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Barstow Heliostat Mirror Glass Characterizations

M. A. Lind
C. Q. Buckwalter

September 1980

Prepared for
Sandia National Laboratories
Livermore, California
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GLASS CHARACTERIZATION

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Pacific Northwest Laboratory
Richland, Washington 99352

FOREWORD

This report is the result of technical analyses performed for Sandia National Laboratories and authorized under Sandia Livermore Laboratories Federal Agency Order 92-8522 in support of the U.S. Department of Energy Solar Thermal Large Power Project. The purpose of the work reported here was to provide background data and specification verification of the glass procured for the Barstow Solar Ten Megawatt Pilot Plant heliostats.

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SUMMARY AND CONCLUSIONS

This report discusses the technical analysis performed on the special run of low iron float glass procured from the Ford Glass Division for the ten megawatt solar thermal/electric pilot power plant to be constructed at Barstow, California. The topics that are addressed include the optical properties and the relative durability of the glass.

Two optical parameters, solar transmittance and optical flatness, were measured as referenced in the specification section of DOE Solicitation ET 78-B-03-2221 and found to be better than the stated tolerances. The average solar transmittance exceeded 0.890 transmittance units. The glass also exhibited optical angular flatness deviations less than ± 1.0 mrad as required.

Both qualitative and quantitative accelerated weathering tests were performed on the glass in order to compare its durability to other soda lime float glass and alternate composition glasses of interest to the solar community. In both the quantitative leaching experiments and the more qualitative room temperature and elevated temperature water vapor exposure experiments the heliostat glass exhibited the same characteristics as the other soda-lime silicate float glasses.

As a final test for mirroring compatability, selected samples of the production run of the glass were sent to four different commercial manufacturers for mirror coating. None of the manufacturers reported any difficulty silvering the glass. No defects or durability problems were encountered despite the fact that the glass was powder packed and stored approximately six months prior to mirror coating. The solar reflectance of the sample mirrors varied from 0.907 to 0.931 depending on manufacturer.

Based on the tests performed, the glass meets or exceeds all optical specifications for the Barstow heliostat field. It is comparable in durability to other commercial soda-lime silicates. After six months of powder packed storage, there was no indication that silvering the glass posed any problems, but it is not known what the effects of additional storage will be.

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INTRODUCTION

This report describes the technical analysis performed by the Pacific Northwest Laboratory (PNL) for Sandia National Laboratories at Livermore (SNLL) on the special run of low iron glass procured under DOE solicitation ET 78-B-03-2221 for the Barstow Ten Megawatt Pilot Plant. The primary purpose of the work described in this document was threefold. First PNL was requested to verify that the glass procured from the Ford Glass Division met the specifications for optical quality as outlined in the solicitation. Next an attempt was made to resolve early questions concerning the durability and weatherability of the glass relative to other commercial soda-lime silicate glasses. Experiments were also conducted to determine if the specific packing and storage conditions for the glass would have any adverse effects on the commercial silvering of the glass.

Glass samples pulled periodically during the special production run were used to evaluate optical flatness and solar transmittance. The optical flatness was evaluated using a laser ray trace apparatus. The solar transmittance was evaluated using the spectral hemispherical transmittance weighted to two different terrestrial solar irradiance distributions.

The durability/weatherability of the Ford glass was compared with that of other soda-lime silicate glasses and several alternate composition glasses in three separate experiments. Quantitative leaching experiments were performed at elevated temperatures in distilled water to yield data on the rate of glass dissolution. More qualitative results, which tend to agree with the leaching tests but are simpler and faster to perform, are obtained by exposing the glass to 100% humidity at 90°C for five days. The leach products remaining on the glass cause a hazy appearance which can readily be compared to other glass types. More nearly real time testing which exposed the glass to humidity in the 90-100% range at 22°C for eight months yielded similar although less dramatic results to the more accelerated tests.

Two major concerns developed shortly after the glass was produced concerning the method of packaging and the length of storage on the acceptability of

the glass for the commercial silvering process. These concerns were alleviated by sending representative samples of the stored glass to four different mirror manufacturers for silvering. None of the manufacturers reported difficulties in silvering. The visual and optical quality of these mirrors were compared with mirrors deposited on "fresh" glass.

OPTICAL PROPERTIES OF THE GLASS

Samples of glass were extracted from the Ford Tulsa Glass Plant special production run of low iron float glass at the beginning of each eight-hour shift during the time of the special production run between July 25 and July 28, 1979. These samples were taken from a 30-40 cm (12-16 in.) wide strip cut across the entire width of the line (>3.3 m). Each strip was further cut into approximately 60 cm (24 in.) contiguous segments to allow easier handling and shipping. All samples were labeled with production time and location of sample and sent directly to PNL for evaluation.

It was agreed by PNL, SNLL and Ford that the number and type of samples chosen would adequately represent the optical quality of the entire production run. More frequent sampling was deemed unnecessary because of the inherent stability of the high volume float glass production process.

Each sample was examined for optical flatness using the laser ray trace technique described below. Afterwards, smaller 5 x 5 cm (2 x 2 in.) samples were cut from two locations on the ribbon and measured for spectral hemispherical transmittance. The locations correspond to approximately 60 cm (24 in.) from the edge of both the left and right sides of the glass ribbon.

Solar Transmittance

The spectral hemispherical transmittance of the glass was measured on a Beckman 5270 spectrophotometer using 15 cm (6 in.) integrating sphere. The accuracy of the measurement is believed to be better than ± 0.002 transmittance units. The spectral data was weighted to the NASA AM 1.5 terrestrial solar spectral irradiance data (TSSID)⁽¹⁾ using a best fit approximation

routine to obtain the solar transmittance. The solar transmittance for the date and time the sample was produced for both the right and left side of the line are shown in Table 1. The solar transmittance was also measured by Ford glass^(a) and found to agree with the values in the table to within a few tenths of one percent.

TABLE 1. Solar Transmittance of Ford Heliostat Glass

<u>Date of Sample</u>	<u>Time of Sample</u>	<u>Solar Transmittance</u>	
		<u>Right Side</u>	<u>Left Side</u>
7/25/79	4:00 pm	0.889	0.890
7/26/79	12:00 M	0.890	0.892
7/26/79	8:00 am	0.893	0.894
7/26/79	4:00 pm	0.894	0.895
7/27/79	12:00 M	0.892	0.893
7/27/79	8:00 am	0.894	0.892
7/27/79	4:00 pm	0.893	0.894
7/28/79	12:00 M	0.892	0.894

Since the DOE solicitation referenced Moon's AM 2 data,⁽²⁾ rather than the more accurate and more recent NASA data for the TSSID, a short experiment was performed to verify that the two distributions yield nearly the same result for the solar transmittance. For this experiment four 3-mm thick glass samples of varying iron content were supplied by Ford. These samples were measured using the same techniques described above. The data was weighted using both the NASA and Moon TSSID's. The results are shown in Table 2. The high transmittance samples like those of the special production run show solar weighted transmittance values that differ by less than 0.005 transmittance units. Thus the two TSSID's yield equivalent results to within the error of the measurement.

(a) V. Lindberg, Ford Glass Technical Center, Lincoln Park, MI.

TABLE 2. The Effect of Iron Content and TSSID on the Solar Transmittance Value

<u>Sample</u>	<u>NASA AM 1.5</u>	<u>Moon AM 2</u>
A	0.913	0.914
B	0.854	0.849
C	0.650	0.627
D	0.513	0.485

The above results indicate that the special run of glass exceeded the solar transmittance of 0.880 specified in the solicitation. Most of the glass exceeded the specification requirements by more than 0.010 transmittance units regardless of the TSSID used for the weighting.

Optical Flatness

The effective optical flatness or figure evaluation was performed as specified in the solicitation (see Ref. 3). In this test a laser beam is directed at 45° to normal incidence onto a sheet of glass as shown in Figure 1. The second surface reflection is detected by a linear position detector. The deviation of the second surface reflection is monitored as a function of position as the sample is translated under the laser beam. The optically flat table is computer-controlled to take measurements at 0.24 cm (0.1 in.) intervals and record the location of the geometric mean of the beam. A simple geometrical calibration converts changes in the position of the reflected beam to angular deviation due to the non-flat figure of the glass.

Note that the recorded deviation in the reflected beam is a function not only of optical flatness and surface parallelism, but also of optical homogeneity (uniformity in the index of refraction). It has been shown in previous experiments⁽³⁾ that index inhomogeneity and surface parallelism are second order effects when compared with relative flatness across the draw for float glass. It was also shown that the figure along the draw direction is nearly an order of magnitude flatter than the figure across the draw of float glass.

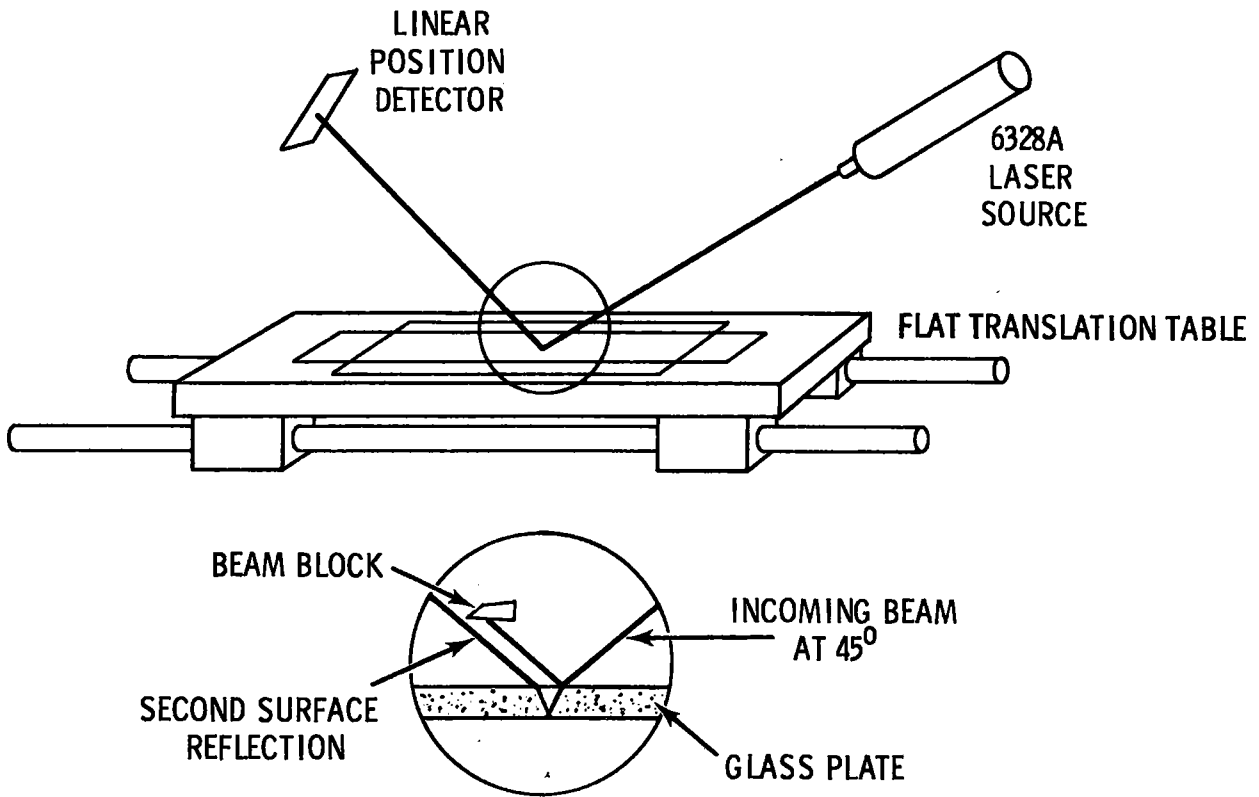


FIGURE 1. Schematic Representation of the Laser Ray Trace Apparatus used for Glass Figure Evaluation

Thus a single measurement of the figure across the draw is usually sufficient to determine the figure of the entire sheet of glass.

The raw data is corrected by computer to take out the overall bow or warp in the glass that would normally be removed in forming the glass to a heliostat support structure. This is done by computing an average curve for the raw data using a running average technique. The average curve is allowed to vary in slope by a maximum of one milliradian per foot. The average curve is subtracted from the raw data to yield a deviation curve. The number of points in the deviation curve that exceed specified angular deflection limits are counted. The data is then reported as the fraction of glass area that exceeds the preset threshold limits.

The figure data for the low iron glass run is shown in Table 3. The data are an average of the samples taken from the slice across the draw of the glass ribbon at the times indicated. Shown is the fractional area of the ribbon that gave corrected deviations greater than ± 0.25 mrad, ± 0.50 mrad, and ± 1.00 mrad.

TABLE 3. Optical Figure of Ford Heliostat Glass

<u>Date of Sample</u>	<u>Time of Sample</u>	<u>± 0.25 mrad</u>	<u>± 0.50 mrad</u>	<u>± 1.00 mrad</u>
7/25/79	4:00 pm	0.28	0.06	0
7/26/79	12:00 M	0.30	0.06	0
7/26/79	8:00 am	0.28	0.06	0
7/26/79	4:00 pm	0.36	0.17	0
7/27/79	12:00 M	0.31	0.10	0
7/27/79	8:00 am	0.29	0.07	0
7/27/79	4:00 pm	0.27	0.08	0
7/28/79	12:00 pm	0.27	0.03	0

The specification in the solicitation calls for an effective figure such that 90% of the glass area deflects a reflected beam of collimated 45° incident light less than or equal to 1.5 mrad from the specular direction and 99% of the glass area deflects the beam less than or equal to 2.5 mrad. All the samples of this glass measured showed deviations less than ± 1.5 mrad.

RELATIVE DURABILITY OF THE GLASS

Shortly after the special run of Ford low iron glass was produced, a number of questions arose regarding the durability of this glass against moisture attack. While the determination of the absolute durability of glass in an accelerated test is the subject of current debate, the ranking of different glasses for relative durability (and probable weatherability) is a much easier task, although not very quantitative. In light of the controversy

over the special run of glass, three experiments were performed to determine if this glass behaved significantly different than other commercial flat glasses.

Nine different commercial flat glasses including the special Ford glass were used in the durability experiments for comparison purposes. Six of these glasses were soda-lime silicates produced by different float glass manufacturers. The remaining glasses were an aluminosilicate (CGW 0317), an aluminoborosilicate (CGW 7809) and a modified soda-lime silicate (B 270). The compositions of these glasses as determined by inductively coupled argon plasma emission spectroscopy (ICP) analysis is shown in Table 4.

The data in Table 4 are normalized to the atomic concentration of the abundant oxide. The glass samples are dissolved in KOH prior to analysis to allow aspiration into the argon plasma, thus the concentration of potassium was not measured. The accuracy of the technique is 2-5%. The detectability is element-dependent, but usually exceeds 1 ppm.

The most quantitative of the three experiments is the glass leaching experiment described below. A more rapid although purely qualitative experiment is to expose the glass to a 90-95°C 100% humid environment for several days and compare the visual appearance. Since it can be argued that both the above techniques exceed normal weathering conditions by a sufficient amount to render the results meaningless, a third experiment exposing the glass to 100% humidity at 25°C was also undertaken.

As a side experiment on the water vapor tests an attempt was made to determine if the weatherability of the tin rich surface of the float glass offered any advantage over the tin poor side. No differences were found in the high temperature tests, but significant differences favoring the tin rich side were found in the room temperature tests.

Quantitative Leaching Experiments

One method for comparison of chemical durability in glasses is a static leach test. In this test the approximate surface area to solution volume ratio ($SA/SV \approx 10 \text{ m}^{-1}$), the temperature (90°C), and the initial solvent pH (5.5)

TABLE 4. Approximate Weight Percent of the Oxide in Glass as Determined by ICP Analysis

Element	Common Oxide	LOF Normal	Ford Normal	Ford Low Iron	PPG Low Iron	PPG Normal	Guardian Normal	Schott B270	Corning 0317	Corning 7809
Al	Al ₂ O ₃	0.16	0.17	0.17	0.17	0.19	0.23	0.10	17.	9.4
B	B ₂ O ₃				Δ ⁽¹⁾				Δ	8.6
Ba	Ba ₂ O ₃				Δ			2.3		
Ca	CaO	8.5	8.6	8.6	8.7	8.7	8.7	7.5	0.51	2.4
Cr		Δ			Δ				Δ	Δ
Cu	CuO	0.18	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ
Fe	Fe ₂ O ₃	0.20	0.26	0.14	0.14	0.21	0.17	0.12	0.25	0.15
Li				Δ						
Na	Na ₂ O	15.	15.	15.	15.	16.	17.	9.9	14.	11.
Mg	MgO	4.0	4.0	4.0	3.9	3.9	4.1	0.12	3.5	Δ
Mo									Δ	Δ
Ni		Δ		Δ	Δ	Δ		Δ	Δ	
P		Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	
Pd		Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ
Si	SiO ₂	76.	75.	75.	76.	76.	75.	76.	65.	68.
Sr	SrO			Δ				Δ		
Ti	TiO ₂	Δ			Δ	Δ	Δ	0.44	0.81	0.52
Zn	ZnO	Δ			Δ	Δ		4.3	Δ	Δ

(1) Δ indicates significant trace quantities detected.

are held constant. All the surfaces of the 3 x 6 x 13 mm samples are uniformly abraded to size with 600 grit silicon carbide paper. The surface abrasion enhances the surface area slightly and probably accelerates the initial leaching process but it insures uniformity of results in comparison studies. The samples are suspended in the solution via a polyethylene thread and allowed to leach for a specified time period (1, 3, 7, 14, and 28 days in these experiments) in the sealed container. After the specified time period the samples are removed from the leachate and the leachate is cooled to room temperature. The pH is taken and a chemical analysis of the solution is done by ICP. The procedure is outlined in more detail elsewhere.⁽⁴⁾

The most significant results of the experiment are shown in Figure 2. The data are normalized to the initial glass composition using the notation

$$\text{leachability} = \left(\frac{\text{mass of element in leachate}}{\text{mass of fraction of element in solid prior to leaching}} \right) \cdot \left(\frac{1}{\text{surface area of sample}} \right)$$

Figure 2a shows the amount of silicon in solution versus time for the four generic types of glasses tested. Figure 2b shows the same curves for the amount of sodium present in solution. Figure 2c shows the changes in pH of the solution as a function of time. The main point to be made here is that although large differences in the glass dissolution kinetics are apparent between the generic types of glasses tested, all the soda lime silicates including the special run of low iron glass behave in a very similar fashion. The durability of the heliostat glass in this test is indistinguishable within the error of the measurement from any of the other soda lime silicate glasses.

Some additional observations can be made from this experiment which lead to plausible mechanisms for the degradation process. If soda-lime silicate is chosen as a reference glass, the effect of barium and aluminum on durability is very noticeable. The addition of barium and zinc increases silicon dissolution to three times that of soda-lime silicate, while the addition of aluminum decreases dissolution by approximately an order of magnitude. The

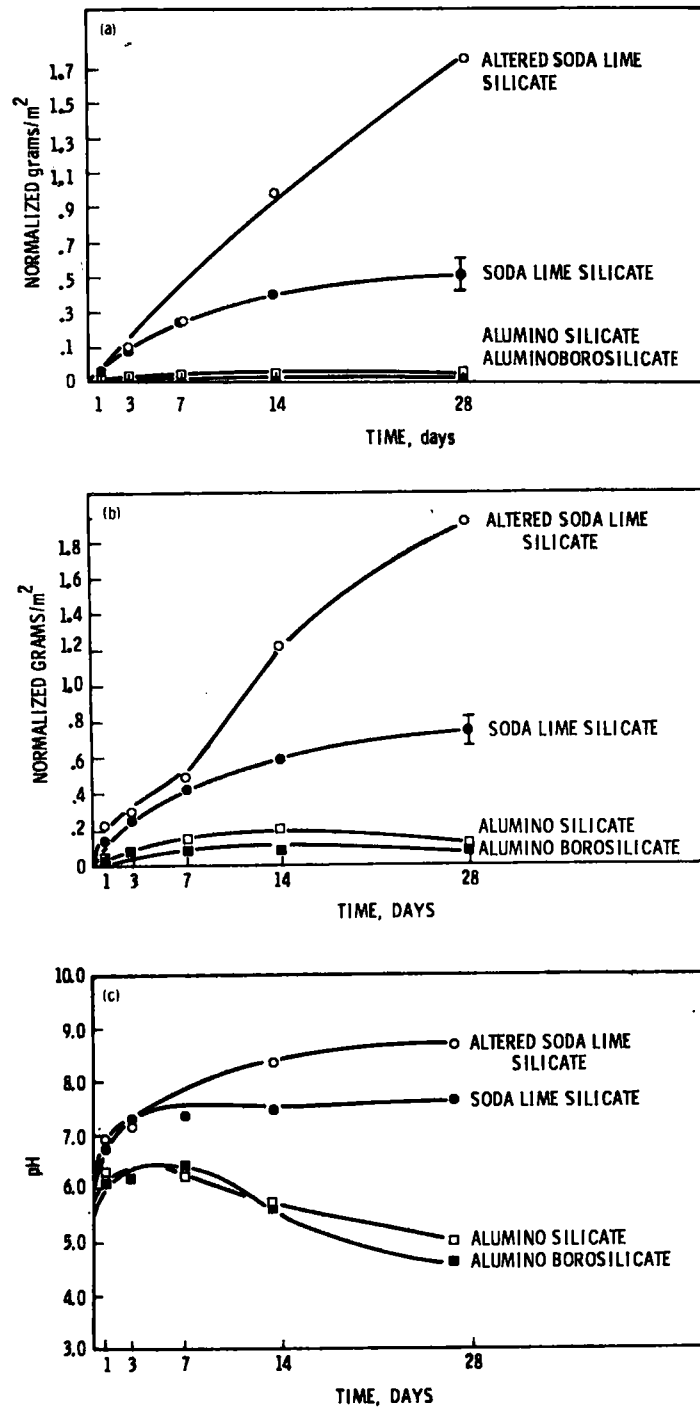


FIGURE 2. Leaching Bath Analysis for Four Generic Types of Glass as a Function of Time in Solution for a) Silicon, b) sodium and c) pH

sodium data exhibit analogous behavior. The pH data show a final leachate pH range of 4.6 to 8.6 or four orders of magnitude with respect to hydrogen ion concentration.

Interpretation of the data is necessarily couched in terms of the first order mechanisms thought to be involved in glass leaching. These mechanisms are ion exchange with the alkali ions in the glass and hydrogen ions in water, and a hydroxyl attack of the silicon structural matrix.⁽⁵⁻⁷⁾

The leachate pH is a result of water equilibrium. As hydrogen ions exchange with the sodium ions in the glass, an excess of hydroxyl ions are left in solution resulting in a basic pH. Since there are more hydroxyl ions present, the incidence attack on the glass matrix is increased and high silicon dissolution rates are noticed.

The opposite effect also can occur because the glass can react with hydroxyl ions, producing an excess of hydrogen ions in the solution. This kind of glass dissolution seems to inhibit ion exchange and dissolution of the matrix formers (Si, Al, B, etc.). The lowest dissolution rates are noticed when the final leachate pH is acidic. Hydroxyl ions may be attracted to the glass due to the presence of aluminum. Aluminum hydrolysis is effective in an acidic medium and is accelerated in a basic environment due to the availability of hydroxyl ions.

There is also an intermediate case of glass dissolution where both ion exchange and hydrolysis via hydroxyl ions are equally favored. In this case the leachate pH remains in the neutral regime and intermediate leach rates are noticed, relative to the two cases mentioned above.

This kind of consistent behavior in the dissolution kinetics lends itself to classification of glasses according to leach rates and final leachate pH. The classes suggested are cooperative, inhibitive, and competitive dissolution. With reference to the glasses leached in this experiment, the alumino- and aluminoborosilicate glasses fit the inhibitive dissolution kinetics, the altered soda-lime silicate fits the cooperative case, and soda-lime silicate is borderline between cooperative and competitive dissolution.

The degradation of mirrors has been attributed in part to the glass dissolution at the Ag/glass interface.⁽⁴⁾ A positive effect on saving this interface has been reported when doping the glass with lanthanide ions, which have high hydrolysis constants.⁽⁴⁾ If application of the simplistic theory of glass leaching presented above is applied to the mirror technology, the type of glass substrate that fits into this scenario is one where inhibitive dissolution is favored. To bias a glass toward this type of dissolution, a glass substrate containing elements possessing large hydrolysis constants may be effective in prolonging the life of mirrors used in solar heliostats. This assumption may be valid provided that some other effects such as the silver-to-glass bonding or silver agglomeration do not play the dominant roll in the mirror degradation process. At this time, the exact mechanisms for mirror degradation in the field are still poorly understood.

Qualitative Water Vapor/Temperature Experiments

Glass samples from the same manufacturers as used in the previously described leaching experiments were used in the qualitative water vapor experiments. Two experiments were conducted, one at 95°C for 17 days and the other at 25°C for 236 days. Samples approximately 2.5 cm (1 in.) square were cleaned sequentially with trichloroethane, acetone and ethyl alcohol, rinsed with deionized water, blown dry and placed on a rack inside a sealed container as shown in Figure 3. The samples were placed in a horizontal position on the stainless steel rack. The lower section of the container was filled with deionized water.

Several samples from each manufacturer were used. Samples of float glass were arranged so that at least one specimen from each manufacturer had the tin rich side up and one had the tin rich side down. Thus any differences due to the tin doping during production should be evident.

The results of these experiments are very similar to a similar series of tests conducted by Sandia National Laboratories at Livermore.^(a)

(a) John Vitko and Jim Shelby, private communication.

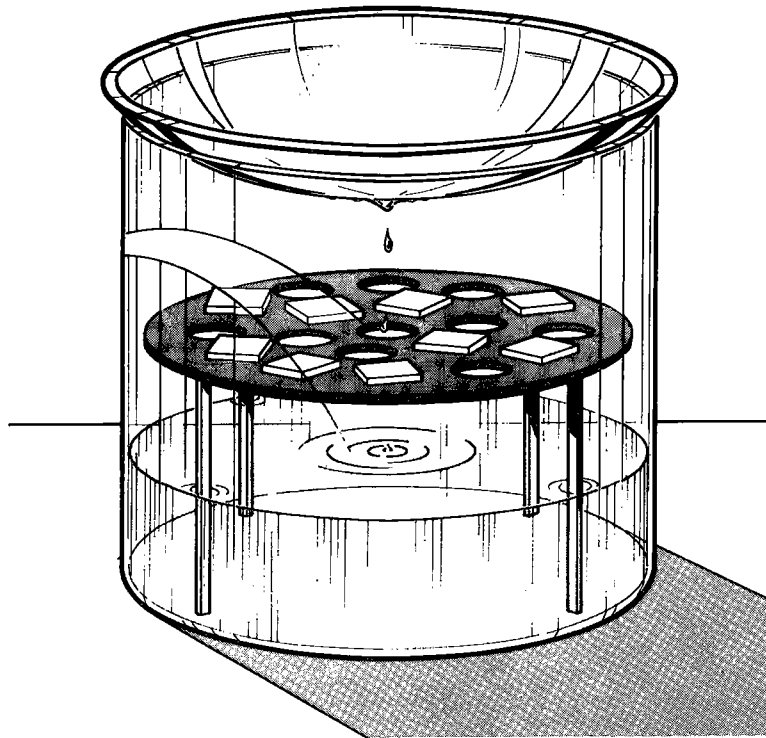


FIGURE 3. Diagram of Container Holding Glass Samples for Water Vapor Testing

Elevated Temperature Results

The deionized water in a pyrex container was heated to $95 \pm 2^\circ\text{C}$. The water vapor was allowed to condense and run off the samples for a period of 17 days. At the end of that time period the samples were removed, rinsed with deionized water and blown dry.

The differences in the visual appearance between the four generic types of glass were readily apparent. The samples were photographed using the setup shown in Figure 4. In this arrangement, light scattered from the roughened upper surface of the sample stands out as bright areas on the photographs. A dark photograph indicates a smooth surface free of leach products. Since the light is scattered only from the one surface and the depth of field of the camera system is less than 0.1 mm, it is possible to compare both surfaces without interference.

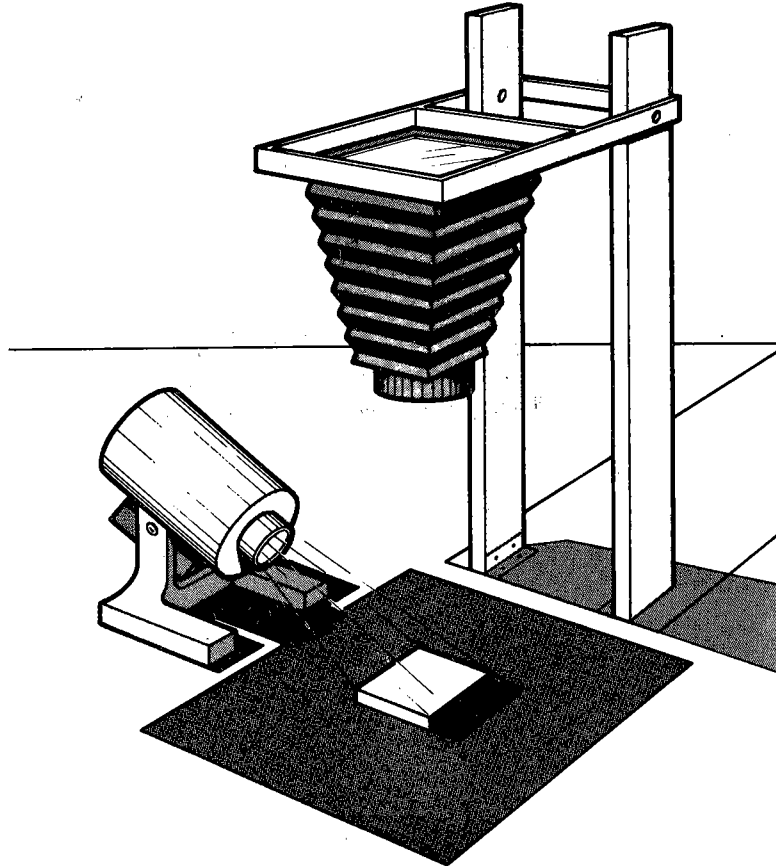


FIGURE 4. Diagram of the Camera Setup used to Photograph the Water Vapor-Exposed Samples.

The resultant photographs are shown in Figures 5-9. The letter "T" at the upper right hand side of each photograph designates the tin rich side of the glass. The surface of the glass which faced up for the duration of the test accumulated condensation for long periods of time (usually days) before sufficient water was present to overcome surface tension and runoff. On the lower surface which faced down during the experiment, the water quickly accumulated (usually within hours) into a droplet and fell off.

The samples in Figure 5 designated FL in the upper left hand corner are the special low iron run float glass. Note that the sample to sample variability is large. The photographs show only representative samples from the

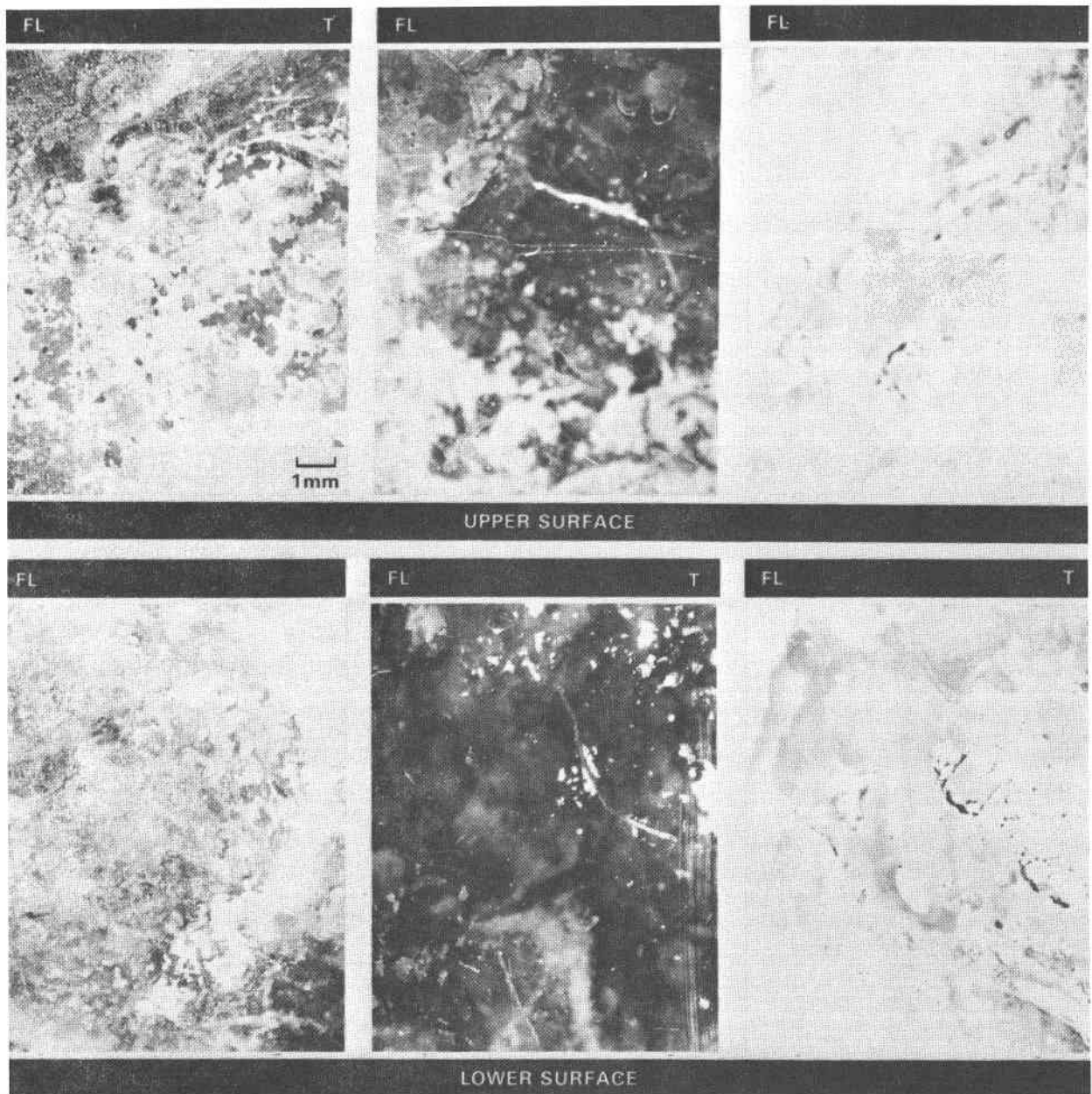


FIGURE 5. Surface Corrosion of the Special Run of Low Iron Float Glass after the 17-Day, 95°C Water Vapor Test

sample set run during the experiment. The special run of glass showed no appreciable differences from the conventional soda-lime silicate float glasses of the other manufacturers tested as shown in Figures 6-8.

Several additional observations are illustrated in Figures 5-9. In general, the lower surface of the glass has a slightly more degraded appearance than the upper surface, regardless of whether or not it is the tin rich or tin poor side. There is no obvious evidence that the tin rich side of the glass has degraded less than the tin poor side in either case.

An attempt was made to rank the samples on the basis of a change in specular transmittance and diffuse reflectance. However, the sample to sample scatter in the data was nearly an order of magnitude larger than any systematic differences. Therefore, no useful correlations could be made.

Figure 9 shows the results of the same test performed on the aluminosilicate, the aluminoborosilicate, and the modified soda-lime silicate glasses. No noticeable degradation was observed for either the aluminosilicate or the aluminoborosilicate glasses. The small specks in the photograph are the result of handling and scratching of the glass prior to the experiment. The modified soda-lime silicate exhibited quite different behavior. The degradation was characterized by small surface pits and scales rather than the apparent accumulation of leach products as seen in the normal soda-lime silicates.

Room Temperature Results

The usual argument made against accelerated testing such as described previously is that unless a direct correlation can be established with an identical material exposed to real time stresses, the results are always questionable. Since very little good data is publicly available from long-term environmental testing of different generic types of glasses, a semi-accelerated test was run for an extended period (236 days).

The glass samples were prepared as described in the previous section and placed in a polyethylene container with the water maintained at $22 \pm 2^\circ\text{C}$. The container remained sealed for the full term of the experiment. Upon

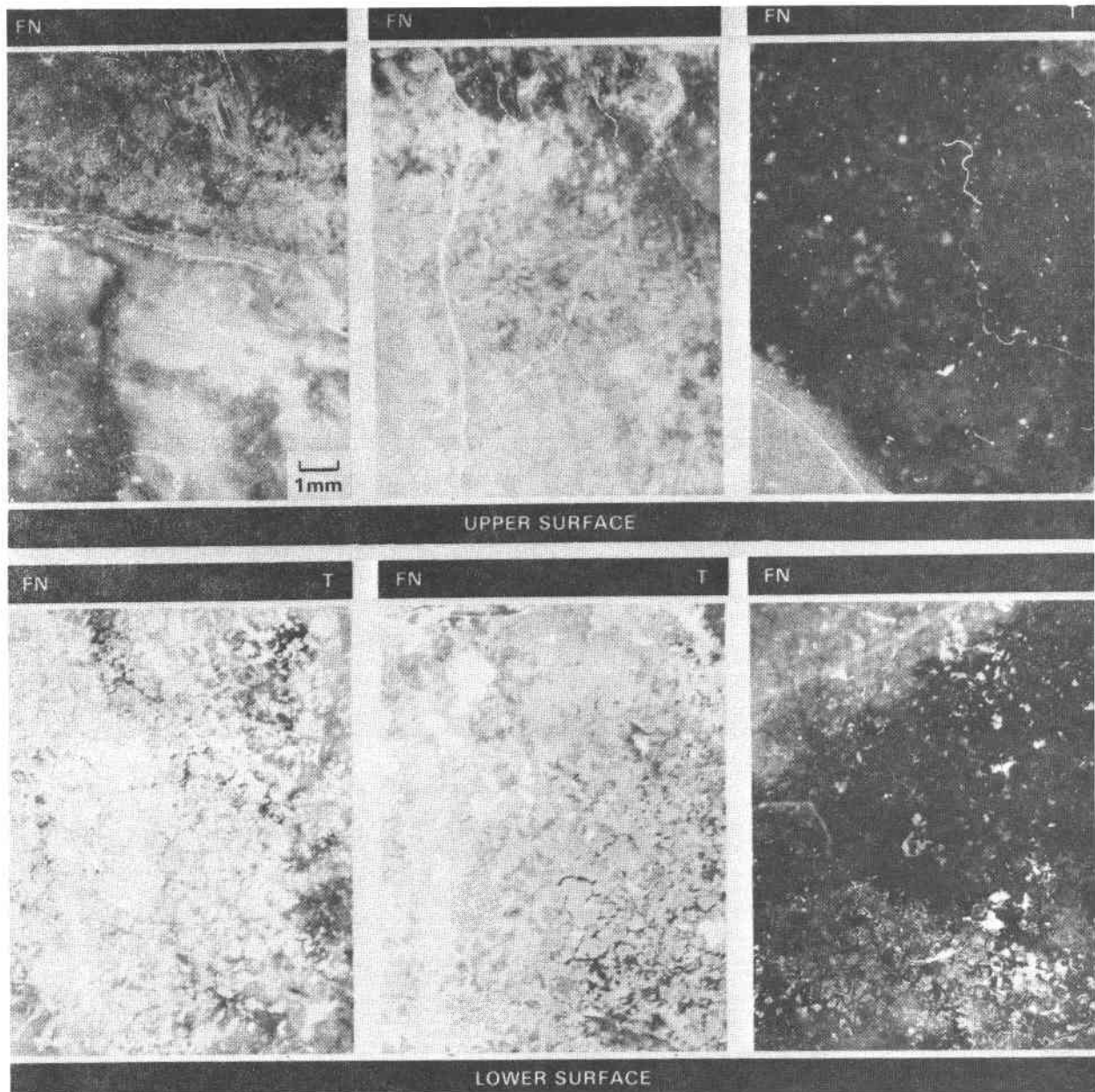


FIGURE 6. Surface Corrosion of Normal Float Glass from the Same Manufacturer as in Figure 5 after the 17-Day, 95°C Water Vapor Test

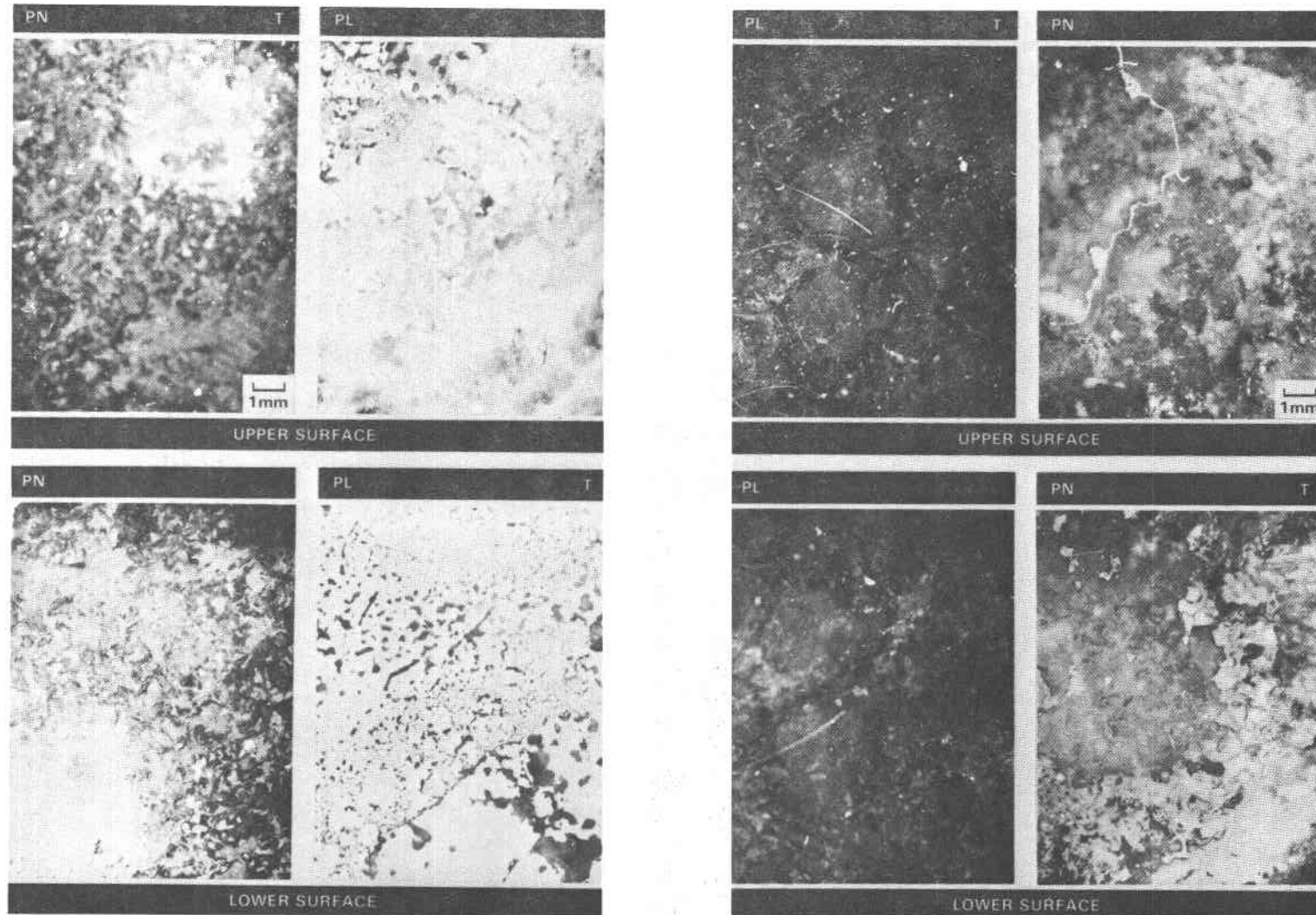


FIGURE 7. Surface Corrosion of Low Iron and Normal Float Glass From a Different Manufacturer After the 17-Day, 95°C Water Vapor Test

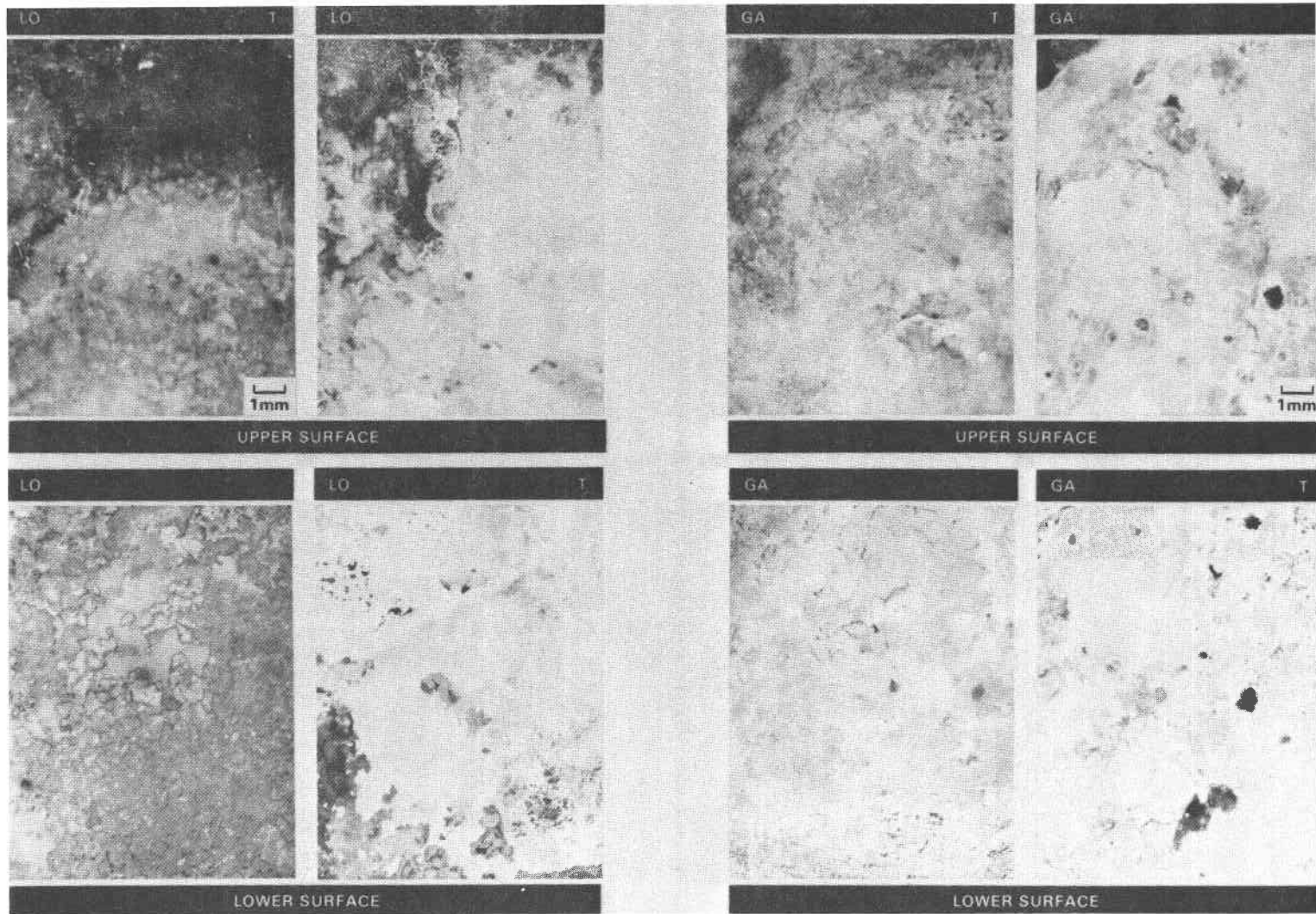


FIGURE 8. Surface Corrosion of Normal Float Glass From Two Different Manufacturers After the 17-Day, 95°C Water Vapor Test

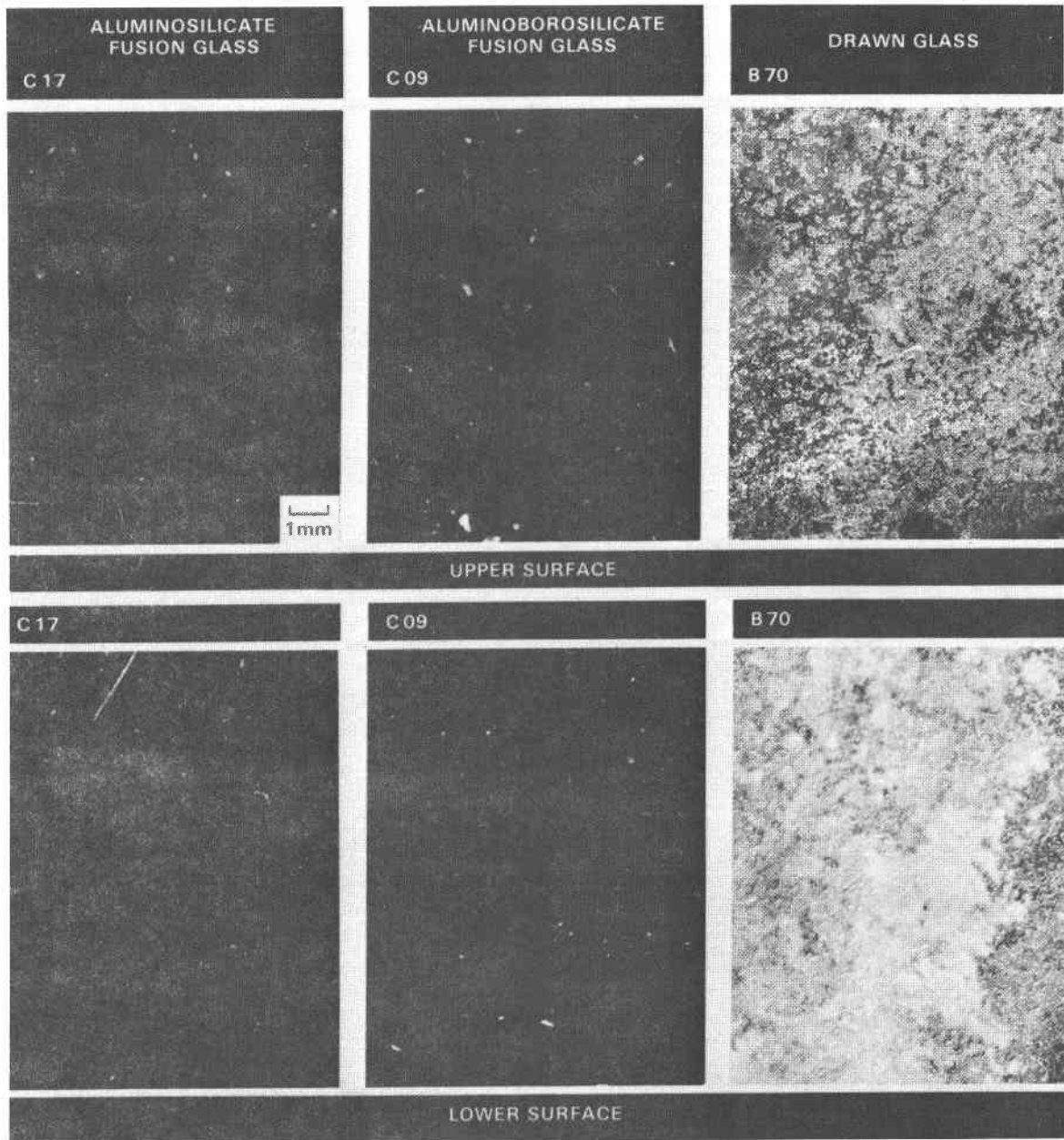


FIGURE 9. Surface Corrosion of Three Other Generic Glass Types After the 17-Day, 95°C Water Vapor Test

opening, significant moisture condensation was noted on the lower surface of the samples; much less moisture was noted on the upper surface. The samples were rinsed with deionized water and blown dry as before.

Visual examination of the samples revealed a relatively minor amount of degradation. Most noticeable was the formation of a thin ($\approx 1000\text{\AA}$) interference film on the tin poor side of all the soda-lime silicate float glasses. This was true for all the samples regardless of up/down orientation. The film was visually comparable to the 100-150-nm thick films observed on some 40-year-old soda-lime silicates collected from south facing vertical windows in the desert areas of southeast Washington.⁽⁸⁾ The tin rich side of these samples weathered considerably better than the tin poor side of the samples, especially when the tin poor side was facing down. There were no obvious differences between any of the soda-lime float glasses from different manufacturers.

Microscopic examination of isolated cloudy areas of the samples (~ 1 mm dimensions) revealed a network of fine pits in the glass and some areas where the interference films appeared to have broken away from the surface. Resource constraints prevented a more thorough surface examination of these samples.

The aluminosilicate and aluminoborosilicate glass again showed no changes in visual appearance. Unlike in the higher temperature experiment, the modified soda-lime silicate glass was also visually unchanged.

SILVERING OF THE GLASS

Since the heliostat glass was to be stored for a relatively long time (~ 12 months) before mirroring and many mirror manufacturers claim that long-term glass storage may be detrimental to mirror quality,⁽⁹⁾ an experiment was conducted to see if glass stored for July to February in a Tulsa warehouse presented any special problems. The glass was powder packed by the manufacturer in crates of approximately 50 lights, 1.14 x 3.40 m (48 x 134 in.). One crate was randomly selected and four lights from the center of the crate cut into 60 x 70 cm (24 x 30 in.) pieces. These pieces were sent to four different mirror manufacturers for mirroring.

After silvering, the mirrors were returned to PNL for visual and optical evaluation and durability testing. The visual and optical data are summarized below. The durability testing is covered in a companion report entitled "Adhesion and Chemical Vapor Testing of Second Surface Silver/Glass Solar Mirrors" by L. S. Dake and M. A. Lind. In addition, some of the same powder-packed glass was subjected to further accelerated aging to determine if the powder pack might add to the mirror silvering and durability problem.

Qualitative Results

The mirror manufacturers were instructed not to apply any special treatment to samples. Specifically they were not to do any extra cleaning or scrubbing that was not a part of their routine procedure.

All four mirror manufacturers reported that they had no trouble applying the wet process silver to the glass surface. Visually the mirrors contained no fogging, staining or other defects associated with substandard substrates. The mirrors made on the stored glass appeared no different from those on fresh glass. Subsequent storage of the finished mirrors at PNL for six months revealed no latent defects.

Simultaneously with the above experiment, several samples of the powder-packed glass were extracted from the same crate for accelerated aging. Six samples (12 x 12 cm) were cleaned by rinsing with deionized water and wiping the surface with a soft cloth to remove the powder pack. Six similar samples were left uncleaned. All the samples were stacked vertically in contact with one another in a 95°C, 100% humidity chamber for 72 hr. The samples were removed, rinsed with deionized water and blown dry.

These samples were then silvered at PNL for comparison. The wet process silver was applied after an abrasive scrub of ceric oxide as is done on the manufacturing lines.⁽⁹⁾ The "clean" glass stack showed qualitatively the same non-uniformity in the silver coating as the "powder-packed" glass. Both sets of samples showed slight staining of the silver in localized areas due primarily to the leach products formed on the glass surface. Some pinholes in the silver were present on both sets of samples. There was no evidence

to suggest that the powder pack was in any way more detrimental to the silvering process after high humidity exposure than non-powder pack.

Optical Properties

The solar reflectance of the mirror samples produced by the four manufacturers was calculated from the spectral hemispherical reflectance. A typical spectral reflectance curve is shown in Figure 10. The range of solar weighted values obtained from each manufacturer's mirrors are shown in Table 5.

TABLE 5. Solar AM 1.5 Reflectance of Mirrors Produced by Different Manufacturers on the Low Iron Float Glass

<u>Manufacturer</u>	<u>Range of Reflectance</u>
B	0.911-0.912
C	0.922-0.931
F	0.907-0.912
G	0.911-0.914

Since glass of identical optical characteristics was supplied to the manufacturers, the differences in solar reflectivities must be linked with the specifics of the silvering process employed on the individual lines. Resources were not available to perform a detailed investigation of the differences. However, the spectral hemispherical reflectance data revealed some interesting trends.

A plot of the difference in spectral reflectance between two of the samples is shown in Figure 11. Here the 0.922 C mirror reflectance has been subtracted from the 0.911 B mirror reflectance. This curve is typical in shape to all the difference curves that were calculated. The primary differences are due to an apparent absorption band centered between 360 nm and 390 nm. No explanation for the absorption phenomena has been generated as of

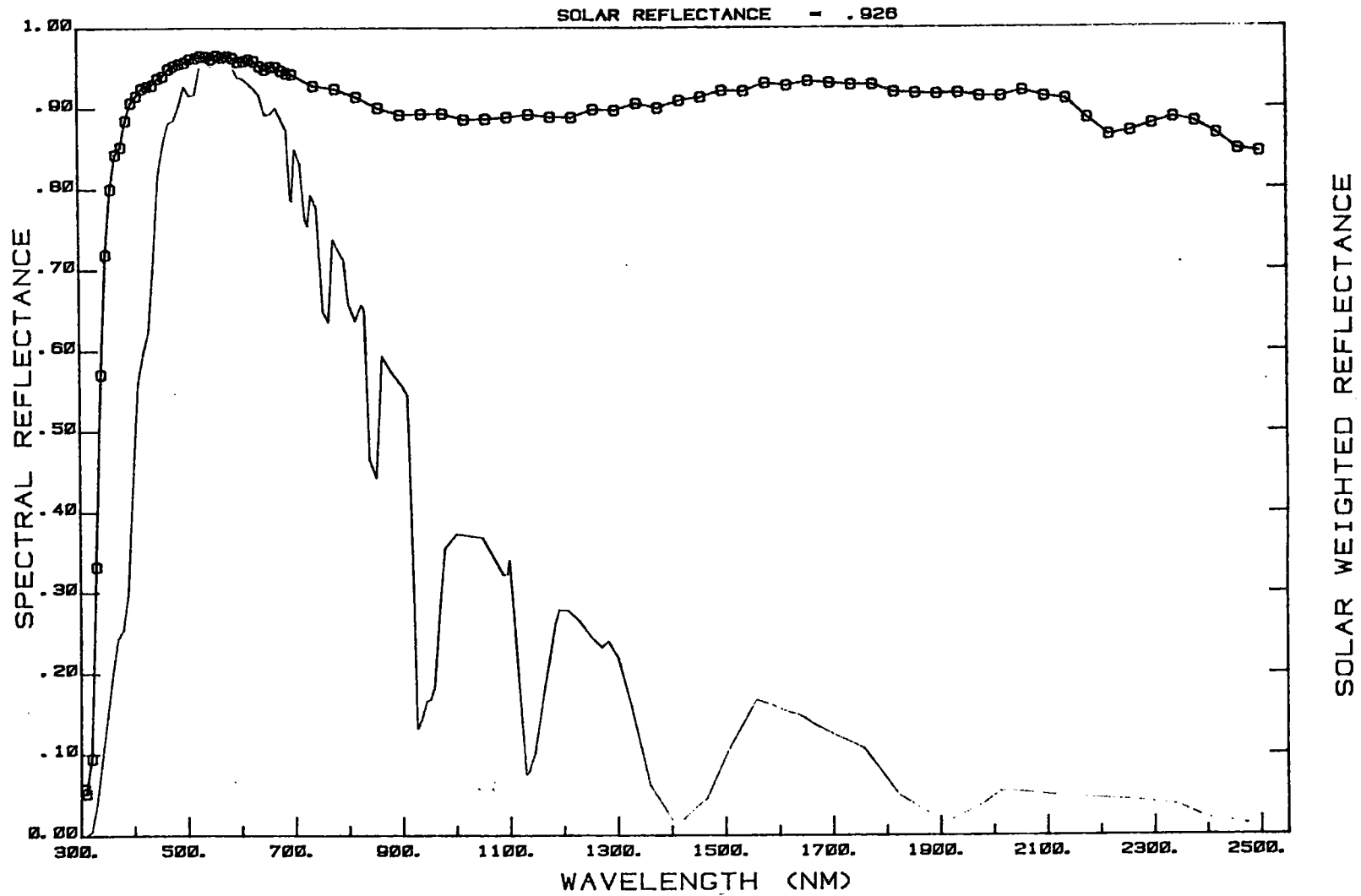


FIGURE 10. Typical Spectral Reflectance Curve for the Silvered Mirrors Produced on the Special Run of Low Iron Float Glass. The lower curve is the NASA AM 1.5 spectral irradiance distribution used to calculate the solar weighted reflectance.

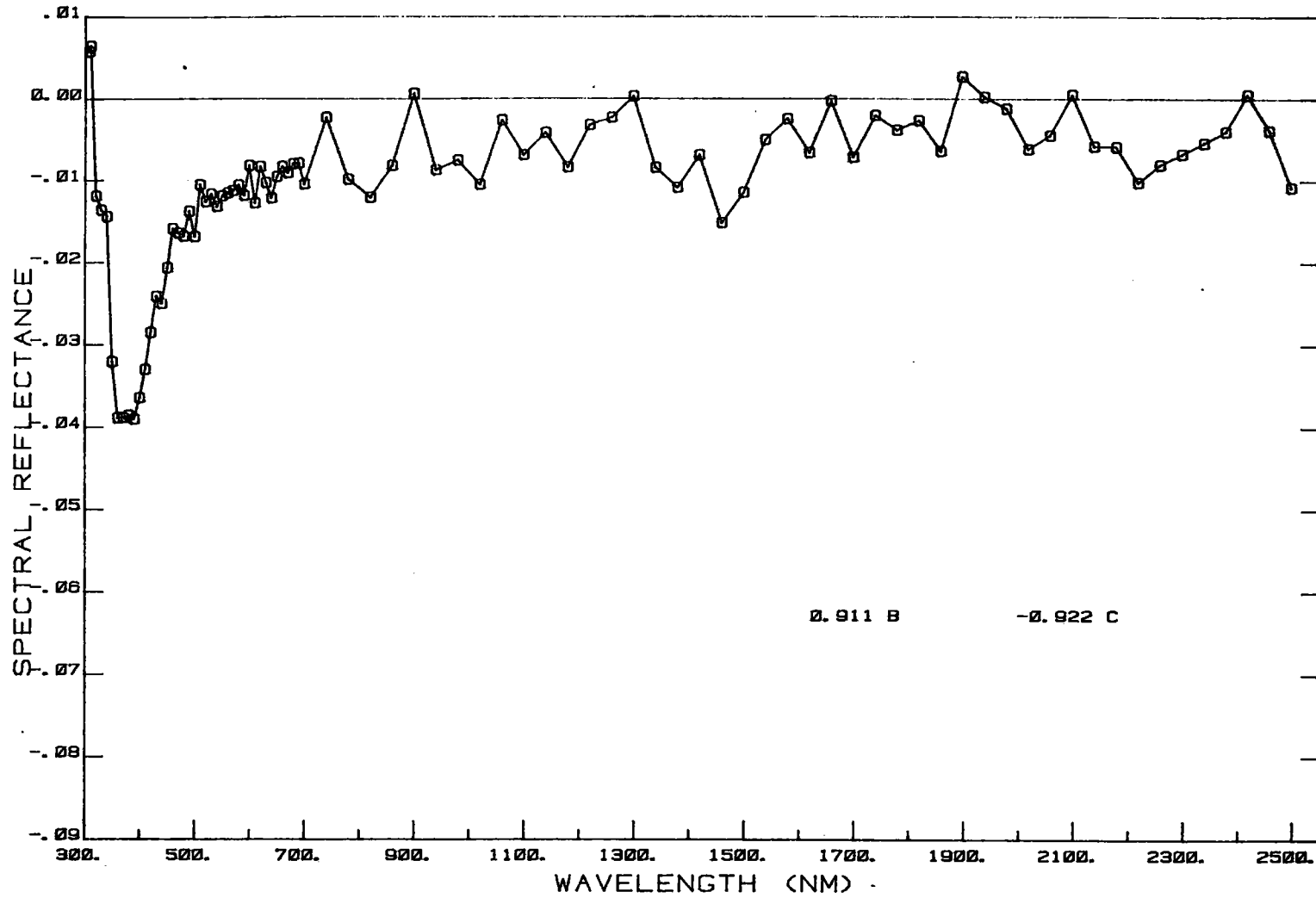


FIGURE 11. Spectral Difference Curve for Two Second Surface Silver Mirrors Produced by Different Manufacturers on the Same Substrate Material

this report. The scatter in the data at wavelengths greater than 700 nm is due to instrument drift and not a function of the silvering process.

CONCLUSIONS

The special run of low iron glass procured for the heliostats in the Barstow Ten Megawatt pilot plant has been examined for optical properties, durability, and mirroring properties. The glass exceeds all specifications for optical transmittance and figure as outlined in the DOE solicitation. The durability is comparable to all other soda-lime silicate float glass, but not as good as the aluminosilicate and aluminoborosilicate glasses that were examined. There was no apparent difficulty in silvering the glass after more than six months of powder-pack storage. The solar reflectance of the mirrors made from the glass varied from 0.907 to 0.931 depending upon the mirror manufacturer.

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