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Thermal Power Systems
Advanced Solar Thermal Technology Project

Glass for Solar Concentrator Applications

April 1, 1979

Prepared for
U.S. Department of Energy
by

Jet Propulsion Laboratory
California Institute of Technology
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Prepared by the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy through an agreement with the National Aeronautics and Space Administration.

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PREFACE

This work was performed by the Applied Mechanics Division of Jet Propulsion Laboratory, California Institute of Technology.

ACKNOWLEDGMENT

The author gratefully acknowledges the contributions from many individuals from industry and government that made this report possible. Special recognition is given to Sandia Corp., McDonnell Douglas Astronautics-West, and Corning Glass Works. Recognition is given to members of the JPL solar-thermal power development team, including Dr. Marc Adams and Hugh Maxwell of the JPL Materials Development Group.

ABSTRACT

Materials for highly reflective surfaces for application to solar thermal power systems are treated in this report. The primary consideration is on the use of second-surface glass mirrors with comparison to alternate candidates.

Flat, parabolic, and Fresnel lens systems are contenders for solar thermal concentrators of various power requirements. The emphasis in this report is on glass for parabolic reflective surfaces. The technology status and experimental data on glass, metallic and polymeric concentrators are presented.

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SECTION I

INTRODUCTION

With the increasing interest in the conversion of the sun's energy to do useful work for mankind, the solar-thermal power system is attractive and has been for considerable time. For some of the historical aspects, see References 1 through 6. The use of reflective surfaces, i.e., mirrors, for redirection and concentration of the solar light rays is becoming more important. This report treats the properties of basic glass materials in general and glass of second-surface mirrors in particular. These subjects are vast and are extensively documented in the literature. In this report, however, the emphasis is on the glass and mirror technology useful to the designer of high performance solar concentrators.

Primary consideration is given to high reflectance glass mirrors with a secondary emphasis on coated metal reflectors. The approach is to survey the most promising candidates from a historical data base, present status, and future capability. The aspects treated include efficiency of solar reflectances, effect of dust and contamination accumulation, stability of reflective metallization, environmental effects, cleaning effects, and projected price structure.

Because of the large number of figures and tables in this report they are listed separately at the end to minimize searching and to facilitate their use.

SECTION II

GLASS

A. GENERAL

There are many different types of glass that are available for solar concentrator reflection surfaces. Over 100,000 types of glass are known, and probably 750 types are produced commercially. In the selection of the specific glass surfaces to be used various factors should be considered, such as optical and mechanical properties, durability, resistance to hail, rain and other environmental influences, and thermal expansion.

Categorizing glasses by their method of production, the majority are fusion, float or sheet (drawn) glass. By chemical composition, the primary types are the following:

(1) Soda-lime

(2) Lead-alkali

(3) Borosilicate

(4) Aluminosilicate

(5) Fused silica

The elemental composition of common glasses is shown in Table 1. The borosilicates and aluminosilicates are found to be superior for solar concentrator applications. The character of these and other types of glasses are treated in the following section.

B. PHYSICAL PROPERTIES

Glass has been defined as an inorganic product of fusion which has cooled to a rigid condition without crystallizing (Reference 7). Thus, glass is a rigid fluid. But some organic rigid liquids can be properly called organic glass; therefore, glass should not be limited to inorganic materials. However, all glasses referred to commercially as glass are inorganic. The typical atomic structure is shown in Figure 1b.

The general physical properties of typical glasses applicable to solar concentrator designs are summarized in this report. The wide variability of the data is apparent and the physical properties of glass composition are complex (Figure 2). The two best references for the solar glass designer are Strand (Reference 8) and Corning Glass Work's Properties of Glasses and Glass-Ceramics (Reference 7), although many other fine treatises exist. See References 9 through 67.

General engineering data on the characteristics of glass for solar thermal concentrators are summarized in Tables 2 through 8 and Figures 5 through 23. Mechanical, data transmittance, index of refraction, viscosity, and thermal data are given. For further details concerning the specific parameters, the reader is referred to the reference indicated. Some of the more important tests pertaining to glass, taken from ASTM literature, are shown in Table 9. Other documents and reports containing information on high solar transmittance glass are References 68 through 110.

C. SOLAR CONCENTRATOR MIRRORS

The general concepts for concentrating solar energy are sketched in Figure 3a for the parabolic mirror system and in Figure 3b for the more advanced Fresnel lens concentrator. A simplified drawing of a section of a conceptual glass mirror system, the primary subject of this report, is shown in Figure 4. A mirror may consist of many more layers than those shown. For example, the inner protective coating and the sealant may both consist of multiple layers. Commercial mirrors usually have different types of metallic coatings, sealants, and protective overcoatings which vary in number and thicknesses.

Major problems exist in translating the conceptual mirror designs into durable, low cost, high reflectance systems that will withstand the environmental elements over the projected long life of 20 or more years.

The physics of the light reflection from a typical second-surface glass mirror, in simplified form, is shown in Figure 24a. Multiple reflections are not shown. The incident light ray undergoes spreading due to reflection, this is known as the specular component of the reflected light, while the electromagnetic radiation reflected and emitted from the glass surface over the remaining part of the hemisphere is known as the diffuse component. The objective in the fabrication of a high performance glass mirror system is to concentrate as much of the light beam as possible into the specular component, and hence into the cavity receiver for eventual conversion into power.

For comparison, a front-surface metallic mirror of aluminum is shown in Figure 24b. Coated polymeric surfaces are not shown, but may become future candidates as the technology evolves.

SECTION III

PERFORMANCE OF REFLECTIVE SURFACES

A. EFFICIENCY OF REFLECTION OF THE SOLAR SPECTRUM

The investigation of the efficiency of solar concentrators includes data from in-house JPL measurements, Sandia Corp., McDonnell Douglas Astronautics Company-West and other vendor supplied information. These data have been tabulated along with explanatory notes, when applicable, in Tables 10 through 13.

High reflectance, in the 80-96 percent range, is needed for an efficient solar mirror surface, and the higher the better. From the data in Tables 10 and 11, it is seen that when silvered Corning fusion glass 0317, Schott B270 and fusion glass modified 7806 (low ferrous content) are determined to have superior reflectance. The modified 7806 glass is yet to be put into production; however, due to the nature of the fusion process, it is expected to be satisfactory when available in limited quantities next year.

The greenish color imparted to glass by the presence of iron is highly undesirable (Figure 25) and ways have been investigated in the glass industry to overcome the effect of its absorption. From purely economic considerations, the removal of iron has certain practical limits. At present, a number of approaches appear successful, including the addition of flourides and phosphates to counter the effect (Reference 88). Another approach is to use the fusion process in making the glass. In this process, the iron remains in the glass but is converted largely to the ferric state (96% Fe_2O_3, 4% FeO) and the infrared absorption effect is significantly reduced. The physics and chemistry of the role of iron in glasses is complex and beyond the scope of this report.

Total solar hemispherical measurements of 0317 fusion glass shown in Table 10 (item 29) were performed at JPL using a Model MS 250, Gier Dunkle reflectometer (Gier Dunkle Instrument Inc., Santa Monica, CA). A total hemispherical reflectance of 93 percent was obtained. Other measurements show values as high as 95 percent. Recent mirror reflectance data measured at a single wavelength (500 nanometers) by Sandia Corp. are included in the table. Where the coefficients are measured at other frequencies, they are given in parentheses below the coefficient.

Four generalized coefficients, R_1 and R_2, and the standard deviation parameters, σ_1 and σ_2, can be utilized to describe the reflectance of solar energy from a given material. See Reference 98. Assuming the reflectance profile can be described as the sum of two normal distributions, the equation is:

$$R(\Delta\theta) \quad \alpha \; R_1 \exp\left[\frac{-\Delta\theta^2}{2\sigma_1^2}\right] + R_2 \exp\left[\frac{-\Delta\theta^2}{2\sigma_2^2}\right]$$

where R is the reflectance and $\Delta\theta$ is the deviation of the reflected beam from the specular direction. This equation gives remarkable fit to the measured data. Where known, these coefficients are shown in the tables. The general theoretical relationship between reflection and transmission for glass is shown in Figure 26 along with the recent data for thin Corning fusion glass 0317 with good metallization. The metallization aspects are treated later in this report.

Recent solar reflectance data of Sandia Laboratories, for thin solar concentrator glass of 0.058 inch thickness, is given in Figure 27. The angular deflection of light transmission has been compiled in Figure 28.

Aluminosilicate glasses, such as 0317 fusion, have excellent optical flatness for glasses as thin as 2.794 mm (0.110 inch) to 2.287 mm (0.090 inch). However, for very thin glass, these data show that optical flatness is not as good with 46 percent of the transmitted beam power outside 1 milliradian and 22 percent for 2 milliradians half-angle respectively (Reference 96). Similar types of measurements are needed for mirrors.

Angular deviations from the first and second surfaces, for various float glasses after light incident at 45°, are shown in Figure 29 (Reference 96). In general, other data indicates the with draw direction to be smoother than the across draw direction. Similar measurements for other reflection angles are needed.

It is important to match the thermal coefficient of expansion over the postulated service temperature (-30° to +150°F). Where available these coefficients are shown in Table 10 for high reflectivity glasses.

For front-surface coated aluminum reflectors, Alcoa's Type S460667 is reported to have a total hemispherical reflectance of 92 percent, while the Kingston Industries, Inc., Kingflux, exhibits about 85 percent. JPL measurements of Kingflux aluminum found 85.4 percent. An exposure experience of approximately 15 years of shipboard applications indicates considerable durability for this latter surface.

Preliminary price information on glass and aluminum reflective surfaces has been accumulated in Tables 10 and 11. Initial estimates show glass to be cheaper than front-surface aluminum. Solar mirror panel quality glass in relatively large quantities, the order of one million square feet, may be obtained in the near future for 0.65 - 0.80 dollar per square foot. The silver metallization in mass production may be obtainable in the range of 0.5 - 1.00 dollar per square foot of additional cost. Although the front-surface mirrors are more expensive at the present time, this situation could change rapidly as the solar concentrator technology matures.

B. GLASS CUTTING AND FORMING

In order to successfully fabricate a solar concentrator, cutting and 3-dimensional surface forming must be undertaken. These are very formidable problems for the thin glass needed for solar concentrators. Research is required to perform these operations on large sheets with low breakage. Corning fusion glass, type 0317, in thicknesses of 1.5 mm (0.060 inch) and 1.02 mm (0.040 inch) is difficult to cut, according to JPL experience. One conceptual possibility for cutting is laser melting.

Three dimensional cold forming has been proposed as a method to fabricate the parabolic curved surface, and this method may be feasible for thin glass. Simplified, this is shown schematically in Figure 30. Basically, the thin glass sheet is pulled against the substrate, in this case cellular glass with an adhesive bond surface. Air pressure forces the plastic cover against the glass and this configuration is held until the glass-substrate interface bond is formed.

C. DURABILITY

Of the surfaces studied, glass appears to have the most durable characteristics to withstand low humidity environments. Egyptian glasses over 2,000 years old are strong evidence for its stability. Atmospheric water vapor readily attacks glass as do other environmental components such as hail and sand. Cleaning solutions also attack glass. On the basis of the available data, glass appears to be very resistant to environmental forces in general. However, the durability of the underlying metallic coating is of prime importance for obtaining high reflectivity for extended times.

A possible method for assessing the aging effects on mirrors exposed to the natural environment would be the evaluation and testing of automobile side-view mirrors. This methodology is used in Reference 121. At least two manufacturers, General Motors (Buick) and Mercedes-Benz, are reported to have produced high quality silvered side mirrors for many years. These two manufacturers maintained a strict quality control for their outside mirrors while most other companies did not; moreover, most other manufacturers use mirrors with less reflective materials than silver. Buick's experience in quality mirrors goes back to the early 1920's.

JPL has obtained both types of environmentally aged mirrors including approximately 58-year old Buick mirrors, for evaluation. Of course, the outdoor exposure may be appreciably less than this if the auto was garaged. Therefore, an attempt was made to select for analysis those mirrors with the most corroded mirror fixture. Visual inspection of both the glass and metallization shows that they are in excellent condition. This preliminary evidence indicates that high quality, long-lived mirrors for solar power applications can be successfully designed.

D. METALLIZATION

Second-surface glass mirrors require a high quality, protected metal coating to meet the extended service life for solar concentrators. Some evidence indicates that even higher performance reflective surfaces may be achieved by combinations of metals, such as silver and aluminum, or the use of more innovative techniques.

Silver is the metallic reflective coating that is the most straight-forward to apply and it is commonly used on second-surface glass mirrors for many applications. The chemical method is more economical than vacuum-deposited silver and is most frequently used in commercial mirroring processes.

The silvering reaction is:

$$2AgNO_3 + 2NaOH \rightarrow 2NaNO_3 + Ag_2O + H_2O$$

$$Ag_2O + \text{Reducing Agent} \rightarrow 2Ag + H_2O$$

Typical protective coatings used in the mirror industry are the following:

(a) 753.4 mg/m^2 (70 mg/ft^2) of silver

(b) 161.5 mg/m^2 (15 mg/ft^2) of copper

(c) 86,114 mg/m^2 (8 mg/ft^2) of mirror sealant

The reflectivity of vacuum deposited silver for 0317 fusion glass has been established by Sandia Corp. to be superior to the chemical process but only results in one percent greater reflectivity over the spectrum (Table 10, items 27 and 28). A solar hemispherical reflectance of 95 $\pm$ 1 percent was obtained with the former method. The reflectivity of common base metals is shown in Figure 31 and Table 14. These data show that silver has the highest reflectivity above the ultraviolet range while aluminum is a better reflector in the ultraviolet range. The efficiency of the silvering process is shown in Tables 15 and 16. The effect of oxidation of aluminum reflectivity with time is shown in Figure 32. Further information on reflective surfaces and their degradation due to solar exposure is given in the following section.

SECTION IV

ENVIRONMENTAL DEGRADATION EFFECTS

Degradation of high-performance surfaces can occur due to environmental effects, such as dust, sand, and miscellaneous contamination. Little is known of the long-term effect of these environments on mirror surfaces. However, in general, the effects vary with the type of material, length of exposure, site location, type of coating(s) and cleaning techniques. Preliminary JPL data indicates, however, that bare plastics tend to accumulate dirt with a greater tenacity than glass. A detailed treatment of these subjects is beyond the scope of this summary and is planned to be treated in another report (Reference 105).

The general effects of reflectance degradation for desert-soiled mirrors is shown in Tables 18 and 19 and Figure 33 shows the dust-rain effects in the Sandia Corp. program (Reference 115). A decrease in reflectance of 12% due to dust is noted. Wavelength dependence is shown in Figure 34 (Reference 103). Preliminary information indicates that upside-down stowage for the mirror appears to be better compared to face-up stowage. This is true in spite of the fact that overnight dew or frost may run off and sometimes clean the mirrors during morning deployment in the latter case.

Various cleaning methods are under consideration but further research is required to identify the type of cleaning agent that will minimize damage to the concentrator surface over an extended period of time. The various cleaning procedures are summarized in Tables 20, 21 and a summary of previous glass cleaning effects is shown in Figure 35. At this time, the aluminosilicate and the borosilicate glasses are predicted to be superior on the basis of these tests. (Reference 113).

SECTION V

CONCLUSIONS

In this survey, four general types of promising reflectors for solar concentrator applications have been identified. They are summarized in Table 22. On the basis of presently available transmission data, Corning fusion glass, type 0317 and Schott glass, type B270, and float glass are recommended for parabolic solar concentrators due to their good potential reflectance, availability, durability, thermal expansion characteristics and projected price structure.

For future applications, however, modified Corning 7806 fusion glass and coated, anodized aluminum surfaces bear watching because of their possible importance. For the Fresnel lens type of solar concentrator, special glass and plastic materials appear to be superior.

Additional test data on the durability of metallic surfaces of high reflectance mirrors are needed in order to prove that environmentally resistant mirror systems can be achieved. Preliminary observations of the good stability characteristics of 58-year old auto mirrors indicate that this can probably be realized.

Although this survey of glass and mirrors treats many engineering parameters, it is by no means exhaustive and should be regarded as preliminary information. Data are frequently based upon a limited number of samples and some metallizations and glasses are not completely characterized. The data are sufficient, however, to indicate the trends.

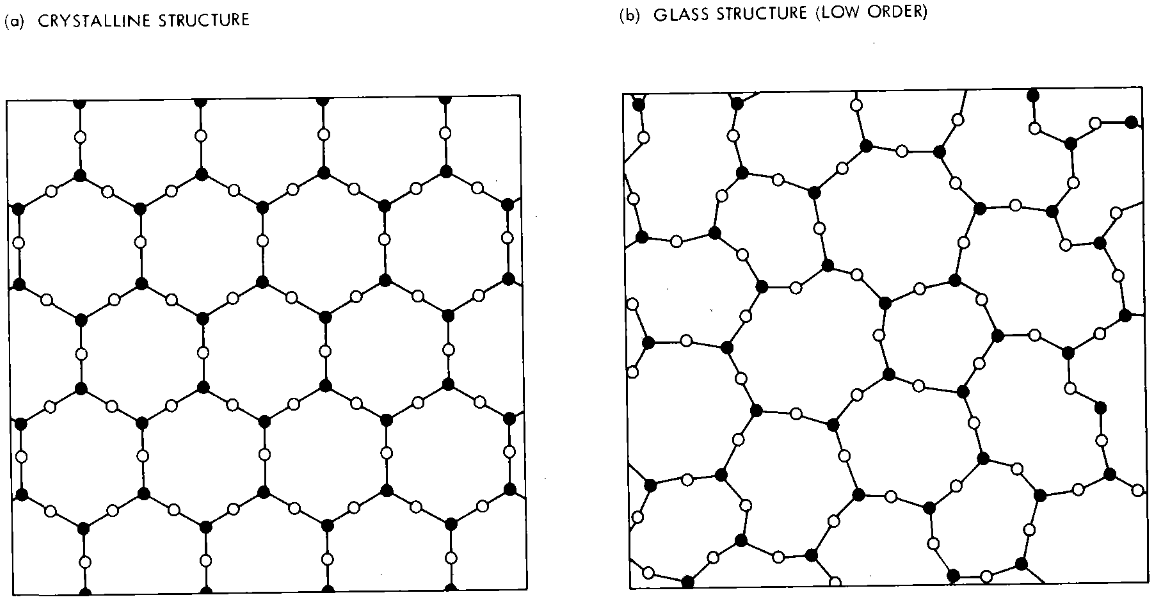


Figure 1. Glass Structure (Ref. 39)

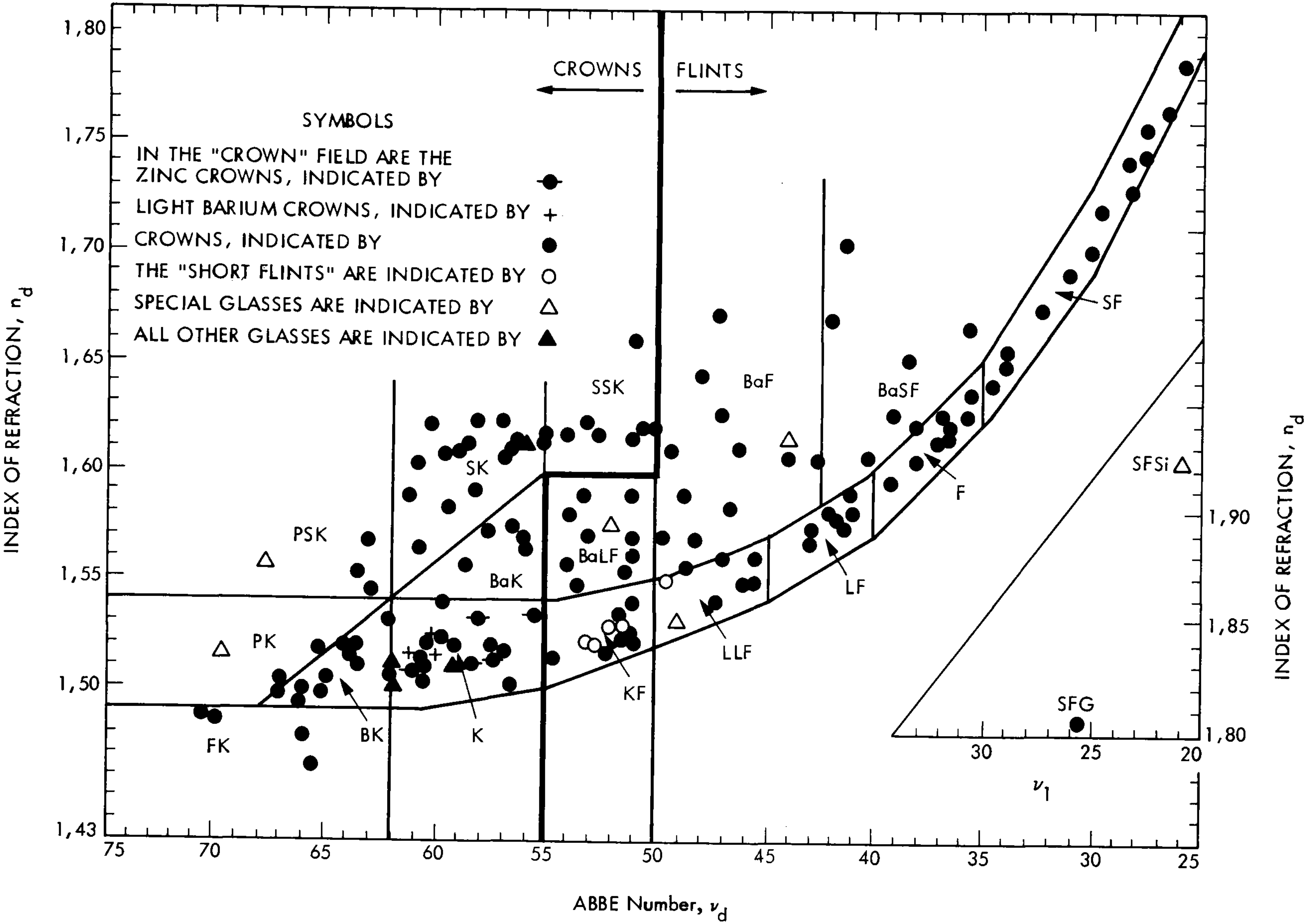
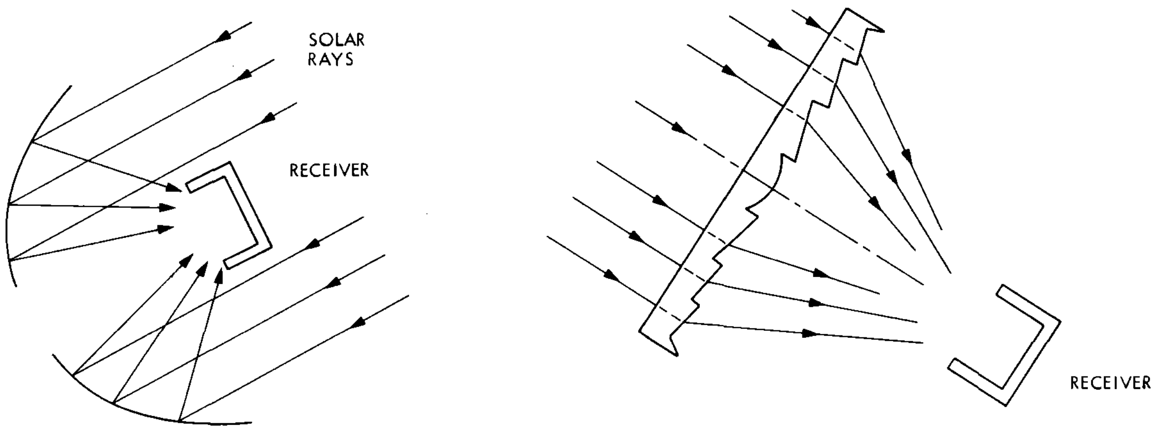


Figure 2. Classification of Optical Glasses (Ref. 36)



(a) PARABOLIC CONCENTRATOR SYSTEM

(b) FRESNEL LENS CONCENTRATOR SYSTEM

Figure 3. Simplified Sketch of Two Types of Solar Concentrators

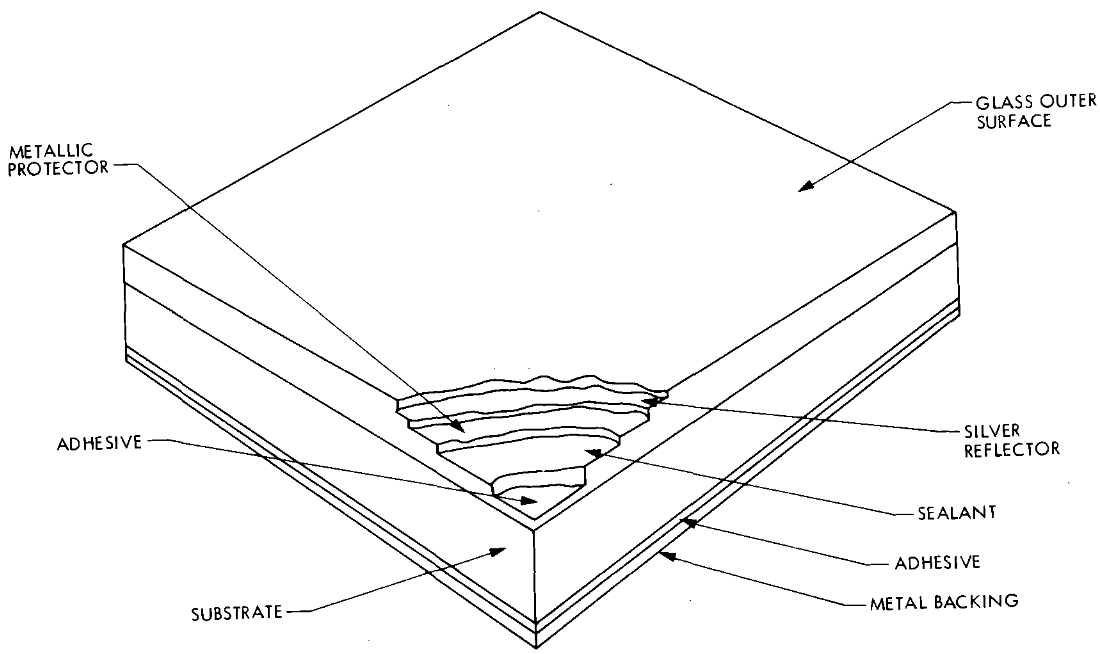


Figure 4. Section of a Conceptual Glass Solar Concentrator Mirror System

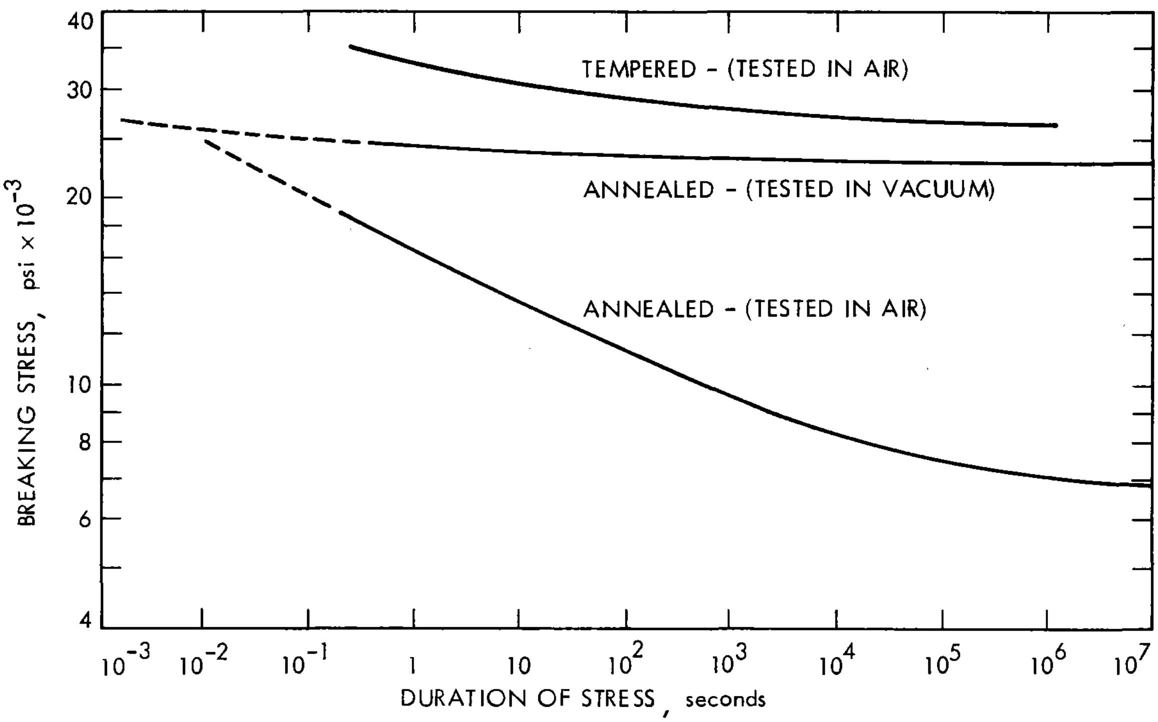


Figure 5. Stress Time Characteristics of Glass (Ref. 36)

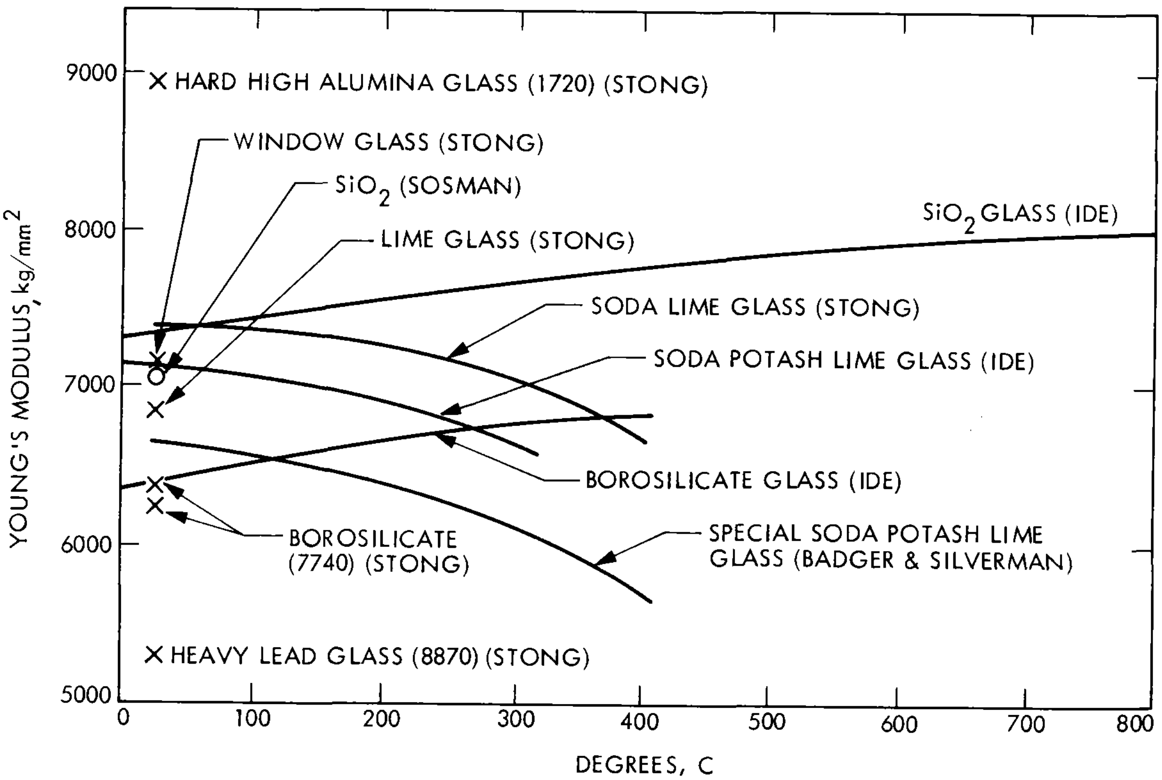


Figure 6. Young's Modulus of Various Glasses (Ref. 36)

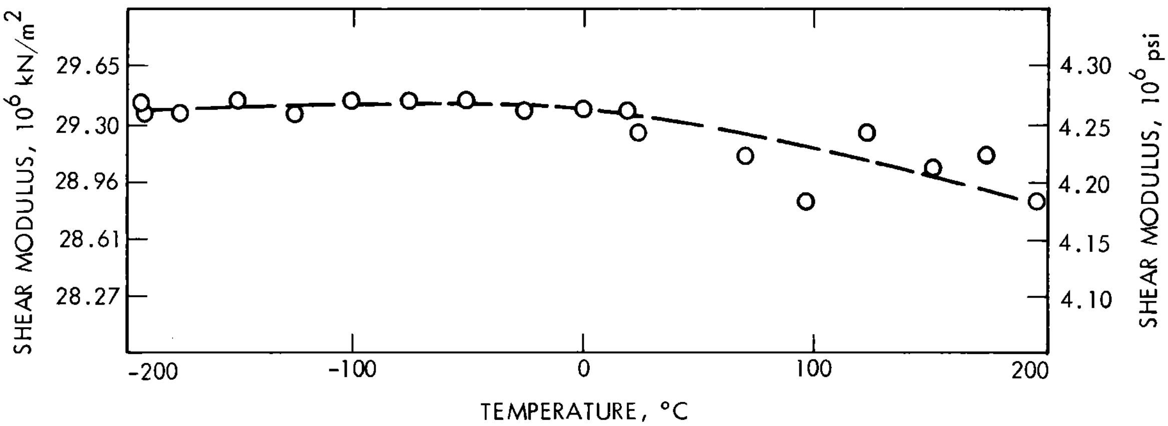


Figure 7. Shear Modulus of 0211 Microglass as a Function of Temperature (Ref. 114)

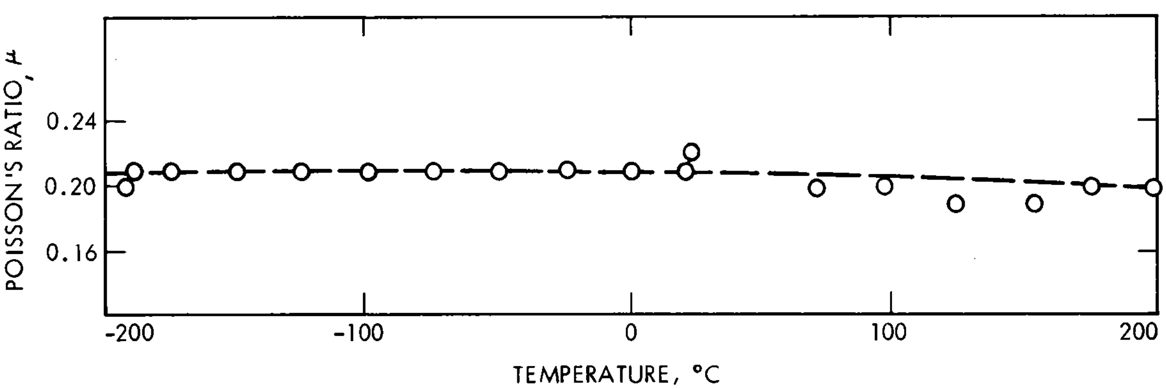


Figure 8. Poisson's Ratio as a Function of Temperature; 0211 Microglass (Ref. 114)

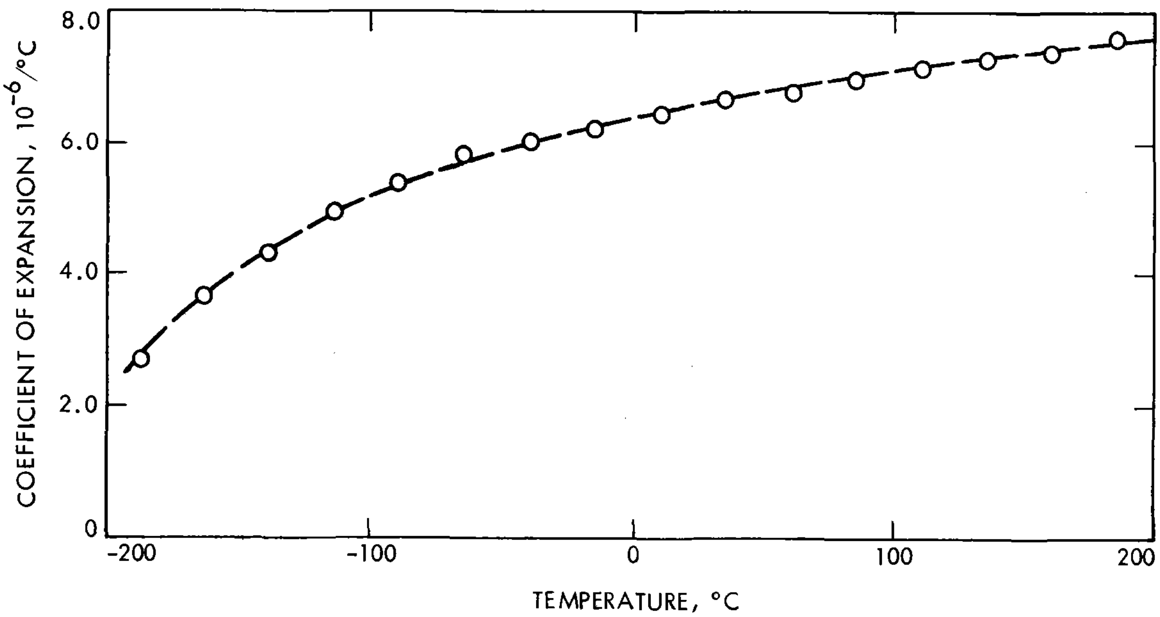


Figure 9. Instantaneous Coefficient of Thermal Expansion of 0211 Microglass as a Function of Temperature (Ref. 114)

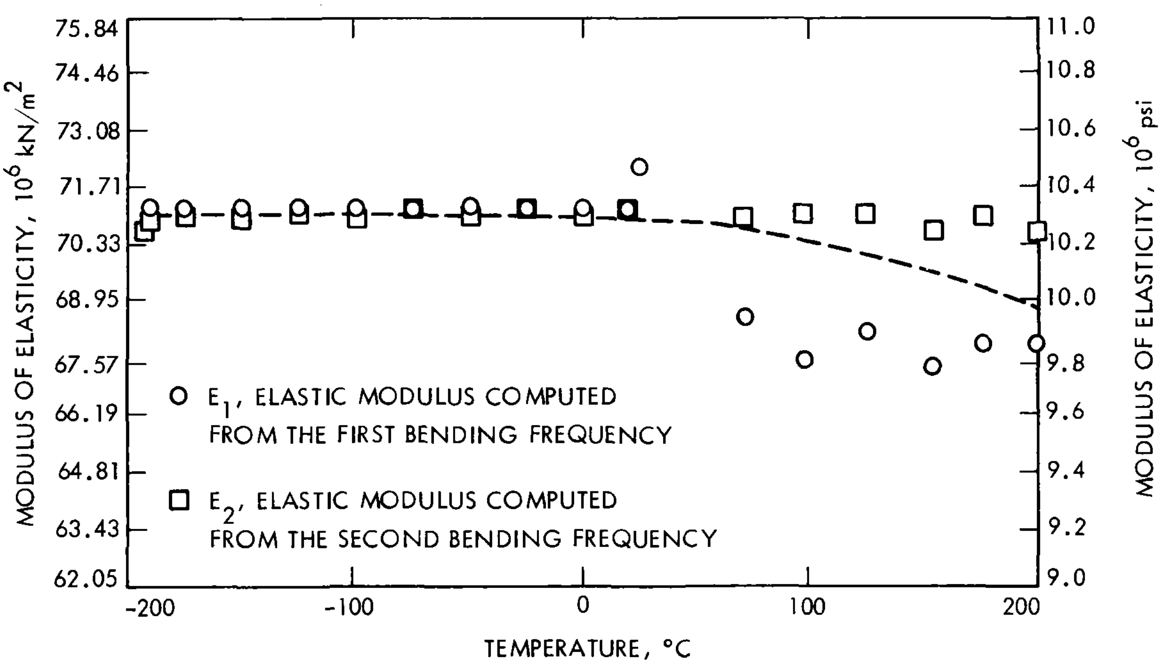


Figure 10. Modulus of Elasticity as a Function of Temperature for 0211 Microglass (Ref. 114)

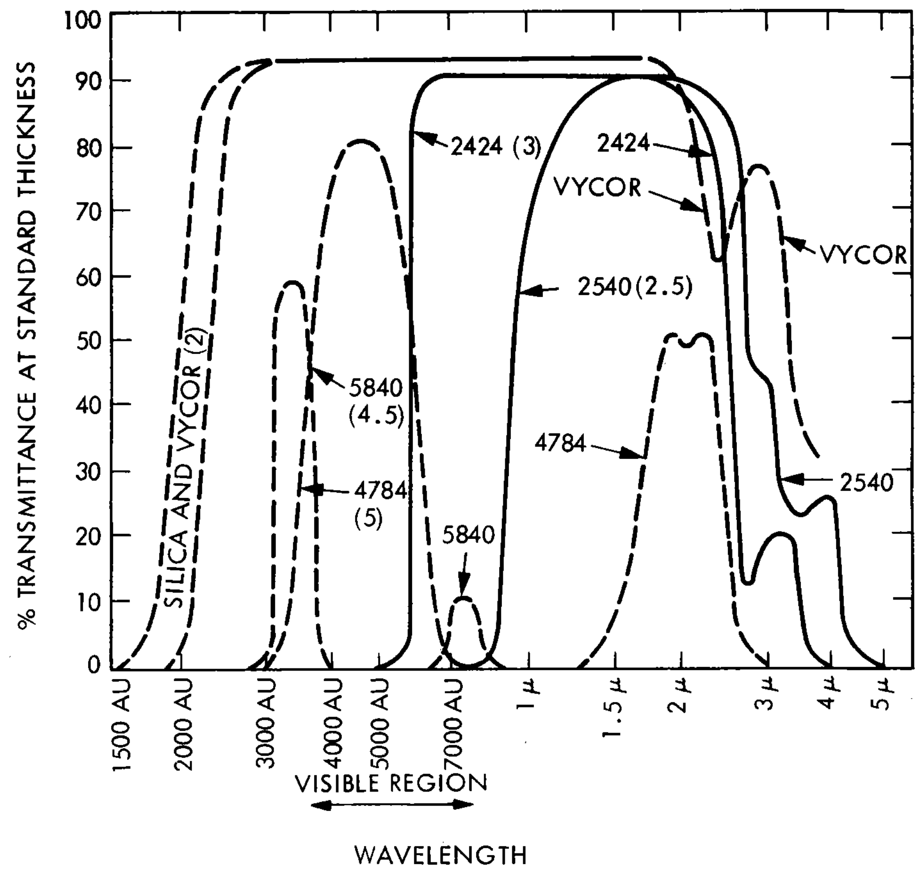


Figure 11. Transmission Curves of Selected Glasses (Ref. 36)

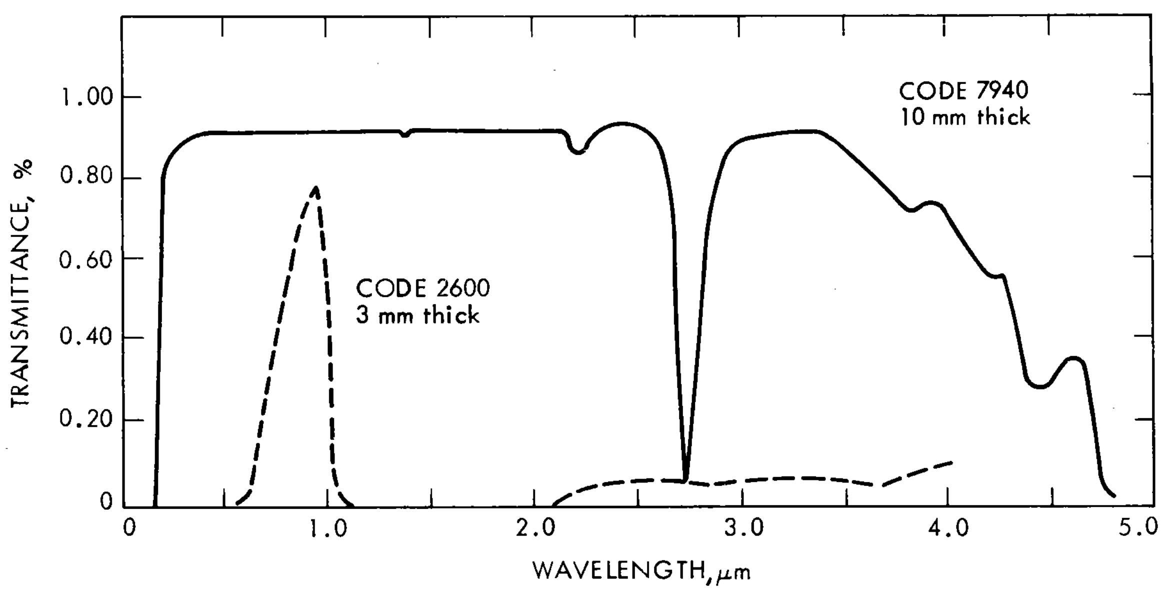


Figure 12. Transmittances of Two Glasses in UV, Visible and Near-Infrared (Ref. 7)

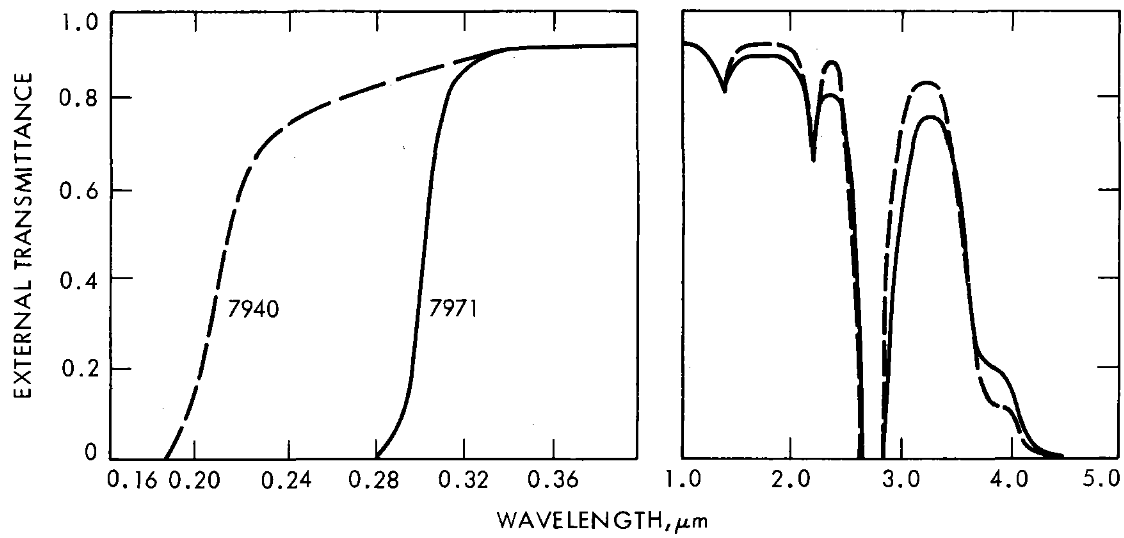


Figure 13. The External Transmittances of Fused Silica Corning No. 7940 and U.L.E. Modified Fused Silica Corning No. 7971, Both Thicknesses 10 mm. (Ref. 53)

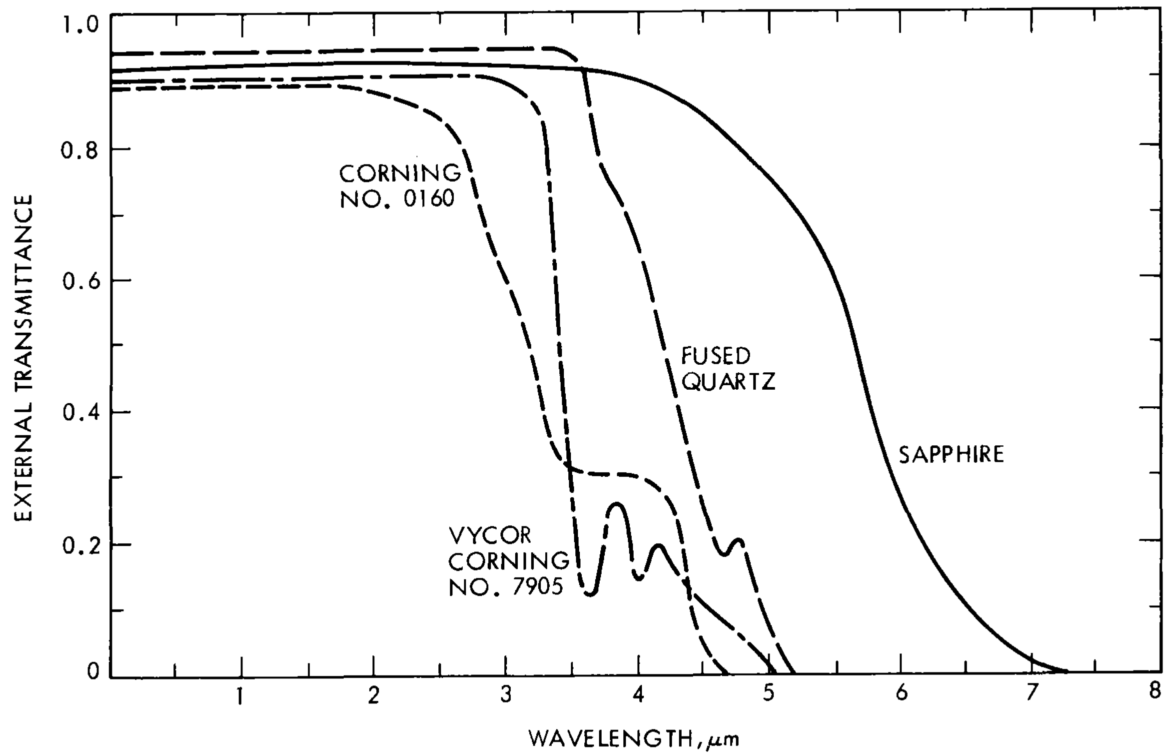


Figure 14. The External Transmittances of Corning No. 0160 and No. 7905 (Vycor) Glasses, as Compared With Common Samples of Fuzed Quartz and Sapphire, all Thicknesses 2 mm (Ref. 53)

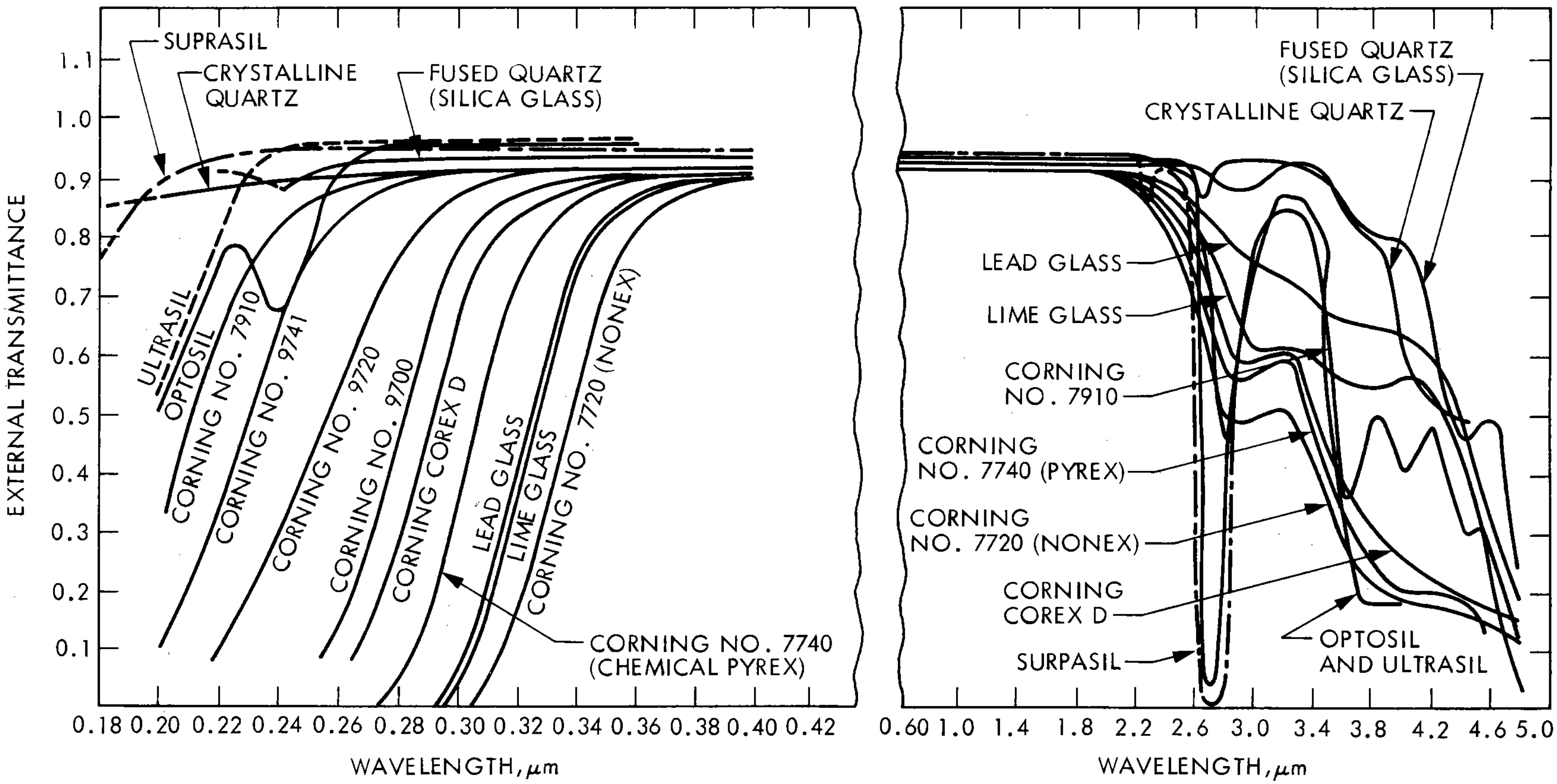


Figure 15. The External Transmittance of Several Samples of Corning and Amersil Glasses. (Ref. 53)

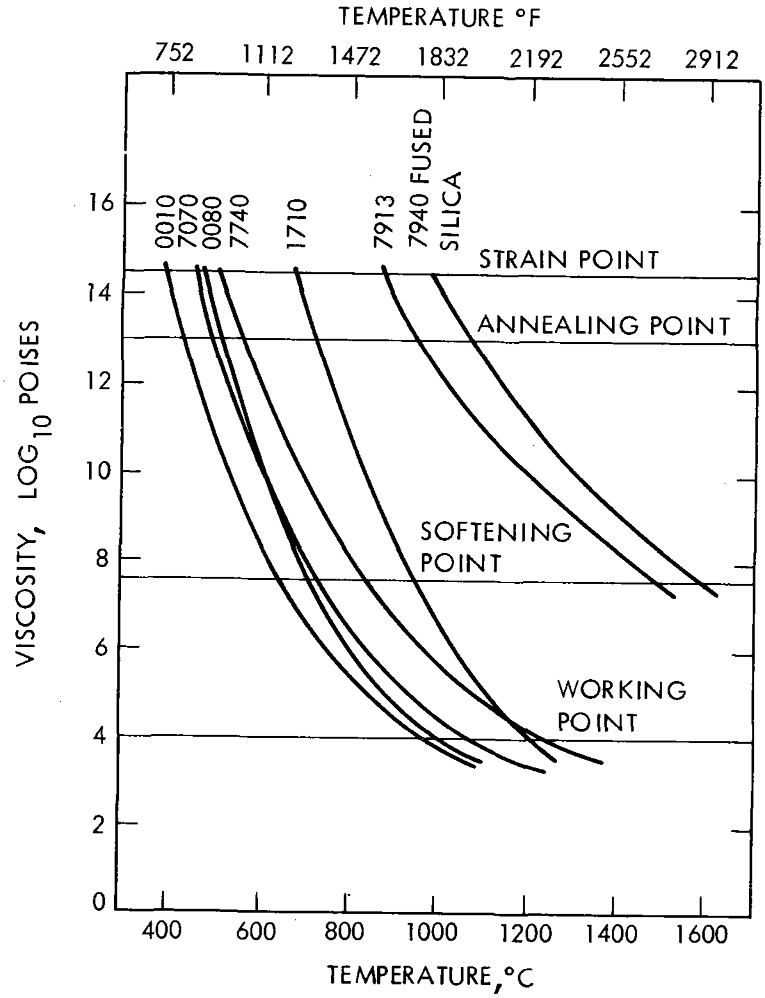


Figure 16. Viscosity - Temperature Curves (Ref. 7)

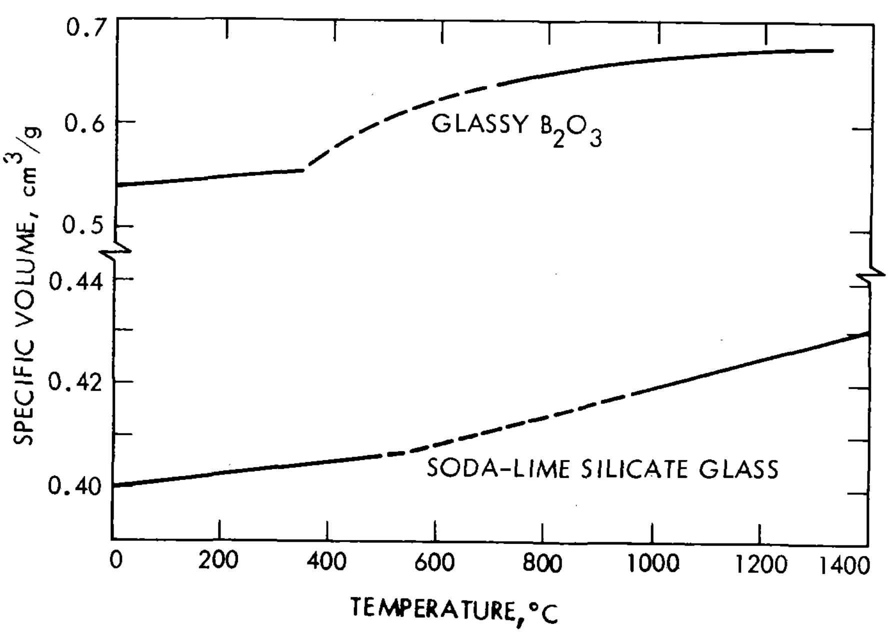


Figure 17. Specific Volume of Glass as Related to Temperature (Ref. 39 and 110)

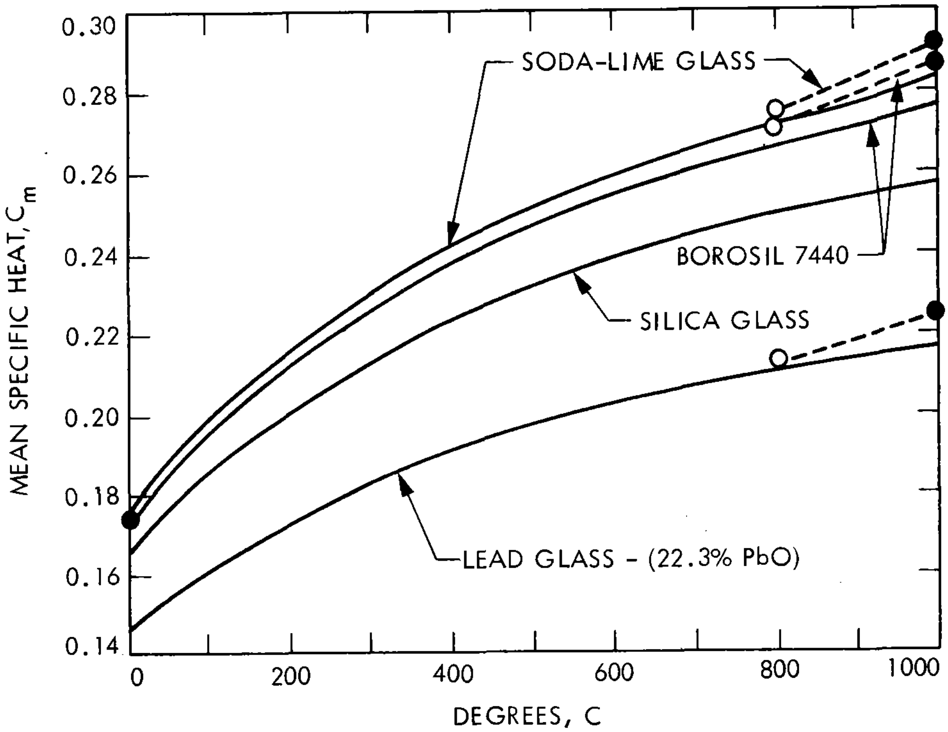


Figure 18. Mean Specific Heat of Glasses (Ref. 36)

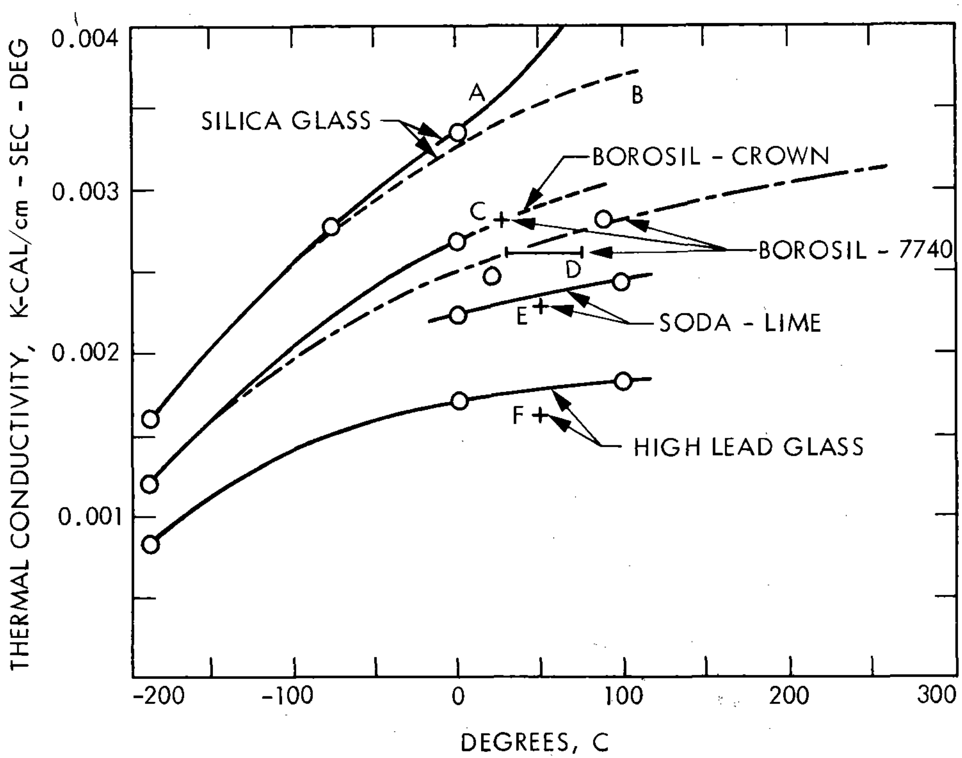


Figure 19. Thermal Conductivity of Glasses (Ref. 36)

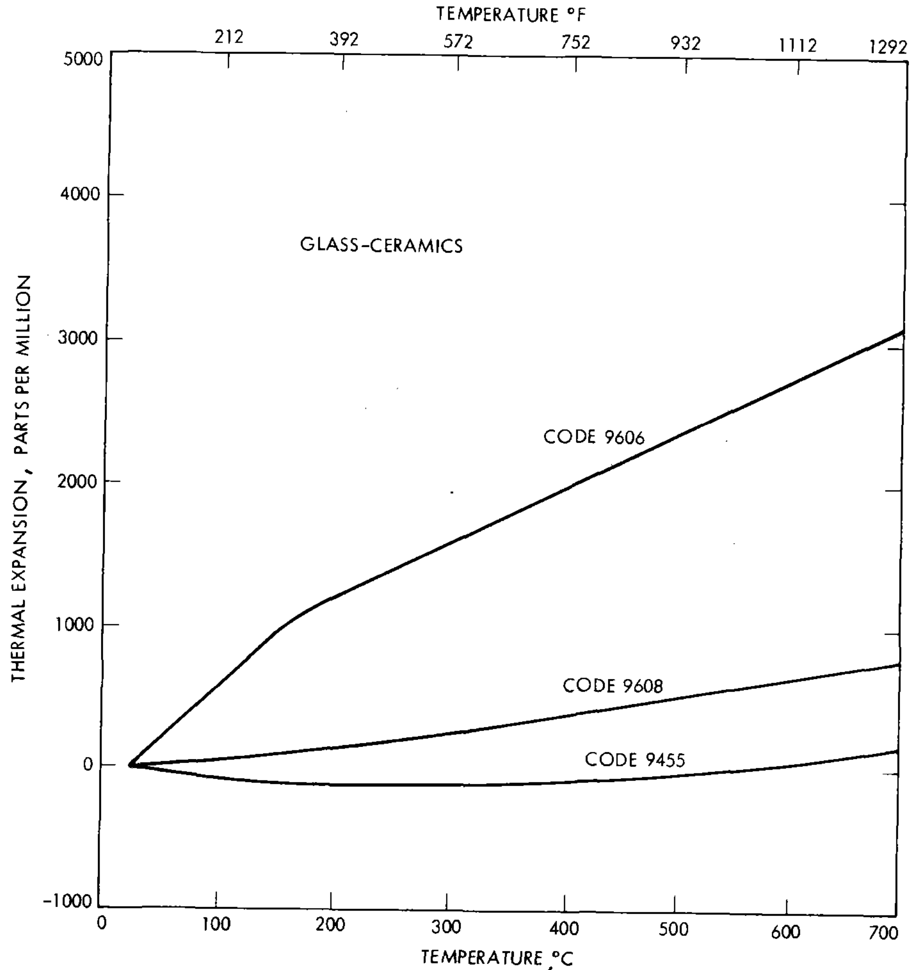


Figure 20. Thermal Expansion of Three Glass Ceramics (Ref. 7)

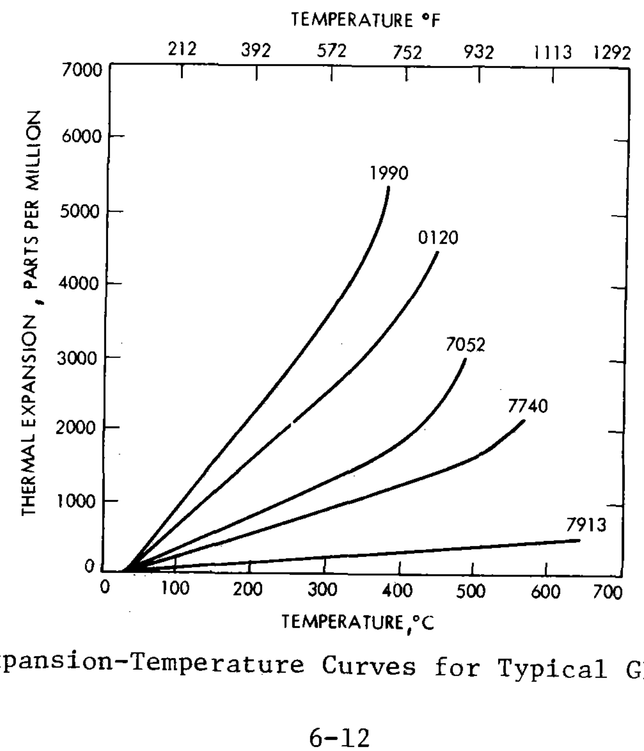


Figure 21. Expansion-Temperature Curves for Typical Glasses (Ref. 7)

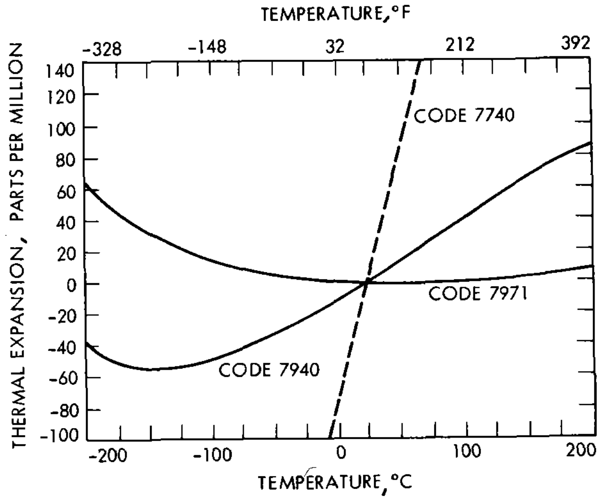


Figure 22. Thermal Expansion of Three Glasses (Ref. 7)

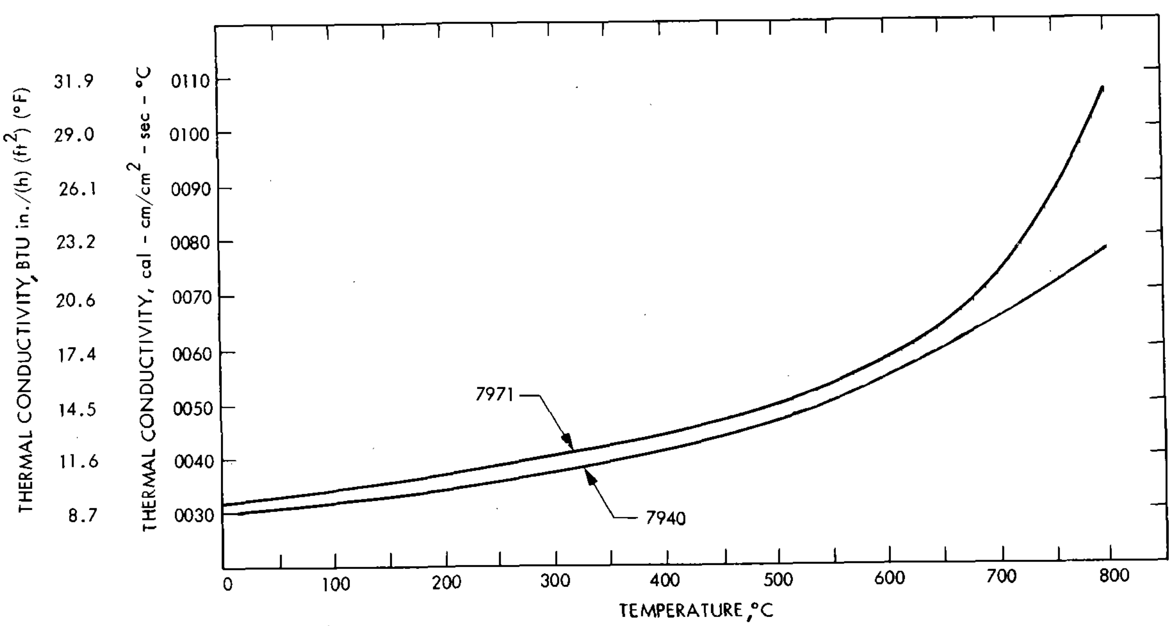


Figure 23. Thermal Conductivity vs. Temperature (Ref. 7)

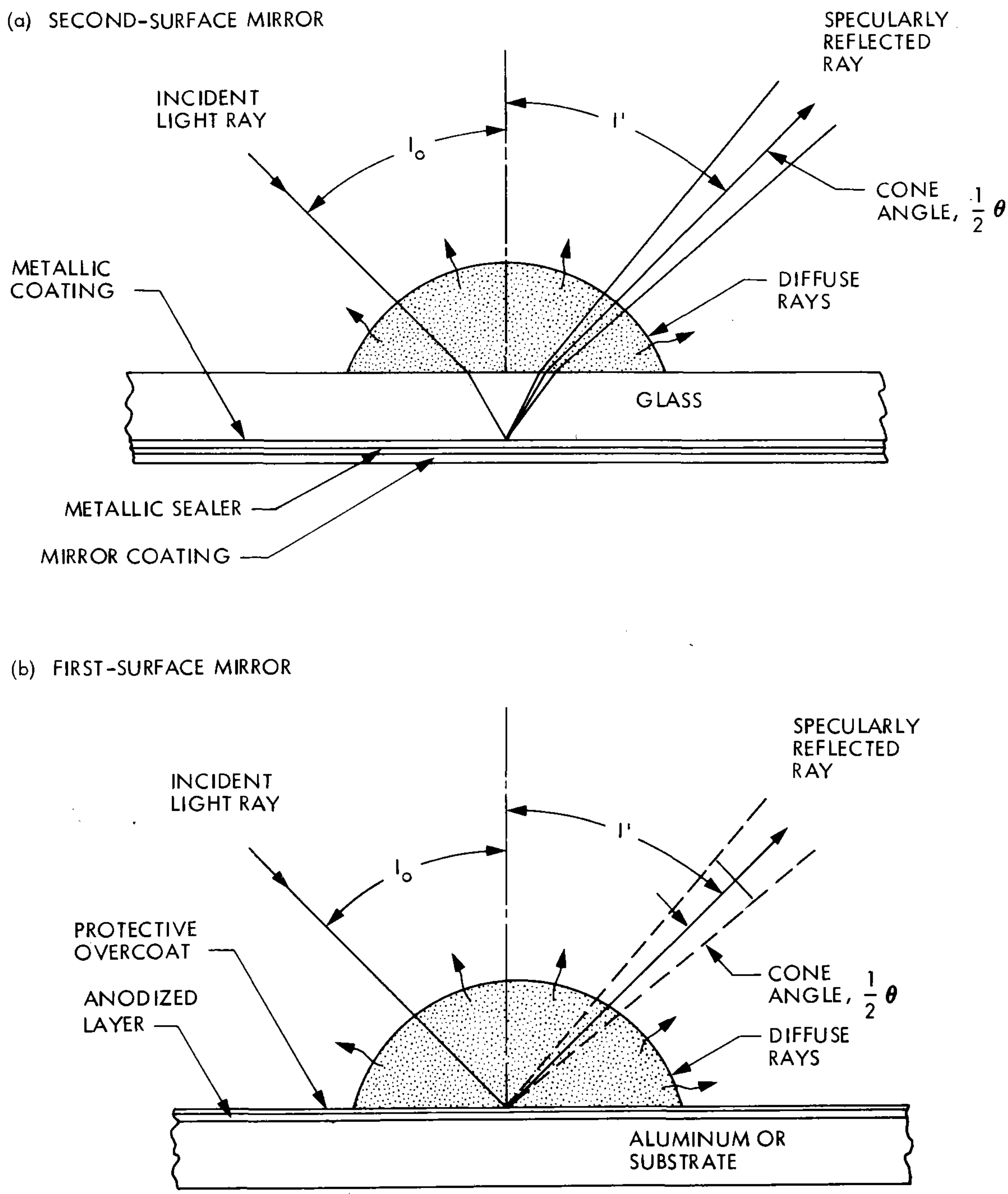


Figure 24. Solar Reflectance

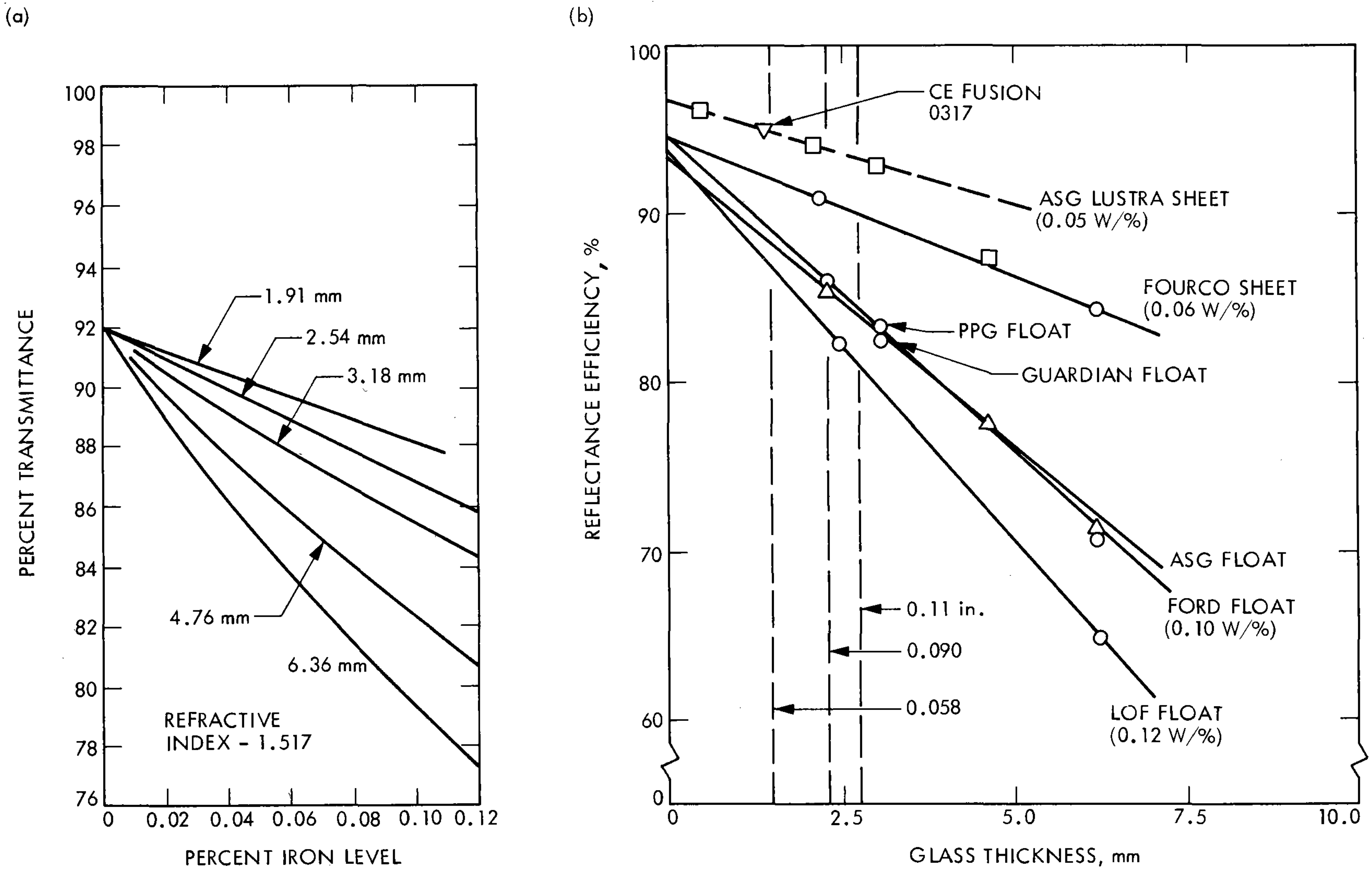


Figure 25. Reflectance Properties (Ref. 103)

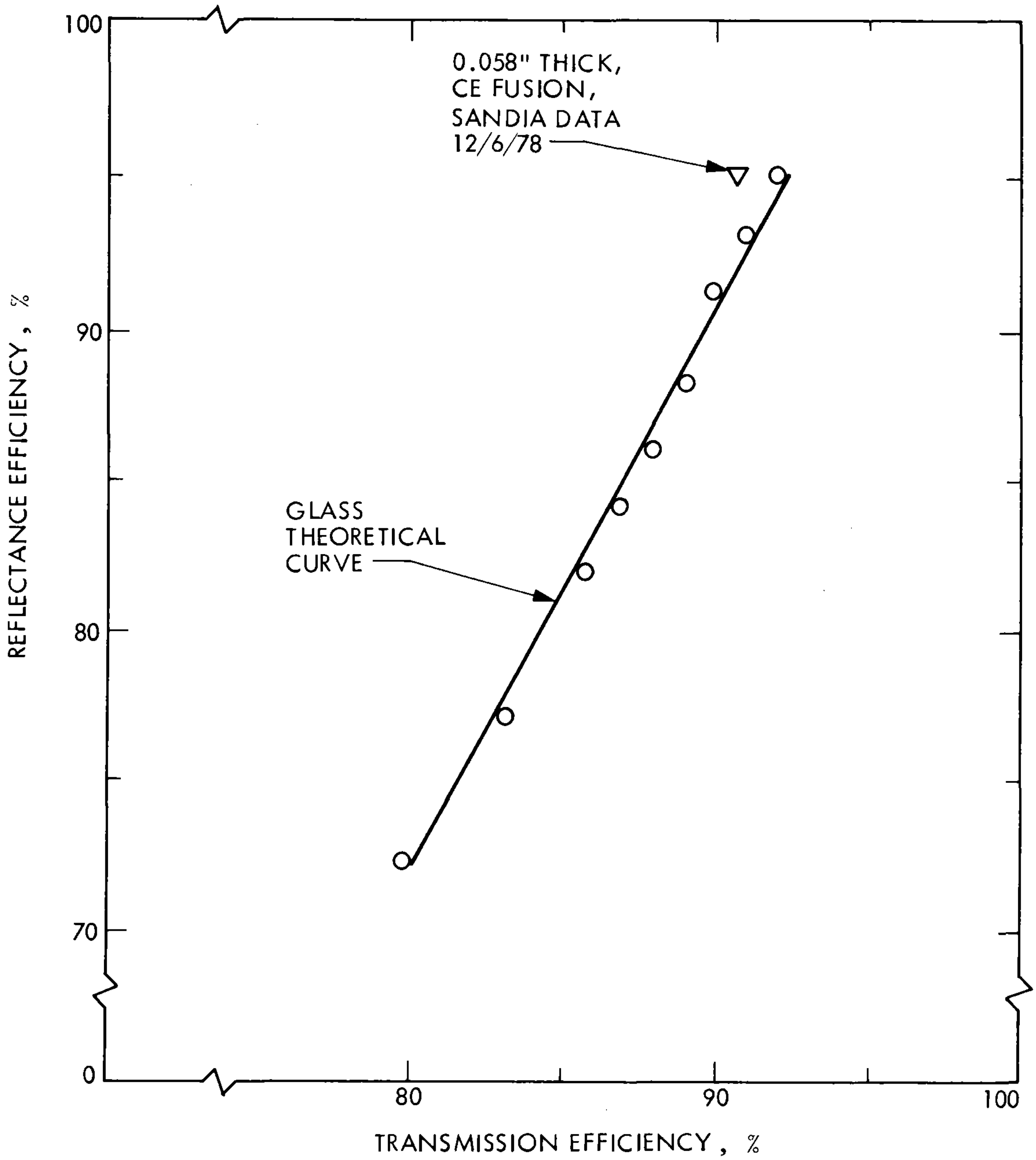


Figure 26. Glass Transmission and Reflection Efficiencies (Ref. 103)

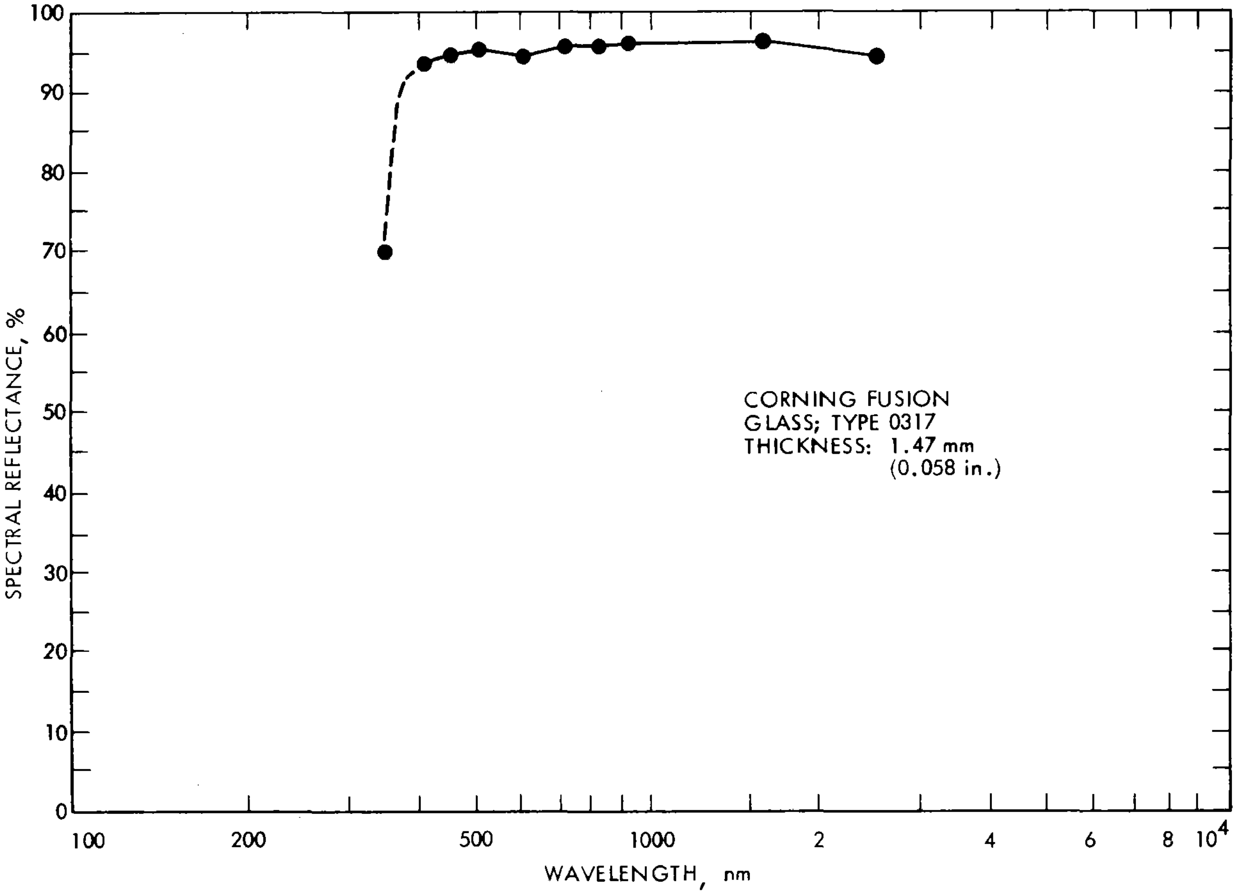


Figure 27. Reflectivity vs. Wavelength for Fusion Low Iron Glass (Ref. 111)

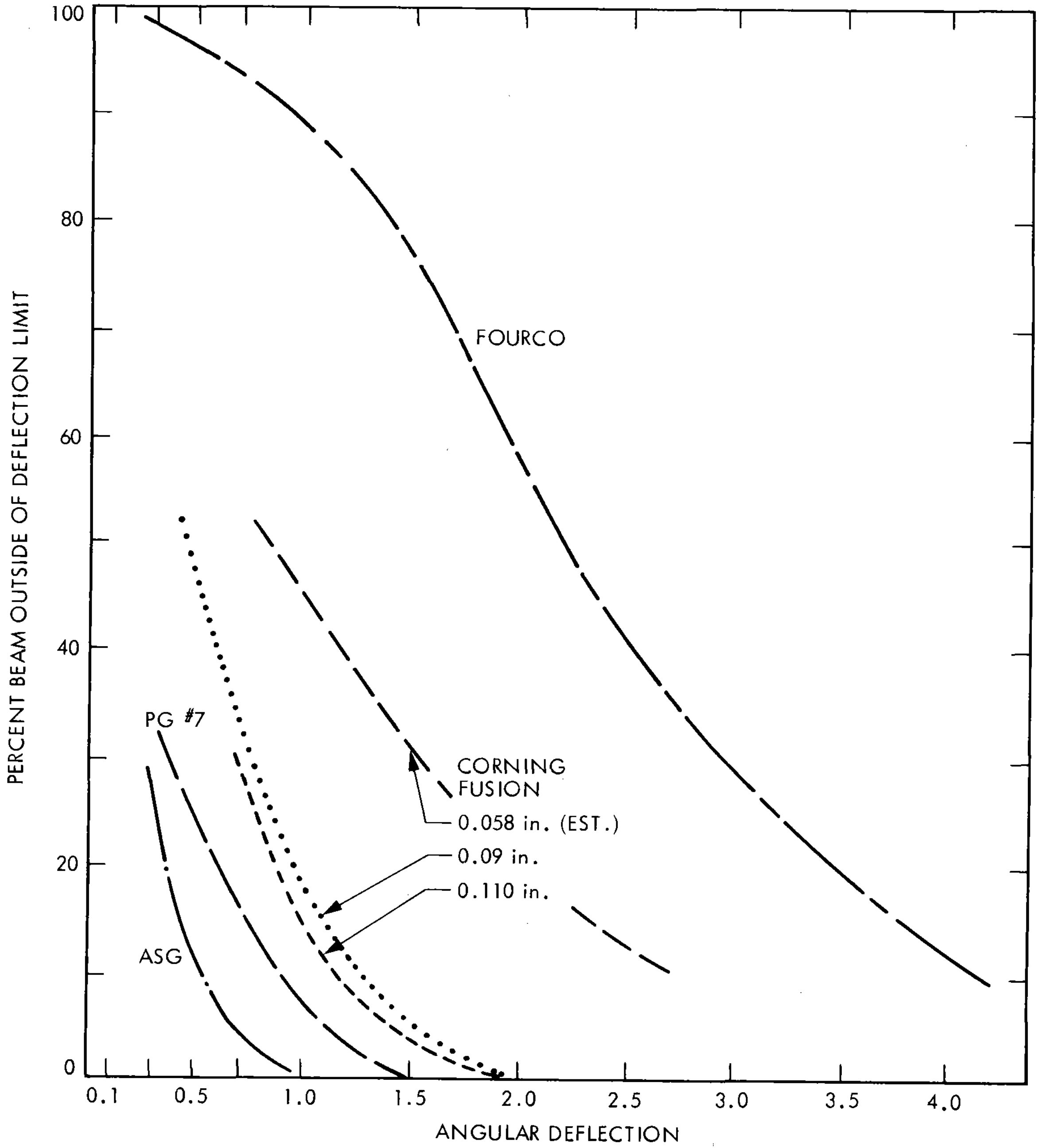


Figure 28. Percent Beam vs. Angular Deflection (Ref. 96)

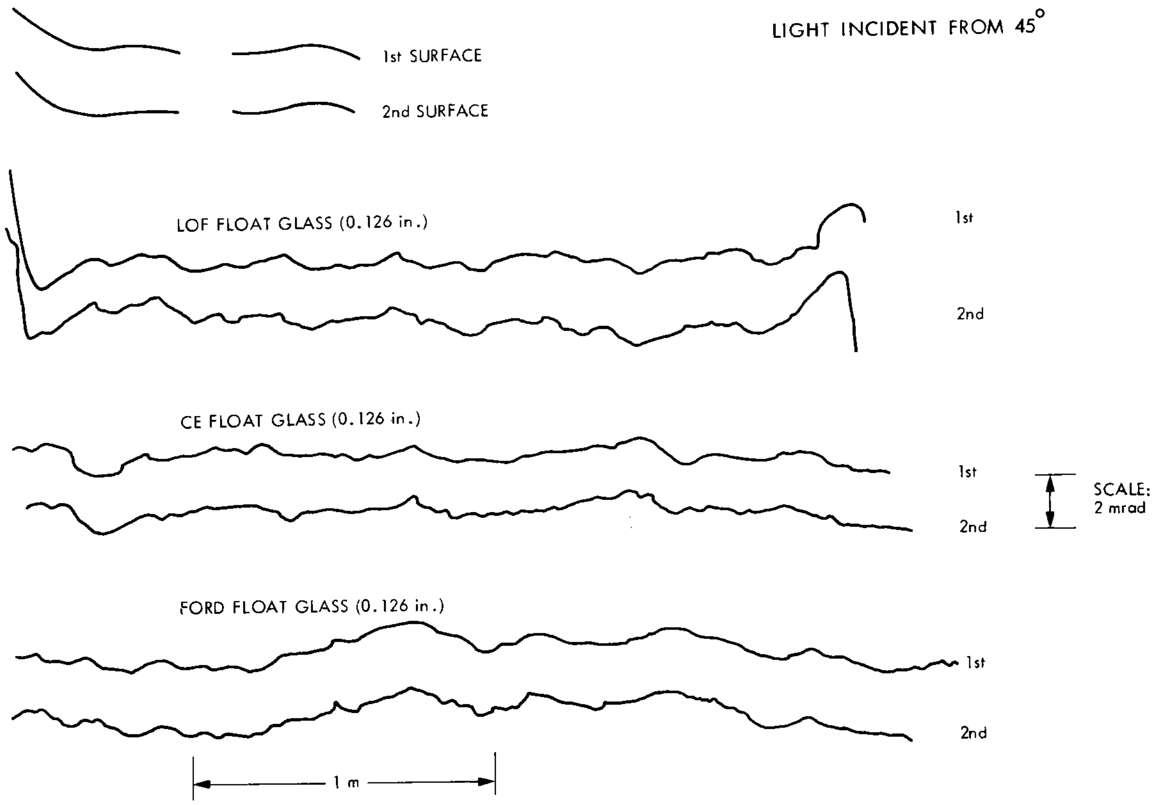


Figure 29. Angular Deviation From Specular Direction for First and Second Surface Reflections (Ref. 96)

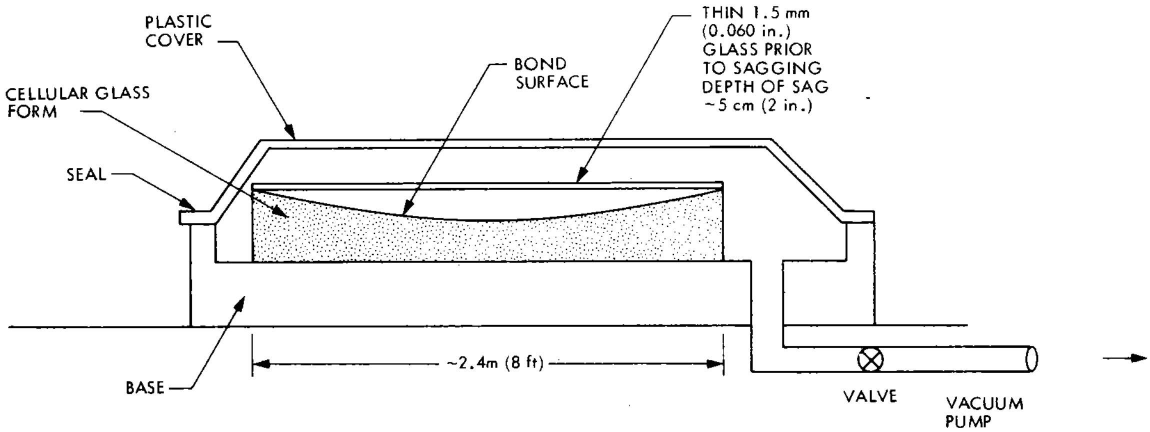


Figure 30. Schematic of Proposed 3D Vacuum Forming Technique

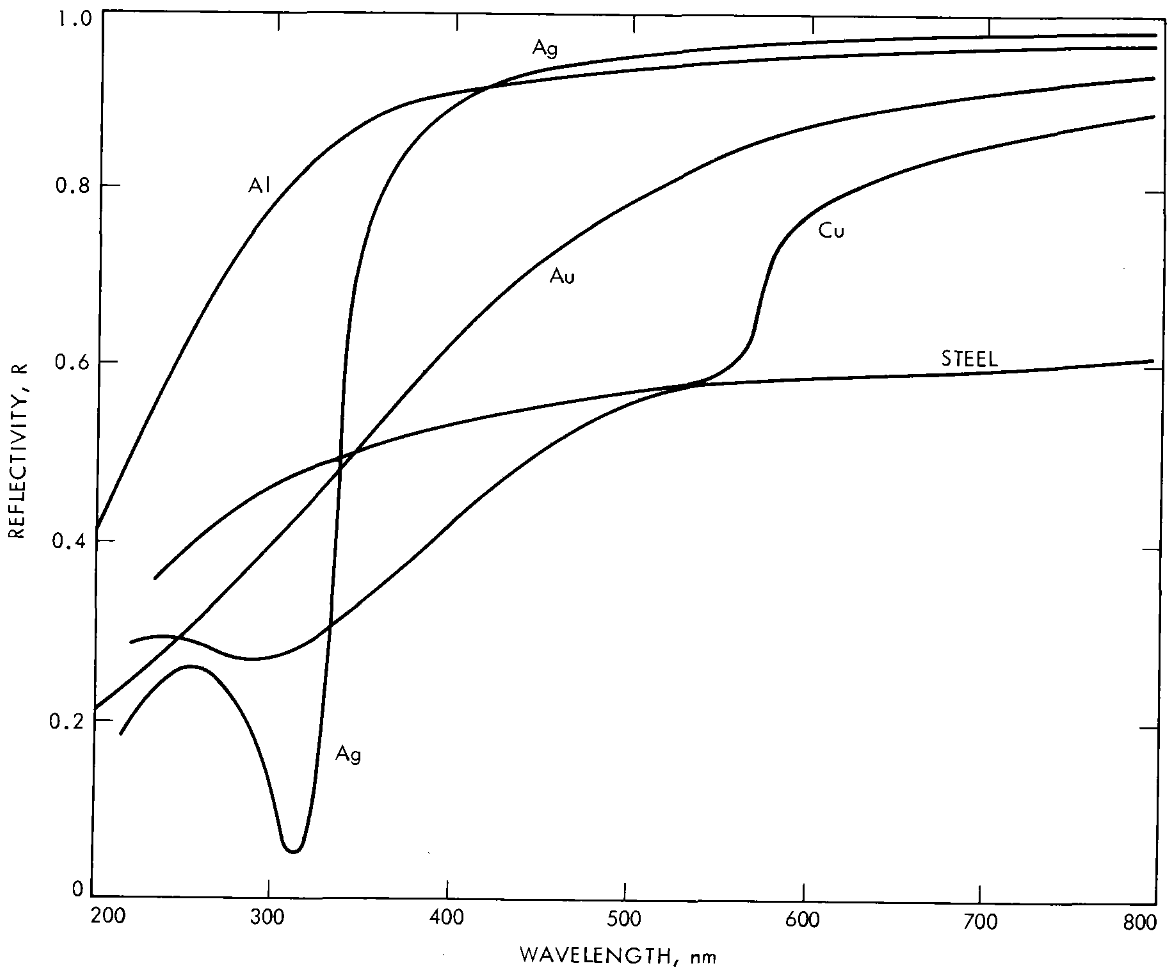


Figure 31. Reflectivity of Some Common Metals for Normal Incidence as a Function of Wavelength (Ref. 104)

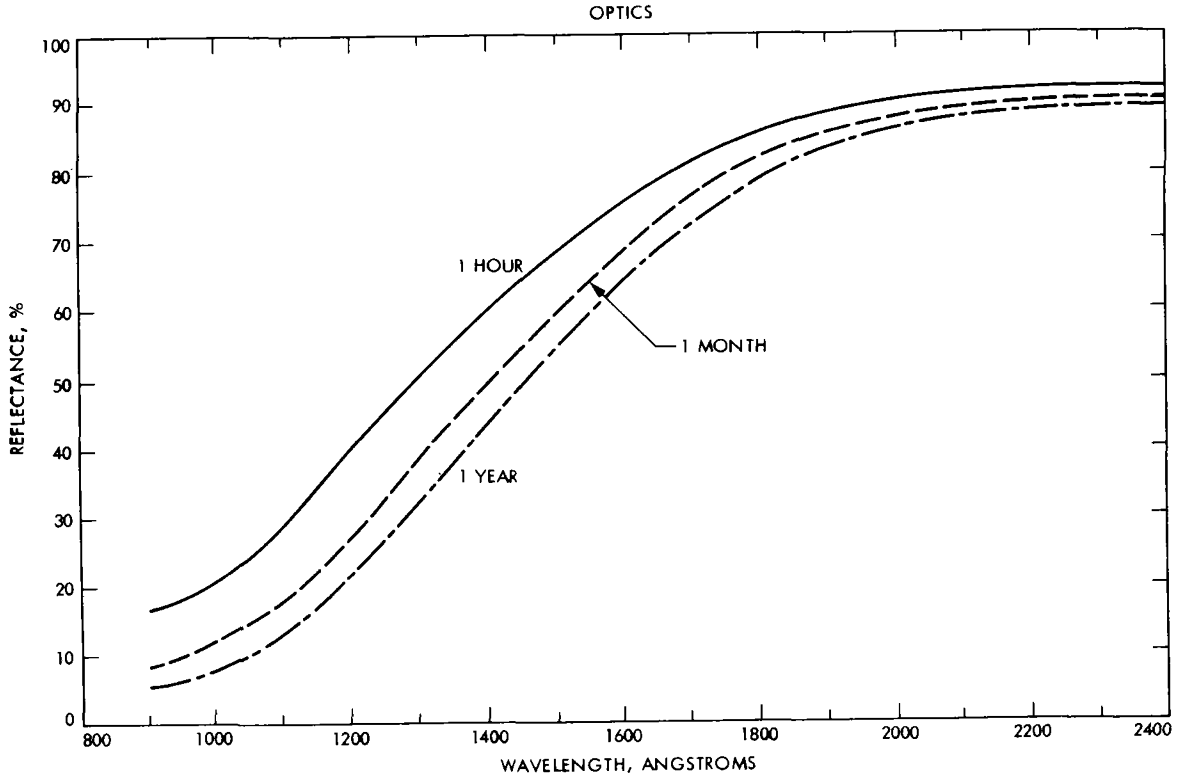


Figure 32. Degradation of Reflectance on Clean Aluminum Mirrors vs. Wavelength (Ref. 53)

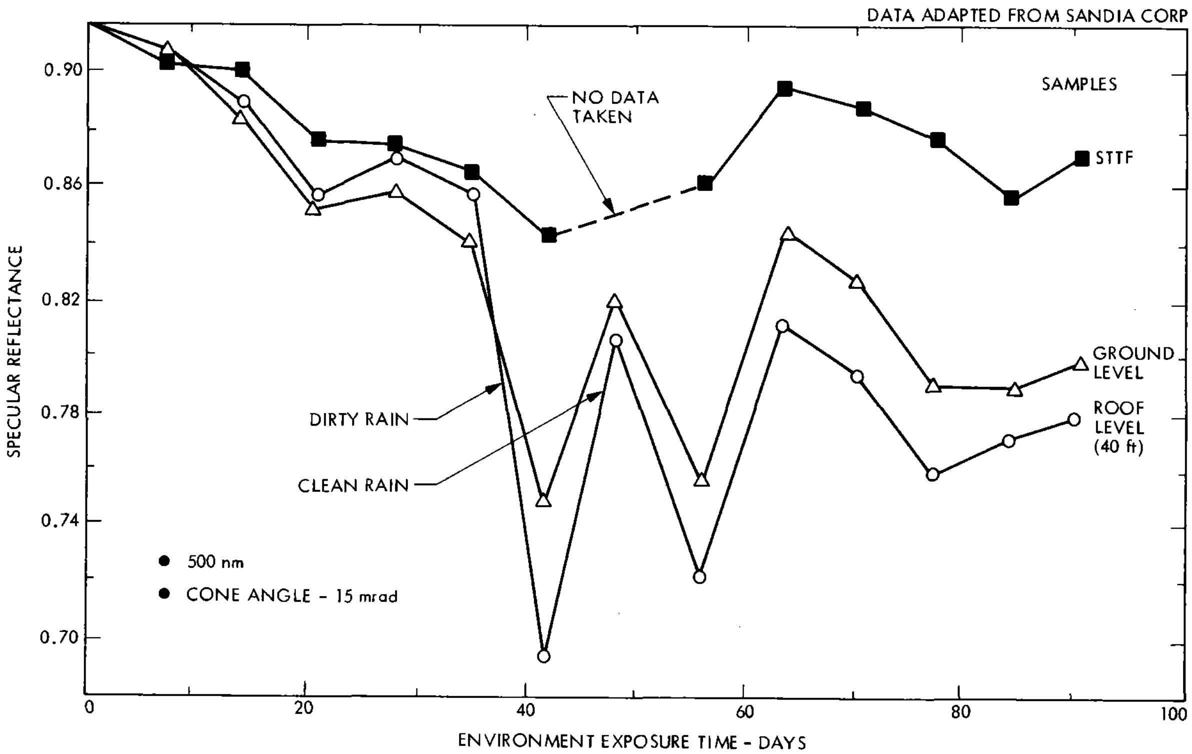


Figure 33. Glass Mirrors: Specular Reflectance vs. Environmental Exposure Time Location - Albuquerque, NM - 1978

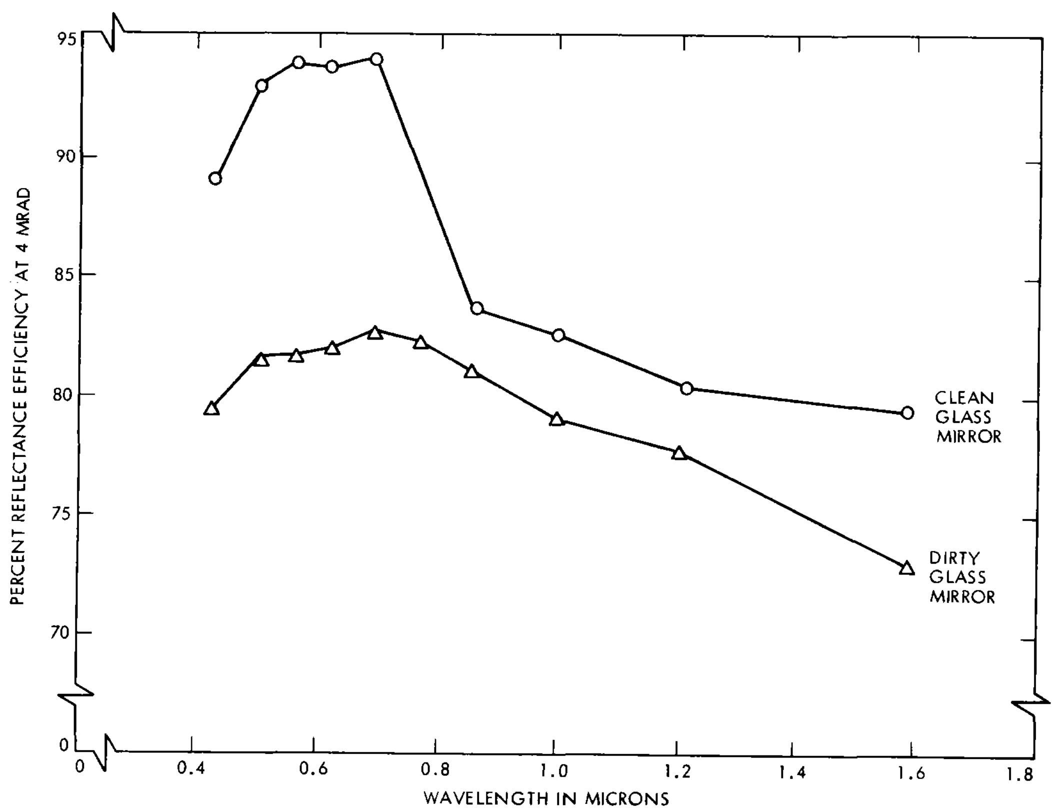


Figure 34. Percent Reflection Efficiency vs. Wavelength (Ref. 103)

Visual Appearance

Visual evaluations were made under artificial daylight (MacBeth Examolite type TC-440) and with an intense concentrated beam light source (Burton Lamp). The specimens were examined in both reflected and transmitted light and were evaluated as follows:

A. (excellent) - No spots and/or haze are visible when examined with the concentrated beam light source less than 6 in. from the specimen.

B. (good) - A few spots and/or a slight haze are visible only with lighting conditions as for A.

C. (fair) - Many spots and/or much haze are visible only with lighting conditions as for A.

D. (poor) - Some spots and/or haze are visible without the concentrated beam light source, but with artificial daylight.

E. (very poor) - An excessive accumulation of weathering products is readily visible with artificial daylight.

Any appearance degradation which could not be removed by scrubbing with a cloth and water is considered to be permanent damage.

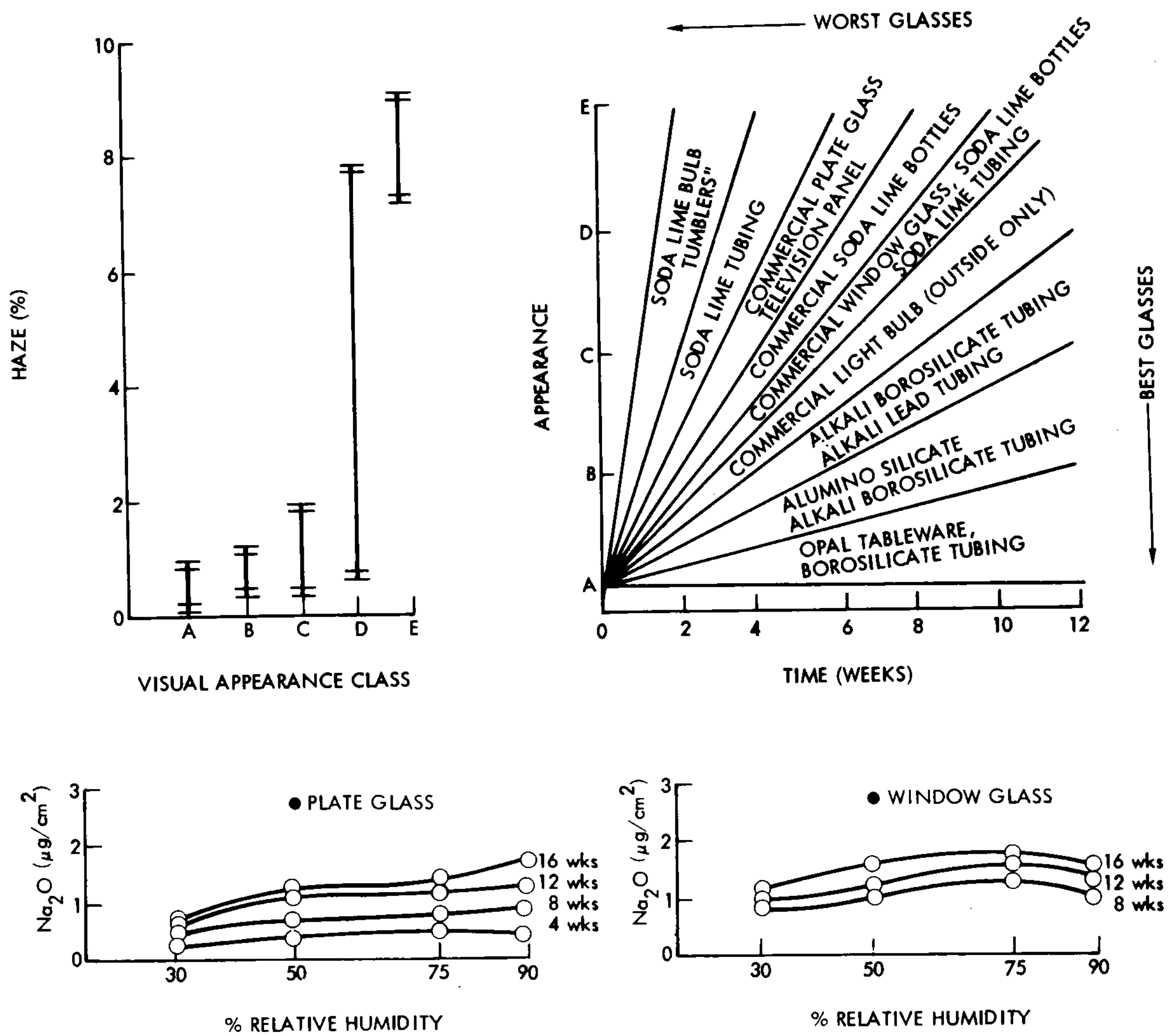


Figure 35. Cleaning Effects (Ref. 113)

Table 1. Analysis and Properties of Representative Glasses (Ref. 39)

Type of Glass	Analysis, Percent by Weight					Softening Temp. °C	Coefficient of Expansion $(^{o}C)^{-1} x10^{-7}$
	SiO_2	Modifiers	Al_2O_3	B_2O_3	PbO		
Fused Silica	99.9	-----	-----	----	---	1667	5.5
96 percent Silica (Vycor)	96.0	-----	-----	4.0	---	1500	8.0
Boro-silicate (Pyrex)	80.5	4.2	2.2	12.9	---	820	32.0
Alumino-silicate	57.7	9.5	25.3	7.4	---	915	42.0
Soda-lime Silica	73.6	25.4	1.0	----	---	696	92.0
Lead-alkali	54.0	11.0	-----	----	35	630	89.0

Table 2. Glass Physical Properties

Type of Glass	Specific Gravity g/cm^3 (lbs/ft^3)	Young's Modulus $10^3 kg/mm^2$ $(10^6$ psi)	Thermal Expansion* cm/cm°C (in/in°F)	Refractive Index	Poisson's Ratio
Soda Lime	2.47 (154)	7.1 (10.2)	$93.6x10^{-7}$ $(52x10^{-7})$	1.512	0.22-0.24
Alumino-silicate	2.52-2.64 (154.6-157.2)	8.8-8.9 (12.5-12.7)	$42.1\text{-}46.1x10^{-7}$ $(23.4\text{-}25.6x10^{-7})$	1.53-1.547	0.24-0.25
Boro-silicate	2.13-2.48 (132.8-154.6)	5.0-6.9 (7.1-9.8)	$32\text{-}51.5x10^{-7}$ $(17.8\text{-}28.6x10^{-7})$	1.473	0.2-0.23
96% Fused Silica	2.18 (135.9)	6.9 (9.8)	$7.6\text{-}8x10^{-7}$ $(4.2\text{-}4.4x10^{-7})$	1.458	0.19
Fused Silica	2.2 (137.2)	7.4 (10.5)	$5.6x10^{-7}$ $(3.1x10^{-7})$	1.459	0.16

* Over the range 0 to 300°C or -18 to 572°F

Source: Corning Glass Works

Table 3. Modulus of Rupture Design Values (Adapted from Ref. 9)

Nominal Thickness -cm (in)	Approximate Variation -cm (in) Max.	Min.	Flat Plates (Regular Temper) $-N/m^2$ (psi)	Curved Plates (Regular Temper) $-N/m^2$ (psi)
0.3175 (0.125)	0.287 (0.133)	0.28 (0.110)	96.5M (14,000)	89.6M (13,000)
0.476 (0.1875)	0.056 (0.220)	0.475 (0.187)	137.8M (20,000)	117.2M (17,000)
0.635 (0.25)	0.66 (0.260)	0.559 (0.220)	172.35M (25,000)	137.8M (20,000)

Table 4. Temperature Characteristics of Glasses

Glasses	T^oC	Softening Point (^oC)	Thermal Expansion (Linear) Parts/^oC
Iron-sealing	24	484	$132x10^{-7}$
Soda-borosilicate	25	693	$50x10^{-7}$
Fused quartz	25	1667	$5.7x10^{-7}$

Table 5. Coefficients of Thermal Expansion (Ref. 118)

Type of Glass	Temperature Interval	Coefficient ($x10^{-4}$)	Temperature Interval	Coefficient ($x10^{-4}$)
1. Barium flint	22-494	0.088	519-550	0.331
2. Plate glass	20-508	0.108	540-560	0.401
3. Light crown	24-422	0.104	494-507	0.548
4. Borosilicate crown	22-498	0.090	539-562	0.393
5. Medium flint	23-402	0.097	452-478	0.396
6. Commercial glass	23-445	0.107	510-534	0.309
7. Pyrex	21-471	0.036	552-571	0.151
8. Schott-Genosser flask	19-414	0.056	540-562	0.404
9. Soda tubing	21-372	0.120	506-525	0.234

Table 6. Refraction Indices of Glass - Relative to Air (Ref. 118)

Type of Glass			Wavelength in Microns					
	0.361	0.434	0.486	0.589	0.656	0.768	1.20	2.00
Zinc Crown	1.539	1.5281	1.523	15.17	1.514	1.511	1.505	1.497
Higher Dispersion Crown	1.546	1.533	1.527	1.520	1.517	1.514	1.507	1.497
Light Flint	1.614	1.594	1.585	1.575	1.571	1.567	1.559	1.549
Heavy Flint	1.705	1.675	1.664	1.650	1.644	1.638	1.628	1.617
Heaviest Flint	---	1.945	1.919	1.890	1.879	1.867	1.848	1.832

Table 7. Refractive Indices vs Temperature for Optical Grade Glass, Corning No. 7913 (Vycor) (Ref. 116)

λ, μm	n, 28°C	n, 526°C	dn/dT (10^{-6}/°C)	n, 826°C	dn/dT (10^{-6}/°C)
0.26520	1.49988	1.50799	+16.3	1.51438	+18.2
0.28936	1.49074	1.49831	+15.2	1.50418	+16.8
0.29673	1.48851	1.49587	+14.8	1.50164	+16.5
0.30215	1.48694	1.49423	+14.6	1.49990	+16.2
0.3130	1.48416	1.49121	+14.2	1.49679	+15.8
0.33415	1.47949	1.48622	+13.5	1.49158	+15.2
0.36502	1.47415	1.48065	+13.1	1.48570	+14.5
0.40466	1.46925	1.47547	+12.5	1.48027	+13.8
0.43584	1.46628	1.47234	+12.2	1.47708	+13.5
0.54607	1.45960	1.46544	+11.7	1.46992	+12.9
0.5780	1.45831	1.46407	+11.6	1.46849	+12.8
1.01398	1.44968	1.45526	+11.2	1.45924	+12.0
1.12866	1.44831	1.45373	+10.9	1.45779	+11.9
1.254	1.44677	1.45222	+10.9	1.45627	+11.9
1.36728	1.44554	1.45095	+10.9	1.45504	+11.9
1.470	1.44422	1.44965	+10.9	1.45370	+11.9
1.52952	1.44356	1.44896	+10.8	1.45306	+11.9
1.660	1.44206	1.44750	+11.0	1.45157	+11.9
1.701	1.44137	1.44677	+10.8	1.45088	+11.9
1.981	1.43750	1.44291	+10.9	1.44702	+11.9
2.262	1.43298	1.43839	+10.9	1.44258	+12.0
2.553	1.42825	1.43373	+11.0	1.43824	+12.5

Table 8. Temperature Coefficients of Refractive Index (Ref. 36)

Glass	dn/dT x 10^6	α x 10^6	dF/F dT x 10^6	dP/P dT x 10^6
Silica (n - 1 = 0.460)	+9.3	0.6	-19.6	+20.8
513-637 Borosilicate crown	+1.4	7.8	+5.1	+10.5
517-602 Silicate crown	-1.1	9.2	+11.3	+7.1
571-430 Light flint	+2.5	(9.1)*	+4.7	+13.5
755-275 Dense flint	+7.8	8.0	-2.3	+18.3
573-574 Light barium crown	+0.4	(8.3)*	+7.6	+9.0
610-574 Dense barium crown	+4.1	(7.1)*	+0.4	+13.8

*Probable values.

Table 9. ASTM Tests Pertaining to Glass
(Ref. 24 and 58)

1. Test for Annealing Point and Strain Point of Glass by Beam Bending, C 598, Vol. 17.

2. Definition of Terms Relating to Glass and Glass Products, C 162, Vol. 17.

3. Standard Reference Materials for Glass and Glass Products, Vol. 17.

4. Recommended Practices for Glass Stress Optical Coefficient, C 770, Vol. 17.

5. Test for Hydrophobic Contamination on Glass by Water Condensation, C 812, Vol. 17.

6. Test for the Softening Point of Glass, C 338, Vol. 17.

7. Test for Analyzing Stress in Glass, F 218, Vol. 17, 43.

8. Test for Young's Modulus, Shear Modulus and Poisson's Ratio for Glass and Glass-Ceramics by Resonance, C 623, Vol. 17.

9. Test for Linear Expansion . . . E 228, Vol. 10, 17, 41, 44.

10. Hydrophobic Contamination Test on Glass by Contact Angle, C 813, Vol. 17.

Table 10. Summary of Reflective Surfaces for Solar Concentrator

No.	Producer/ Supplier	Material Type	Glass Thickness mm (in)	Hemispherical Solar Reflectance	Glass Thickness mm (in)	Solar Transmittance	Reflectance at 500 nm* R_1	σ_1 (m rad)	R_2	σ_2 (m rad)	Coef. Thermal Expansion -cm/cm°C	Cost† \$/Mft²	Remarks
1	Alcoa	Alzak	0	0.85	0	0	0.56 (505)	0.42	0.33	10.1	NA	NA	Aluminum
2	Alcoa	S460666	0	0.32	0	0	--	--	--	--	NA	NA	Aluminum
3	Alcoa	S460667	0	0.92	0	0	--	--	--	--	NA	NA	Aluminum
4	ISC	90-10	0	0.90	0	0	0.86	--	--	--	--	1.50	Silver plated brass
5	ISC	80-20	0	0.88	0	0	0.80	--	--	--	--	1.50	Requires overcoat Cu-Zn 80% Cu, 20% Zn
6	ISC	70-30	0	0.91	0	0	0.81	--	--	--	--	1.50	
7	3M	Scotchcal 5400	0	0.85	0	0	0.86	1.9	--	--	--	0.5 (E)	Estimated cost
8	Corning	Code 7806 (fusion)			1.14 (0.045)	0.88	--	--	--	--	70 (-7) (0-300°C)	1.40	>10 Mft², \$0.45
9	Corning	Code 0317 (fusion)	--	--	2.29 (0.090)	0.910	--	--	--	--	88 (-7) (0-300°C)	0.65-0.80 1.10-1.80	Without metallization With metallization
10	Corning	Code 0317 (fusion)	--	--	1.52 (0.060)	0.909	--	--	--	--	88 (-7) (0-300°C)		
11	Corning	Code 0317 (fusion)	--	--	2.8 (0.110)	0.903	--	--	--	--	88 (-7) (0-300°C)		
12	Schott B270	B270 (Rolled)	--	--	3 (0.120)	0.913	--	--	--	--	NA	0.5-0.8	Without metallization
13	PPG Works	#6 (Float)	--	--	3.17 (0.125)	0.881	--	--	--	--	86 (-7) (25-300°C)	2.15	>10⁷ft², \$0.60-0.65
14	ASG	(Float)	--	--	3.17 (0.125)	0.847	--	--	--	--	85 (-7) (0-300°C)	0.30	
15	Sheldahl	Aluminized Teflon	NA	0.87	--	--	0.80	1.3	0.07	30.9	NA	NA	
16	Kingston Ind.	Kingflux (Al)	0	<0.85	0	0	0.65 (498)	0.37	0.23	16.1	NA	2.00	Similar to Alzak; JPL measurements, 85.4% small quantities
17	Corning	Microsheet Al	--	0.95	0	0	0.77 (550)	1.1	0.18	6.2	NA	NA	
18	Carolina Mirror Co.	2nd Surface Ag Glass	--	0.83	0	0	0.92	0.15	--	--	NA	NA	
19	Payne Co.	Microglass	0.15 (0.006)	0.94	--	--	--	--	--	--	NA	NA	
20	Payne Co.	Microglass	0.30 (0.012)	0.93	--	--	--	--	--	--	NA	NA	

* Measurements at other wavelengths are shown in parentheses. Data from R. B. Pettit.

† These costs are preliminary and are being updated.

(Continued next page)

Table 10 (Cont.). Summary of Reflective Surfaces for Solar Concentrator

No.	Producer/ Supplier	Material Type	Glass Thickness mm (in)	Hemispherical Solar Reflectance	Glass Thickness mm (in)	Solar Transmittance	Reflectance at 500 nm* R_1	σ_1 (m rad)	R_2	σ_2 (m rad)	Coef. Thermal Expansion -cm/cm°C	Cost† $/Mft^2	Remarks
21	CE	Glass (float) (Soda lime)	-- --	-- --	3.17 (0.125)	0.838	--	--	--	--	85 (-7) (0-300°C)	0.50	
22	Ford	Glass (float) (soda lime)	--	--	3.17 (0.125)	0.844	--	--	--	--	85 (-7) (0-300°C)	0.40	
23	Fourco	Glass (float) (Soda lime)	--	--	3.17 (0.125)	0.891	--	--	--	--	--	NA	
24	Liberty Mirrors	Cr coated front surface glass	3.17 (0.125)	0.65	--	--	--	--	--	--	32-93(-7) (20-300°C)	NA	Special measurements
25		Lead-sulfide front surface glass	3.17 (0.125)	0.25	--	--	--	--	--	--	32(-7) (20-300°C)	NA	Auto side mirrors applications only
26	Schott-Jena	Tempax (sheet)	--	--	--	--	--	--	--	--	32 (-7) (20-300°C)	NA	
27	Corning	Code 0317 (fusion low Fe)	1.47 (0.058)	0.95 ±1	--	--	--	--	--	--	88 (-7) (0-300°C)	+	Sandia data + see item #9 vacuum deposited silver
28	Corning	Code 0317 (fusion low Fe)	1.47 (0.058)	0.94 ±1	--	--	--	--	--	--	88 (-7) (0-300°C)	+	Sandia data + see item #9 chemically deposited silver
29	Corning	Code 0317 (fusion low Fe)	1.47 (0.058)	0.926	--	--	--	--	--	--	88 (-7) (0-300°C)	+	JPL measurements old glass. 12/1/78
30	3M	Metallized Polyester	0.07 (0.0028)	0.86	--	--	0.86 (E)	1.9 (E)	--	--	--	0.50	Measurements @AM2 20% degradation/7 yrs.
31	Flabeg Corp.	Crown Glass (float)	3.17 (0.125)	TBD	--	--	--	--	--	--	70 (-7) (0-300°C)	--	Resin and/or Mylar reverse side sealant
32	Corning	7806 (modified) (fusion)	0.050(E)	0.95 (E)	--	--	--	--	--	--	70 (-7) (0-300°C)	--	

* Measurements at other wavelengths are shown in parentheses. Data from R. B. Pettit.

† These costs are preliminary and are being updated.

E Estimated

Table 11. Glass Survey Summary (Ref. 96)

Manufacturer	Process	Composition	Thickness		Solar Transmittance		Optical Flatness % Power Outside		Approximate Cost	
			Tested	Possible	Measured	Possible	1 mrad	2 mrad	1M, ft^2	>10M, ft^2
ASG	Lo-Iron Float	Soda Lime	0.125		0.847				0.30	
	Sunadex-Twin Ground	Soda Lime		>4mm		>0.91	0*	0*	1.30	
CE	Float	Soda Lime	0.125		0.838		18	1	0.50	
	Heliolite-Twin Ground	Soda Lime				0.91	0*	0*	1.30	
Corning	0317 Fusion	Aluminosilicate	0.110	>0.020	0.903		15	0	0.65 - 0.80	
	0317 Fusion	Aluminosilicate	0.090		0.910		19	0	0.65 - 0.80	
	7806 Fusion	Lime Borosilicate	0.045		0.876**	>0.91			1.40	0.45
Fourco	Rolled	Soda Lime	0.125		0.891		90	57		
Ford	Float	Soda Lime	0.125	>0.105	0.844	>0.88	5	0	0.40	
Guardian	Float	Soda Lime		>0.085		>0.88			1.00	
LOF	Float	Soda Lime	0.125		0.831		7	0		
PPG	Mid-Iron Float	Soda Lime	0.125		0.866		8	0		
	Lo-Iron Float	Soda Lime	0.125	>0.060	0.881	>0.89	20	4	2.15	0.60 - 0.65

* Based on Measurements of ASG Tinted Twin Ground Glass

** Measured by R. Pettit, SLA, Total Hemispherical Solar Transmittance

Table 12. Reflectance Efficiency of Glass Mirrors at AM2 (Ref. 103)

Glass (Wt Percent Iron Oxide)	Mirror Manufacturing and Silvering Process	Thickness in mm (In.)	Specimen No.	Over Solar Spectrum using Beckman 125 mrad	At Wavelength of 560 nm using Specular Photometer			Over Solar Spectrum using Specular Spectro Photometer		
					16 mrad	8 mrad	4 mrad	16 mrad	8 mrad	4 mrad
ASG Ind Lustra Sheet (0.05 - 0.06)	Buchmin Industries Mirrorlab Process	0.7 (0.028)	134.1	96.0				94.0	94.0	
		2.4 (0.093)	110.1	94.0				93.0	92.0	86.0
			110.2	94.0				92.0	92.0	88.0
	Gardner Mirror and Process	3.2 (0.125)	65.3	91.4	95.5	95.0	93.5			
			65.13	93.5	94.5	94.0	93.5			
			65.15	93.5	94.5	94.5	93.5			
			65.16	94.3	95.0	95.0	94.0	92.0	93.0	87.0
			67.3	91.9	95.5	94.5	94.0			
	Binswanger Mirror Co. Mirrorlab Process	4.7 (0.187)	114.1	88.0				86.0	86.0	
Fourco Sheet (0.06)	Tyre Bros. Two Part London Laboratory Process	2.3 (0.090)	32.3	93.1	95.0	94.0	90.0			
			50.2	90.4	96.0	96.0	94.0			
			50.3	90.3	97.0	96.0	96.0			
			50.4	90.7	96.5	96.5	96.0			
			50.5	90.3	95.0	95.0	92.0			
		6.4 (0.250)	33.3	86.8	89.0	89.0	88.0			
			51.2	83.9	94.0	94.0	88.0			
			51.3	84.4	93.0	92.0	88.0			
			51.4	84.5	93.0	93.0	91.0			
			51.5	84.3	91.0	90.0	88.5			
PPG Industries Float (0.05)	Buchmin Industries Mirror Lab Process	3.2 (0.125)	1	92.0	95.0	95.0	95.0	90.0	89.0	81.0
			2	92.0	95.0	95.0	95.0	89.0	88.0	81.0
			3	92.0	95.0	96.0	95.0	90.0	89.0	84.0
(0.07)		2.4 (0.093)	111.1	88.0		95.0		87.0	86.0	82.0
			111.2	88.0				87.0	86.0	81.0
(0.10)		3.2 (0.125)	86.1	83.5				83.3	82.8	77.1

(Continued next page)

Table 12 (Cont.). Reflectance Efficiency of Glass Mirrors at AM2

Glass (Wt Percent Iron Oxide)	Mirror Manufacturer and Silvering Process	Thickness in mm (In.)	Specimen No.	Over Solar Spectrum using Beckman 125 mrad	At Wavelength of 560 nm using Specular Photometer			Over Solar Spectrum using Specular Spectro Photometer		
					16 mrad	8 mrad	4 mrad	16 mrad	8 mrad	4 mrad
Ford Motor Float (0.09 - 0.10)	Buchmin Industries Mirrorlab Process	2.4 (0.093)	52.2 52.3 52.4 52.5 52.6	85.7 85.7 85.9 86.0 86.1	96.5 94.5 94.0 96.0 93.0	96.0 94.5 93.5 95.0 93.0	96.0 94.0 93.0 95.0 93.0			
		3.2 (0.125)	65.x 65.22	83.3 83.2	91.0 91.0	91.0 91.0	86.0 88.0	81.9 81.0	81.9 81.0	78.0 76.0
		6.4 (0.250)	6.001 6.002	70.7 70.7	89.0 89.0	88.5 89.5	88.5 88.5			
Guardian Ind Float (0.10)	Buchmin Ind Mirrorlab Process	3.2 (0.125)	66.3	82.5	93.5	92.5	92.0			
ASG Industries Float (0.10 - 0.13)	Binswanger Mirror Co. Mirrolab Process	2.4 (0.093)								
		3.2 (0.125)	Lot No. 2 B-1 B-2 B-3	83.7 84.2 83.7 84.8	92.0 92.0 92.0 92.5	91.0 92.0 92.0 92.0	90.5 86.0 89.5 87.5	81.6 83.1 82.3 84.8	82.1 83.1 82.3 84.8	78.5 78.8 75.9 80.9
		4.8 (0.188)	Lot No. 1	77.9	88.0	88.0	81.5	76.0	76.0	71.8
	Buchmin Ind. Mirrorlab Process	6.4 (0.250)	64.22	71.1	88.0	88.0	88.0	71.0	71.0	66.0
LOF Float (0.12)	Tyre Bros. 2-Part London Lab Process	2.5 (0.100)	29.3	82.4	93.0	92.0	92.0			
		6.4 (0.250)	30.1	64.7	81.0	79.0	75.0			

Table 13. Solar Transmission Efficiencies of Some Coatings (Ref. 103)

Supplier	Specimen Identification	Over Solar Spectrum using Beckman	At Wavelength of 550 nanometer using Specular Photometer		
		125 mrad	16 mrad	8 mrad	4 mrad
De Soto Inc.	1091-3-51 Fluorocarbon Acrylate	99.9	100	99.5	99.0
	1091-6-51 Polyurethane	99.9	99.5	98.5	98.5
	1091-10-51 Thermosetting Silicone	99.7	98.5	98.5	98.0
Rohm and Haas Co.	R&H No. 5	99.6	99.5	100	99.5
	R&H No. 7	99.7	99.0	99.0	98.0
	R&H No. 12	99.3	99.0	98.5	97.0
PPG Industries	PPG No. 2	99.5	100	99.5	99.5
	PPG No. 5	99.5	99.0	98.5	99.0
DuPont Co.	500 S IMRON	99.5	100	100	100
	326 L Acrylic	98.5	99.5	99.5	99.0
	RK-63654	99.3	99.0	99.0	97.0
O'Brien Corp.	874-C-200	99.5	100	99.0	99.5
	5-73C	99.4	99.0	99.0	98.0

Table 14. Optical Properties of Metals (Ref. 53)
Percent Normal-Incidence Reflectance of Freshly Evaporated Mirror Coatings of Aluminum, Silver, Gold, Copper, Rhodium, and Platinum, from the Ultraviolet to the Infrared*

λ, μm	Al	Ag	Au	Cu	Rh	Pt
0.220	91.5	28.0	27.5	40.4	57.8	40.5
0.240	91.9	29.5	31.6	39.0	63.2	46.9
0.260	92.2	29.2	35.6	35.5	67.7	51.5
0.280	92.3	25.2	37.8	33.0	70.7	54.9
0.300	92.3	17.6	37.7	33.6	73.4	57.6
0.315	92.4	5.5	37.3	35.5	75.0	59.4
0.320	92.4	8.9	37.1	36.3	75.5	60.0
0.340	92.5	72.9	36.1	38.5	76.9	62.0
0.360	92.5	88.2	36.3	41.5	78.0	63.4
0.380	92.5	92.8	37.8	44.5	78.1	64.9
0.400	92.4	95.6	38.7	47.5	77.4	66.3
0.450	92.2	97.1	38.7	55.2	76.0	69.1
0.500	91.8	97.9	47.7	60.0	76.6	71.4
0.550	91.5	98.3	81.7	66.9	78.2	73.4
0.600	91.1	98.6	91.9	93.3	79.7	75.2
0.650	90.5	98.8	95.5	96.6	81.1	76.4
0.700	89.7	98.9	97.0	97.5	82.0	77.2
0.750	88.6	99.1	97.4	97.9	82.6	77.9
0.800	86.7	99.2	98.0	98.1	83.1	78.5
0.850	86.7	99.2	98.2	98.3	83.4	79.5
0.900	89.1	99.3	98.4	98.4	83.6	80.5
0.950	92.4	99.3	98.5	98.4	83.9	80.6
1.0	94.0	99.4	98.6	98.5	84.2	80.7
1.5	97.4	99.4	99.0	98.5	87.7	81.8
2.0	97.8	99.4	99.1	98.6	91.4	81.8
3.0	98.0	99.4	99.3	98.6	95.0	90.6
4.0	98.2	99.4	99.4	98.7	95.8	93.7
5.0	98.4	99.5	99.4	98.7	96.4	94.9
6.0	98.5	99.5	99.4	98.7	96.8	95.6
7.0	98.6	99.5	99.4	98.7	97.0	95.9
8.0	98.7	99.5	99.4	98.8	97.2	96.0
9.0	98.7	99.5	99.4	98.8	97.4	96.1
10.0	98.7	99.5	99.4	98.9	97.6	96.2
15.0	98.9	99.6	99.4	99.0	98.1	96.5
20.0	99.0	99.6	99.4			
30.0	99.2	99.6	99.4			

*The reflectance of a good evaporated mirror coating is always higher than that of a polished or electroplated surface of the same material.

Table 15. Solar Efficiency of Silvering Processes* (Ref. 103)

Silvering Process	Silver Thickness gm/m^2	Over Solar Spectrum using Beckman	At of 550 nm using Specular Photometer		
		125 mrad	16 mrad	8 mrad	4 mrad
Peacock Laboratory	1.35 (125 mg/ft^2)	85.0	93.5	91.0	62.0
London Laboratory 2 part	0.86 (80 mg/ft^2)	84.3	91.0	90.0	88.5
London Laboratory 3 part	0.84 (78 mg/ft^2)	84.5	93.0	92.5	85.0
Hilemn	0.82 (76 mg/ft^2)	84.1	92.5	91.5	79.0
Mirrolab	1.01 (94 mg/ft^2)	85.3	92.5	90.0	59.5

*6.4 mm (1/4 inch) thick Fourco sheet glass was used.

Table 16. Solar Efficiency versus Silver Thickness (Ref. 103)

Type Glass and Thickness in **millimeters (inches)**	Specimen No.	Silver Deposition in grams per square meter	Beckman Spectro Photometer (Over Solar Spectrum)	Specular Photometer (550 nm)			Specular Spectrophotometer (Over Solar Spectrum)		
			125 mrad	16 mrad	8 mrad	4 mrad	16 mrad	8 mrad	4 mrad
Fourco Sheet Glass 6.4 mm (1/4-inch)	58.4	0.65 (60 mg/ft^2)	83.7	91.5	90.0	81.0			
	59.3	0.86 (80 mg/ft^2)	84.1	91.5	91.0	89.0			
	60.1	1.01 (94 mg/ft^2)	86.3	92.5	90.0	59.5			
	61.3	1.08 (100 mg/ft^2)	83.1	90.0	88.0	82.0			
	62.1	1.29 (120 mg/ft^2)	84.7	92.0	90.5	85.5			

(Continued next page)

Table 16 (Cont.). Solar Efficiency versus Silver Thickness

Type Glass and Thickness in millimeters (inches)	Specimen No.	Silver Deposition in grams per square meter	Beckman Spectro Photometer (Over Solar Spectrum)	Specular Photometer (550 nm)			Specular Spectrophotometer (Over Solar Spectrum)		
			125 mrad	16 mrad	8 mrad	4 mrad	16 mrad	8 mrad	4 mrad
ASG Industries Float Glass 2.4 mm (3/32-inch)	87.1	0.65 (60 mg/ft^2)	85.0	92.0	92.0	91.0			
	88.1	0.86 (80 mg/ft^2)	85.0	93.0	92.0	92.0			
	89.1	1.01 (94 mg/ft^2)	86.0	93.0	92.0	88.0	83.6	83.2	77.2
	90.1	1.08 (100 mg/ft^2)	85.0	93.0	93.0	93.0			
	91.1	1.29 (120 mg/ft^2)	85.0	92.0	92.0	92.0			

Table 17. Properties of Coated Chemically Deposited Silver Mirrors (Ref. 103)

Specimen No.	Company	Coating	Measuring Instrument	Specularity	Efficiency at the following Wavelengths in Nanometers										Avg Over Solar Spectrum
					426	498	561	623	691	774	860	1008	1208	1594	
99-2	DuPont	500 IMRON	Specular Spectro Photometer	16	60	79	85	86	90	90	91	93	93	83	85
				8	58	77	83	85	86	89	89	91	91	82	83
				4	55	73	79	83	83	85	86	88	88	81	80
			Specular Photometer	4			83								
102-2	Sierracin	FX-103	Specular Spectro Photometer	16	60	80	88	90	93	94	95	98	97	75	87
				8	59	80	87	90	92	93	95	96	95	75	86
				4	59	80	87	89	90	92	95	96	94	71	85
			Specular Photometer	4			82								
104-1	Textar Plastics	C-254	Specular Spectro Photometer	16	58	76	84	90	90	92	93	96	96	87	86
				8	58	75	83	88	89	92	93	95	96	87	86
				4	57	75	82	87	88	90	93	94	96	80	84
			Specular Photometer	4			82								
101-2	DuPont	RK3637	Specular Spectro Photometer	16	57	79	86	90	90	92	93	95	96	90	87
				8	56	77	85	88	90	91	91	94	94	88	85
				4	56	77	83	88	90	90	90	92	94	83	84
			Specular Photometer	4			84								

Table 18. Reflectance Degradation of Desert Mirrors Exposed for 184 Days (Ref. 103)

Supplier	Coating Identification	Initial Values at Various Acceptance Angles in Milliradians (mrad): Over Solar Spectrum using Beckman, 125 mrad	At Wavelength of 550 nanometer using Specular Photometer: 16 mrad	8 mrad	4 mrad	Exposure at Fort Irwin in Mojave Desert: Exposure (days)	Results
ROHM and HAAS Co.	70-2 (R&H No. 1)	93.5	87.0	83.5	75.0	165	Coating Failed
	71-2 (R&H No. 2)	96.8	95.5	95.0	94.0	166	Coating Failed
	72-2 (R&H No. 3)	97.3	96.5	95.5	92.6	184	Corrosion Starting
	73-1 (R&H No. 4)	97.2	96.5	95.0	92.0	184	Corrosion Starting
	74-2 (R&H No. 5)	97.6	94.0	90.5	82.0	184	Slight Crazing
	76-1 (R&H No. 6)	97.1	96.0	96.5	94.0	184	Extensive Crazing
	76-1 (R&H No. 7)	97.1	95.0	94.5	92.5	184	Slight Crazing
	77-2 (R&H No. 8)	96.8	93.0	90.5	82.5	184	Extensive Crazing
	78-1 (R&H No. 9)	97.6	95.0	94.5	92.0	184	Extensive Crazing
	79-2 (R&H No. 10)	97.9	94.0	92.5	84.5	185	Coating Failed
	80-1 (R&H No. 11)	97.6	95.5	95.0	87.0	184	Severe Corrosion
	81-1 (R&H No. 12)	95.4	90.0	89.0	85.0	184	Moderate Crazing
O'Brien Corp.	69-1 (6-73C)	95.4	93.0	90.5	82.5	165	Coating Failed
	68-1 (874-C-200)	96.3	90.5	87.0	71.0	184	Coating Failed

Table 19. Reflectance Degradation as a Function of Wavelength for Desert Soiled Mirrors (Ref. 103)

Specimen Number	Mirror Glass	Mirror Condition	Instrument	Specularity	Solar Reflectance Efficiency at the Following Wavelengths in Nanometers										Average Value Over Solar Spectrum
					426	498	561	623	691	774	860	1008	1208	1594	
65.16	ASG Ind Lustra Sheet 3.2 mm (0.125)	Dirty	Beckman	125	92.5	95.5	96.5	96.0	94.5	92.0	90.5	89.5	89.5	92.0	92.9
			Specular Spectro Photometer	16	83.6	87.7	89.4	88.5	92.2	86.8	85.4	83.9	84.7	89.9	87.0
				8	83.6	87.7	89.4	88.5	90.1	86.8	85.4	83.9	84.7	89.2	87.0
				4	79.6	81.7	81.7	82.1	82.8	82.4	81.2	79.2	77.9	73.0	80.0
			Specular Photometer	16			96.5								
				8			96.0								
				4			95.5								
		Clean	Beckman	125	94.0	96.5	98.0	97.0	96.5	94.5	92.0	90.5	90.5	93.5	94.3
			Specular Spectro Photometer	16	90.9	93.7	94.5	93.7	95.2	91.7	90.5	89.8	89.5	94.6	92.0
				8	91.1	93.7	95.6	94.4	92.5	90.0	89.4	80.2	89.5	93.8	93.0
				4	89.1	93.1	94.0	93.8	94.3	80.0	83.8	82.6	80.5	79.6	87.0
			Specular Photometer	16			95.0								
				8			95.0								
				4			94.0								

Table 20. Washing of Model Heliostat Using Different Washing Solutions (Ref. 103)

Company	Exposure Time (days)	Reflectance Efficiency (%)		Washing Solution Application					Rinse Solution Application				Drying Time (min)
		Dirty	Clean	Pressure (psi)	Time	Quantity (gal.)	Nozzle	Dwell Time (sec)	Pressure (psi)	Time (sec)	Quantity (gal.)	Nozzle	
McGean	20	59.1	64.75	80	35 sec	0.83	80.10	30	80	90	3.2	65.16	20
Turco	29	56.52	63.54	40	3 min	2	80.04	60	50	105	4.0	90.20	20
TEC	39	N/A	N/A	150	80 sec	4	Graco Gun	60	150	145	5.0	Graco Gun	30

Table 21. Washing of SRE Heliostats using McGean Chemical's Washing Solution (Ref. 103)

Heliostat No.*	Prewash Reflectance Efficiency (percent)	Postwash Reflectance Efficiency (percent)	Application Time		Solution Quantity		Solution Type		Nozzle Size	
			Wash (min)	Rinse (min)	Wash (gal.)	Rinse (gal.)	Wash	Rinse	Wash (gpm)	Rinse (gpm)
H_1	65.9	78.2	1.0	5.0	1.50	14.0	A69M	Deionized Water	1	5
H_2	56.1	76.5	1.0	3.7	1.25	8.75	A69M	Deionized Water	1	5
H_3	69.2	87.5	1.0	3.0	0.75	8.0	A69M	Deionized Water	1	5
H_4	73.3	84.0	1.0	2.0	1.25	5.75	CB120	Deionized Water	1	5
IH1	$\frac{76.8}{72.2}$	$\frac{85.1}{86.6}$	1.4	2.8	1.60	7.75	CB120	Deionized Water	1	5

* H_1, H_2, H_3 = Acrylic first surface mirrors, H_4 = Laminated mirror, 1H1 = 3/32 mirror bonded to foam core laminated mirror

Table 22. Summary Table -- Identification of Reflective Surfaces for Solar Concentrator Applications

Type of Reflective Surface	Thermal Expansion	Reflectance	Durability	Price	Present Availability
Glass, fusion Type 0317	Superior	Superior	Excellent	Good	Superior
Glass, fusion Type 7806 (Modified)	NA†	Superior (Est.)	Superior (Est.)	Good (Est.)	NA
Glass, Schott Type B270	Superior	Superior	Excellent	Superior	Good
Glass, float‡	Good	Good	Superior	Good	Excellent
Aluminum	Fair*	Superior** Good	Good	Fair	Superior

* For cellular glass substrate

** If overcoated

† NA = Not available

‡ Recent preliminary measurements indicates that the characteristics of float glass may be approaching those of fusion glass.

SECTION VIII

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