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REFLECTANCE AND AGING STUDIES OF HELIOSTAT MIRRORS

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A brief review of the principles involved in making reflectance measurements of mirrors over the solar spectrum including air mass correction is given. Using these principles, reflectance measurements of different commercial silvering processes on the same glass showed no significant differences between the processes studied, including vapor-deposited silver. In addition, reflectance measurements were made of bare silver, silver/copper, silver/copper/paint over glass, together with transmission measurements on the same glass. Based on these results, a correlation between transmission and reflectance efficiency after mirroring was developed. Subsequently, these mirrors, as well as candidate first-surface mirrors, were subjected to Mojave Desert, CA environmental conditions for time periods up to $3\frac{1}{3}$ years. Of the mirrors tested, second-surface glass mirrors and first-surface aluminized acrylic mirrors exhibited the greatest weathering properties.

1. Introduction

In the Central Receiver System, solar radiation is concentrated by a large field of heliostats that reflect and superimpose the sun's rays onto a receiver-boiler mounted on top of a central tower. The heliostats consist of mirrors mounted to a tracking system that has the capability of following the sun's seasonal and diurnal paths through the sky.

To select the optimum mirror concept, studies were conducted consisting of measurements of reflectance resulting from different silvering processes, glass transmission measurements on candidate glasses, and weathering tests on mirrors made from these glasses as well as on first-surface mirrors.

2. Measurement techniques

The reflectance measurements consisted of measuring the energy striking the mirror's surface and comparing it to the measured energy reflected. The spectral characteristics of the solar spectrum available to strike a mirror's surface on the earth's surface were taken into consideration because the wavelengths that are absorbed by the earth's atmosphere are not available for conversion to thermal energy. Consequently, to depict the average sunlight for the North American Continent, an Air Mass Two (AM2) correction was used, which can be thought of as radiant flux from the sun reaching sea level with the sun angle 60° from the zenith as viewed through a "standard" atmosphere [1]. Mirror efficiency can be measured and integrated over a large number of wavelengths depending upon the accuracy required. As a reasonable compromise between cost and accuracy, the cumulative energy column for $m=2$ (AM2) from the studies of Sheklein [2] was divided into 10% energy increments, and solar reflectance efficiency was obtained by averaging the 10 measurements taken at the wavelengths corresponding to the midpoints of the 10% energy increments (fig. 1). On specimen No. GD-S3, a difference of 1% was seen between the 10 point averaging method versus the exact integral. All reflectance and transmission measurements made in this study were hemispherical weighted to an AM2 correction.

A Beckman model DK-2A spectroreflectometer, with reference samples made from Eastman White Reflectance Standard, was employed to determine values of hemispherical reflectance at the wavelengths described.

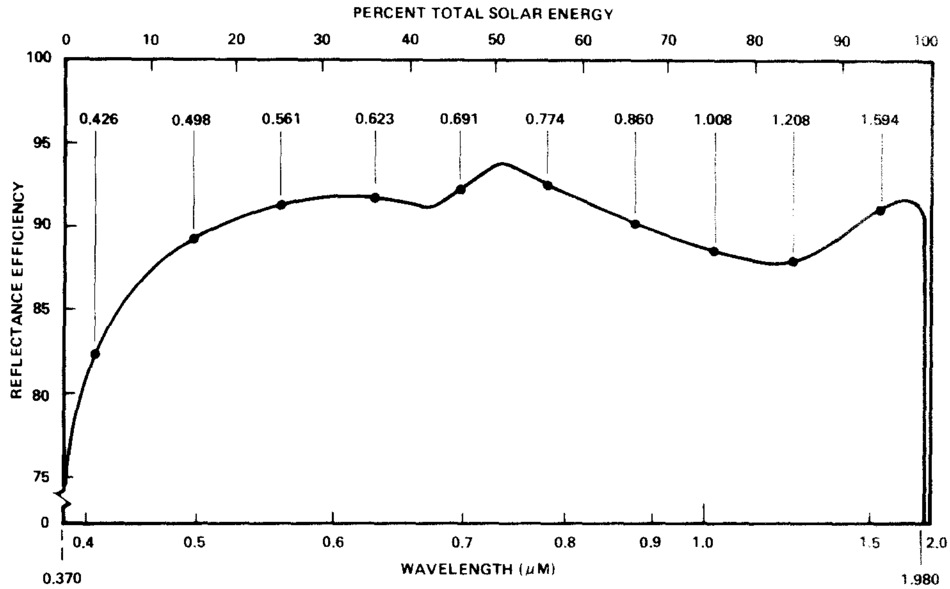


Fig. 1. Typical ten-point air mass two spectral measurement.

3. Experimental results

Reflectance efficiency was measured on second-surface glass mirrors using glass taken from one large light measuring $\frac{1}{8} \times 47\frac{1}{2} \times 131\frac{1}{2}$ in.^{3} ($0.32 \times 121 \times 334$ cm^3) and depositing silver by both chemical and vapor deposition methods. The results, shown in table 1, together with earlier measurements on bare silver [3] indicate that the reflectance efficiencies of both application methods are comparable and that, of the different commercial silvering processes studied, no significant differences were found in terms of achieving higher reflectance efficiency. These measurements, except for the bare silver measurements which were made on the front surface, were made

Table 1
Reflectance measurements of silvered mirrors

Mirror manufacturer	Silver deposition	Surface being measured	Specimen no.	Efficiency (%)
theoretical [4]	vapor	front	–	99
Mirrorlab [3], Texas	chemical	front	–	98
Donelley, Michigan	vapor	second	D-1	90
		second	D-2	89
Buchmin Ind., California	chemical	second	BCHM-1	92
	chemical	second	BCHM-2	92
Binswanger Mirror Co.,	chemical	second	BNS-1	92
Arizona	chemical	second	BNS-2	92
Carolina Mirror Corp.,	chemical	second	CRL-1	91
N. Carolina	chemical	second	CRL-2	91
Gardner Mirror Corp.,	chemical	second	GD-s1	90
N. Carolina	chemical	second	GD-s2	91
	chemical	second	GD-s3	91
	chemical*	second	GD-s4	91
	chemical*	second	GD-s5	91
	chemical*	second	GD-s6	91
Mechanical Mirror Works,	chemical	second	MMW-1	90
New York	chemical	second	MMW-2	90

*Enhanced solaflect formula.

on a special low-iron-content float glass, 3.2 mm ($\frac{1}{8}$ inch) thick, manufactured by PPG Industries.

To see if mirror backing paints would increase the mirrors' reflectance efficiency, mirrors with a white and grey mirror backing paint were studied with the idea that a white mirror backing paint would be more efficacious. To test this hypothesis, both mirror backing paints were removed, and reflectance efficiency, before and after paint removal, were made. The results (table 2) show that removal of the paint did not lower the reflectance efficiency, indicating that the paint does not enhance reflectance efficiency. This fact is of some interest in cases where the lamination with a

Table 2
Reflectance measurements of mirrors with and without backing paint

Specimen no.	Color paint	Mirror manufacturer	Reflectance efficiency: before paint removal	Reflectance efficiency: after paint removal
BNS-1	grey	Binswanger Mirror Co.	90	90
BNS-2	grey	Binswanger Mirror Co.	90	90
114-1 (A)	white	Binswanger Mirror Co.	87	87
114-1 (B)	white	Binswanger Mirror Co.	87	87

glass back light is made directly to the copper without the use of any mirror backing paint. The fact that there is no loss in reflectance efficiency of a silver–copper system is somewhat surprising, inasmuch as one can see bright light source through these mirrors when they are held up to the light coming from the source.

The paint was removed without damaging or removing the copper by softening the paint with dimethylformamide for 5 to 10 min. The grey paint was an alkyd melamine type, and the white, an acrylic, both manufactured by Glidden-Durkee Division of SCM Corporation. Transmission measurements of these mirrors before and after paint removal were essentially zero.

Reflectance and transmission measurements were made on various commercial grades of glass of different thicknesses and iron content. The results are shown in table 3, and the reflectance properties are plotted in fig. 2 with curves from an earlier study [3] to illustrate the strong dependency of reflectance efficiency on iron content and glass thickness.

Using a ray trace technique, equations for correlating reflectance efficiency with transmission efficiency were developed and are illustrated in fig. 3. To test this correlation, values for R_2, R_1 and G were needed.

To solve for R_2, the reflectance efficiency at the silver–glass interface, the limiting case of zero sample thickness was used. For the mirrors studied R, the average reflectance efficiency at zero thickness (average value of y intercept in fig. 2), was $(96 \pm 2)\%$. The glass transmission efficiency (G) would be 1 for a zero sample thickness since

$$G = e^{-\alpha t}, \tag{1}$$

where α = absorption coefficient, and t = glass thickness, and substituting $t = 0$, $G = e^{-0}$ or 1.

The reflectance efficiency at the front surface R_1 would equal 0.04 from Snell's law

Table 3
Glass reflectance and transmission measurements

Glass manufacturer	Glass thickness mm (in.)	Reflectance efficiency (%)	Transmission efficiency (%)
PPG Industries clear float	2.38(3/32)	89	87
	3.18(1/8)	86	86
	6.35(1/4)	79	82
Ford Motor Co	2.38(3/32)	91	88
	3.18(1/8)	89	87
	6.35(1/4)	81	83
PPG Industries low-iron float	3.18(1/8)	92	88
LOF Solar 90 sheet	3.18(1/8)	94	90

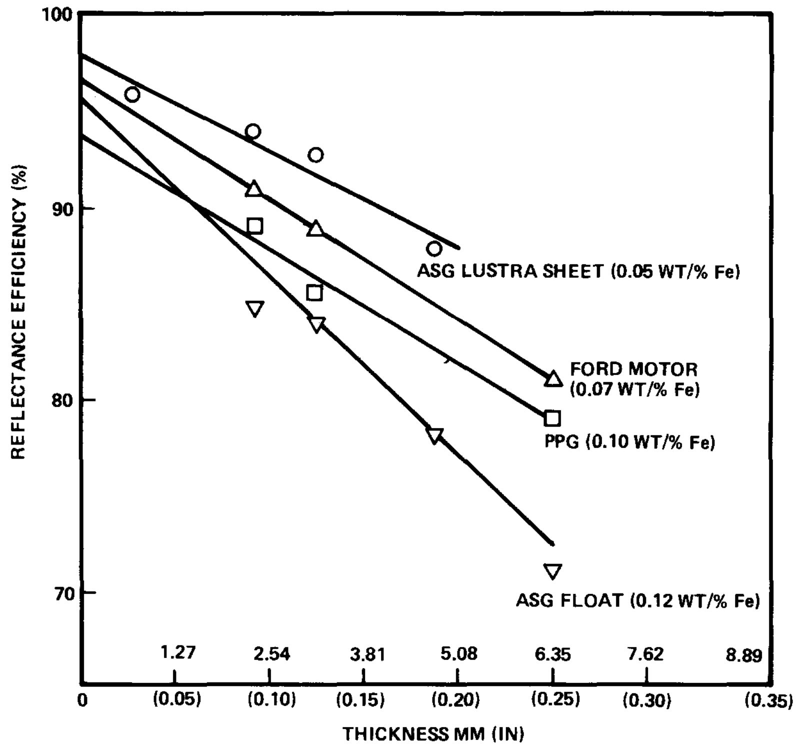


Fig. 2. Total reflectance efficiency for various mirrors.

with $N=1.51$ (index of refraction for float glass). Substituting these values in eq. (2)

$$R=R_1+G^2R_2(1-R_1)^2/(1-G^2R_1R_2), \tag{2}$$

a value for the reflectance efficiency at the silver–glass interface of $R_2=0.96$ was obtained.

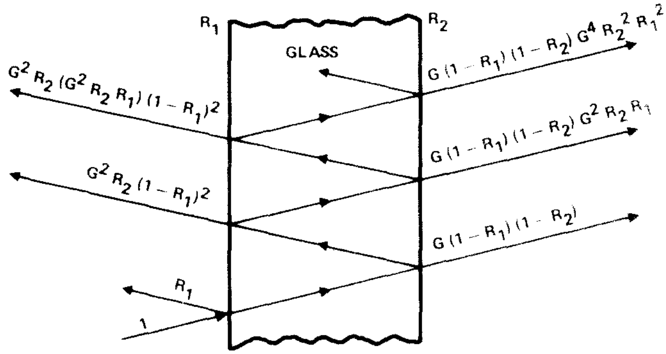
Having solved for R_2, the correlation between reflectance efficiency of silvered glass mirrors with the transmission properties of the glass could be calculated using eqs. (2) and (3)

$$T=G(1-R_1)(1-R_2)/(1-G^2R_1R_2) \tag{3}$$

for given values of G. In eq. (2), values of $R_1=0.04$ and $R_2=0.96$ were used while in eq. (3), values of $R_1=R_2=0.04$ were used.

The results are plotted as a straight line in fig. 4 together with experimental results which were taken from table 3 and shown as circled dots. The actual reflectance efficiencies are higher than can be explained by experimental error from the derived equations using a value of 0.96 for the reflectance efficiency for the silver–glass interface. However, if a theoretical efficiency of 99% for pure silver is used for R_2, the results, which are plotted as a dashed line in fig. 4, agree with the experimental results.

Aging studies were conducted on second-surface glass mirrors and first-surface



$$\%T = G(1 - R_1)(1 - R_2)[1 + G^2 R_2 R_1 + G^4 R_2^2 R_1^2 + \cdots]$$

$$= \frac{G(1 - R_1)(1 - R_2)}{1 - G^2 R_1 R_2}$$

$$\%R = R_1 + G R_2^2 (1 - R_1)^2 [1 + G^2 R_2 R_1 + G^4 R_2^2 R_1^2 + \cdots]$$

$$= R_1 + \frac{G^2 R_2 (1 - R_1)^2}{1 - G^2 R_1 R_2}$$

WHERE

R_1 = REFLECTANCE FROM PART SURFACE OR 0.04

FROM $R = [(N - 1)/(N + 1)]^2$

R_2 = REFLECTANCE FROM BACK SURFACE OR 0.04 FOR TRANSMISSION MEASUREMENTS AND 0.96 FOR REFLECTANCE MEASUREMENTS, AND

G = TRANSMISSION EFFICIENCY IN THE GLASS

Fig. 3. Equations developed by R. Surowiec of Ford Motor Co. glass division.

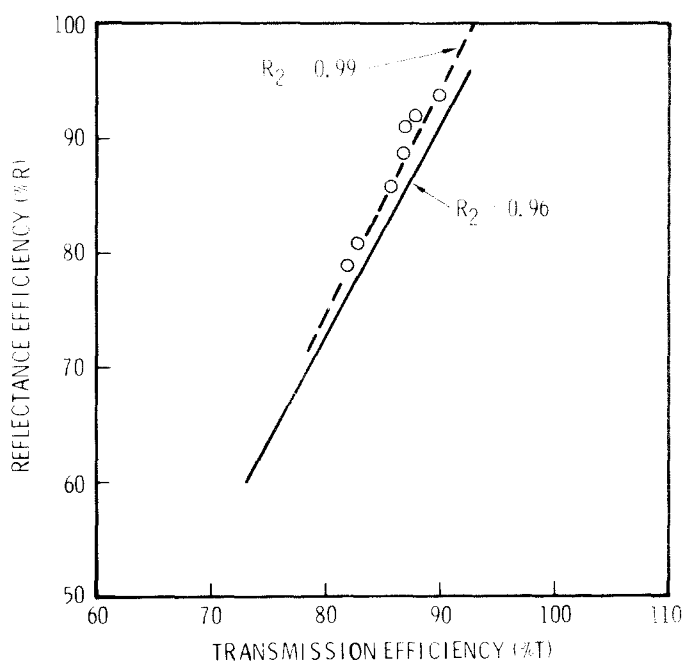


Fig. 4. Expected reflectance efficiency as a function of transmission efficiency.

mirrors by exposing test specimens measuring approximately 15.2×15.2 cm^2 (6×6 in.^{2}) on a 45° south-facing rack at Fort Irwin, CA which is approximately 64.4 km (40 miles) north of Daggett, CA the site of the 10 MW Solar Power Plant.

First-surface mirrors were prepared for the most part by depositing clear transparent coatings over bare chemical-deposited silver in glass lights measuring $0.32 \times 30.5 \times 61.0$ cm^3 ($\frac{1}{8} \times 12 \times 24$ in.^{3}), which were subsequently cut into specimens $0.32 \times 15.2 \times 15.2$ cm^3 ($\frac{1}{8} \times 6 \times 6$ in.^{3}). Some 55 different coatings were studied which were prepared by a variety of different companies. These coatings were for the most

Table 4
Exposure results for first-surface mirrors

Specimen no.	Coating manufacturer	Coating type or identification	Exposure (days)	Remarks
150	3M (FEK 244)	acrylic	132	OK
84	PPG Ind	no. 4	132	failed
69 & 149	O'Brien	UV5-73C	164	failed
70–81	Rohm and Haas	no. 1 to 12	164 to 885	failed
68	O'Brien	UV873-200, 2C	183	failed
105	Owens Illinois	type 650	190	failed
125–132	Desoto	1091-1 to -8	190 to 811	failed
99–101	Dupont	no. 1 to 3	463 to 811	failed
102	Sierricin	FX-103	567	failed
103	Textar Plastics	C-254	645	failed
108	3M (Scotchcal 5400)	acrylic	811	slight crazing
63	Sheldahl	822-12A	1139	failed

Table 5
Exposure results for second-surface glass mirrors

Specimen no.	Mirror paint	Mirror manufacturer	Exposure (days)	Remarks
64	PPG Ind	Buchmin Ind	132	no corrosion
65*	PPG Ind	Buchmin Ind	132	no corrosion
66*	–	Guardian Ind	530	no corrosion
67*	Gardner	Gardner Mirror Co.	530	no corrosion
50	Draggert	Tyre Bros	530	no corrosion
54	PPG Ind	PPG Ind Lab	532	slight edge attack
85*	Glidden acrylic	Binswanger Mirror Co.	803	no corrosion
87–91	Glidden	Binswanger Mirror Co.	803	no corrosion
115	Glidden Acrylic	Binswanger Mirror Co.	803	no corrosion
55	Peacock	Peacock Lab	1163	no corrosion
56–57	PPG Ind	Carolina Mirror	1163	no corrosion
58–62	PPG Ind	Buchmin Ind	1163	no corrosion
52*	PPG Ind	Buchmin Ind	1200	slight edge attack
51	Draggert	Tyre Bros	1200	no corrosion

*Laminated mirrors with glass back light.

part proprietary in nature; consequently, identification of the coatings was unavailable. These coatings could be applied on a conventional mirror line by replacing the standard mirror backing paint with these coating formulations resulting in a highly transparent first-surface mirror that would be more cost effective than mirrors made with conventional metallized films bonded to a rigid substrate. However, for comparison purposes, an aluminized acrylic film bonded to glass was also tested. The results (table 4) show that these coatings were not weatherable. Failure usually occurred by moisture permeating through the coating or from the edge and attacking the silver. The conventional first-surface mirror using aluminized acrylic film showed some promise of weatherability. After 811 days of exposure, only some slight crazing was observed.

Second-surface glass mirrors, on the other hand, are more durable. Exposure times up to 1200 days have resulted in mirrors exhibiting only some slight edge attack as shown in table 5.

References

[1] F. N. Benning, Solar Energy 12 (2) (1968).
[2] A. V. Sheklein, Geliotekhnika 3 (1967).
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[4] Applied Optics and Optical Engineering, ed. R. Kinglake (Academic Press, New York, London, 1965) p. 313.