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Low-Cost
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Glass for Low-Cost Photovoltaic Solar Arrays

F.L. Bouquet

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The JPL Low-Cost Solar Array Project is sponsored by the Department of Energy (DOE) and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays.

ABSTRACT

In photovoltaic systems, the encapsulant material that protects the solar cells should be highly transparent and very durable. Glass satisfies these two criteria and is considered a primary candidate for low-cost, photovoltaic encapsulation systems. In this report, various aspects of glass encapsulation are treated that are important for the designer of photovoltaic systems. Candidate glasses and available information defining the state of the art of glass encapsulation materials and processes for automated, high volume production of terrestrial photovoltaic devices and related applications are presented. The criteria for consideration of the glass encapsulation systems were based on the LSA (Low-cost Solar Array) Project goals for arrays: (a) a low degradation rate, (b) high reliability, (c) an efficiency greater than 10 percent, (d) a total array price less than \$500/kW, and (e) a production capacity of 5×10^5 kW/yr.

The glass design areas treated herein include the types of glass, sources and costs, physical properties and glass modifications, such as antireflection coatings.

PREFACE

The research described in this report was carried out at the Jet Propulsion Laboratory, Applied Mechanics Technology Section, California Institute of Technology, and was sponsored by the U.S. Department of Energy through an agreement with the National Aeronautics and Space Administration.

ACKNOWLEDGMENT

Contributions to this study were made by the personnel of Battelle-Columbus Laboratories. Their report "Review of World Experience and Properties of Materials for Encapsulation of Terrestrial Photovoltaic Arrays", ERDA/JPL-954328-76/4 is used as a major source of data for this report.

In addition, special contributions to the study are acknowledged from the Applied Mechanics Technology Section, Applied Mechanics Division, Jet Propulsion Laboratory, California Institute of Technology as follows:

R. F. Holtze
H. G. Maxwell

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SECTION I

GENERAL

A. FORMS OF GLASS

Glass is available in over 10,000 types and many different forms (References 1-16). Although flat glass is undoubtedly the most familiar type, glass is available with a wide variation of physical characteristics such as sagged (curved) or foamed. The detailed physical properties of the glass vary widely depending upon the manufacturing process and the chemical composition. The processability, environmental durability and prices of photovoltaic glass vary widely from different procurement sources.

It is the purpose of this report to briefly identify the above properties and characteristics of glass applicable for terrestrial photovoltaic encapsulation systems. See References 17-31. The first basic characteristic is the form of the glass and these are listed below.

1. Flat Glass

Flat glass can be classified as sheet, plate or float. Sheet glass is the most common form used in ordinary windows. Plate or float glass is used when exceptionally clear and accurate vision is needed, such as automobile windows. Although sheet glass is taken from the melting furnace with no additional polishing, plate glass is carefully ground and polished to smooth the surface. Float glass, however, is made by floating a ribbon of glass on a surface of hot, molten metal to produce smoother, more perfect parallel surfaces. Flat glass is available in many sizes and thicknesses. Typical available thicknesses vary from 0.7 mm (0.028 inch) to 2.54 mm (1.0 inch). Without special manufacturing capability, the maximum dimension is $\sim$3.05 meters (120 inches).

2. Cloth

Glass comes also in the form of continuous fibers that can be incorporated into another material or be weaved into cloth.

3. Laminated Glass

Especially strong glass can be made using laminated layers of plastic and glass. Upon breakage, the plastic layer becomes elastic and stretches. This holds the broken pieces of glass together and is considerably safer than other types.

4. Bullet-Resistant Glass

In thicknesses of several inches, multilayered laminated glass will stop projectiles even at short range.

5. Tempered Safety Glass

Unlike laminated glass, tempered safety glass is a single sheet that has been given special heat treatmen . Although it appears to be similar to other types of glass in weight and thickness, it can be up to five times as strong against impact. It may be used as an alternate to laminated glass.

6. Foam Glass

Foam glass is made with many tiny bubbles throughout the material matrix and is extremely lightweight. It is used principally in special situations, such as insulation or on chemical equipment.

7. Heat-Resistant Glass

This type of glass is high in silica and usually contains boric oxide. Its low coefficient of thermal expansion permits it to withstand severe temperature shock without breaking.

8. Coated Glass

Glass for special applications is available in many coated forms. Metallic or other surface coatings can be applied to produce superior transmissivity, reflectance or thermal control. Coatings are applied through sputtering vacuum deposition or ion implantation on the surface. Tin oxide coatings are used to increase surface conductivity in some electrical applications.

9. Insulation

When glass fiber batting is made from relatively impure materials for insulation purposes, it is called rock or mineral wool.

10. Glass fibers

Large special glass fibers are used for light transmission while small glass fibers are used for strengthening materials. The fibers may be continuous (see cloth above) or discontinuous as used in fiberglass.

Many other categories of glass exist such as optical, photochromic, heat conducting and photosensitive glass. The reader is referred to the References, especially Reference 1, 5 and 32, for further details on glass forms. However, the emphasis in this report is on the types of glasses useful in photovoltaic applications which are treated in the following section.

B. DIFFERENT TYPES OF GLASS FOR PHOTOVOLTAIC APPLICATIONS

Considerable experience with glass encapsulation for space and terrestrial applications has evolved. See Reference 28. So far, over 8 years experience have accrued on terrestrial modules under controlled conditions. The major features of the terrestrial experience to date with encapsulation systems in which glass constituted at least one component of the system can be summarized in terms of glass weatherability and encapsulation design (including optical coupling). Two general classes of glasses, soda-lime - silica and borosilicate, have exhibited acceptable weatherability over periods as long as about 16 years as covers in photovoltaic arrays. When hermetic seal function has been maintained, arrays have not experienced any serious degradation in electrical output attributable to lack of performance of the glass itself. Glass failures per se have stemmed from the material's fragility under shock loading. See Section IV in this report entitled Glass Performance.

Because of the necessity to use most glasses in a preformed shape, the selection of candidate glasses and processes for employing them depends heavily upon the array or module design. Moreover, the availability of many glasses in only limited shapes and forms also dictates that the selection be design dependent. Accordingly, the representative samples of candidate glasses given in the tabulation below are matched to selected design concepts. See Table 1.

The two main types of glasses useful for low-cost photovoltaic modules that have emerged from JPL research are soda-lime and borosilicate. The soda-lime glass with low iron content is preferred because of its high transmissivity, availability and low cost. Examples are ASG's Sunadex^R, ASG's Solarex^R, and Fourco's Clearite^R. Low expansion borosilicate glass is exemplified by Corning's type 7070 or 7740 (Pyrex^R). Also, Schott's Tempax^R is a special borosilicate glass that is extremely resistant to thermal shocks.

Further details on the physical properties of glass for photovoltaic applications are given in the following section.

C. PHYSICAL PROPERTIES

The type of glass needed for photovoltaic applications has low distortion and low solar absorptance properties. Since iron is a known element that reduces optical transmittance, it is important that the glass should have low-iron content. The effect of iron on solar transmittance for various glass thicknesses is shown in Figure 1. Reduction of optical transmission in the module glass, of course, results in a corresponding reduction in electrical cell output. See Section IV entitled Glass Performance.

The general properties of glass can be arbitrarily divided into 12 categories. See Table 2. Glasses have properties that can vary over wide ranges depending upon the chemical composition. For example, typical ranges are shown in Tables 3 and 4. Silicon properties are shown in Table 3 for comparison. The borosilicates come closest to matching the coefficient of expansion of the silicon solar cell.

Glass is composed primarily of SiO_2 but a few other oxides (such as B_2O_3 or P_2O_5) can form similar networks, and yet others (such as Al_2O_3) enter into the SiO_2 network. See Table 5. Many other oxides (e.g., Na_2O, CaO, PbO) depolymerize the network by breaking up oxygen-to-oxygen bonds; their oxygen attaches itself to a free bond, while the metal atom, in the ionic state, is distributed randomly. Depolymerization lowers the bond strength, thus also the melting point and the viscosity at a given temperature, making the glass more suitable for manufacturing purposes. See Table 6. Ninety percent of all glass produced is

Table 1. Property Data For Selected Candidate Encapsulation Materials (Ref. 28.)

Property[a]	Soda-Lime-Silica Glasses							Borosilicate Glasses				
	0.7 mm GE 008	1 mm Corning 0080	2-mm OI R-6	3-mm ASG Sunadex (very-low-iron rolled)	3-mm ASG Lustraglass (low-iron sheet)	3-mm Fourco Clearlite (low-iron sheet)	3-mm PPG Float (typical window glass)	Corning 7070	?-mm Corning 7740	1-mm OI KG-33	OI ES-1	10-mm GE 776
Transmittance												
Visible, at 500 nm, percent	91.5	92	90	91	92	91.9	90	-	90	92	-	92
IR, at 1000 nm, percent	92	92	92	90	86	86.5	64	-	88	91	-	93
Range >10 percent, μm	0.29-4.7	0.3-4.5	0.32-4.2	-	-	-	-	-	-	0.28-3.5	-	-
Refractive Index	1.512	1.51	1.52	1.519	1.510	1.516	1.518	1.469	1.474	1.47	1.47	1.472
Density, 10^{-3} kg/m^3	2.48	2.47	2.53	2.5	2.5	-	2.5	2.13	2.23	2.23	2.12	2.22
Thermal Conductivity, w/mK @ 273 K	-	1.05	1.02	0.91	0.91	-	0.94	-	1.09	1.13	1.09	-
Expansion Coefficient, 10^{-7}/C	93	93.5	93	88	88	92.2	86	32	32.5	32	33	33
Youngs Modulus, 10^{10} N/m^2 (10^6 psi)	6.9 (10)	7.0 (10.2)	-	-	-	-	6.9 (10)	5.1 (7.4)	6.[illegible] (9.1)	-	-	-
Poissons Ratio	0.24	0.22	-	-	-	-	0.22	0.22	0.20	-	-	-
Strain Point, C	-	473	486	500	500	-	-	456	510	513	430	475
Annealing Point, C	515	514	525	550	550	-	-	496	560	565	476	525
Softening Point, C	700	696	700	780	780	-	721	-	821	825	745	775
Chemical Composition, percent[b]												
SiO_2	72.3	73.6	-	-	-	-	73.1	70/72[c]	80.5	-	-	78.0
Na_2O	16.3	16.0	-	-	-	-	13.6	0/1.5	3.8	-	-	-
K_2O	0.3	0.6	-	-	-	-	0.03	0.5/1.5	0.4	-	-	-
Li_2O	-	-	-	-	-	-	-	1-2/-	-	-	-	-
CaO	5.0	0.3	-	-	-	-	8.87	0.1/-	-	-	-	-
MgO	3.5	3.6	-	-	-	-	3.89	0.2/-	-	-	-	-
Al_2O_3	1.9	0.6	-	-	-	-	0.12	1.1/-	2.2	-	-	-
Fe_2O_3	-	-	-	0.02	0.05-0.08	0.06	0.09	-	-	-	-	-
B_2O_3	-	-	-	-	-	-	-	28/25	12.9	-	-	15.0
ZnO	-	-	-	-	-	-	-	-	-	-	-	-
TiO_2	-	-	-	-	-	-	-	-	-	-	-	-
As_2O_3	-	-	-	-	-	-	-	0/1.0	-	-	-	-
Weatherability[d]	C	C	B/C	B	B	B	B	B	A	A	B	B

(a) Information compiled from various sources.
(b) Compositional information provided to indicate approximate chemistry of glass because manufacturers often have several batch formulations for same glass, all of which provide similar properties.
(c) Data from two different sources.
(d) Estimated ranking: A = no weatherability problem anticipated; B = may weather under some circumstances; C = weathering could be a problem.

Table 1. Property Data For Selected Candidate Encapsulation Materials (Continuation 1)

Property[a]	Special or Development Glasses						
	Honeywell low-reflectivity glass	1-mm Corning 0211 (micro-sheet cover glass)	PPG NESA	OI Passivation	OI EE-5	Innotech IP 530	GE 351
Transmittance							
Visible, at 500 nm, percent	~98	92	75-80		-	-	-
IR, at 1000 nm, percent	~90	92	55-60		-	-	-
Range >10 percent, μm		0.32-4.5	-		-	-	-
Refractive Index		1.523	2.0		1.53	-	1.68
Density, 10^{-3} kg/m^3		2.57			2.57	-	3.78
Thermal Conductivity, w/mK @ 273 K		0.96			1.30	-	-
Expansion Coefficient, 10^{-7}/C		73.8			31	80	44
Young Modulus, 10^{10} N/m^2 (10^6 psi)		7.4 (10.8)			-	-	-
Poissons Ratio		0.22			-	-	-
Strain Point, C		508			628	-	-
Annealing Point, C		550			672	-	-
Softening Point, C		720			860	495	635
Chemical Composition, percent[b]	Honeywell Systems Research Center demonstrations facility will produce low-reflectivity surfaces on low-iron-sheet glass by etching process		Electrically conductive SnO_2 coating applied to sheet or float glass substrate	Thick-film technology being developed for solar cells under Contract NAS3-19441	Alkali-free alumino silicate which seals to silicon	Hermetic passivation glass for silicon devices	Glass for encapsulating diodes
SiO_2		65.5					
Na_2O		7.1					
K_2O		7.1					
Li_2O		-					
CaO		-					
MgO		-					
Al_2O_3		2.3					
Fe_2O_3		-					
B_2O_3		10.0					
ZnO		-					
TiO_2		2.7					
As_2O_3		-					
Weatherability	-	B	B/A	-	A	-	-

(a) Information compiled from various sources.
(b) Compositional information provided to indicate approximate chemistry of glass because manufacturers often have several batch formulations for same glass, all of which provide similar properties.
(c) Data from two different sources.
(d) Estimated ranking: A = no weatherability problem anticipated; B = may weather under some circumstances; C = weathering could be a problem.

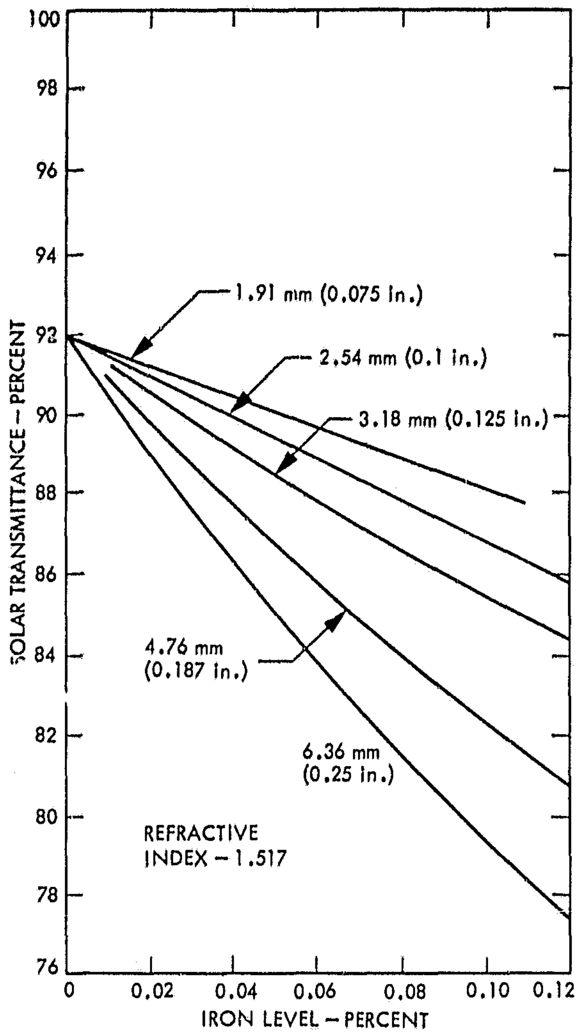

Figure 1. Solar Transmission for Soda-Lime Glass vs. Iron Level (Adapted from Ref. 26)

Table 2. Properties Which Characterize Glass

1.	Solar Transmittance	7.	Thermal Conductivity
2.	Chemical Durability	8.	Mechanical Properties
3.	Economics of Production	9.	Electrical Properties
4.	Optical Properties	10.	Density
5.	Thermal Expansion	11.	Viscosity
6.	Dimensional Stability	12.	Surface Tension

Table 3. Ranges of Physical Properties of Glass Types Compared to Silicon

Type of Glass	Specific Gravity g/cm3 (lbs/ft3)	Young's Modulus 10^3kg/mm^2 (10^6 psi)	Thermal Expansion* cm/cm°C ($\times10^{-7}$) (in/in°F)	Refractive Index	Poisson's Ratio
Soda-Lime	2.47 (154)	6.9-7.1 (10-10.2)	85-93.6 (47.2-52.0)	1.51-1.52	0.22-0.24
Aluminosilicate	2.45-2.64 (145.8-157.2	7.3-8.9 (10.3-12.7)	42.1-88 (23.4-48.9)	1.506-1.547	0.24-0.25
Borosilicate	2.13-2.48 (132.8-154.6)	5.0-6.9 (7.1-9.8)	32-77 (17.8-42.8)	1.473	0.2-0.23
96% Fused Silica	2.18 (135.9)	6.8-6.9 (9.7-9.8)	7.6-8 (4.2-4.4)	1.458	0.19
Fused Silica	2.2 (137.2)	7.1-7.4 (10.0-10.5)	5.6 (3.1)	1.459	0.16
Silicon	2.4 (149.6)	10.9 (15.5)	30 (16.6)	**	0.22

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

**Opaque in the visible range.

Source: Corning Glass Works

Table 4. Range of Physical Properties of Glass

Property	Range
Density (g/cm^3)	2.13 -- 5.42
Color	Clear to multicolors
Index of Refraction	1.458 -- 1.560
Young's Modulus kg/m^2	5000 -- 12,000
Poisson's Ratio	0.16 -- 0.28
Knoop Hardness KHN_{100}	363 -- 593
Log Resistivity ohm-cm (25^oC)	12.4 -- 20.3
Dielectric Constant at 1 MHz, (20^oC)	3.8 -- 15.0
Viscosity	
Strain Point (^oC)	340 — 956
Anneal Point (^oC)	363 -- 1084
Softening Point (^oC)	600 -- 1580
Working Point (^oC)	862 -- 1252

Note: Viscosity is very important during glass manufacturing. For complete definitions see the glossary. Briefly, the working range is the viscosity at which glass is easily formed. The softening point is where the glass will sag appreciably under its own weight. The annealing point is the temperature at which locked-up stresses can be relieved. The strain point is where the glass becomes rigid.

Table 5. Comparative Analysis and Properties of Specific Representative Glasses with Respect to Silicon

Type of Glass	Analysis, Percent by Weight							Softening Temp. °C	Coefficient of Expansions $(^{\circ}C)^{-1} \times 10^{-7}$
	SiO_2	Modifiers	Al_2O_3	B_2O_3	PbO	Na_2O	CaO		
Fused Silica	99.9	---	---	---	---	---	---	1580	5.5
96 percent Silica (Vycor)	96.0	<0.2	---	4.0	---	<0.2	---	1530	8.0
Aluminosilicate									
Typical	57.7	9.5	17-25.3	4-7.4	---	1	5.5	915	---
Corning 1720	62	---	17	5	---	1	8	915	42
Soda-Lime Silica									
Corning 0080	73.6	---	0.6-1.0	---	---	16-17	0.3-5	695	93.5
Borosilicate								---	---
Corning 7070	70-80.5	4.2	1.1-2.2	12.9-28	1.2	0-1.5	0.1	820	32.0
Corning 7740	81	---	2-2.2	13	---	3.8-4	---	821	32.5
Lead Alkali	35-63	11.0	---	---	21-58	7.6	0.3	630	89.0
Lustraglass ASG-low Iron	---	---	---	---	---	---	---	780	88
Silicon	100*	0	0	0	0	0	0	~1350	30

*Silicon

Table 6. Thermal Properties of Some Specific Glasses*

Property	Corning Glass Works Code Number and Type			
	7940 Fused Silica	7740 Borosilicate	1720 Aluminosilicate	0080 Soda-Lime Silica
Viscosity, poise	Temperature °C			
$10^{14.5}$ (strain point)	956	510	667	473
10^{13} (annealing point)	1084	560	712	514
$10^{7.6}$ (softening point)	1580	821	915	695
10^{4} (working point)	---	1252	1202	1005
Coefficient of linear expansion x $10^{-7}/^{o}C$	5.5	33	42	92
Typical Uses	High temperature, aerospace windows	Chemical, baking ware	Ignition tube	Container, sheet, plate

*Data compiled from Properties of Glasses and Glass-Ceramics, Corning Glass Works, Corning, New York, 1973.

†Produced by vapor deposition.

††Multiply poise by 0.1 to get N-s/m^2 or Pa-sec.

soda-lime which is generally used for windows, tumblers, and other mass-produced glassware. Its relatively high thermal expansion makes it subject to fracture by thermal shock; glasses of lower expansion (such as borosilicates and aluminosilicates) are used for chemical and high temperature applications. These latter glasses have increased amount of boron oxide (13%) and aluminum oxide (25%) respectively.

The Corning type 7740 is a general purpose borosilicate glass that has a slightly higher coefficient of thermal expansion (i.e., 32.5) and a higher alkali content than 7070. It has been found to have greater residual stresses than the 7070 so has not been as widely used. Schott 8330 is quite similar to the 7740.

General engineering data on glass for solar applications are shown in Figures 2-7. Thermal expansion, conductivity, viscosity, and strength data are plotted. In addition, volume and surface resistivity, power factor and dielectric strength are presented in Figures 8-12.

Some of the more important tests pertaining to glass, taken from ASTM literature are shown in Table 7. Other information on high transmissivity glass is given in Section IV entitled Glass Performance, Spectral Characteristics.

The wide variability of the data is apparent and the physical properties of glass composition are complex. The two best references for the solar glass designer are Strand (Reference 5) and Corning Glass Works' Properties of Glasses and Glass Ceramics (Reference 1), although many other fine treatises exist.

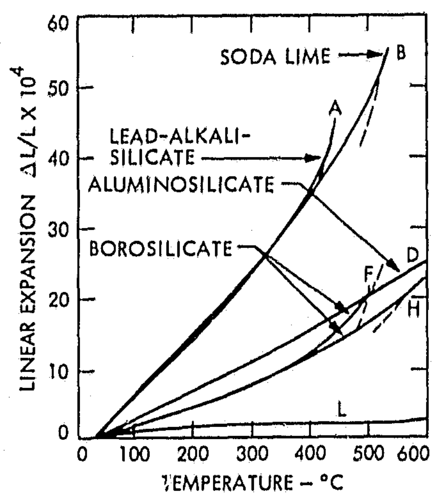

Figure 2. Linear Expansion of Glasses with Temperature (Adapted from Phillips Ref. 32)

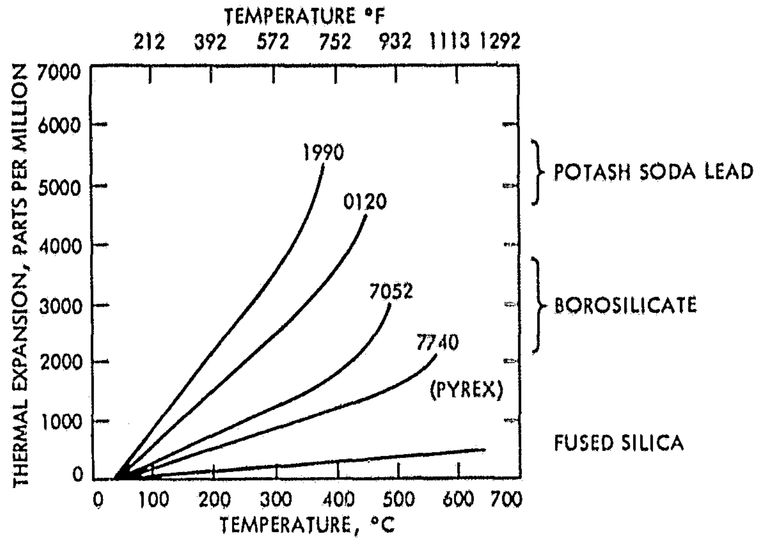

Figure 3. Expansion-Temperature Curves for Typical Corning Glasses (Ref. 1)

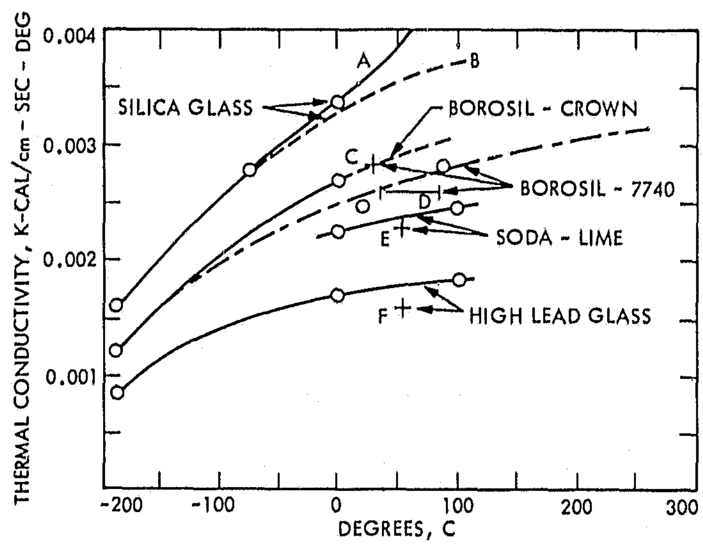

Figure 4. Thermal Conductivity of Corning Glasses (Ref. 11)

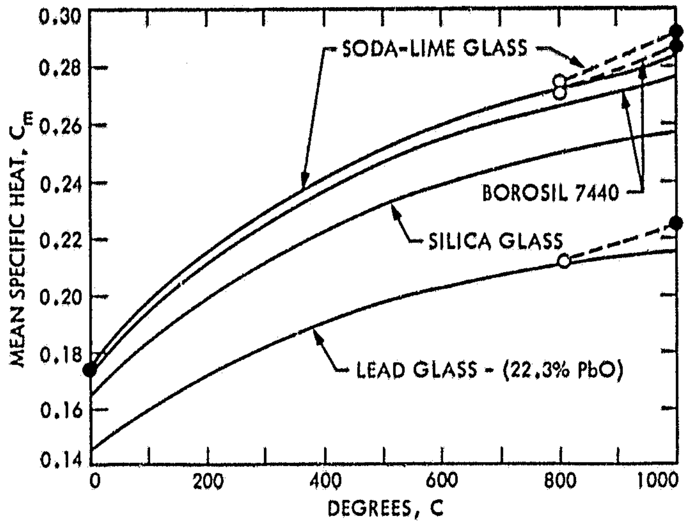

Figure 5. Mean Specific Heat of Corning Glasses (Ref. 11)

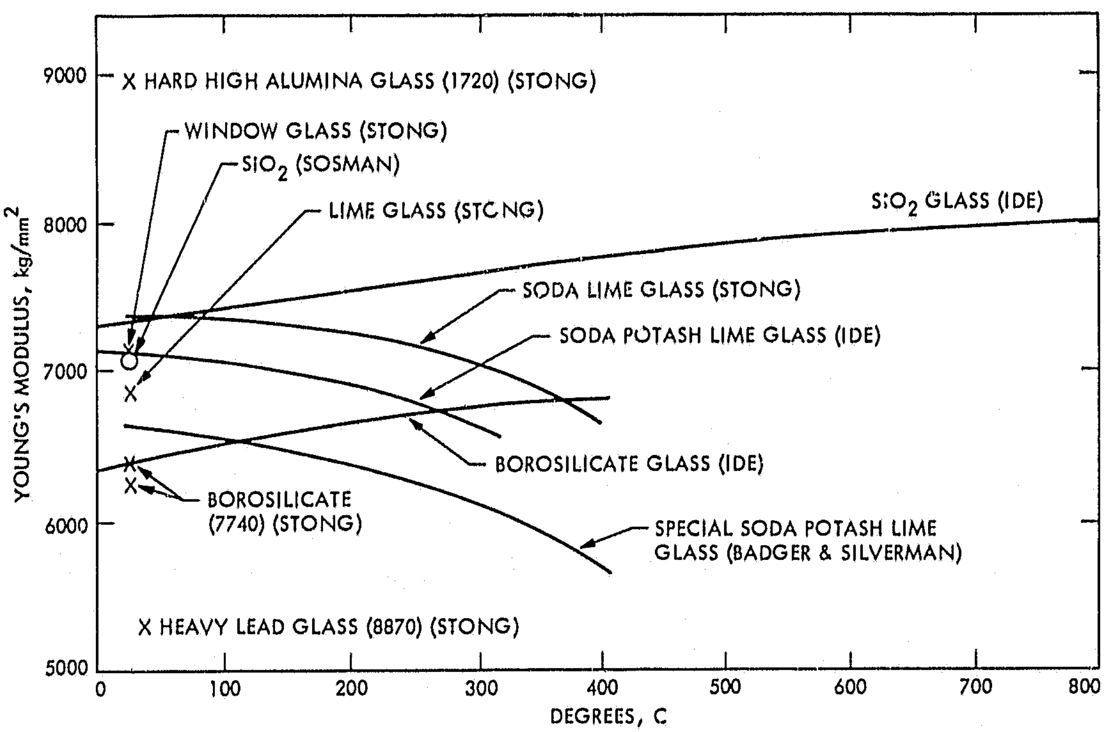

Figure 6. Young's Modulus of Various Glasses (Ref. 11)

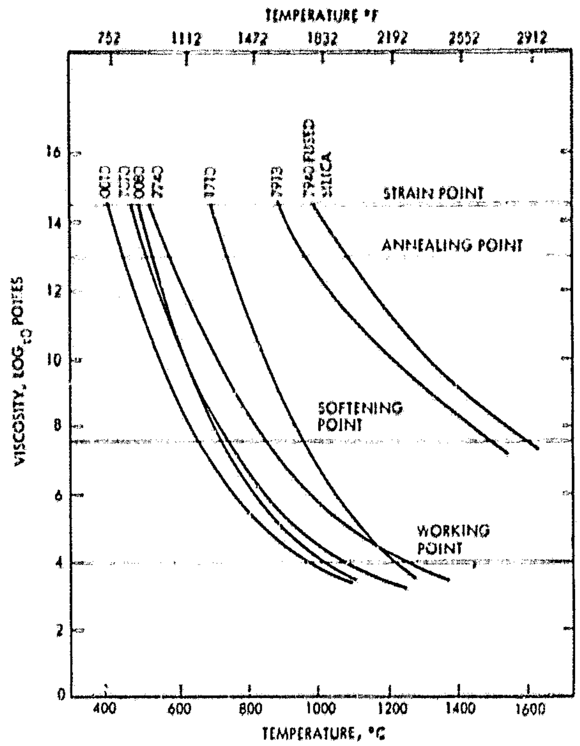

Figure 7. Viscosity - Temperature Curves of Various Corning Glasses (Ref. 1)

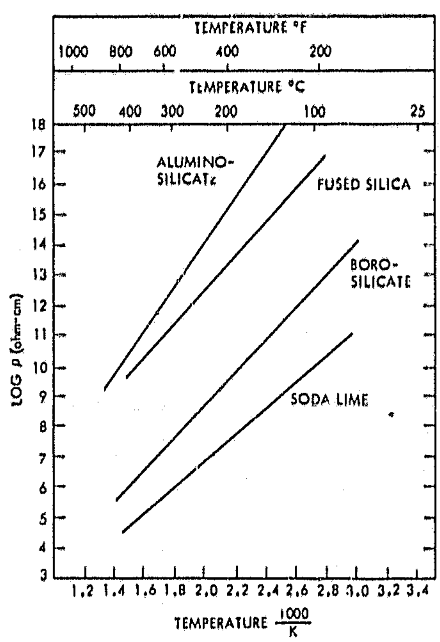

Figure 8. Volume Resistivity for Various Corning Glasses (Ref. 1)

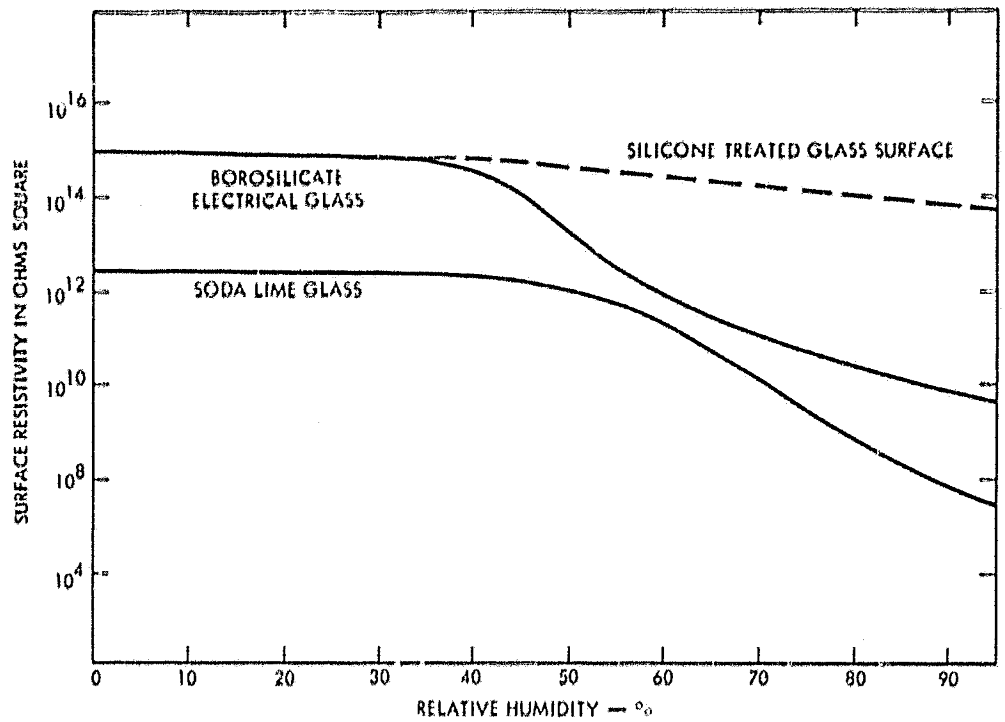

Figure 9. Surface Resistivity of Corning Glasses vs. Relative Humidity (Ref. 1)

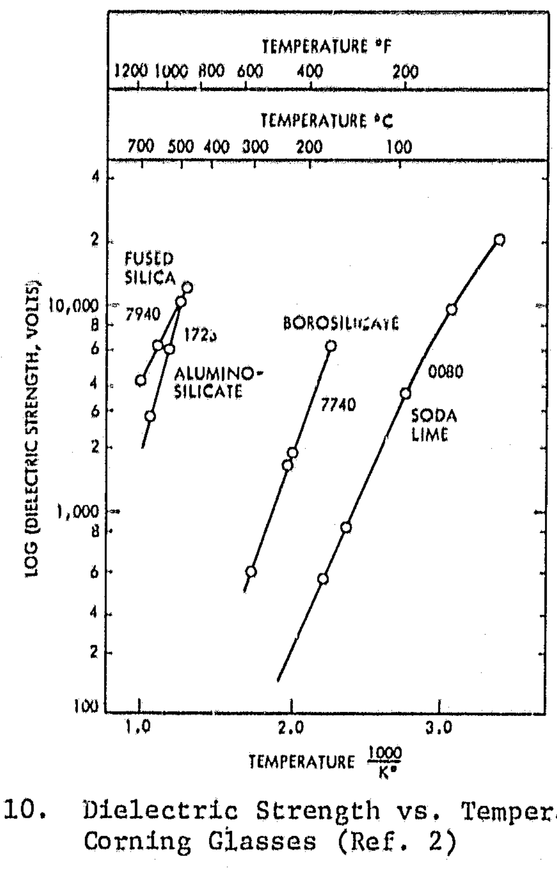

Figure 10. Dielectric Strength vs. Temperature for Corning Glasses (Ref. 2)

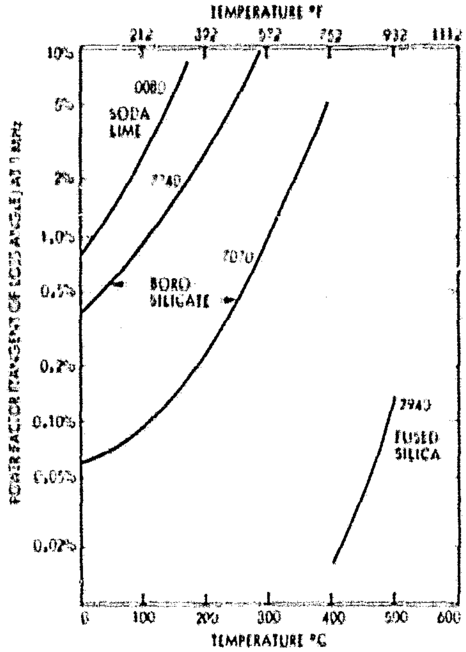

Figure 11. Power Factor vs. Temperature for Corning Glass (Ref. 1)

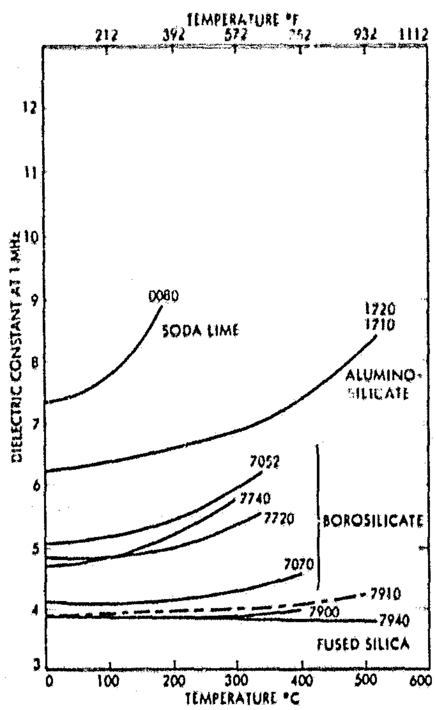

Figure 12. Variation of Dielectric Constant with Glass Temperature for Various Corning Glasses (Ref. 1)

Table 7. ASTM Tests Pertaining to Glass

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.

D. COMMERCIAL SOURCES OF GLASS

A list of the domestic sources of glass compiled as a result of this study is shown in Table 8. The literature of glass manufacturers and glass processors is very extensive. Therefore, only important sources are listed.

Table 9 shows a list of foreign manufacturers of flat glass. See Reference 25. Sources of foreign glass are not unlimited, however. One glass industry spokesman has stated that their current sources of supply are straining the entire European glass production capability. Therefore, research is needed to determine the extent of future glass sources.

Glass thicknesses of interest in photovoltaic applications are in the range of 0.7 mm (0.028 in.) to 6.35 mm (0.25 in.). Typical U.S. suppliers of low-cost soda-lime glass are ASG, PPG, Ford, LOF, and Fourco. Thicknesses and sizes vary with the particular supplier and availability may change with time. Table 10 shows the typical thickness, weight/unit area and maximum size of thin float glass available from one manufacturer. Only photovoltaic thicknesses are included. Table 11 gives the trade names and producers of glass of potential interest to photovoltaic designers. Properties are given in Table 1.

Table 8. List of Domestic Glass Manufacturers and Sales Contacts

Manufacturers	
ASG Industries, Inc. P.O. Box 929 Kingsport, TN 37662 Attn: W. Cooke	Fourco Glass Company P.O. Box 2230 Clarksburg, WV 26301 Attn: J. McVaney
PPG Industries, Inc. One Gateway Center Pittsburg, PA 15222 Attn: C.R. Frownfelter	Guardian Industries Corp. 43043 W. Nine Mile Road Northville, MI 48167 Attn: D. Wiley
Ford Motor Company Glass Division 3000 Renaissance Center P.O. Box 43343 Detroit, MI 48243 Attn: P. Bender	Corning Glass Works Corning, NY 14830 Attn: A.F. Shoemaker
Libby Owens Ford Company Technical Center 1701 E. Broadway Toledo, OH 43605 Attn: H.R. Swift	Jena Glaswerk Schott & Gen. Inc. 11 East 26th Street New York, NY 10010 Attn: J. Schrauth
CE Glass Division 825 Hylton Rd. Pennsarken, NJ 08110 Attn: T. Martin	Armor World Wide Glass Company 9401 Ann Street Santa Fe Springs, CA 90670 Attn: A. Krieger (Sunadex^{R} and Solartex^{R})
	Northwestern Industries, Inc. 2501 West Commodore Way Seattle, WA 98199 Attn: T. McQuade (Sunadex^{R} and Solartex^{R})

Table 9. List of Foreign Manufacturers of Flat Glass (Ref. 25)

Nippon Sheet Glass Co. Ltd.
8-4-Chome, Doshomachi
Nigashi-Ku, Osaka, Japan

Central Glass Co. Ltd.
Kowa-Hitotsubashi Bldg., 7,
Kanada-Nishiricho 3 Chome
Chiyoda-Ru Tokyo 101, Japan

Saint-Gobain Industries
62 Boulevard Victor-Hugo
P.O. Box 124
92209 Neuilly-Sur-Seince, France

Exprover S.A.,
Parc Seny, Rue Charles Lemaire, 1
Boite No. 7, 1160 Brussels, Belgium

Pilkington Aci Limited
470 Collins Street
Melbourne, Victoria
3000, Australia

Flachglas Ag Delog-Detag
650 Gelsenkirchen-Rotthausen,
Auf der Reihe 2,
Postfach 669, Germany

Australian Consolidated Ind. Ltd.
550 Bourke Street
Melbourne, Victoria
3000, Australia

Erste Osterreichische
Mashinglasind, Ag
2345 Brunn/Gebirge,
P.O. Box 9,
Austria

Pilkington Glass Ltd.
101 Richmond Street West
Toronto M5H 1V9, Ont., Canada

Pilkington Brothers Ltd.
St. Helens, Merseyside, Wa10 3TT
England

Asahi Glass Co. Ltd.
1-2, Marunoichi 2-Chome,
Chiyoda-Ku, Tokyo 100, Japan

BSN-Gervais Danone
Boussois Souchon Neuvesel
22, Bd Malesherbes
Paris 8, France

Jena Glaswerk Schott & Gen., Inc.
11 East 26th Street
New York, NY 10010

Glaverbel S.A.
Chaussee de la Hulpe 166
B-1170
Brussels, Belgium

Glaceries de St. Roch S.A.
Exprover S.A.
Avenue Louis 430
B-1050
Brussels, Belgium

Glaces de Boussois
22 Boulevard Malesherbes
Paris 8, France

Compagnie de Saint Gobain
Fabrica Pisana
Via Aurelia #1
56100
Pisa, Italy

Cristaleria Espanola S.A.
Almagro 42
Madred 4, Spain

Sklo Union
N.P.
Teplice - Retenice
Czechoslovakia

Vidrierias de Uodio S.A.
Carmen 20
Llodio, Alava, Spain

Table 10. Availability of Float Glass from One Manufacturer

Type of Glass	Thickness: Nominal mm (inches)	Thickness: Tolerance mm (inches)	Weight/ Unit Area kg/m^2 (lb/ft^2)	Maximum Size Standard m x m (inches x inches)
Clear Float	3.175 (1/8)	±0.79 (±1/32)	8.02 (1.64)	1.52 x 2.03 (60 x 80)
	6.35 (1.4)	±0.79 (±1/32)	16.03 (3.28)	3.1 x 5.08 (122 x 200)

NOTE: Other thicknesses up to 25.4 mm (1.0 inch) are available.

Table 11. Trade Names and Suppliers of Glass Materials

Glass Trade Designation	Glass Supplier
ASG Sunadex	ASG Industries, Inc., Kingsport, TN
ASG Lustraglass	ASG Industries, Inc., Kingsport, TN
Corning 7940 Fused Silica	Corning Glass Works, Corning, NY
Corning 7740 Borosilicate	Corning Glass Works, Corning, NY
Corning 7070 Borosilicate	Corning Glass Works, Corning, NY
Corning 7059 Borosilicate	Corning Glass Works, Corning, NY
Corning 0211 Microsheet	Corning Glass Works, Corning, NY
Corning 0080 Soda-Lime	Corning Glass Works, Corning, NY
Corning 1720 Aluminosilicate	Corning Glass Works, Corning, NY
Corning 1723 Aluminosilicate	Corning Glass Morks, Corning, NY
Corning 8871 Potash Lead	Corning Glass Works, Corning, NY
Fourco Clearlite	Fourco Glass Co., Clarksburg, WV
General Electric 776 Borosilicate	General Electric Co., Richmond Heights, OH
General Electric 008 Soda-Lime	General Electric Co., Richmond Heights, OH
General Electric 351	General Electric Co., Richmond Heights, OH
Innotech IP 530	Innotech Corp., Norwalk, CT
Owens-Illinois KG-33 Borosilicate	Owens-Illinois, Inc., Toledo, OH
Owens-Illinois ES-1 Borosilicate	Owens-Illinois, Inc., Toledo, OH
Owens-Illinois EE-5	Owens-Illinois, Inc., Toledo, OH
Owens-Illinois R-6 Soda-Lime	Owens-Illinois, Inc., Toledo, OH
PPG Float	PPG Industries, Inc., Pittsburgh, PA
PPG NESA	PPG Industries, Inc., Pittsburgh, PA
Schott 8330 Borosilicate	Schott Optical Glass, Inc., Duryea, PA

E. COSTS OF GLASS

Various factors should be considered when investigating glass. Three of these factors are considered briefly below, namely:

(1) Type of glass: sheet, float or plate.

(2) Batch formulation.

(3) Energy consumed in glass manufacturing.

The cost of glass varies with the type of glass. The costs of glass purchased in large quantities have been summarized previously and are shown in Table 12. (See References 7, 25, and 28.) Basic prices in quantaties of the order of one million to 10 million square feet vary from \$3.23 to \$23.13 per square meter (\$0.30 to \$2.15 per square foot, 1978 dollars). Note that the highest price listed (\$2.15/ft^2) was for low-iron glass which has the highest transmittance of solar energy. However, the majority of the glass produced by the glass industry is approximately 3 mm (0.11 inch) thick, and consequently it is cheapest. Glass of thinner or thicker dimensions will usually cost more. The wide range of prices depends upon the details of production and marketing within the glass industry and insight into the various aspects are given later in the discussion below.

Estimates of low-volume glass costs from one manufacturer for several thicknesses iron content, and state of temper are shown in Figure 13. See Reference 33. The data have been normalized to \$/m^2 and refer to 1978 dollars.

The thicknesses of interest for solar photovoltaic applications are between 3.175 mm (0.125 in.) and 6.35 mm (0.250 in.). If the glass is too thin, the breakage is unacceptable; if too thick, the glass absorbs too much sunlight which results in reduced solar cell output. Panel costs from another source (Reference 34) are shown in Table 12 for the three types of photovoltaic glass, namely soda-lime, low-iron tempered glass and borosilicate.

Table 14 gives the typical prices in 1980 dollars for two types of commonly used low-iron ASG glass. In truckload quantities, at the Midwest factory, the price per square area varies primarily with cutting costs. For example, Solartex 5 mm thick, costs \$5.3/m^2 — \$6.56/m^2 at the factory depending upon the cutting needed.

In small quantities, on the West or East coast, prices for small amounts ($\sim 10^3$ ft^2) are $\simeq$\$8.6/m^2 — \$10.98/m^2. The higher prices reflect shipping costs and other costs. Whereas the Sunadex is very low-iron glass, the price differential is much higher than Solartex, with slightly more iron content. This explains the greater public purchases of the latter glass.

As mentioned previously, the actual costs and availability of glass are influenced by a number of factors besides type, volume, and thickness, such as unused industry capacity, batch formulation, acceptable tolerances and other factors. Glass manufacturing is an energy-intensive process which depends strongly on high-volume production to make low-priced products. The effects of product quality and shape, furnace size, type, and pull rates, glass type, and

Table 12. Typical Large Volume Glass Costs
(Adopted from Ref. 25)

Manufacturer	Process	Composition	Thickness		Approximate Cost Per Sq. Ft.*	
			Tested	Possible	1 M Sq. Ft.	>10 M Sq. Ft.
4	Lo-Iron Float	Soda-Lime	0.125		0.31	0.31
4	Lo-Iron Twin Ground	Soda-Lime		>4 mm	1.30	
2	Float	Soda-Lime	0.125		0.50	
2	Lo-Iron Twin Ground	Soda-Lime			1.30	
7	Fusion	Aluminosilicate	0.110	>0.020	0.65-0.80	
8	Fusion	Aluminosilicate	0.090		0.65-0.80	
9	Fusion	Aluminosilicate	0.060		0.45-0.70	
14	Fusion	Lime Borosilicate	0.045		1.40	0.45
3	Float	Soda-Lime	0.125	>0.105	0.40	
15	Float	Soda-Lime		>0.085	1.00	
6	Lo-Iron	Soda-Lime	0.125	>0.060	2.15	0.60-0.65

*1978 Costs

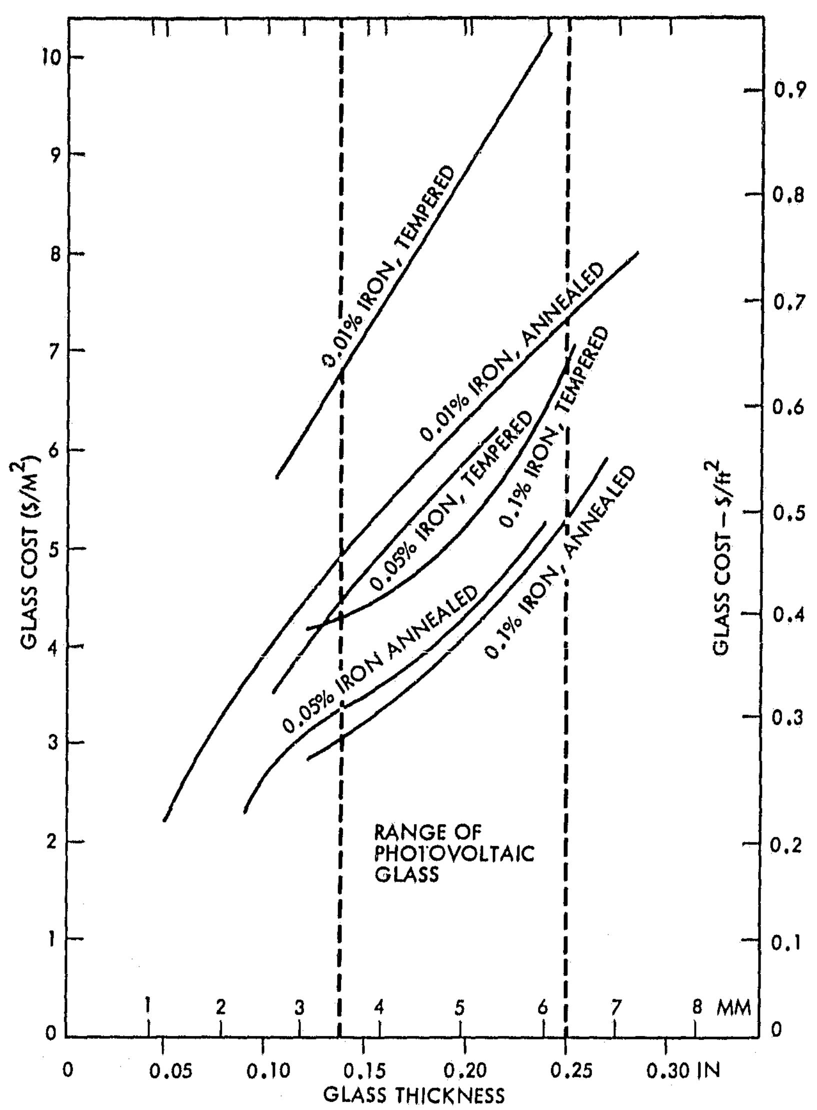

Figure 13. Glass Cost Data (Ref. 33) (in 1978 Dollars)

Table 13. Typical Prices for Medium Thickness Glass (Ref. 34)

Type of Glass	Panel Cost	
	$\$/m^2$	$\$/ft^2$
Soda-Lime	3.15	0.30
Low-Iron Tempered Glass	7.50	0.70
Borosilicate	5-15	0.46-1.39

Table 14. Typical Prices for Low-Iron Soda-Lime Glass (1980 Prices)

Type of Glass	Thickness mm (in.)	Prices for Given Quantities $\$/m^2$ ($\$/ft^2$)	
		Large (>40k lbs)	Small (<<40k lbs)
ASG Solartex ∿0.05% Iron	3 (0.118)	4.9 - 8.9 (0.46- 0.83)	8.6 (0.80)
	5 (0.197)	5.3 - 6.56 (0.49- 0.61)	10.98 (1.02)
ASG Sunadex ∿0.01% Iron	3 (0.118)	7.6 -10.4 (0.71- 0.97)	11.4 (1.06)
	5 (0.197)	10.1 -12.8 (0.94- 1.19)	14.53 (1.35)

secondary (postforming) operations on production volume costs, or energy input, are important. The parameters are not independent but combine to create a complex set of factors unique to a particular product, tank, or plant.

Product quality (such as optical perfection) is an important factor for most glass products. Very few bubble-containing-glass products could be sold for windows; yet, if consumers would accept lower quality products, slightly higher production rates could result in lower prices. The dimensional and optical quality requirements for container glass are low compared to those for other types of glass. This is one of the reasons why the price per metric ton of container glass shipped is less on the order of 70 percent less than that of flat glass.

Product shape and size also affect the manufacturing cost per unit weight of glass. Complex shapes are more costly to manufacture per unit weight of glass than simple shapes because the equipment required is complex. Any shape that can be formed continuously rather than by intermittent pressing or blowing can usually be made at lower cost. Similarly, the greater the thickness of the part, assuming equal processing difficulty, the lower is the unit-weight manufacturing cost (but not necessarily selling price). Very thin glass can be more difficult to form, and is particularly difficult to handle and ship, so costs are commonly higher than those of higher volume standard-size items of the same glass.

Lowest possible prices of uncoated, untempered sheet and float glass are compiled in Table 15; the Department of Commerce data are based on "shipment value" and are reported to reflect manufacturers' wholesale prices, which are considerably lower than retail prices. The data is in 1975 dollars.

Note that average sheet-glass prices have gone up while average float- and plate-glass prices have gone down, reflecting the change in process technology. Some of the thicker float glass being produced today is coated for esthetic purposes, or to control heat transfer (e.g., windows). A large amount of flat glass is thermally tempered, and used in special applications, such as automotive side windows and patio doors. Tempered glass is currently priced two to three times higher than ordinary annealed glass.

The total quantity of flat glass produced in 1974 was about 2.6×10^8 m^2 (2.8×10^9 ft^2), for which about 2/3 was produced by the float process. The projected market of 5×10^6 m^2/yr for photovoltaic arrays in 1985 could be accommodated by only a 2 percent increase in production capability.

The type of glass affects processing costs from the standpoint of batch material costs, refractory wear (i.e., tank life), fuel consumption (melting temperature), and production rate (longer melting time). Borosilicate glasses are considered to be very difficult to melt compared to soda-lime-silica glasses for all the above reasons. Fuel consumption may be 50 percent higher because of reduced throughput and higher temperatures. Raw material costs are typically two to four times those for conventional soda-lime-silica glasses, depending on the glass composition (i.e., property requirements). B_2O_3, K_2O, Li_2O, PbO, ZnO, and many other oxide components of "special" glasses are available only as refined or synthesized compounds which are much more costly than naturally occurring minerals such as sand, feldspar, and limestone used in soda-lime-silica glasses. An example is shown below to illustrate that the specially refined ingredients of a glass

Table 15. Lowest Possible Prices for Annealed Flat Glass (Ref. 28)

Glass Description	Price, $/m^2 ($/ft^2): Calculated From U.S. Department Commerce Statistics Published in Current Industrial Reports, Flat Glass[a] 1973	1974	First Half 1975	Local Distributor (Retail), January, 1976
Sheet Glass, average	1.45 (0.135)	1.58 (0.147)	1.75 (0.163)	---
Single strength (3/32 in.)	---	---	1.68 (0.156)	3.98 (0.37)
Double strength (1/8 in.)	---	---	1.82 (0.169)	5.06 (0.47)
Thin and tinted	---	---	3.10 (0.288)	---
Plate and Float Glass, average	3.31 (0.308)	3.16 (0.294)	2.84 (0.264)	---
Not over 1/8 in.	---	---	2.04 (0.190)	3.77 (0.35)
1/8 to 1/4 in.	---	---	3.50 (0.325)	---
Over 1/4 in.	---	---	5.11 (0.475)	---

[a] Department of Commerce data are based in "shipment value" and are reported to reflect manufacturers' wholesale prices.

batch are costly. Simplified glass batch formulations and raw-material costs for a typical container glass* and a low-expansion borosilicate glass (Corning 7070) have been calculated in Tables 16 and 17, respectively. These glass compositions represent two materials which might be used as terrestrial solar-cell encapsulants, the soda-lime-silica because of low price, and the latter for its low expansion. The raw-material cost differs by a factor of 5, but this difference by itself should not be considered indicative of glass prices, since quality, production volume, and other factors affect pricing. However, the tables show that soda ash and boric acid account for about half the material costs for each of these glasses. Raw-material costs, when combined with lower production volume and melting difficulties, account for borosilicate glasses being priced three to eight times above similar products made from soda-lime-silica glass. Currently, about half the boron compounds produced in the U.S. go into glass and ceramic products, so any dramatic increase in the demand for borosilicate glass could result in a "tight" market for boron compounds (Reference 36).

Of the total energy used by the glass industry, 65-85% is utilized in melting the glass. When the energy content of the raw materials used in glass making

*The composition of container glass (Table 16) is similar to soda-lime glass used for the tubings and flat shapes.

Table 16. Simplified Batch Formulation and Raw-Material Costs for Soda-Lime-Silica Container Glass (Ref. 28)

Name	Parts per 100 Parts Glass	Oxide Factor	Delivered Cost, $/1000 kg[a]	Batch Cost, $/1000 kg Glass	Composition of Typical Container Glass, weight percent					
					SiO_2	Na_2O	K_2O	CaO	MgO	Al_2O_3
Feldspar	9.35	0.066	40	3.74			0.62			
		0.055				0.5				
		0.672			6.3					
		0.193								1.80
Soda ash	22.73	0.585	80	18.18		13.3				
Dolomite	8.26	0.218	15	1.24					1.8	
		0.304						2.5		
Limestone	12.68	0.560	20	2.54				7.1		
Sand	66.1	1.0	14	9.25	66.1					
				$35.11	(72.4)	(13.8)	(0.62)	(9.6)	(1.8)	(1.8)

[a]Cost data from Reference 35 adjusted to reflect 1976 first quarter prices for Ohio area.
Note: Numbers in parentheses are nominal values.

Table 17. Simplified Batch Formulation and Raw-Material Costs for Low-Expansion Borosilicate Glass (Ref. 28)

Name	Parts per 100 Parts Glass	Oxide Factor	Delivered Cost, $/1000 kg[a]	Batch Cost, $/1000 kg Glass	Composition of Corning 7070, Weight Percent							
					SiO_2	Na_2O	K_2O	CaO	MgO	Al_2O_3	B_2O_3	Li_2O
Boric acid	44.44	0.563	270	119.99							28.0	
Potash	0.733	0.682	340	2.49			0.5					
Dolomite	0.329	0.218	20	0.07					0.07			
		0.304						0.1				
Spodumene	4.01	0.080	130	5.21								0.32
		0.274	---							1.1		
		0.646	---		2.59							
Lithium carbonate	2.92	0.404	2000	58.40								1.18
Sand	67.41	1.0	14	9.44	67.41							
				$195.60	(70.0)	(0.0)	(0.5)	(0.1)	(0.2)	(1.1)	(28.0)	(1.5)

[a]Cost data from Reference 35 adjusted to reflect 1976 first quarter prices for Ohio area.
Note: Numbers in parentheses are nominal values.

is considered, the energy consumption increases. Table 18 summarizes the total energy content for flat glass. Energy consumed in other types of glass production are shown for comparison. The data are only for producing primary or raw products, and may not reflect the energy in a finished item. For steel, yield losses associated with secondary forming operations to fabricate wrought products cause the total energy content of the finished products to be about double that of the raw steel; for aluminum the losses are only about 10 percent more. For some glass products, such as glass containers, no secondary forming operations are involved because the containers are final products. However, although the manufacturer uses energy to temper flat glass, it still requires less energy than any other of the materials in Table 18.

In summary, raw material costs, manufacturing costs, volume purchased and other factors influence the price of glass for photovoltaic applications significantly. Soda-lime will probably continue to be more economical than the high transmissivity, low-iron tempered glass or low expansion borosilicate. Average sheet glass at $1.82/m^2$ ($0.17/ft^2$) in 1975 dollars represent rock bottom costs for soda-lime glass. Prices in 1978 dollars, however, were postulated to be in the $3.23-5.38/m^2$ ($0.30-0.50/ft^2$) for this same type of glass when purchased in large quantities $\sim$1-10 million ft^2. Estimates of glass prices in terms of 1975-1980 dollars are summarized in Table 19.

Table 18. Total Energy Consumed in Manufacturing Various Types of Materials (Ref. 28)

Material	Approximate Density, 10^{-3} kg/m^3 (lb/ft^3)	Energy Content (1970) Per Unit of Product	
		Weight	Volume
		10^6 J/kg (10^6 Btu/ton)	10^6 J/m^3 (10^6 Btu/ft^3)
Glass containers	2.50 (156)	21.1 (18.2)	52.8 (1.42)
Primary aluminum	2.72 (170)	203.9 (175.8)	554.6 (14.9)
Raw steel	7.84 (489)	22.4 (19.3)	175.6 (4.72)
Polyvinyl chloride resin	1.40 (87.4)	96.3 (83.0)	134.8 (3.63)
Polystyrene resin	1.06 (66.1)	134.2 (115.7)	142.3 (3.82)

Table 19. Estimates of Prices of Photovoltaic Glass for Large Quantities

Thickness: 3.175 (0.125 inches)

Large Volume Purchase

Type of Glass	Price $\$/m^2$ ($\$/ft^2$)		
	1975	1978	1980 (Est.)
Soda-lime	1.83	3.34-5.38	3.87- 6.24
	(0.17)*	(0.31-0.50)	(0.36- 0.58)
Low-iron Tempered	---	7.50	8.70
	---	(0.70)	(0.812)
Borosilicate	---	5-15	5.8 -17.4
	---	(0.46-1.39)	(0.53- 1.61)

*Price from Table 11.
Note: Price increase of 8% assumed per year.

SECTION II

GLASS PROCESSING

A. GLASS IMPROVEMENTS

Three major areas exist where improvements in photovoltaic glass can be made:

(1) Reduction of iron content

(2) Tempering

(3) Anti-reflection coatings

1. Improvement of Bulk Effects

As stated previously, improvement of the solar transmission characteristics of glass is possible by reduction of the ferrous oxide (FeO) component which gives a greenish tinge. See Figure 1.

2. Tempering

Two general methods are available for strengthening glass (a) tempering in air and (b) tempering by chemical diffusion. In both methods, advantage is taken of the fact that brittle materials such as glass tend to fracture in tension at a surface. Glass virtually never breaks in compression or internally. Therefore, in a sheet of glass that is subjected to bending, it is desirable to have the residual compression in the surface area. This is accomplished by quenching (usually by an airflow) the surfaces while the glass is in a plastic state. The surfaces of the glass are at lower temperatures as a result of the quench, but there is no residual stress immediately after the quench because the core is plastic. However, on cooling thereafter, the core will attempt to contract a greater amount than the surface because it falls through a greater temperature interval. On reaching room temperature, there is a tension in the core and a compression in the surface. This can increase the strength of the glass to twice that of ordinary annealed glass. Upon breakage, the stored energy will be released so that the glass breaks into many small pieces. Consequently, glass cannot be cut after tempering. Thermal tempering of soda lime glass is practical only for thicknesses greater than 3 mm (1/8 inch). Thermally strengthened glass is glass that is strengthened to a lower degree than is tempered glass.

Glass can be tempered by a chemical method to a strength 10 times that of ordinary glass. In this method, the surface of glass containing sodium is exposed to a solution of potassium ions. Chemical exchange takes place and the "wedging in" of the larger potassium ions causes surface compression. This occurs over the outermost 4 microns of the glass surface. This process can be used to strengthen complex shapes or sheets as thin as 1 mm (0.040 in.). The outer surface of aircraft laminated windshields consits of chemically strengthened glass bent elastically to conform to the curved-windshield geometry during an autoclave lamination process. (References 37-38). Thicker pieces of glass would not permit cold bending to the desired aerodynamic configuration and would require preforming, followed by strenthening, to form a curved part. Although the technique is normally used for premium quality glass products, a salt-spray treatment followed by chemical strengthening in the annealing lehr is being developed as a high-speed process for making lighter weight glass containers (Reference 39) and may eventually be applicable to photovoltaic glass.

Laminated safety glass is either annealed, tempered, or chemically strengthened glass which is laminated either to additional glass sheets or to organic polymers (Reference 40). Polyvinyl butyral film is the most commonly used adhesive layer. Automotive and some aircraft windshields consist of two pieces of tempered glass laminated with polyvinyl butyral. Boeing 747 and Lockheed L-1011 aircraft windshields have high-impact-resistance organic polymers as the inner sheets and chemically strengthened glass as an abrasion-resistant outer sheet (Reference 41).

3. Anti-Reflective Coatings

For many years, coatings have been applied to optical components to control the reflectivity of light, both across a broad spectrum and in selected wavelength ranges. In addition, methods exist for chemically treating surfaces to reduce light reflection. Aspects of this "surface technology" were reviewed in this study because coating and/or surface treatments can affect (1) the efficiency of the glass transmission (2) the selection, processability, and/or compatibility of encapsulation materials, and (3) the cost of the glass. The discussion below treats briefly selected information on the following topics:

(a) Reflection losses from uncoated surfaces

(b) Single-layer antireflection coatings

(c) Low-reflectivity glass surfaces

a. <u>Reflection Losses from Uncoated Surfaces</u>. Light impinging on a material is either reflected, transmitted, or absorbed, depending on the optical properties of the material and the adjacent media. In the simple case of a low-absorption material such as glass, most of the light is transmitted or reflected. The reflection losses at each surface are related to the difference in index of reflection between the environment (n_1) and the material (n_2) by the Fresnel equation (References 42-43).

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$$

For window glass ($n_1 = 1.52$) and air ($n_2 = 1.0$), the reflection loss from the front surface of the glass is 4.3 percent. If the glass does not absorb any of the 9.57 percent of the transmitted light, and the back boundary is air, 4.1 percent (0.957 x 4.3) is reflected from the back surface of the glass resulting in a total transmission of 91.6 percent. This total value is typical for common soda-lime-silica glasses, and is not significantly affected by thickness, unless the absorption is high (as with tinted or colored glasses).

The reflection loss at the back surface of the glass may be reduced by employing a pottant between the glass and the solar cells. Since organic pottants commonly have refractive indices between 1.4 and 1.5, reflection losses are reduced 2.8% to 4% respectively.

b. Single-Layer Antireflection Coatings. Because solar-cell efficiency depends on the amount of light actually absorbed by the cell as well as the conversion efficiency, it is desirable to reduce reflection losses which occur at both the front and back surfaces of the cover material. In the preceding discussion of reflection losses from bulk (uncoated) materials, it was shown that a coating material with an index intermediate between that of air and the glass is effective in reducing reflection loss from the glass surface. If the coating material is applied as a coating ($1/4\ \lambda$) such that the light is "in phase" as it passes through the coating, still lower reflection losses can be obtained. For quarter-wavelength optical coatings, reflection losses (R) for a particular wavelength are given by the equation:

$$R = \left(\frac{n_1^2 - n_o n_2}{n_1^2 + n_o n_2}\right)^2$$

where n_o = index of the environment, n_1 = index of the coating material, and n_2 = index of the bulk material (References 42-45). However, the thickness of the optical coating is critical for meeting the "in-phase" criterion, which occurs when the otpical thickness,

$$n_1 t_1 = \frac{\lambda}{4}, \frac{3\lambda}{4}, \text{ etc. (Reference 42)}$$

Because the indices of materials vary with wavelength, the in-phase coupling occurs at a specific wavelength and interference occurs at adjacent wavelengths. This results in a reflection minimum at the design wavelength, above and below which reflection losses increase (Reference 46).

On examination of the equation above, it can be observed that reflection losses will be essentially zero when $n_1^2 = n_o n_2$, or when the coating has an index $n_1 = \sqrt{n_o n_2}$. For an air-glass interface, a coating material with index $n_1 = \sqrt{1 \times 4.0} = 2.0$ would give optimum antireflection characteristics if deposited in the proper optical thickness according to the equation above.

MgF_2 ($n \approx 1.39$) has the lowest index of those inorganic materials which are reasonably stable in the environment, adhere well to glass, and are reasonably abrasion resistant. It reduces the single-surface reflection loss to about 1.26 percent, or one-quarter that of uncoated glass. Its use has become common on space solar-cell covers, as well as aircraft-instrument covers, camera lenses, and other glass-covered optical components used in protected environments (References 47-49).

c. <u>Low-Reflectivity Glass Surfaces</u>. In this section, methods of producing weather-resistant, low-reflectivity glass surfaces by chemical etching, ion bombardment, and the application of organic coatings are discussed because the technology is especially relevant to terrestrial solar-cell encapsulation systems. The use of these methods on low-iron glass should produce efficient photovoltaic systems.

Chemical etching of soda-lime glass in HF baths to reduce surface specular reflections has been used by the glass industry for some time, and this method has been pursued actively by Motorola under LSA contract for JPL. By the proper control of treatment conditions, an etched layer with an effective quarter-wavelength thickness can be obtained. The layer actually reduced reflection losses rather than changing the reflection from specular to diffuse. Nicoll (Reference 50) produced such films on window glass by exposing samples above HF solutions (1-5 percent) at room temperature. True interference films were formed only with glasses containing substantial CaO, leading him to speculate that the process formed CaF_2 films rather than a porous skeleton film. Thomsen, also at RCA (Reference 51), produced low-reflection films on glass by immersing the material in warm fluosilicic acid (H_2SiF_6). Recently, one US company has revived the latter process for treating the surfaces of thermal collector covers made of window glass (Reference 52).

If two-layer "coatings," produced by treatment in two baths of different potency, are used, the sharp minimum in the reflection curves can be changed to a broad band characterized by double minimums, one on each side of the 500-nm peak in the solar spectrum. Reflectance from one sample was less than 1 percent from 350 to 800 nm, with a broad minimum in the visible range (Reference 53).

It has been found that exposure of glass to fluoroboric acid vapor produced better results than use of HV vapor or hydrofluorosilicic acid-bath processes (References 54 and 55).

Polymeric coatings with low indices of refraction also offer potential for reducing the reflectivity of glass surfaces. NASA-Ames investigators have used plasma polymerization to deposit fluorocarbon films on moisture-sensitive alkali-halide windows while Bell Laboratories has used a plasma-polymerization process to deposit silica coatings from organosilanes (References 56-58). USSR researchers have combined fluoropolymer and lead germanate for making durable AR coatings (Reference 59).

Ion Bombardement is another technique which can be used to lower the reflectivity of glass surfaces (Reference 60). Data for untreated and krypton-treated glass shows that transmission in the visible range is increased by 1.9-5.8 percent by the treatment (References 61-62).

B. BONDING TO GLASS SURFACES

If we are to bond wood, metal or other surfaces to glass, a primary criterion for adhesion of these materials is needed. The primary problem is that an ordinary glass surface contains microfissures that permit water vapor to penetrate beneath the adherent material and to promote delamination. Consequently, for many applications, a primer system is required to seal the microfissures against water penetration.

There are many materials that adhere satisfactorily to glass. Silicone primers can be used as an adherent surface and they are available from a number of sources, such as Dow Chemical. Selection of the exact primer varies with the type of coating or adhesive system being used (References 63-65). The effectiveness of a given primer varies with the type of product being used even though they are of the same polymer type. Factors such as fillers, curing agents and degree of cure can have an effect on the strength of the adhesion.

JPL has completed a recent contract that treats the general theory of bonding agents. For further details, see Reference 66.

SECTION III

GLASS AGING

Upon exposure to the natural solar environment, glass undergoes degradation to a greater or lesser extent depending on a number of factors. Primary among these is the natural humidity in the air which attacks glass. Other factors include chemical composition, temperature cycling and attack by atmospheric pollutants.

Although glass is a very good barrier in protecting the solar cells from the external environment, it is not perfect. Certain gasses, such as helium, can diffuse through it although at a low rate.

Most glasses do not turn color upon exposure to the ultraviolet component in sunlight. However, some glasses will turn colors dependent upon the chemical composition. A recent study of glass aging has been completed by Battelle (Reference 25) and Sandia (to be published). Experiments thus far have indicated that the aluminosilicate glasses are the most resistant to accelerated aging test environments. The borosilicates are next with soda-lime glass being more susceptible to environmental weathering. Dust contaminants are probably a factor, either through chemical reactions with the glass surface or accelerated aging due to effects of cleaning solvents. The reader is referred to these reports for further details as well as the following (References 23 and 67). A summary of recent general observations on glass are given in Table 20.

Dimensional stability with time is very important in many applications including long-lived photovoltaic arrays. If the glass is not carefully annealed and aged, it may undergo a slight contraction with time. This effect presumably causes changes in some glass properties, such as density, index of refraction and strength.

In summary, the aging response of glass encapsulation is found to vary strongly with the local environment and this should be considered in long-lived photovoltaic encapsulation systems.

Table 20. Summary of Recent Observations on Glass Weathering

1. The data on weathering of glasses are inconsistent. The error limits encountered in corrosion studies are quite large.

2. Aluminosilicate glasses are usually more durable than soda-lime-silicate glasses such as low-iron float glass.

3. Glasses are usually more durable in acid environments than in alkali environments.

4. Glass corrosion in high pH environments, above 12, is due to the dissolution of the entire glass network. This process shows a linear time dependence.

Table 20. Summary of Recent Observations on Glass Weathering (Continuation 1)

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5. Environments which tend to remove leach products from the glass surface usually lead to less corrosion than those which cause build-up of these products on the surface.

6. Corrosion of common glasses in water is usually due to an exchange between alkali ions from the glass and protons from the water. This process is diffusion-controlled and exhibits a square root time-dependence.

7. Large quantities of water are less corrosive than are thin films of water.

8. Glasses under stress due to bending, etc., will usually undergo faster corrosion rates than otherwise.

9. Glass usually lasts longer in low-humidity than in high-humidity environments.

10. Most glasses can usually be pitted by particles of all sizes, such as sand.

11. Small particles trapped in the cracks in the glass surface are the most difficult to remove.

12. Weathering of glass surfaces is usually related to the type of cleaning agent used.

SECTION IV

GLASS PERFORMANCE

A. GENERAL

The ability of glass to function successfully in the terrestrial solar environment for long periods of time is dependent upon the design parameters. Important parameters include the following:

(1) Spectral characteristics

(2) Hail resistance

(3) Wind resistance

(4) Abrasion effects

B. SPECTRAL CHARACTERISTICS

1. Transmissivity

A primary characteristic of glass for photovoltaic applications is the transmissivity. The light is reflected and/or transmitted through the surface as specular (direct) and diffuse (scattered) components. Of course, the purpose of a good design configuration is to maximize both the specular and the diffuse components that penetrate the glass and impinge on the solar cell. Iron content is a main contributor to reduction in transmission of sunlight. Figure 14 shows the reduction of solar cell output for various percentages of iron in glass. See Reference 33.

Silicon solar cells utilize the sunlight in the frequency range of approximately 400 - 1.1 nm. The index of refraction of soda-lime glass varies slowly over this region. Figure 15. It is important that the glass chosen for solar cell encapsulation have high transmissivity in this range. Data on solar transmission in glass of various thicknesses and compositions are shown in Table 21.

The spectral transmissivity of soda lime glass is shown in Figure 16 compared to other types of glasses, while Figure 17 shows a spectral distribution for 6.35 mm (0.25 in.) thick clear float glass. The transmission versus wavelength for a special low-iron Schott glass (Solawite^{R}) is shown in Figure 18 along with the percent solar radiation in 4 separate frequency ranges as given by Schott.

Because of its low coefficient of expansion, borosilicate glasses may prove useful in special encapsulation systems in which the glass is integrally bonded to the silicon cells. See Reference 28. Experiments have indicated that this is possible except for either very thin glass or solar cell dimensions.

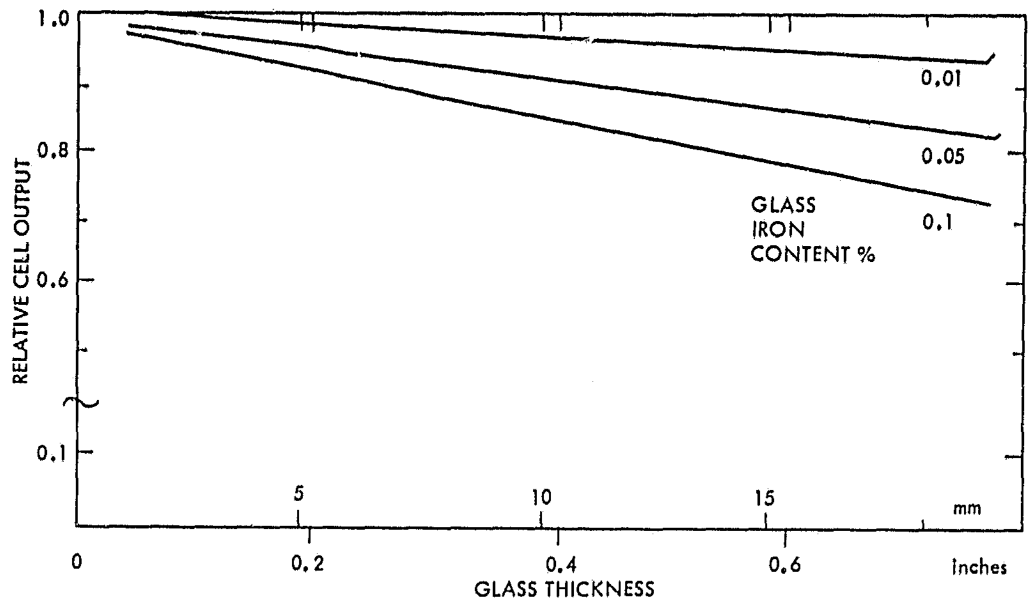

Figure 14. Relative Cell Output Versus Glass Thickness (Ref. 33)

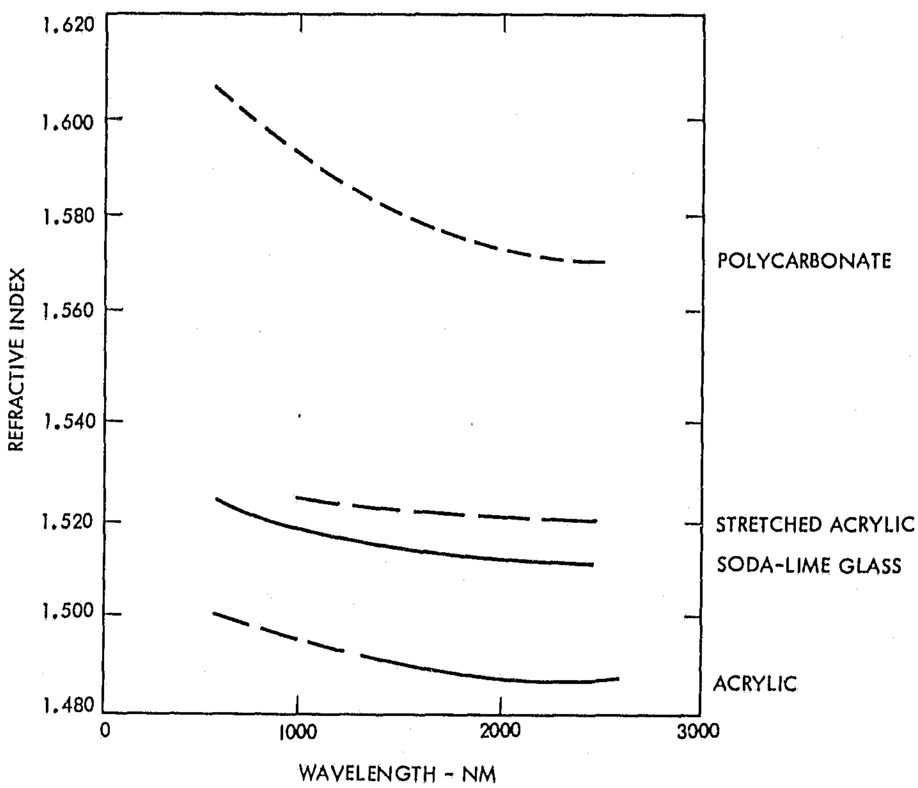

Figure 15. Refractive Index Versus Wavelength for Several Transparent Materials (Ref. 28)

Table 21. Solar Transmittance Properties of Manufactured Glass (Adapted from Reference 25)

Manufacturer	Process	Composition	Thickness		Solar Transmittance	
			Tested	Possible	Measured	Possible
4	Lo-Iron Float	Soda Lime	0.125		0.847	
2	Float	Soda Lime	0.125		0.838	
7	Fusion	Alumino-silicate	0.110	>0.020	0.903	
8	Fusion	Alumino-silicate	0.090		0.910	
9	Fusion	Alumino-silicate	0.060		0.909	
14	Fusion	Lime Borosilicate	0.045		0.876[a]	>0.91
10	Rolled	Soda Lime	0.125		0.891	
3	Float	Soda Lime	0.125	>0.105	0.844	>0.88
15	Float	Soda Lime		>0.085		>0.88
1	Float	Soda Lime	0.125		0.831	
5	Mid-Iron Float	Soda Lime	0.125		0.866	
6	Lo-Iron Float	Soda Lime	0.125	>0.060	0.881	>0.89
11	B270 Sheet Rolled	Soda Lime	0.120		0.913	

[a]Normal hemispherical transmittance of split and flattened tubing.

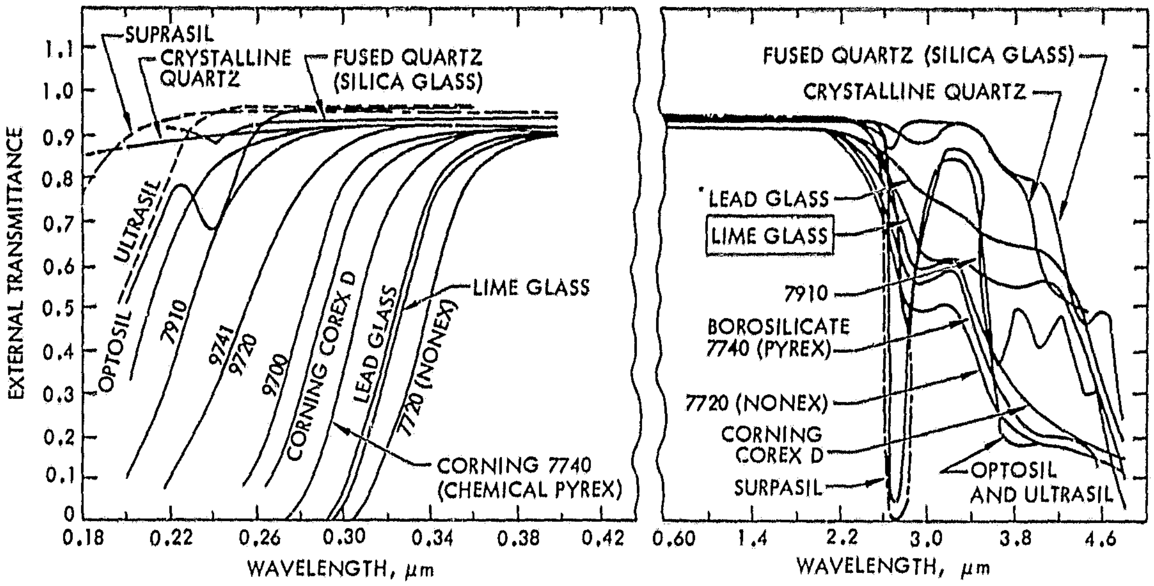

Figure 16. The External Transmittance of Several Samples of Corning and Amersil Glasses (Ref. 8)

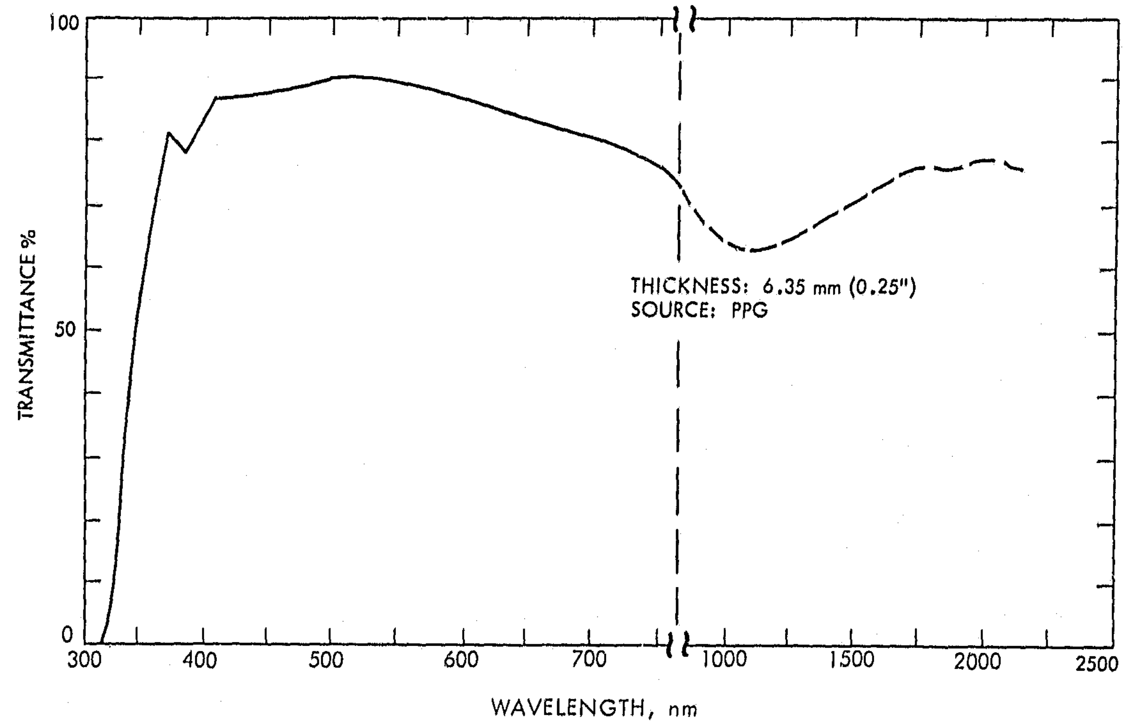

Figure 17. Spectral Transmittance Versus Wavelength for 1/4 Inch Clear Float Glass

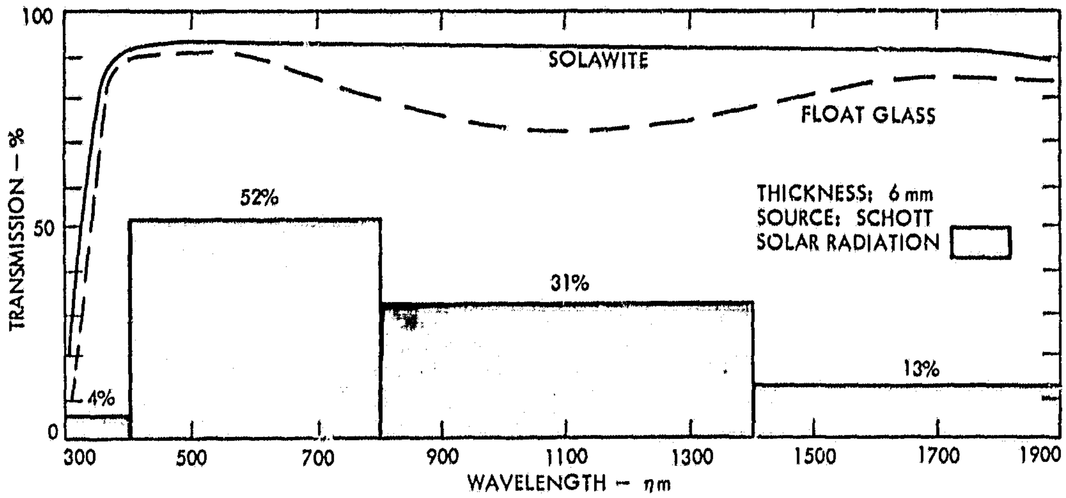

Figure 18. Transmission Versus Wavelength for Schott Low-Iron Silicate Solawite[R]

2. Performance Degradation from Dust

JPL test results show that recent environmental particles on glass can reduce the light transmission and hence electrical output of the solar cells if uncleaned. The exact amount varies with a number of environmental factors, such as altitude, geographical location, etc. See Figure 19. Rain and/or snow can sometimes clean the glass appreciably.

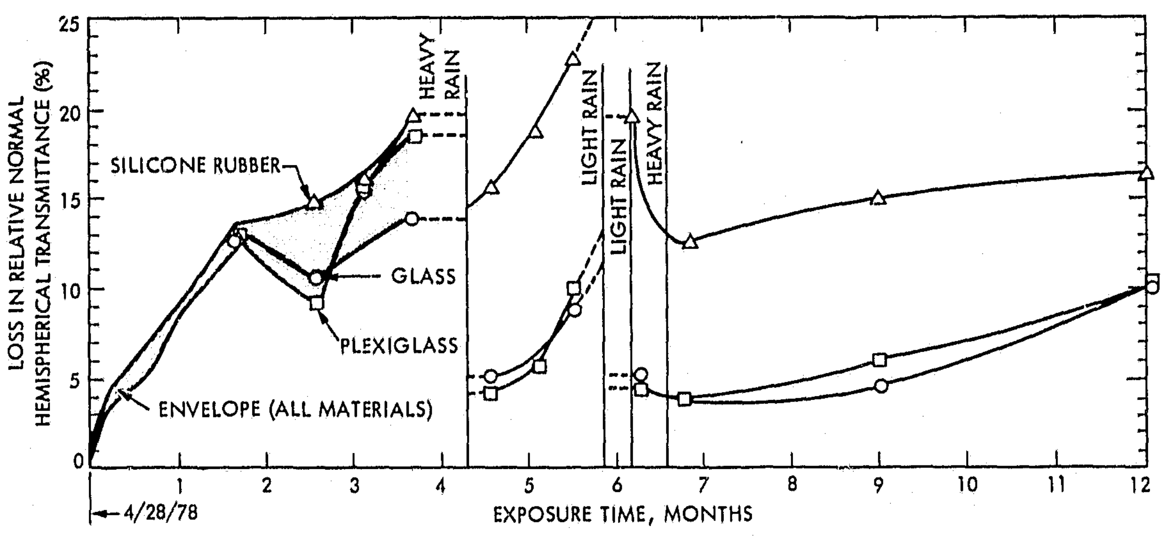

Figure 19. Relative Transmittance of Materials After Exposure at AQMD Site (Outdoor Material Exposure)

The effects of dirt on the solar module electrical output as measured by the decrease in short circuit current are shown in Figure 20 for the Los Angeles locale. See Reference 68. In general, electrical power degradation of 3-6% per month can be expected without cleaning near industrial areas.

A number of effective cleaning materials are currently available for glass. The techniques of washing using high pressure (500-1000 psi) water with a sheeting agent is reported to be very good in comparison to other methods. Cleaning materials and techniques are beyond the scope of this report. (See References 25 and 67.)

C. HAIL RESISTANCE

JPL has performed studies directed toward assessment of the risk of hail to photovoltaic systems. See References 67 and 70. Fortunately, not all photovoltaic arrays must be designed for hail impact because it is a regional phenomenon in the US, occurring primarily in the Midwest. Northern Colorado and Southern Wyoming are noted for their frequent storms of this type. Recently, Sandia Corp. has published a report on an intense New Mexico storm composed of high speed (>50 km/hr) hailstones greater than 6.35 mm (0.25 in.) in diameter (Reference 71). For one glass concentrator, 5% of the exposed glass was damaged. Only glass thinner than 254 mm (0.1 in.) was damaged.

JPL hail test results are summarized in Figure 21. The shaded areas indicate the regions where glass breakage may occur.

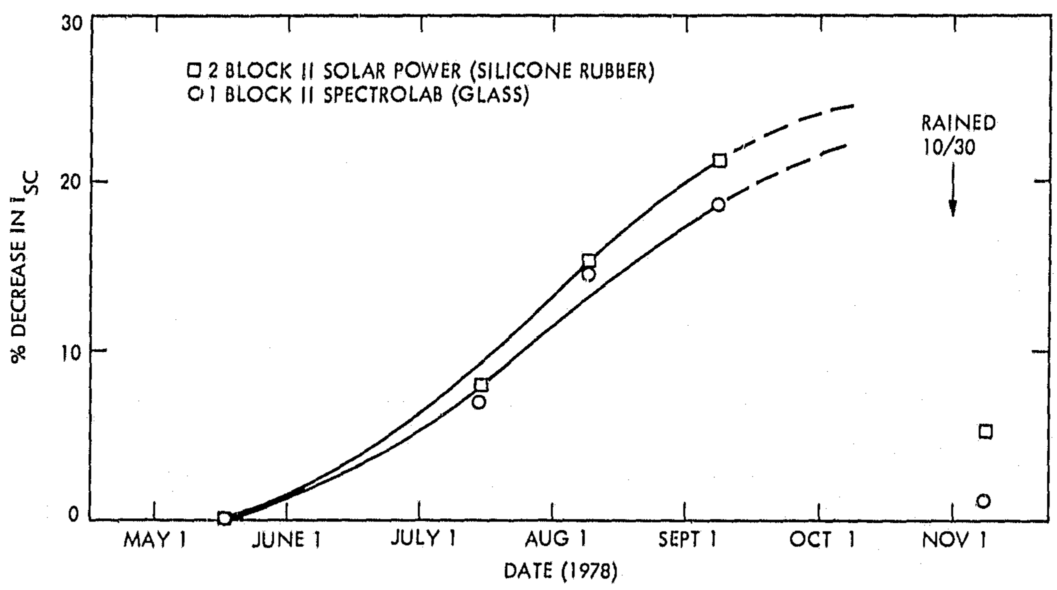

Figure 20. Cumulative Effects of Dirt
(Modules Not Washed)

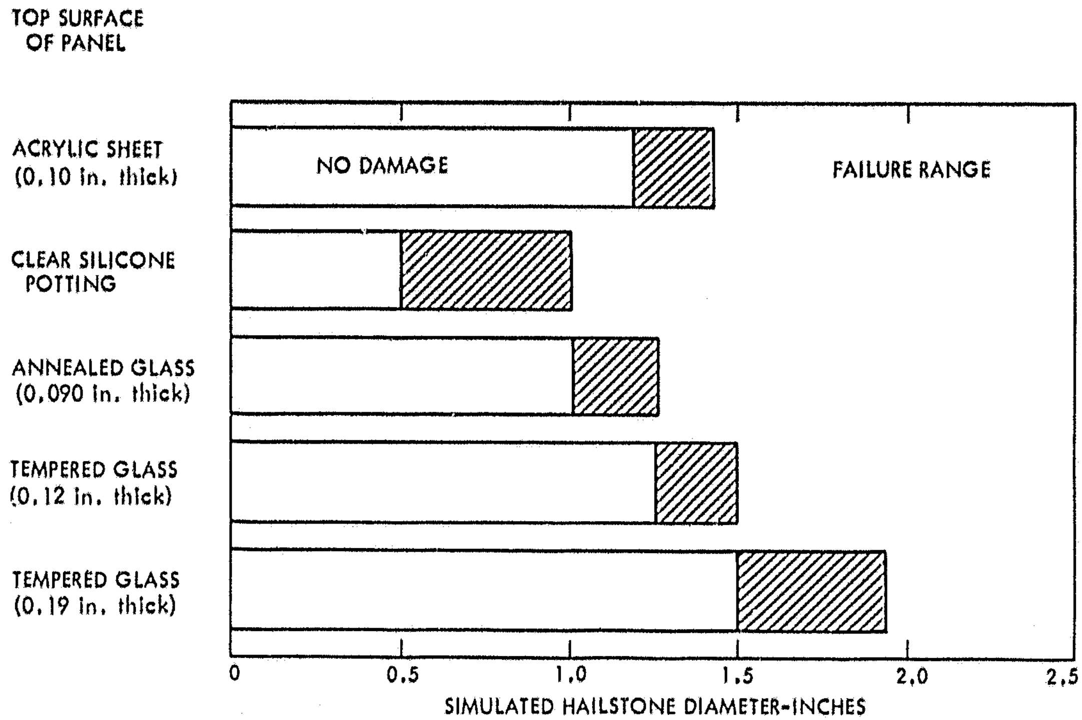

Figure 21. Type of Photovoltaic Panel Material Versus Simulated Hailstone Diameter (Ref. 70)

D. WIND RESISTANCE

An important design parameter for windy sites is the velocity distributions for various photovoltaic module geometries. Considerable analyses have been complated by the Boeing Company under contract with JPL (Reference 72). Once the wind loading is determined, the wind resistance of the various types of glasses can be obtained from conventional architectural sources and the glass companies. Wind load performance data is currently available, for example, from PPG Industries (Reference 73).

Strength is an important property of glass used for photovoltaic applications. Glass strength varies with the conditions of the test and, in general, the results are less than the theoretical strength. At present, it is believed that glass strength depends upon the condition of the surface. Usually strong glass has fewer flaws and scratches. For small test specimens, such as fibers, it appears that they may be stronger than the bulk pieces partly because of this effect as well as others. See Reference 74.

The structural behavior of glass is such that breakage risk must be determined by using statistical theory. Failure always results when a tensile component of stress exceeds the tensile strength of the plate at a particular location. Stress is influenced by plate geometry, support conditions, surface quality, type and rate of loading and other factors.

The probability of breakage for float glass has been calculated for large plates using the finite-element by C. R. Tsai. See Reference 75. The data on probability of glass breakage for short duration loads from PPG (Reference 76) coupled with methods for extending the data to longer loads permits the designer to determine specific thickness requirements. D. M. Moore of JPL has evolved the latter methods (Reference 70). The glass strength versus probability of failure for one minute duration over one square meter is shown in Figure 22.

The results are shown for new sheet and float glass, new plate glass, and weathered glass.

In addition to the strength of the glass encapsulation, the abrasion due to environmental effects may be important. These are treated in the following section.

E. ABRASION EFFECTS

Abrasion tests on 6.35 mm (1/4 in.) thick soda-lime glass have been performed by Taketani and Arden using particles ranging from 3.75 to 22.5 grams.

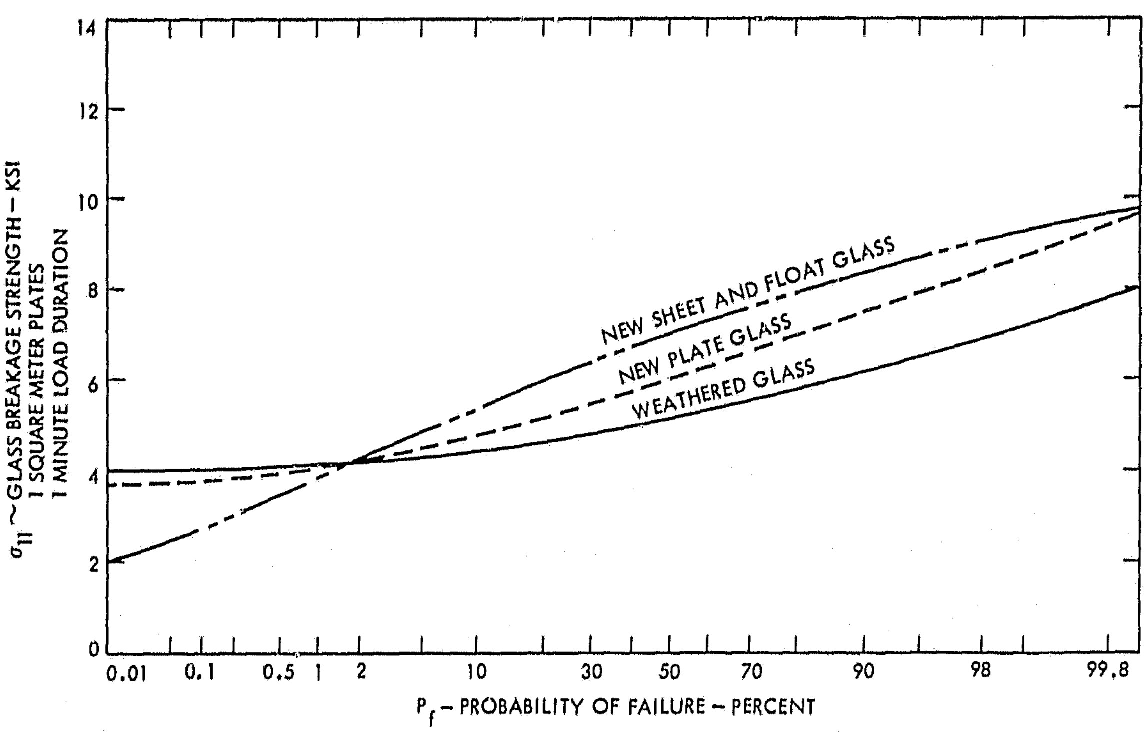

Figure 22. Recommended Design Values for Breakage Strength Versus Probability of Failure for 1 Square Meter, Simply-Supported, Annealed Glass Plates Subjected to a Uniform Normal Pressure Load of 1 Minute Duration

See References 23, 26 and 77. The purpose was to determine relative loss of transmission with abrasive dose, impact velocity and particle size. Velocities between 12-18 meters per second were used. This particular simulation was for the desert environment in the Southwestern United States. The abrasive material, silica flour 105-125 micrometers in diameter, was blown onto the surface at normal incidence.

Figure 23 shows the results of these experiments. A functional relationship exists between the total kinetic energy of the incident particles and the soda-lime glass transmission loss. From this information, and loss in transmission for 6.35 mm (0.25 inch) thick glass in abrasive environments can be estimated. These data indicated that glass was superior to the acrylics tested. For further details, see Reference 77.

Further work on abrasive effects on other types of glass, such as borosilicates, remains to be undertaken. Weathering tests, Reference 78, show that the aluminosilicates and borosilicates are more durable than soda-lime to humidity effects, and the implication is that the same would be true of abrasion tests.

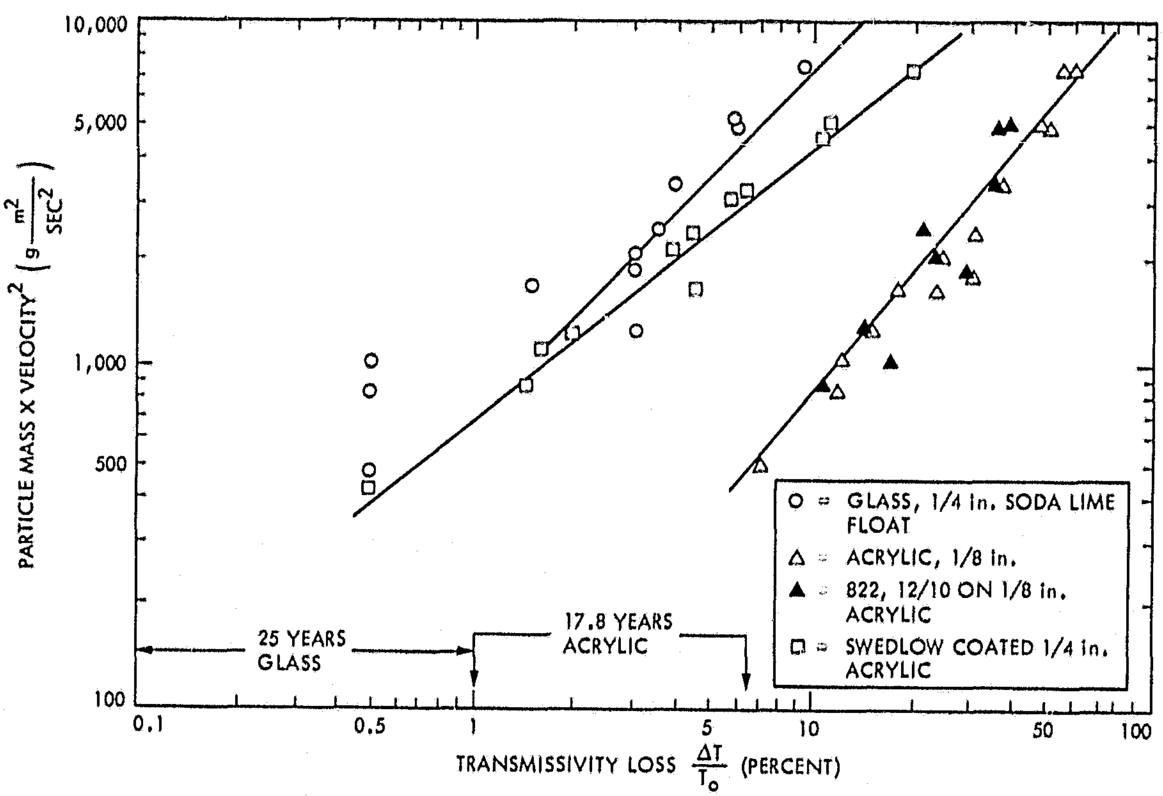

Figure 23. Velocity Parameter Versus Transmissivity Lc . for Soda Lime Glass and Plastic (Ref. 77)

SECTION V

CONCLUSIONS

Considerable research has been performed by JPL and various industrial organizations over the past few years directed toward long-lived, low cost encapsulants suitable for photovoltaic applications. The lack of an organized body of information on the critical properties of glass encapsulants formed the impetus for this report.

The conclusions of this report concerning glass are summarized as follows:

1. The properties of glass are given frequently in terms of average values; therefore, they should be used with caution.

2. Glass properties (particularly expansion) can be tailored to meet a specific application.

3. Processing factors, particularly production volumes, affect the price of glass.

4. Improvements in characteristics of photovoltaic glass can be made in the areas of iron content reduction, tempering and antireflection coatings.

5. Glass is relatively resistant to environmental aging. Tests indicate the borosilicates are less affected than the soda-lime-silicates.

The conclusions concerning the process for selection of candidate glass materials are the following:

1. Soda-lime-silica glasses are, and probably will continue to be, more economical encapsulants than borosilicates on a unit-weight basis.

2. Borosilicate glasses may be necessary for special encapsulation systems in which the glass is integrally bonded to the silicon cells, unless either the glass and/or the cell is extremely thin.

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GLOSSARY

The following definitions have been selected mainly from ASTM Desig. C162-49T, compiled jointly by the American Society of Testing Materials and the American Ceramic Society. Other definitions are marked with an asterisk(*). Those followed by the letters RFP apply to fibrous-glass reinforced plastics and are adopted from Sonneborn.

AMO, AM1, and AM2. These notations refer to the amount of air mass between the sun and the solar cell. AMO would be the response of the solar cell in space, AM1 on earth with the sun vertically overhead and AM2 with the light passing through two air masses.

Anneal. To prevent or remove objectionable stresses in glassware by controlled cooling from a suitable temperature.

Annealing Point. The temperature at which the glass is brought to a temperature high enough to relieve internal stresses throughout, but not so high as to mark or deform it. The upper temperature limit is close to its "annealing point".

Batch. The raw materials, properly proportioned and mixed, for delivery to the furnace.

Bevel. The difference in length between the upper and lower surface of the glass at the edge after cutting.

*Binder (Fibrous Glass). Substances employed to bond or hold the fibers together.

Blank. See lite.

Blister. An imperfection; a relatively large bubble or gaseous inclusion.

Blowpipe. The pipe used by a glassmaker for gathering and blowing by mouth.

Bubbles. Gas inclusions in any glass.

Check. A surface crack or imperfection in glass surface.

Deformation Point. The temperature observed during the measurement of expansivity by the interferometer method at which vicous flow exactly counteracts thermal expansion. The deformation point generally corresponds to a viscosity in the range from 10^{11} to 10^{12} poises.

Devitrification. Crystallization in glass.

Dice. The more or less cubical fracture of tempered glass.

Digs. Deep short scratches.

Feeder. A mechanical device for regularly producing and delivering gobs of glass to a forming unit.

Fiber. An individual filament made by attenuating molten glass. A continuous filament is a glass fiber of great or indefinite length. A staple fiber is a glass fiber of relatively short length (generally less than 17 in.).

Fining. The process by which the molten glass approaches freedom from undissolved gases.

Fine Annealing. Annealing to an extremely low stress and uniform index of refraction.

Flare. An extension of glass remaining or absent from the surface of the glass sheet caused by the cutting process.

Flint glass. (1) A lead-containing glass. (2) Term used by container industry for colorless glass.

Flux. A substance that promotes fusion.

Forehearth. A section of a furnace, in one of several forms, from which glass is taken for forming.

Gaffer. Head workman, foreman, or blower of a glass hand shop.

Gaseous Inclusions. Round or elongated bubbles in the glass.

Gather (n.). The mass of glass picked up by the hand shopworker on the punty or blowing iron.

Gather (v.). To get glass from a pot or tank on the pipe or punty.

Glass Ceramic. A material melted and formed as a glass, then converted largely to a crystalline form by processes of controlled devitrification.

Heat Treated. Term sometimes used for tempered glass. See Tempered glass.

*Lay-up (FRP). The resin-impregnated reinforcing material. Also the process of making a lay-up.

Lehr or Lear. A long, tunnel-shaped oven for annealing glass by continuous passage.

Liquidous Temperature. The maximum temperature at which equilibrium exists between the molten glass and its primary crystalline phase.

Lite. A section of glass sold and/or handled separately such as a 2 ft x 2 ft section. Also called "blank" or "light".

Marver. (1) A flat plate on which a hand gather of glass is rolled, shaped, and cooled. (2) Also the processing of doing same.

*Mat (Fibrous Glass). A layer of intertwined fibers bonded with some resinous material or other adhesive.

Mold. A form (usually metal) in which glass is shaped.

Nu-value. Expressed by the Greek letter ν or by the English letter V. Designates reciprocal dispersive power of glass and is computed as follows:

$$\text{Nu-value} = \frac{\eta_D^{-1}}{\eta_F - \eta_C}$$

where η_D, η_F, and η_C are the refractive indecies at sodium D (5893A), hydrogen F (4861A) and hydrogen C lines (6563A) respectively.

Opal Glass. Glass with fiery translucence. Loosely, any translucent glass.

*Preform (FRP). The process whereby cut strands of roving are drawn by suction onto a shaped screen, sprayed with binder, and cured in an oven. Also, the article made by this process.

*Preloaded (FRP). Containing or combined with the full complement of resin before molding.

Punty. (1) A gathering iron or solid cross section. (2) A device to which ware is attached for holding during fire polishing or finishing.

Ream. Inclusions within the glass, producing a wavy appearance.

Residual Stress. The average tensile stress remaining in the glass after manufacture.

Seam (v.). To slightly grind the sharp edges of a piece of glass.

Seed. An extremely small gaseous inclusion in glass.

Shear Mark. A scar appearing in glassware, caused by the cooling action of the cutting shear.

Size (Textile). Any coating applied to textile fibers in the operation of forming.

Softening Point. The temperature at which a uniform fiber, 0.5 to 1.0 mm in diameter and 22.9 cm in length, elongates under its own weight at a rate of 1 mm per min when the upper 10 cm of its length is heated in a prescribed furnace at the rate of approximately 5°C per min. For a glass of density near 2.5, this temperature corresponds to a viscosity of $10^{7.6}$ poises.

Solarization. Change in transmission of glass as a result of exposure to sunlight or other radiation.

Squareness. The difference between the two corner-to-corner diagonals of a square or rectangular shape.

Stone. An imperfection/ crystalline contaminations in glass.

Stones. Any opaque or partially melted particle of rock, clay or batch ingredient embedded in the glass.

Strain Point. This is the temperature at which the internal stresses are reduced to low values in 4 hours. At this viscosity, the glass is substantially rigid.

Striking. Development of color or opacity during cooling or reheating.

Tempered Glass. Glass that has been rapidly cooled from near the softening point, under rigorous control, to increase its mechanical and thermal endurance. It also may be tempered chemically.

*Textile Fibers (Fibrous Glass). Fibers or filaments that can be processed into a yarn or made into a fabric by interlacing in a variety of methods, including weaving, knitting, and braiding.

Thermal Endurance. The relative ability of glassware to withstand thermal shock.

Total Solar Transmittance. The calculated transmittance of solar energy using the solar data for air mass 1.5 and incident upon a perpendicular surface.

*Twisting (Textile). An operation by which a strand or sliver is given a pre-established number of turns per inch and is thus converted into yarn, thread, or cord.

Vee-Chip. Deep "V" shaped chip at glass edge.

*Warp (Textile). Yarns extending lengthwise in the loom and crossed by the filling yarns.

Wave. Defects resulting from irregularities in the surfaces of glass, making the viewed objects appear wavy or bent.

Weathering. Attack of a glass surface by atmospheric elements.

Wired Glass. Flat glass with embedded wire.

Wool. Fleecy mass of plain glass fibers.

Working Range. The range of surface temperature in which glass is formed into ware in a specific process. The "upper end" refers to the temperature at which the glass is ready for working (generally corresponding to a viscosity of 10^3 to 10^4 poises), while the "lower end" refers to the temperature at which it is sufficiently viscous to hold its formed shape (generally corresponding to a viscosity greater than 10 poises). For comparative purposes, when no specific process is considered, the working range of glass is assumed to correspond to a viscosity range from 10^4 to $10^{7.6}$ poises.