were identified as potential candidates to be used as protective coatings for front surface reflectors. These resins were chosen because they represented a spectrum of chemical compositions, functionality and crosslink density. Silicone resins at all stages of commercialization were included in this investigation. These resins were coded using letters of the alphabet for identification because information on their chemical composition, functionality, and cure is disclosed which is proprietary. The functionality of samples of the candidate resins were measured and reported in Table I. Their functionalities range from greater than 11 to less than 1 weight percent.

The percent of functionality is usually an indication of the reactivity of a resin and its rate of cure. In general, a resin with high functionality is lower in molecular weight and cures faster than a resin with low functionality.

The degree of substitution is an indirect measure of the crosslink density of a resin. The silicon atom in most silicone polymers has four valence bonds. In silicate glasses all of these bonds are used to form a highly crosslinked brittle solid. Replacing these bonding valence sites with nonfunctional organic radicals such as methyl or phenyl diminishes the number of possible cross links and decreases the brittleness. Most silicone resins have degrees of substitution between one and two which means that on an average they have slightly

more than one non-functional organic group per silicone atom. The degree of substitution (ds) and phenyl, methyl and propyl to silicon ratios of the resins are also given in Table I. The relative phenyl and methyl to silicon ratios of the resins identified as candidates for this study represent a broad spectrum. See Table I.

The composition and formulation of the Resin designated E is not provided because it is a highly proprietary product.

Measurement of Optical Properties

Six of the candidate resins formed suitable films on quartz slides for measurements of their absorptions. These resins were designated A, B, C, E, G and H. The absorption of each film was measured every 15 nanometers between 215 and 340 nanometers using a Cary 14 Spectrophotometer. The values within the detection limits were normalized to a film thickness of 1 mil (0.001") and are plotted on Figure 1. The thickness of the films used in the absorption measurements varied from 0.17 mils to 5 mils.

All of the films were very transparent above 340 nanometers and had high absorptions below 240 nanometers but there were significant differences in the amount of absorption and where the absorption started for various resins.

Resins designated A and B had significant absorptions above 290 nanometers. Terrestrial solar radiation contains wavelengths above 290 nanometers and the high energy wavelengths between 290 nanometers and 400 nanometers would be expected to degrade materials which absorb energy in this region. Therefore, exposing Resins A and B to UV radiation should induce more changes than those seen with other resins.

Films of cured resins on quartz slides were also used to obtain their refractive indices by an interferometry technique. The interference bands caused by constructive and destructive interaction of light

waves passing through a thin film can be used to measure the thickness and refractive index of the film¹. The refractive indices of the cured resin films are also shown in Table I. All of the cured resin films have a refractive index of approximately 1.46 except Resin E which is 1.426. It would be desirable to tailor the refractive index of the cured resins so that a gradient of refractive indices could be obtained. Unfortunately, all of the silicone resins which are available have similar refractive indices except for Resin E, and there is only a 7% difference between Resin E and the other silicone resins.

Dirt Pick Up Measurements

Eight resins were coated on 4" x 4" glass squares and measured for transmittance between 350 and 2100 nanometers. Transmittance values were obtained every 75 nanometers between 350 and 650 nanometers and every 150 nanometers between 650 and 2150 nanometers. These samples were exposed outdoors at an angle of 45° South on a building roof top and remeasured for optical transmission at various time intervals. The changes in optical transmission as a function of time are a measure of the amount of dirt, abrasion, and changes in absorptance of the resin coatings. The data from these measurements are tabulated in Tables II, III, IV and V.

Figure 2 shows data for Resin A plotted after two periods of exposure: 6 weeks and 15 weeks.

The results from exposing the samples outdoors show the natural cleaning effects of precipitation. The transmittance readings taken after, 15 and 24 weeks exposure show an increase from the exposure periods which preceded them. This increase is due to the cleaning effect of precipitation which occurred during the exposure periods.

Replicate samples of these exposure samples were prepared and exposed in a similar manner. These samples were washed before the transmittance

¹Abbe-3L Reference Manual, Page 18.

measurements were made. Comparing the transmittance of washed and unwashed samples shows the amount of transmittance which is easily recoverable and what portion of the optical loss is not recoverable. The samples were washed by rinsing the samples with tap water, wiping them with a soft cloth and then blowing them dry with a stream of air.

The samples which were washed before reading the transmittance values were all quite close to the original value after 12 weeks outdoor exposure except for Resin I which has a significant loss in transmittance due to dirt which cannot be removed through gentle washing. See Table VI.

The exposure periods for the samples which were washed are not concurrent with those measured without washing. The exposure of the washed samples was started four months after the initial outdoor exposure studies.

Measurement of Spectral and Specular Reflectance

Four inch by four inch float glass squares, obtained from Libby-Owens-Ford were metallized with aluminum by Coatings Research in Chicago.

The metal was applied using vapor deposition techniques. These metallized float glass squares were coated with the candidate resins. Resins A, B, C, and I were spray coated on the aluminized float glass squares.

The samples which were spray coated with solutions of silicone resin had a disappointingly poor visual appearance after cure. This poor appearance was caused by a dimpling or "orange peel" surface effect and small particles of gelled resin or dirt.

Resins A, B, C, and I formed continuous protective films even though they had poor appearance and, therefore, they were submitted to Battelle Pacific Northwest Laboratories (BPNL) for specular and spectral reflectance measurements.

Resins E, F, H, and J were coated on aluminized float glass squares using a dip coating procedure. The coating obtained by dip coating Resin E was much better than the attempt of spray coating Resin E and it is likely that the specularities of Resins A, B, C, and I would have been higher if they had been dip coated. Resins D, K, L, and M were dropped from the evaluation because we could not obtain thin cohesive protective films with these resins. Resin G was dropped from the list of candidates because it became very soiled in the outdoor exposure tests and the percent transmission after 15 weeks of exposure outdoors was only slightly more than 60% of the original value. The solar weighted spectral reflectances are shown in Figure 3.

The best reflectance in terms of both total spectral reflectance and specularity was obtained with the aluminized float glass square coated with Resin E. This sample had a solar weighted spectral reflectance average of 89.7% for radiation between 300 and 2100 nanometers. The specular reflectance at incident beam angles of 10 and 45 are shown in Figure 4. See Exhibit A of the Appendix for a description of terms and how the specularity was measured. This information was supplied by Dr. Michael Lind of Battelle Pacific Northwest Laboratories, who made the reflectance measurements. The spectral and specular reflectances of uncoated aluminized float glass are shown in Figure 5. The values provided on the graphs are referenced to BaSO_4 and consequently are probably 2 to 3 percent higher than the true values.

Changes in Specular Reflectance Caused by Exposure to UV Radiation

Float glass squares metallized with aluminum and coated with Resins A, B, C, E, H, and I were exposed in an Atlas Filtered Weather-Ometer for 500 hours. The samples were then sent to Battelle Pacific Northwest Laboratories and remeasured for specular and spectral reflectance.

The spectral reflectances of the samples after 500 hours UV exposure are shown in Figure 6 and the specular reflectances are shown in Figures 7 and 8.

The two resins with good reflectance and specularity and which retained them after exposure to UV were Resins E and H. These are the most promising candidates for the protection of aluminum. See Figure 8.

Resin I showed the greatest amount of degradation both in terms of solar weighted spectral reflectance and specular reflectance. The spectral reflectance dropped from an initial value of 89.7% to 83% after 500 hours of UV exposure. This loss is due to pitting of the resin which was severely spotted. The roughness of the resin surface is displayed by its poor specularity. See Figures 6 and 7b.

The resins which provided the poorest reflectances after exposure to UV were Resins A, B, and I.

Spectral and Specular Reflectance of Silicone Resin Coated Silvered Float Glass Squares

Float glass squares metallized with silver were coated with Resin A, B, C, E, H, and I. The resin coatings were applied using a dipping technique.

Prior to use, the solutions of resin were filtered through a Gelman Micro Pore Filter which removes all particles larger than 1.2 microns and the coatings were applied in a Class 100 Clean Room. The reflectances of the float glass squares metallized with silver were all higher than those of the aluminized float glass squares as might be expected. The specularities of the silver surfaces coated with each resin were lower when compared with the corresponding resin coated aluminum surfaces.

Good adhesion of silver to polymeric coatings is often difficult to achieve and, therefore, a silane coupling agent was used to prime the silver surfaces before the solutions of resin were applied. The silane coupling agent was applied as a 1% solution in aqueous isopropyl alcohol.

The silver metallized glass squares coated with resin looked worse than the aluminized samples and had a haze or blush. This cloudiness is probably due to the Dow Corning® Z6020 coupling agent used to improve the adhesion of the resin to the silver surface.

The visual appearance did not correlate with the specularity measured at 10° and 45°. Reflective surfaces which looked cloudy often had higher spectral reflectance and better specularity than reflectors which appeared visually clear.

Three each of the resin coated silver surfaces were sent to Mike Lind at Battelle Pacific Northwest Laboratories. The widest variation in the solar weighted spectral reflectances of the triplicate samples was 96.2% to 93.2% for the samples coated with Resin A. The lowest spectral reflectance measured, 93%, was on a sample coated with Resin H. The average measured reflectances for silver coated with the six different resins ranged from 94.3% for Resin H to 97.8% for Resin E. See Figure 9. The specular reflectances of some resin coatings had wide variation. There was significant variation in values obtained at various places on each sample and between the three replicate samples. See Figure 10. The variation in specular reflectance measurements was greater on samples with poor specularity than on samples with good specularity. The specularity of the silver protected with Resin E was highest at both 10° and 45° and the variation in specularity was smallest. See Figure 10.

III CONCLUSIONS:

Aluminum, vapor deposited on float glass, has high specular reflectances and can be protected with silicone resins.

Silver, vapor deposited on float glass, is more highly reflective than aluminum; however, good adhesion of silver to both the glass substrate and the protective resin is difficult to achieve. The primers and

adhesion promoters for the protective silicone resin coating must be chosen and used in a way that preserves the high reflectance and specularity of the silver surface. More work is needed to determine the optimum coating techniques which provide uniformly specular, durable protective coatings for silver.

IV FUTURE WORK

This work is continuing under Contract XJ-9-8091-1 monitored by the Materials Branch of SERI in Denver, CO. This additional work is aimed at optimizing the coating formulation, thickness and method of application to provide the best protection in hostile environments. Both silver and aluminum front surface reflectors will be exposed to: high humidity, sulfur dioxide atmosphere, salt spray and natural outdoor weathering to determine the best protective coating. Analyses using optical and electronmicroscopy of samples which corrode should aid in an understanding of the mechanism of corrosion. This information will allow us to develop coatings which minimize corrosion of the reflective surface.

TABLE I

CANDIDATE SILICONE RESIN COATINGS

SUBSTITUTION				FUNCTIONALITY		COATING	
RESIN	ds	Ph/Si	Me/Si	%SiOH	%SiOMe	THICKNESS	R. I. n_D^{25}
A	1.60	.85	.75	0.86	--	1.07	1.4598
B	1.38	.75	.63	4.03	--	1.29	1.4656
C	1.50	.95	.55	1.24	--	0.82	1.4590
D	1.00	.70	.30*	5.91	--	0.55	1.4599
E	PROPRIETARY					0.26	1.4257
F	1.70	.30	1.40	0.17	6.84	0.73	1.4578
G	1.64	.40	1.24	0.81	6.32	4.97	1.4588
H	1.50	.50	1.00	0.88	1.00	0.33	1.4595
I	1.15	.65	0.50	5.35	--	--	--
J	1.00	.90	0.10	5.34	1.80	--	--
K	1.00	.80	0.20	10.8	0.80	0.8	1.4593

*PROPYL TO SILICON RATIO

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TABLE VI

TRANSMITTANCE VALUES OF WASHED SAMPLES

AFTER 12 WEEKS EXPOSURE OUTDOORS

WAVELENGTH (NANOMETERS)	RESIN A	RESIN B	RESIN C	RESIN D	RESIN E	RESIN G	RESIN H	RESIN I
350	93.1	93.1	91.7	98.4	94.5	77.3	85.6	79.4
425	98.3	97.7	96.6	95.4	100.5	90.3	93.2	84.7
500	98.8	98.3	97.7	96.1	100	95	95	86.1
575	98.9	98.3	97.8	95.6	100	96.7	96.1	86.2
650	98.3	97.8	97.8	95.6	99.4	97.2	96.1	85.8
800	97.5	97.5	97.5	95	98.1	97.5	97.5	89.3
950	96	96.6	96.6	94.6	97.3	97.3	97.3	87.3
1100	96.5	96.5	97.2	95.2	97.2	98.6	97.9	88.3
1250	96.5	97.2	97.2	95.2	97.9	98.6	98.6	88.4
1400	97.3	98	98	95.3	98.6	98.6	98.6	88.1
1550	97.4	98	98	96.7	99.3	99.3	98.7	89
1700	96.8	97.5	98.1	95	98.1	95.6	99.3	88.7
1850	98	98	98.7	95.4	98.7	99.3	100	89.6
2000	97.4	98	98.7	95.4	97.4	99.3	99.3	89.6
2150	95.5	96.1	96.7	91.6	98	96.1	99.3	89.1

TABLE II

TRANSMITTANCE VALUES OF UNWASHED SAMPLES

AFTER 6 WEEKS OUTDOOR EXPOSURE

WAVELENGTH (NANOMETERS)	RESIN A	RESIN B	RESIN C	RESIN D	RESIN E	RESIN G	RESIN H	RESIN I
350	85.2	94.1	86.1	94.1	95.5	76.4	89.7	92.6
425	89.6	95.7	90.9	96.9	99.3	80	93.3	96.9
500	86.3	92.3	88.7	94.6	95.8	78.1	95.8	94.6
575	91.1	97	92.3	99.4	101.7	82.8	92.3	99.4
650	100	96.5	97.7	97.7	98.8	93.1	97.7	96.5
800	83.4	80.9	82.2	79.7	83.4	69.9	82.2	79.7
950	88.5	87.2	87.2	87.2	88.5	64.4	88.5	87.2
1100	90.9	89.5	88.1	89.5	90.9	58.7	89.5	89.5
1250	87.5	87.5	87.5	87.5	88.8	55.5	88.8	87.5
1400	86.6	86.6	85.3	85.3	88	53.3	85.3	86.6
1550	86.2	86.2	83.6	84.9	88.8	50.9	86.2	86.2
1700	82.2	83.5	82.2	83.5	84.8	50.6	83.5	84.8
1850	84.9	86.2	83.6	84.9	87.5	50.9	86.2	86.2
2000	83.6	84.9	83.6	84.9	86.2	49.6	84.9	84.9
2150	82	83.3	82	83.3	83.3	48.7	83.3	83.3

TABLE III

TRANSMITTANCE VALUES OF UNWASHED SAMPLES

AFTER 15 WEEKS OUTDOOR EXPOSURE

WAVELENGTH (NANOMETERS)	RESIN A	RESIN B	RESIN C	RESIN D	RESIN E	RESIN G	RESIN H	RESIN I.
350	72	89.7	73.5	88.2	91.1	51.4	77.9	82.3
425	76.9	93.3	78.7	93.3	94.5	55.7	83.6	86
500	75.7	88.7	76.9	88.7	88.7	55.6	81.6	82.8
575	81.6	95.8	84	95.8	95.8	62.7	88.7	91.1
650	80.6	93.1	86.3	93.1	89.7	79.5	85.2	87.5
800	83.4	95.7	90.7	95.7	92	71.1	89.5	90.7
950	89.9	102	97.9	100.6	97.9	76.5	96.6	97.9
1100	92.3	102	99.3	100.6	99.3	78.3	97.9	99.3
1250	90.2	100	97.2	98.6	97.2	79.1	95.8	97.2
1400	89.3	98.6	96	97.3	94.6	78.6	94.6	94.6
1550	88.8	98	95.4	94.1	92.8	78.4	92.8	92.8
1700	88.6	96.2	93.6	93.6	91.1	78.4	92.4	92.4
1850	88.8	95.4	95.4	95.4	91.5	79.7	92.8	92.8
2000	88.8	95.4	94.1	94.1	90.1	79.7	91.5	91.5
2150	87.1	93.5	93.5	93.5	88.4	79.4	91	91

TABLE IV

TRANSMITTANCE VALUES OF UNWASHED SAMPLES

AFTER 18 WEEKS OUTDOOR EXPOSURE

WAVELENGTH (NANOMETERS)	RESIN A	RESIN B	RESIN C	RESIN D	RESIN E	RESIN G	RESIN H	RESIN I
350	63.2	94.1	74.2	84.1	88.2	51.4	72.9	
425	67.2	87.5	79.2	88.4	90.9	61.5	77.9	
500	68.6	84.9	77.1	85.2	86.5	63.1	75.5	
575	76	91.4	84.3	92.3	94.4	71	82.1	
650	84	100	93.1	101.1	102.8	79.8	90.9	
800	81.5	87.1	85.8	91.5	94.4	73.6	87.1	
950	88.5	92.8	93.2	97.5	102	80.5	95.3	
1100	88.1	90.9	92.8	96.5	100.6	82.5	95.1	
1250	86.1	88.8	91.1	94.1	98.6	81.9	93	
1400	82.6	84	86.6	89.3	93.3	81.3	89.3	
1550	83.6	84.9	86.2	87.5	92.8	81	89.8	
1700	83.5	83.5	86	86.8	91.1	79.7	88.6	
1850	86.2	86.6	88.8	91.5	94.1	82.3	91.5	
2000	85.4	86.2	88.8	90.1	92.8	83	90.9	
2150	84.3	83.7	86.5	87.1	89.7	79.4	89.1	

TABLE V

TRANSMITTANCE VALUES OF UNWASHED SAMPLES

AFTER 24 WEEKS OUTDOOR EXPOSURE

WAVELENGTH (NANOMETERS)	RESIN A	RESIN B	RESIN C	RESIN D	RESIN E	RESIN G	RESIN H	RESIN I
350	69.4	89.5	73.6	84	88.1	45.8	75.6	79.8
425	75	93.3	80	88.3	93.3	57.2	83.3	86.6
500	77.7	94.5	82	89.6	93.4	63	85.8	88.5
575	78.9	94.5	83.7	89.7	93.5	65.9	87.5	90.2
650	79.8	95.6	85.8	91.3	94.5	68.4	89.1	91.3
800	84.2	94.9	90.5	92.4	95.5	62.2	92.4	93.7
950	86.4	95.9	92.5	93.2	96.6	66.2	93.9	95.2
1100	87.5	96.5	95.1	90.9	97.9	69.4	95.8	95.8
1250	87	95.2	93.8	92.5	97.2	71.4	94.5	95.2
1400	88.1	96	93.4	92.1	96.7	73.6	96	95.3
1550	89.1	96.1	93.5	89.7	96.1	74.3	94.8	94.8
1700	88.8	95.6	93.7	91.3	95	74.5	95.6	95.6
1850	90.3	96.1	94.2	92.9	95.5	77.5	96.1	95.5
2000	89.8	95.5	94.2	92.3	93.6	78.9	95.5	94.9
2150	88.6	94.3	93	90.5	93	76.5	95.5	94.3

FIGURE 1

ABSORPTION OF RESINS

FIGURE 2

RESIN A - 6 AND 15 WEEKS OUTDOORS UNWASHED

FIGURE 3

SPECTRAL REFLECTANCE OF ALUMINIZED FLOAT GLASS

PERCENT SOLAR REFLECTANCE

Reflectances Referenced to BaSO_4

FIGURE 3 (cont.)

Spectral Reflectance of Aluminized Float Glass

Percent Solar Reflectance

Reflectances Referenced to BaSO_4

FIGURE 4
Specular Reflectance of Aluminized Float Glass

For each resin < Upper curve is at 10° measurement angle
lower curve is at 45° measurement angle

FIGURE 4 (cont.)
 Specular Reflectance of Aluminized Float Glass

For each resin $\left\{ \begin{array}{l} \text{Upper curve is at } 10^\circ \text{ measurement angle} \\ \text{lower curve is at } 45^\circ \text{ measurement angle} \end{array} \right.$

FIGURE 5

Reflectances of Uncoated Aluminized Float Glass

5a

Spectral Reflectance

5b

Specular Reflectance

FIGURE 6

Spectral Reflectance of Aluminized Float Glass After
500 hours on Atlas Weather-Ometer

Percent Solar Reflectance

Reflectances Referenced to BaSO_4

FIGURE 6 (cont.)

Spectral Reflectance of Aluminized Float Glass After
500 hours in an Atlas Weather-Ometer

Reflectance Referenced to BaSO_4

FIGURE 7a

Specular Reflectance of Aluminized Float Glass After
500 hours in an Atlas Weather-Ometer

Figure 7b

FIGURE 8

Specular Reflection of Aluminized Float Glass
after 500 hours in an Atlas Weather-Ometer

FIGURE 9

Spectral Reflectance of Silvered Float Glass

Percent Solar Reflectance

Reflectances Referenced to Ba SO₄

FIGURE 10

Specular Reflectance of Silvered Float Glass

FIGURE 10 (cont.)

Specular Reflectance of Silvered Float Glass

APPENDIX A

SPECULARITY MEASUREMENTS

The basic principle of the specularity measurement performed at PNL is illustrated in Figure 1. A collimated, monochromatic beam of light is incident on a sample. The size, shape and intensity profile of the beam can be tailored as desired. The beam is polarized parallel to the plane of the sample (out of the plane of the figure). The incident beam is reflected from the sample and collected with a simple plano-convex lens of focal length f .

The intensity distribution of the light in the focal plane of the collection lens contains much of the information about the reflecting surface of the sample mirror. The actual information displayed is a convolution of the intensity function of the input beam with the Fourier transform of the reflectance function of the mirror. The problem of extracting useful engineering data can be simplified by an expeditious choice of input illumination functions and image analysis techniques.

Take, for example, the case where the input beam has a uniform circular distribution and the mirror has a non-periodic scattering function. The light scattered by the mirror surface which deviates from the specular direction by an angle θ is displaced by a distance d in the focal plane of the collection lens. Using simple geometry, one can show that for small scattering angles,

$$d \approx f\theta \quad (1)$$

where f is the focal length of the lens. Thus by measuring the distribution of light at the focal plane, one can determine the scattering distribution of the mirror.

In actual practice it is difficult to measure the intensity distribution accurately for a variety of reasons. One technique which PNL is using to circumvent the problem and still obtain useful engineering data employs a variable circular aperture centered on the specular point at the focal plane.

One then measures the integrated intensity as a function of aperture radius for some arbitrarily small value to another arbitrarily large value which collects all the scattered light. The present PNL setup measures the scattered light for $\theta = 0.5$ to 14 milliradians. This range of angles is sufficient to characterize most materials of interest.

The actual system used for making the measurements is slightly more complicated. It is shown schematically in Figure 2. The principle of operation is the same as described above. The additional equipment is required to perform the experiment with reasonable accuracy in the laboratory.

The raw data that is produced is affected not only by the light scattered from the mirror, but also by light scattered from other sources such as the collimating lens and the spatial filter. This "background" scatter may be quantified and subtracted out by measuring a reference mirror or measuring the straight through beam. (PNL uses a well-characterized reference mirror.)

For most specular materials of interest, the amount of reflect flux contained in a cone of 28 mrad ($\theta = 14$ mrad) is within 1% of the flux measured in a hemispherical reflectance measurement. It is therefore convenient to normalize the data to the full aperture value (28 mrad). The corrected and normalized data can then be plotted as a function of angular aperture size (2θ). It should be noted that in using this procedure, large errors can result if the materials are non-specular and the flux contained in the 28 mrad is not close to the hemispherical flux value.

Many surfaces tend to possess Gaussian scattering distributions because the statistics of the surface roughness can be represented by Gaussian distributions. Although this is not generally true, it is still convenient to use the notion of a standard deviation for engineering calculations. Therefore, we also report as the standard deviation (σ) the angular aperture diameter that corresponds to 61% of the total flux contained in the 28 mrad full aperture.

Thus PNL presently reports a σ value which corresponds to the full circular-angular aperture that contains 61% of the reflected (or transmitted)

flux. This value is valid only for fairly specular materials, since we make no attempt to normalize to the hemispherical reflectance of the sample. Caution must be exercised when comparing the PNL values to values obtained by other researchers. The effects of aperture shape and large angle scattering can be significant for many materials.

There are two specific cases where the reported sigma values can be applied to engineering calculations without concern. These are: 1) where the material is an isotropic scatterer and specularity is sufficiently high that the 28 mrad aperture contains all the hemispherical flux, or 2) when Gaussian statistics are applicable and the flux distribution can be extrapolated for large angles. In cases where the materials are non-isotropic scatterers or Gaussian statistics are not applicable, some judgment must be used in applying the result to general engineering calculations. In either case, the results are useful for comparing similar materials.

BASIC PRINCIPLE OF SPECULARITY MEASUREMENT

Figure 1.

OPTICAL CONFIGURATION FOR SPECULARITY MEASUREMENT

Figure 2.