CSP FY01 Milestone Report

"Identify reasons for failure of thin glass mirrors and recommend solutions to industry to avoid further problems in the field"

02/28/01

Summary

Companies within the CSP industry are interested in using solar concentrators comprised of thin glass mirrors bonded to metal substrates. Two operational systems that use this construction have been deployed in Arizona for almost two years (21 months). Recently, several forms of "mirror graying" have been observed on some of these mirror facet elements. These visual imperfections include snake-like bands of discoloration over large areas internal to the mirrors (i.e., away from the edges), edge discoloration (about ½ inch wide), brownish staining, pit corrosion, and corrosion along crack lines. Assistance from Sun♦Lab's Optical Materials Team was requested by industry to quantify the impact of these defects in terms of loss of optical performance and to discover the degradation mechanism(s) so recommendations can be made to avoid future field failure.

We have documented the mirror blackening with digital photography and characterized the optical effects of the degradation by specular reflectance measurements. The loss in specular reflectance in the degraded areas is quite significant; non-degraded areas read 94% while readings in the various degraded regions range between 88-90%. Approximately 5-10% of the area (associated with one 3.1-m diameter facet that was examined) exhibited some level of discoloration after 21 months of field service. Upon completion of the optical characterization, samples of the various types of degradation were submitted to NREL's Measurements and Characterization group for analytical characterization (via bulk and surface techniques) to investigate possible degradation mechanisms. A sample has also been provided to SNL for complementary analytical characterization at Sandia as well.

We have identified a number of possible reasons for failure of thin glass mirrors in the field. However, recommended solutions require further investigation and validation; this is part of our ongoing effort to support industry needs for durable solar mirror materials. We will continue to keep our industry partners appraised of test results and progress. The major findings and recommendations to date, and proposed future activities are presented below; details are discussed in the Technical Results section of this report.

<u>Major Findings</u>

- The pattern of discoloration and corrosion observed in the field exhibits strong similarities to patterns seen in accelerated exposure testing (AET, in which samples

are weathered in the laboratory under controlled, elevated conditions of temperature, relative humidity, and light)

- Corrosion is seen in all types (from three manufacturers) of thin glass samples exposed as small-sized coupons both outdoors and in AET

- Evidence suggests that during service in the field, water wicks in through the adhesive, permeates through the paint, and facilitates corrosion of the metal layers. Significant levels of nitrogen and chlorine were found in the paint layer. Nitrogen suggests the likely presence of amines that, reacting with water, light, or oxygen, can break down into compounds that readily dissolve copper. Once the copper is depleted it can no longer provide galvanic protection for the silver. Chloride ions are well known to corrode both copper and silver.

Prioritized Recommendations

- A more dense/protective paint might prevent failure. Other possibilities would be to coat the paint either with metal or other inorganic (for example, oxides) layers that are highly impermeable to water, or with hydrophobic coatings. Use of non-wicking adhesives might also be advantageous if differential flexing between the thin glass mirrors and the substrate materials can be eliminated. Designs where the back of the glass mirrors are open to the ambient environment (where condensed water can drain or evaporate and is not held in constant intimate contact with the paint by a porous adhesive) coupled with better backside protection (improved paint formulations) could mitigate problems.

- Naugatuck (the only U.S. supplier of thin glass mirrors) is pursuing a new silvering process that will eliminate the back surface copper and include a new back coating paint. The process has been used in Europe for many years and supposedly results in a much more durable mirror. Sun♦Lab will receive samples of this new reflector construction and subject them to appropriate outdoor exposure testing (OET) and AET.

- Strategies that provide an effective edge seal to prevent moisture ingress will be explored. However, we have tested several edge seal strategies; none of the edge seals that were tried have worked (they discolor and become porous or crack). A broader set of candidate edge seal strategies will be evaluated.

Future Activities

- Sun♦Lab will survey standard mirror painting practices and organize a matrix of sample constructions for accelerated exposure testing to identify the most promising combinations of paints and adhesives for use with concentrator designs.

- Ongoing fundamental analysis support will be provided as needed to allow industry partners to make optimal materials selection decisions.

Introduction

For investigation purposes, SAIC provided a completely dissected facet (3.1-m diameter, cut into 0.6-m x 0.9-m samples) from their Arizona test site. The mirror construction (Figure 1) consists of a thin glass (~1 mm thick) superstrate, a silver reflective layer, a copper protective layer, and a back layer of protective paint. The thin glass mirror material is supplied by Naugatuck Glass. An adhesive (3M 966) is generally used to bond the mirror to a metal substrate (3-mil thick #201 stainless steel foil). No edge protection is used by SAIC.

In addition to SAIC, other CSP companies are interested in using thin glass mirror-based concentrators and in problems associated with their optical durability. As part of our ongoing industry support activity, Sun♦Lab personnel have met with concerned CSP industry contacts and kept them appraised of test results. On January 11, 2001 a meeting was held at NREL with representatives of SAIC and Industrial Solar Technology to discuss progress and future plans to resolve this problem. On February 7, 2001 a teleconference was held between Sun♦Lab staff and representatives of SES and Boeing to brief them on the nature of the problem and progress made to date. This report documents our findings and preliminary recommendations.

Technical Results

We have performed three types of analytical characterization. These include: 1) digital photography of the type and extend of visual degradation, 2) specular reflectance measurements of corroded areas to determine the effect upon optical performance, and 3) chemical analysis of bulk and interface regions to identify degradation mechanisms. Such fundamental analyses are essential to understand causes of degradation so that recommendations for improvements can be made to avoid failure. Results from each of these analyses are presented below.

Digital Photography and Specular Reflectance Measurements

The samples degrade in snake-like corrosion bands that occur in the center of the mirrors and follow the edges and some cracks. The corrosion bands are a gray color darker than the mirror, which are difficult to see unless the mirror is cleaned and viewed either outdoors against a clear sky or indoors at an appropriate angle under strong light. There are areas with spots of corrosion that are gold-to-gray in color. To view the snake-like corrosion bands in the digital photographs, the contrast had to be increased. Visually these corrosion bands and spots are very similar to the corrosion bands and spots first observed for small (45-mm x 67-mm) thin glass mirrors laminated with several different types of adhesives and subjected to AET [1-3]. The corrosion initially observed in the small samples was also difficult to see and photograph unless the sample was clean and held at an acute angle under bright light. Often the areas of visual corrosion were less apparent in the photograph than they were on the actual samples, requiring contrast enhancement of the photographs. Samples showed signs of corrosion at the unprotected edges and at the cracks. The mirrors typically had a characteristic dark band around the edges and at cracks and a heavy white hazy discoloration. The reflectors continued to visually and optically degrade with sustained AET until the visual degradation became quite noticeable without any special conditions, even in the photographs as seen in Figures 2 and 3. For the sample used in these figures, and many others, the edges and corners have a narrow band of spots of dark brown to dark gray corrosion and more dark-to-colored bands appeared along the edges. Delamination between the glass and silver begins in these areas of corrosion. Inside the corrosion bands the center is a mottled creamy yellow color to a mottled silver white with spots of silver or gray.

The matrix of small samples subjected to AET is provided in [1]; glass mirror thicknesses of 0.7, 1.0, and 2.4 mm were tested in combination with a variety of adhesives. In general, all small glass mirrors display signs of degradation regardless of adhesive and glass type. This is true for samples of thin glass (≤ 1.0 mm) provided by other (non-U.S.) companies (such as Steinmüller and Schlaich, Bergermann und Partner in Germany). The performance of the thin glass mirrors degrades quicker than the thicker (2.4-mm) glass mirrors tested. None of the edge seals tried have worked; they discolor or become porous and crack (especially among the epoxies). All samples exhibited mirror discoloration, corrosion, and loss of specular reflectance similar to that experienced in the field.

For the large facet samples, although there may have been some glass cracking prior to being cut, after the facet was cut the glass cracked extensively due to stress relief. Photographs were taken with an Olympus Digital Vision D-600L digital camera. In order to observe and print the corrosion features in the photographs, Microsoft PhotoDraw 2000 was used to modify the brightness, contrast, tint, hue, saturation, or color balance. Five samples were characterized; the type of degradation features experienced by each is identified in Table 1. A Field Portable Specular Reflectometer from D&S Instruments was used to measure the specular reflectance of the corrosion features on the SAIC facets at 15-mrad full-cone angle and at a wavelength of 660 nm. The smallest measurement spot size is ~10-mm diameter and many of the features were of the same size or smaller, making accurate data collection difficult. The values obtained with the D&S are superimposed on the digital images over the locations at which they were measured.

<u>Photograph of Complete Facet Section</u>

C2554-27-5; 0.7 mm thick Naugatuck glass mirror; 3M 966 adhesive; 21 Mo. Arizona exposure

This 0.8 x 0.6-m facet section was an excellent representative of the corrosion on the facet because it had all of the forms of “mirror graying” observed on mirror facet elements and the corrosion was dark enough to photograph. These visual imperfections include snake-like bands of discoloration over large areas internal to the mirror, brownish staining at the edge, pit corrosion, and corrosion along crack lines. This section has a glass joint 0.1-m from the edge as shown in Figures 4 and 5. Gray edge discoloration (about 10-12 mm wide) is parallel to the joint on both sides of the glass joint. This corrosion band is slightly darker than the glass and is very difficult to observe unless viewed at an angle under a strong light. There is an area 110-mm wide by 450-mm long of golden-brown to gray spots approximately 1 to 10-mm in diameter along the cut-edge perpendicular to the joint. The brownish staining spots begin approximately 120 mm from the joint and are about 150 to 200-mm long. The gray pit corrosion spots begin approximately 450-mm away from the joint. The snake-like bands of discoloration cover large areas internal to the mirrors (i.e., away from the edges) and are gray. A large area of snake-like bands is approximately 150 to 180-mm from the glass joint and 150-mm from the adjacent cut-edge and about 150-mm wide. Another band is approximately 20 to 40-mm from the cut-edges, about 200-mm wide and is almost as long as the width of the section cut from the facet. Very little modification of the digital image was needed to view the corrosion spots in the photograph.

Table 1. SAIC facet construction

Sample ID	SAIC Facet Section	Feature	Glass	Reflective Layer	Back Coating	Adhesive	Substrate	Edge Protection	Exposure Time (Months)
C2554-27-1	3&5	Spots, snake-like corrosion bands	Naugatuck Thin Glass Mirrors (1 mm thick) Low-Iron	Wet Processed Ag	Acrylic Paint (gray)	3M 966	3 mil thick #201 Stainless Steel	None	~21 (Arizona)
C2554-27-2	3	Snake-like corrosion bands							
C2554-27-3	1-2	Snake-like corrosion bands							
C2554-27-4	2-5	Snake-like corrosion bands							
C2554-27-5	Blank	Spots, snake-like corrosion bands, glass joint, edge corrosion bands							

<u>Photographs and Specular Reflectance of "Mirror Graying" Features on Facet Sections</u>

C2554-27-1B; Corrosion spots

Golden-brown to dark-gray spots approximately 1 to 10-mm in diameter in an area 152-mm wide by 152-mm long adjacent to a cut-edge in facet section C2554-27-1 are shown in Figure 6. The dark gray pit corrosion spots are mixed with the brownish staining spots. Very little modification of the digital image was needed to view the corrosion spots in the photograph. The specular reflectance values measured at the corrosion spots is in dark blue on the photograph with an average specular reflectance of 89.7%. The specular reflectance of the uncorroded area is in light blue with an average specular reflectance of 94.1%. This is a loss in specular reflectance of 4.3%.

C2554-27-5A; Edge corrosion band

The glass joint and edge corrosion band in facet section C2554-27-5 are shown in Figure 7. The gray edge discoloration (about 10-12 mm wide) is parallel to the joint on both sides of the glass joint. This corrosion band is slightly darker than the glass and is very difficult to observe unless viewed at an angle under a strong light. Significant modification of the digital image was needed to view the corrosion band in the photograph. The specular reflectance of the corrosion spots is in dark blue on the photograph with an average specular reflectance of 94.4%. The specular reflectance of the uncorroded area is in light blue with an average specular reflectance of 95.9%. This is a loss in specular reflectance of 1.5%. However, because of the large beam size inherent to the D&S specular reflectometer, the specular reflectance of the corrosion band may be elevated by sampling/measuring areas that may have included non-corroded regions.

C2554-27-5F; Snake-like corrosion band closer to edge joint

An area of a snake-like corrosion band that is approximately 150 to 180-mm from the glass joint and 150-mm from the adjacent cut-edge and about 150-mm wide in facet section C2554-27-5 is shown in Figure 8. This snake-like band of discoloration is closer to the glass edge, is parallel to the joint, and is gray. This band is slightly darker than the glass and is very difficult to observe unless viewed at an angle under a strong light. Significant modification of the digital image was needed to view the corrosion band in the photograph. The specular reflectance of the corrosion spots is in dark blue on the photograph with an average specular reflectance of 94.8%. The specular reflectance of the uncorroded area is in light blue with an average specular reflectance of 94.9%. Two possible reasons for such a small difference in reflectance are that the entire sample area (including the "uncorroded" area) was visually degraded, and the "corroded area" was measured inside the snake-like band (rather than along the band).

C2554-27-5B; Internal snake-like corrosion band

An area of a snake-like corrosion band that is approximately 20 to 40-mm from the cut-edges, about 200-mm wide and almost as long as the width of facet section C2554-27-5 is shown in Figure 9. The snake-like band of discoloration is internal to the mirrors (i.e., away from the glass edges) and is golden and gray. This band is slightly darker than the glass and is very difficult to observe unless viewed at an angle under a strong light. Considerable modification of the digital image was needed to view the corrosion band in the photograph. The specular reflectance of the corroded area is in dark blue on the photograph with an average specular reflectance of 89.6%. The specular reflectance of the uncorroded area is in light blue with an average specular reflectance of 94.1%.

Results of the various specular reflectance measurements are summarized in Table 2.

Table 2. Specular Reflectance of Various Types of Corroded Areas

	Pitting Spots	**Edge Corrosion Band**	**Snake-like Corrosion Band - Internal**	**Snake-like Corrosion Band - Edge Joint**
Figure #	6	7	8	9
Average – Uncorroded area	94.1	95.9	94.9	94.1
Standard Dev.	0.5	0.1	0.4	0.6
Average - Corroded area	89.7	94.4	94.8	89.6
Standard Dev.	3.5	1.1	0.8	6.6
Specular Reflectance Loss	*-4.3*	*-1.5 **	*-0.1 ***	*-4.5*

* The specular reflectance of the edge corrosion band may be high because uncorroded areas may have been included in the measurements because the edge corrosion band is so narrow.

** The specular reflectance of the uncorroded may be low because this may include some darkening measurements since the corrosion band was so large.

Chemical Analysis

X-ray photoelectron spectroscopy (XPS) was used to help understand the degradation mechanisms of solar mirrors that experienced outdoor service exposure. The mirrors exhibited several different types of degradation during field use. Corrosion pits 1-2 mm in diameter consisted of fully oxidized and delaminated silver layers. Corrosion bands, or areas of graying and reduced reflectance, was observed over larger (0.5 m) areas. XPS spectra of several corrosion pits, of the unpainted copper layer, and of the paint itself were taken on a PHI 5600 monochromatic photoemission system. For non-conducting samples such as the paint, an electron flood gun operating at minimum energy and current was used to compensate for photoelectron induced charging. All data was taken with monochromatic Al radiation using a pass energy of 80 eV. Where noted, argon ion sputtering was used to remove surface contamination.

Experimental Analyses

Figure 10 is an XPS survey scan of a corrosion pit. Not surprisingly, the pit consists of oxides of silver and copper. Other elements detected at or near the corrosion pit include carbon, chlorine, nitrogen, oxygen, sodium, and zinc. In order to simplify the complex system of weathered glass, silver, copper, paint, and adhesive, and to determine the origin of the elements detected at the areas of mirror degradation, samples representing the mirrors at different stages of the manufacturing process were procured. Samples of uncoated glass, glass/Ag/Cu, and glass/Ag/Cu/paint were obtained from Naugatuck Glass, the mirror manufacturer. Figure 11 is an XPS survey spectrum of the as-received glass/Ag/Cu and is representative of what the manufactured construction consists of immediately before the application of the paint. The spectrum is typical of what one would expect from a pure copper sample that has been exposed to ambient conditions, i.e. a significant amount of carbon and oxygen, and a small amount of sulfur are observed. This same sample was sputtered with 3 keV Ar^+ to remove the outermost atomic layers. The survey spectrum of the sputtered sample is shown in Figure 12, and essentially is a spectrum of pure copper.

Figure 13 is an XPS spectrum of the paint used to protect the copper layer, and is of an "as-received" sample (not sputtered). Table 3 shows the elemental constituents of the paint and their concentrations as derived from this spectrum.

Table 3. Atomic concentrations of as-received mirror paint (%)

C	O	N	Si	Na	Cl
67	23	6.2	2.9	0.55	0.12

The paint sample analyzed above was subjected to three minutes of 3 keV argon ion sputtering, and another survey spectrum was acquired (Figure 14). This spectrum shows a wider variety of elements present and is probably more representative of the bulk paint constituents rather than the surface contamination layer resulting from exposure of the sample to the atmosphere. Atomic concentrations listed in Table 4 were derived from the spectrum shown in Figure 14.

Table 4. Atomic concentrations of sputtered mirror paint (%)

C	O	N	Si	Zn	Na	Co	Cl
84	7.4	6.5	1.0	0.58	0.43	0.33	0.25

These XPS measurements revealed that the paint is not an electrical conductor, unlike some previously used paints that were heavily (20-30 wt. %) loaded with lead or zinc. The low levels of zinc within the present paint, presumably added by the manufacturer for cathodic protection of the underlying copper, would not be effective in this role while it is imbedded in a nonconducting polymer matrix. In a related development, during discussions with Naugatuck about preliminary AET results, they revealed that their standard mirror product uses a "no-lead" paint. They suggested that use of a "low-lead" paint might provide adequate protection of their mirrors. Samples of both "no-lead" and "low-lead" paint protected thin glass mirrors were supplied to Sun♦Lab. These were tested side-by-side in an AET experiment using a solar simulator chamber. Both types of mirrors were found to degrade at the same rate, implying that the Naugatuck "low-lead" paint does not contain enough lead to effectively protect the copper layer.

Discussion of Mechanisms

There are a number of indications as to the underlying mechanisms of the observed mirror degradation. One is that the degradation appears to be associated with water, as revealed by controlled accelerated aging studies, the observation that the large bands of graying have the appearance of a solvent front, and the known porosity of the acrylic adhesive used to affix the mirrors to their steel backing sheets. Previous work has shown water exposure to be associated with the degradation of silver-based mirrors [4].

Another piece of evidence comes from the XPS data of the sputtered and as-received paint samples. These data show that the paint contains a significant amount of nitrogen. The chemical state of the N is not known and should be investigated with additional techniques such as IR spectroscopy, but common forms of N in paints include polymerized amines, amides, and cyano groups. Amides are known to hydrolyze with the subsequent release of the corresponding amine. Amines in particular are known to complex strongly with copper. Previous copper corrosion studies have shown that ammonium salts are capable of producing vigorous corrosion of copper, even in the absence of oxidizing agents, which usually accelerate the process [5]. In the case of water-penetrated mirrors, oxidants such as water and oxygen are readily supplied to the copper/paint interface because the paint itself is porous.

Useful information concerning problems with the mirror system was provided by Lilly Industries, the maker of the paint used to protect the outermost Cu layer. A technical representative of Lilly reported that Lilly Industries believes that the fundamental problem with the current Naugatuck mirrors is the use of copper due to the great difficulty of keeping it from reacting with the wide variety of oxygen, sulfur, and nitrogen compounds to which the mirrors are invariably exposed. In fact, the paint manufacturer stated that “even 40 coats of paint” would ultimately fail to protect mirrors having copper layers. This supports an earlier claim that “even the best paint is not considered good or durable enough for mirrors which are … used outside” [6]. Although paint formulations have presumably improved since the early 1970’s, recent environmental concerns about paints that contain volatile organic chemicals (VOC’s) has created new challenges for the paint industry. Tens of millions of dollars are spent each year by the automotive industry to protect metal vehicles from corrosion, and silver is much more reactive and difficult to preserve.

Research at Lilly has led to the development of a new technology to completely avoid the use of copper [7]. A chemically applied ~100 Å layer of SnO_2 was found to dramatically increase the chemical resistance of silvered mirrors relative to the older copper protective layer, yet still allow for the adhesion of their preferred paint. The SnO_2 is likely a good diffusion barrier for oxygen and water, and has the additional advantage being immune to further oxidation. The Ag/SnO_2 system would also not suffer from the known problems of copper/silver interdiffusion that a number of workers have implicated in mirror degradation [4]. The SnO_2 process is promising enough that Naugatuck is considering pilot production of mirrors using this process [8]. Other than the patent cited in [7], there is no evidence in the open literature to support Lilly’s claim of greatly increased resistance to weathering. Contact with both Lilly and Naugatuck has resulted in their realizing that additional controlled accelerated aging studies of the SnO_2 protected mirrors would be in everyone’s best interest, and both companies are currently considering supplying NREL with mirror samples for this purpose.

From the above considerations, there are at least two plausible mechanisms for the observed mirror degradation. The first has as its first step an interfacial reaction between the copper and the paint. It is expected that once the protective copper layer has been oxidized, the thin underlying layer of silver degrades quickly. If the paint in fact has amine or amide functional groups as part of it chemical makeup, one would expect an eventual interfacial reaction with copper. Many two-part paints contain free amines before they cure, which would rapidly react with the copper and start its corrosion even as the paint cured. An additional problem with these types of paints is that there exists the possibility of non-stoichiometric mixing. If an excess of one paint component is inadvertently added, the stoichiometric excess can remain as a reservoir of corrosive compounds. Water wicking through the acrylic adhesive would be expected to transport ammonia, free amines, salts such as NaCl (shown from XPS to be a component of the paint), and to concentrate them at the solvent front, where transport through the relatively porous paint would result in corrosion of the copper and subsequent degradation of the silver layer. Previous workers have concluded that "protective" paints that contain chlorine will eventually cause corrosion of the copper layers and subsequent degradation of the silvering [9]. Pinholes in the paint which expose bare copper would be expected to result in locally severe pitting.

The second mechanism of mirror degradation was previously alluded to, the interdiffusion of the copper and silver layers. This mechanism probably operates in tandem with the interfacial reaction between the copper and paint, and could in fact be driven by the supply of reactive compounds to this interface. In this scenario, silver diffusing to the copper/paint interface becomes oxidized, remains at the interface, and thus acts as a steady drain on the supply of elemental silver.

Conclusions and Recommendations

We have identified a number of possible reasons for degradation of thin glass mirrors in the field. However, recommended solutions require further investigation and validation; this is part of our ongoing effort to support industry needs for durable solar mirror materials. We will continue to keep our industry partners appraised of test results and progress.

The current mirror system has little chance of surviving exposure to the elements because the copper protective layer is coated with a reactive paint, and the paint is subjected to moisture and oxygen. If silver is to be used as a reflective material it must be isolated from reactive species.

The pattern of discoloration and corrosion observed in the field exhibits strong similarities to patterns seen in AET. Corrosion is seen in all types (from three manufacturers) of thin glass samples exposed as small-sized coupons both outdoors and in AET.

Evidence suggests that during service in the field, water wicks in through the adhesive, permeates through the paint, and facilitates corrosion of the metal layers. Significant levels of nitrogen and chlorine were found in the paint layer. Nitrogen suggests the likely presence of amines and other chemicals that, reacting with water, light, or oxygen, can break down into compounds that readily dissolve copper. Once the copper is depleted it can no longer provide galvanic protection for the silver. Chloride ions are well known to corrode both copper and silver. A more dense/protective paint might prevent failure. Other possibilities would be to coat the paint either with metal or other inorganic (for example, oxides) layers that are highly impermeable to water, or with hydrophobic coatings. Use of non-wicking adhesives might also be advantageous if differential flexing between the thin glass mirrors and the substrate materials can be eliminated. Designs where the back of the glass mirrors are open to the ambient environment (where condensed water can drain or evaporate and is not held in constant intimate contact with the paint) coupled with better backside protection (improved paint formulations) could mitigate problems.

Another approach would be to provide an effective edge seal to prevent moisture ingress. However, we have tested several edge seal strategies; none of the edge seals that were tried have worked (they discolor and become porous or crack). A broader set of candidate edge seal strategies will be evaluated.

Naugatuck (the only U.S. supplier of thin glass mirrors) is pursuing a new silvering process that will eliminate the back surface copper and include a new back coating paint. The process has been used in Europe for many years and supposedly results in a much more durable mirror. Sun♦Lab will receive samples of this new reflector construction and subject them to appropriate OET and AET.

Sun♦Lab will survey standard mirror painting practices and organize a matrix of sample constructions for AET to identify the most promising combinations of paints and adhesives for use with concentrator designs. As a starting point, a large number of mirror backing paints and sealants identified in [10] will be reviewed. Discussions with major paint and adhesive manufacturers will provide an update of more recent formulations for consideration.

Acknowledgements

The digital photography and specular reflectance measurements were made and documented by Cheryl Kennedy. The chemical analyses were performed and documented by Craig Perkins. Rod Mahoney at SNL is coordinating complementary chemical analyses at SNL. Testing of 1.2-mm thick samples of Naugatuck thin glass mirrors having a no-lead protective paint and a low-lead protective paint was carried out by Kent Terwilliger. Field-weathered samples were provided by SAIC; unweathered samples were supplied by Naugatuck Glass. A number of useful conversations were held with technical representatives at Naugatuck Glass and Lilly Industries.

References

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Figure 1. Construction of Mirror Samples

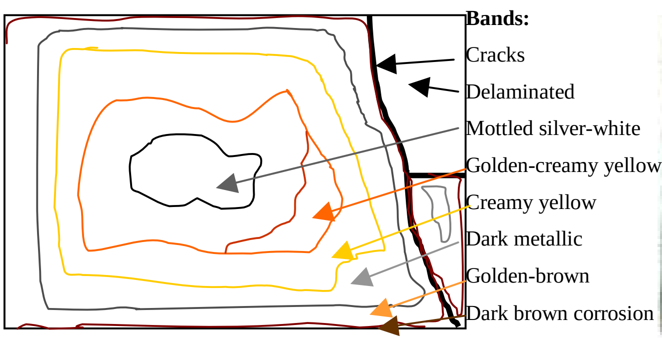

Figure 2. Line drawing of corrosion bands for small sample R1558-49-2 after 25 Mo. Total AET = 18 months in XENO + 7 months in WOM

Figure3. Digital photograph of corrosion bands for small sample R1558-49-2 after 25 Mo. Total AET = 18 months in XENO + 7 months in WOM

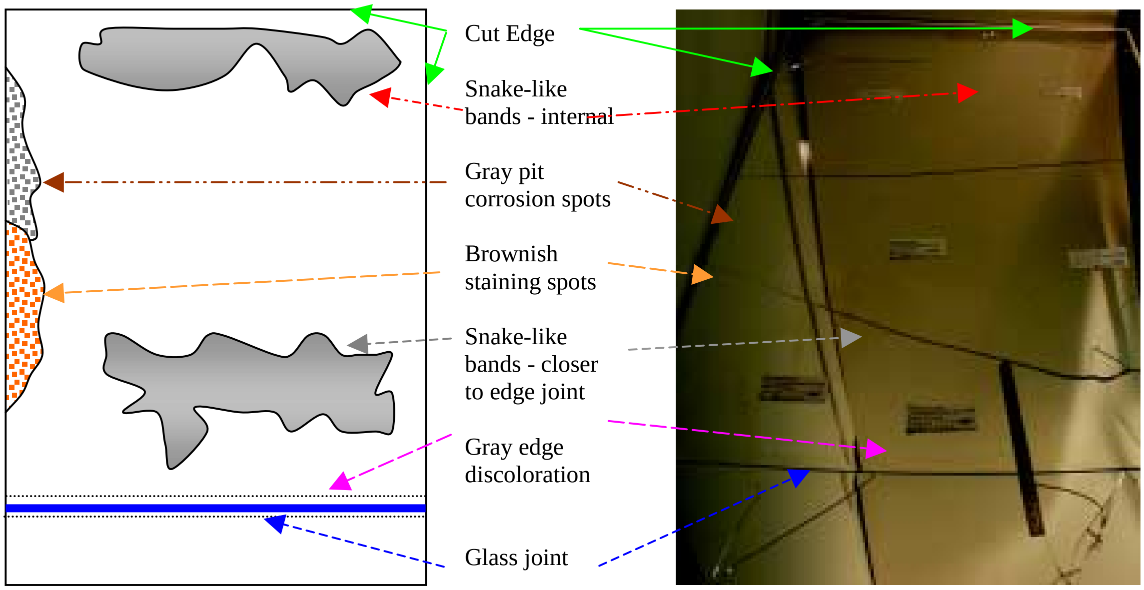

Figure 4. Line drawing of "mirror graying" for facet section C2554-27-5 after 21 Mo. of exposure in Arizona

Figure 5. Digital photograph of "mirror graying" for facet section C2554-27-5 after 21 Mo. of exposure in Arizona

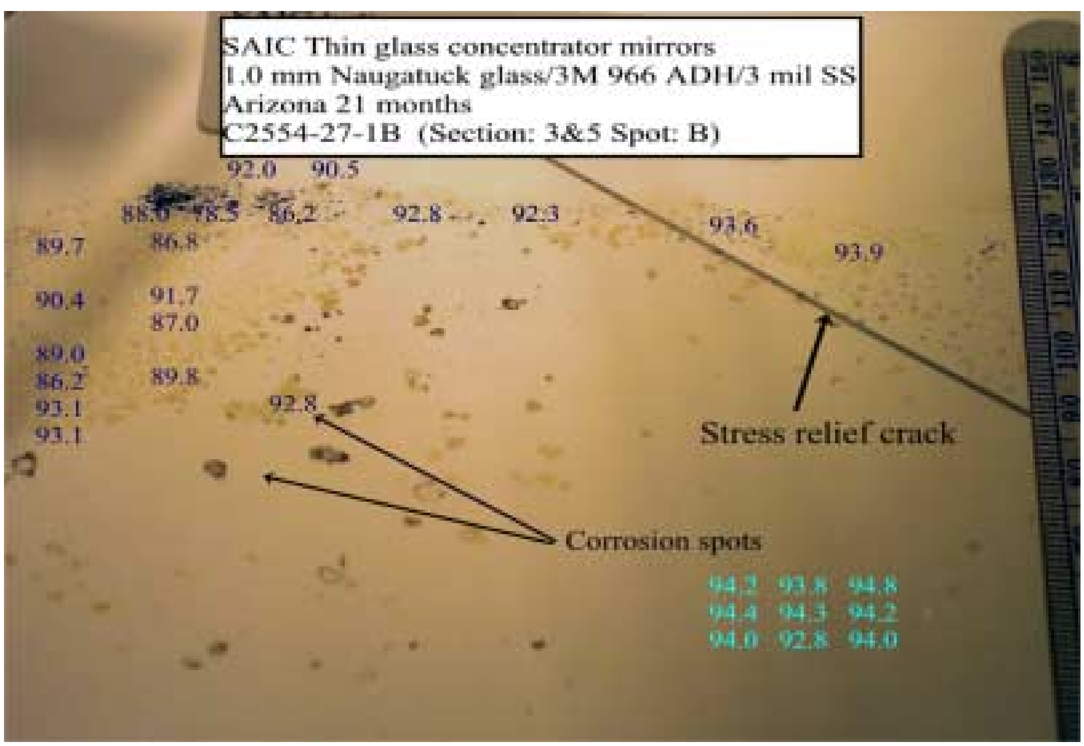

Figure 6. Digital photograph and specular reflectance of brownish staining and dark gray pit corrosion spots for facet section C2554-27-1 after 21 Mo. of exposure in Arizona.

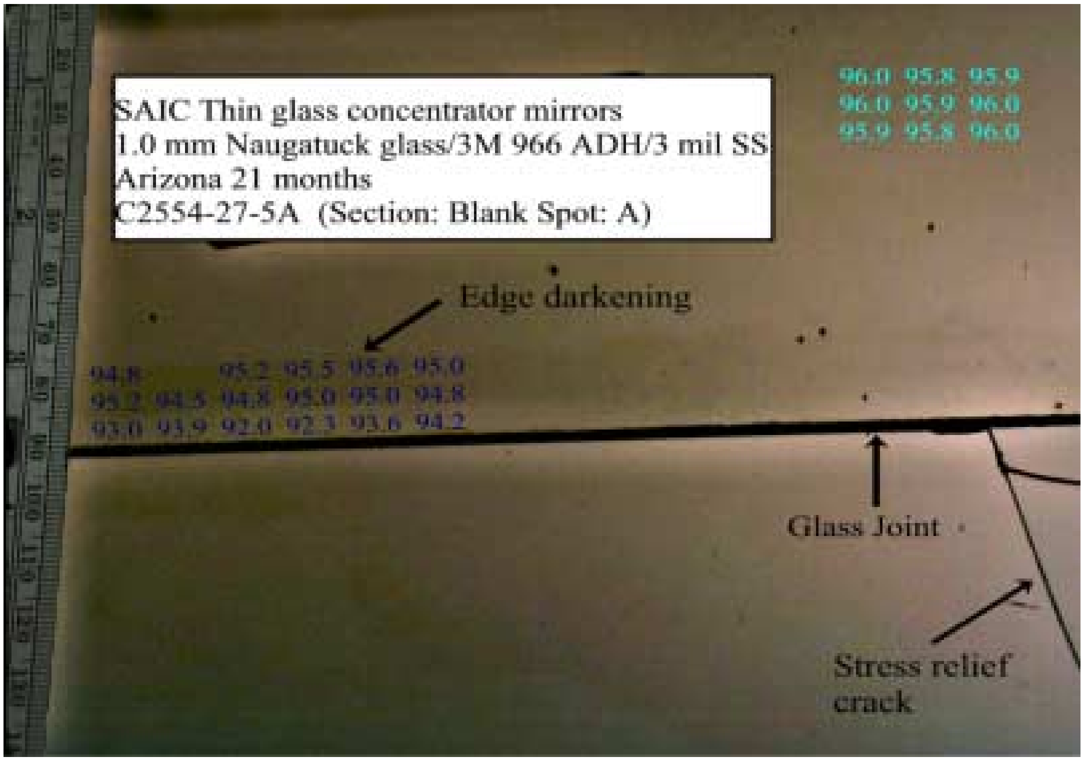

Figure 7. Digital photograph and specular reflectance of band of edge darkening at glass joint for facet section C2554-27-5 after 21 Mo. of exposure in Arizona.

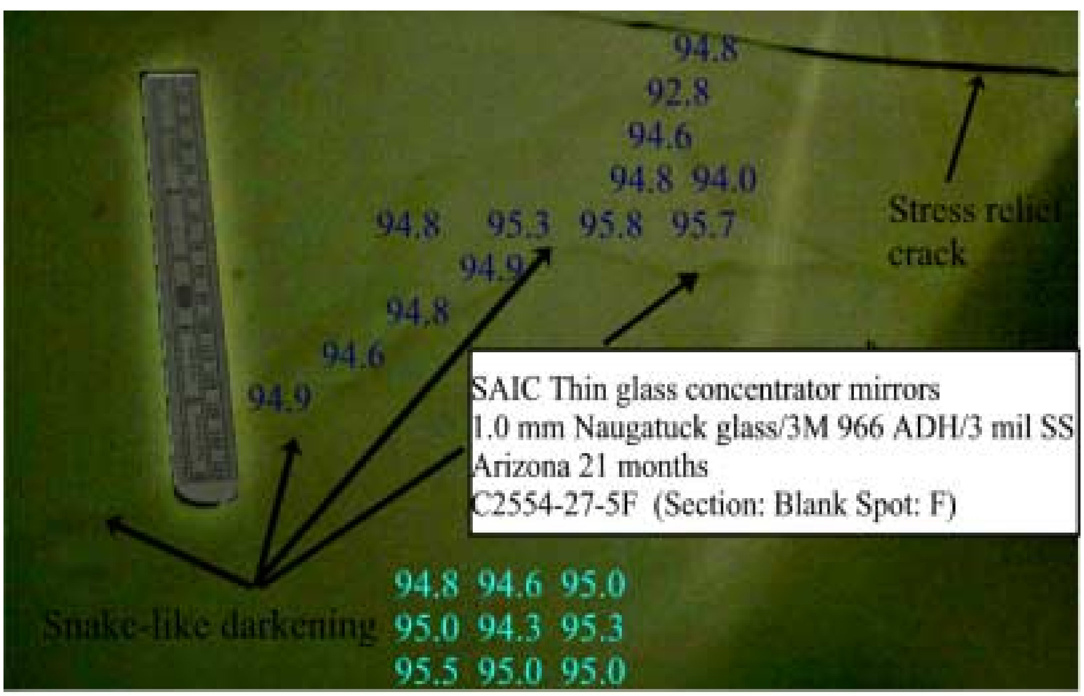

Figure 8. Digital photograph and specular reflectance of internal snake-like corrosion bands for facet section C2554-27-5 after 21 Mo. of exposure in Arizona

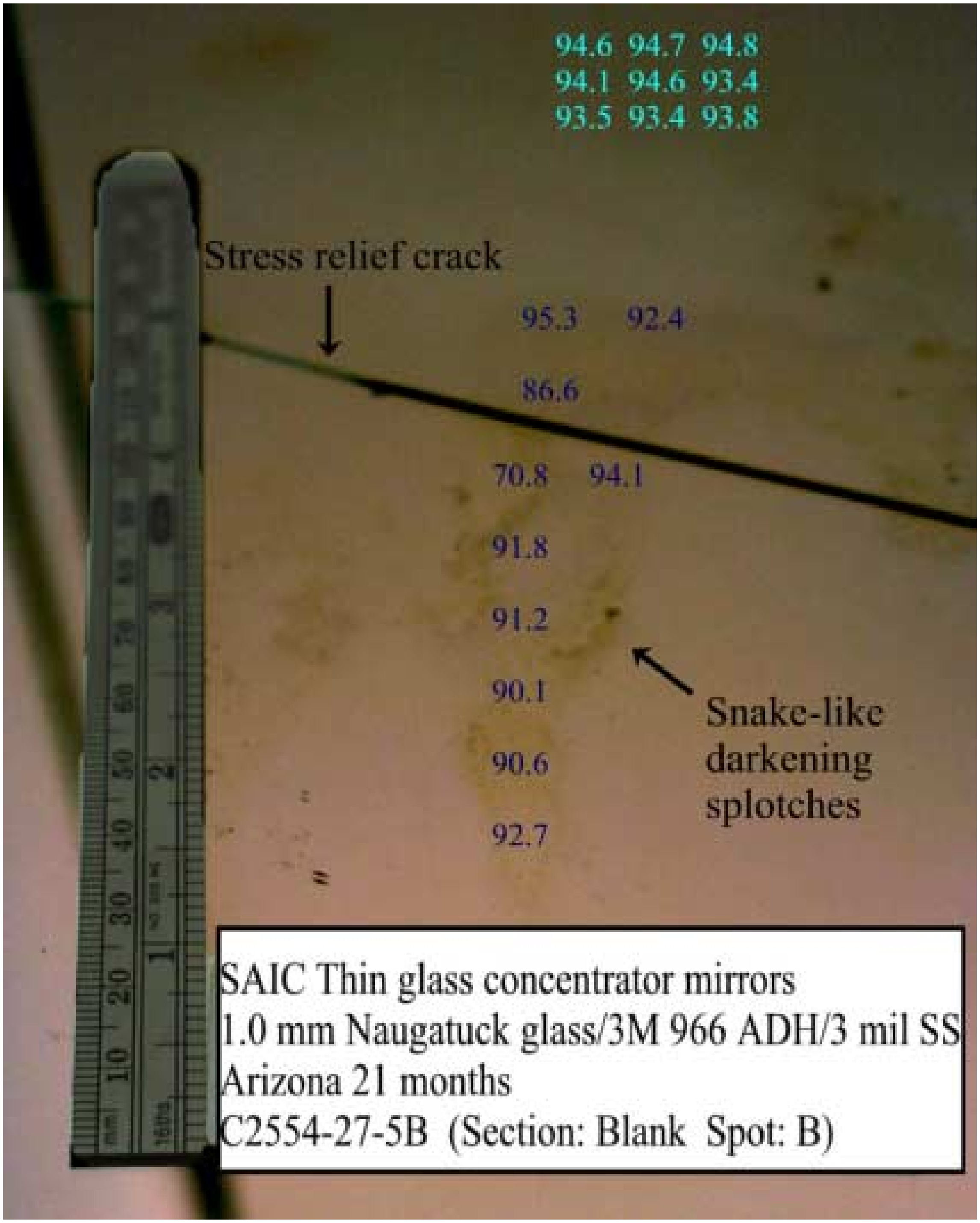

Figure 9. Digital photograph and specular reflectance of snake-like corrosion bands closer to edge joint for facet section C2554-27-5 after 21 Mo. of exposure in Arizona.

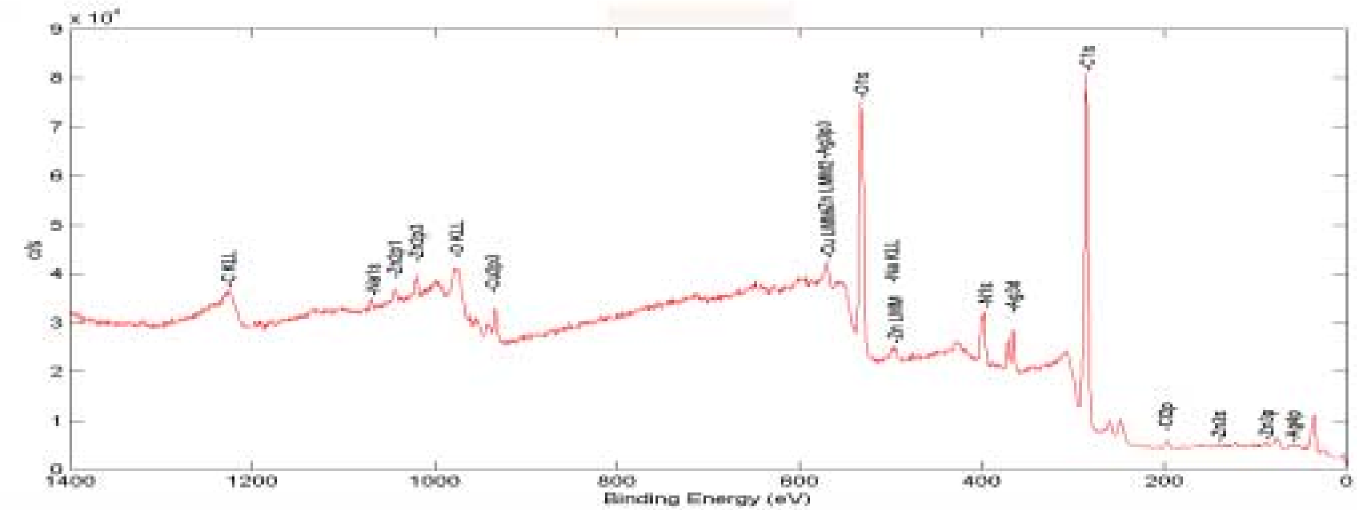

Figure 10. XPS survey of corrosion pit on mirror.

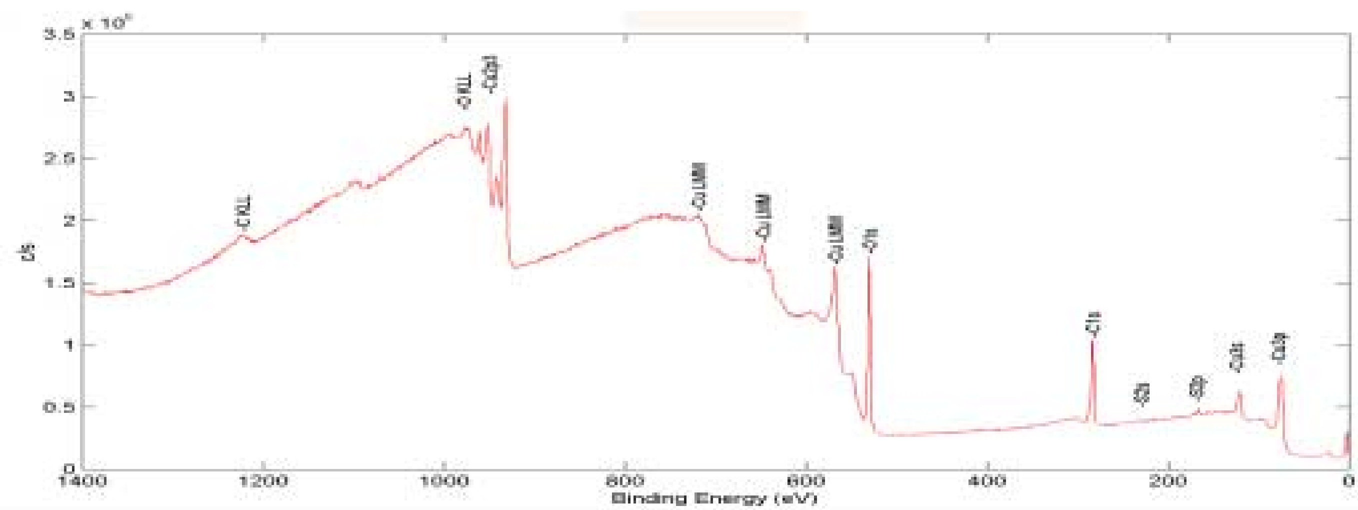

Figure 11. XPS survey of as-received copper layer of mirror.

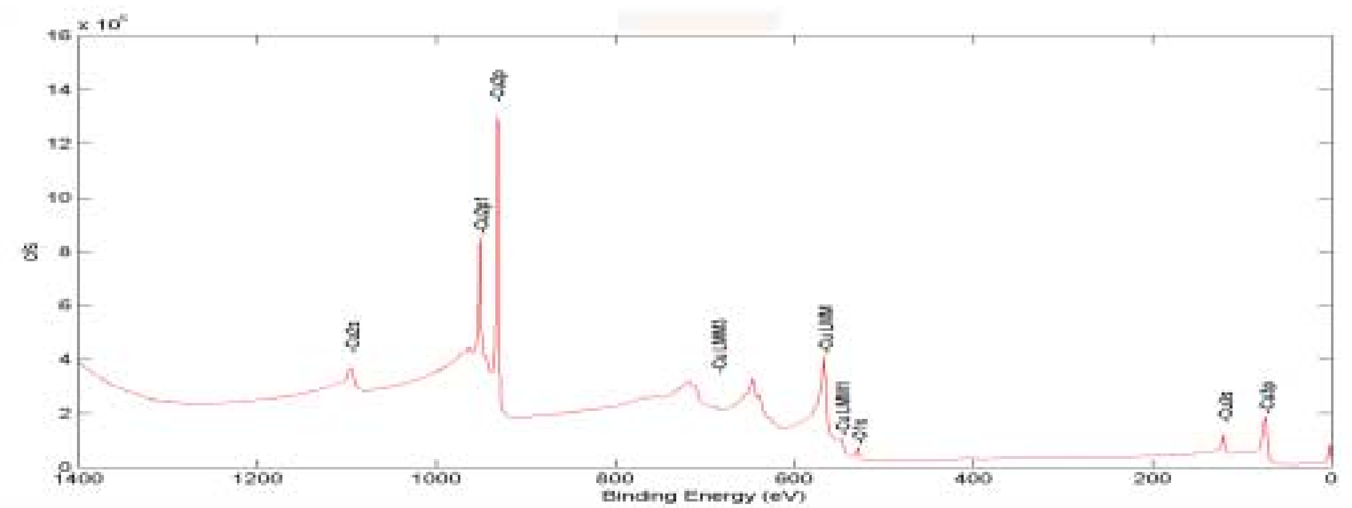

Figure 12. XPS survey of Ar^+ sputtered copper layer of mirror.

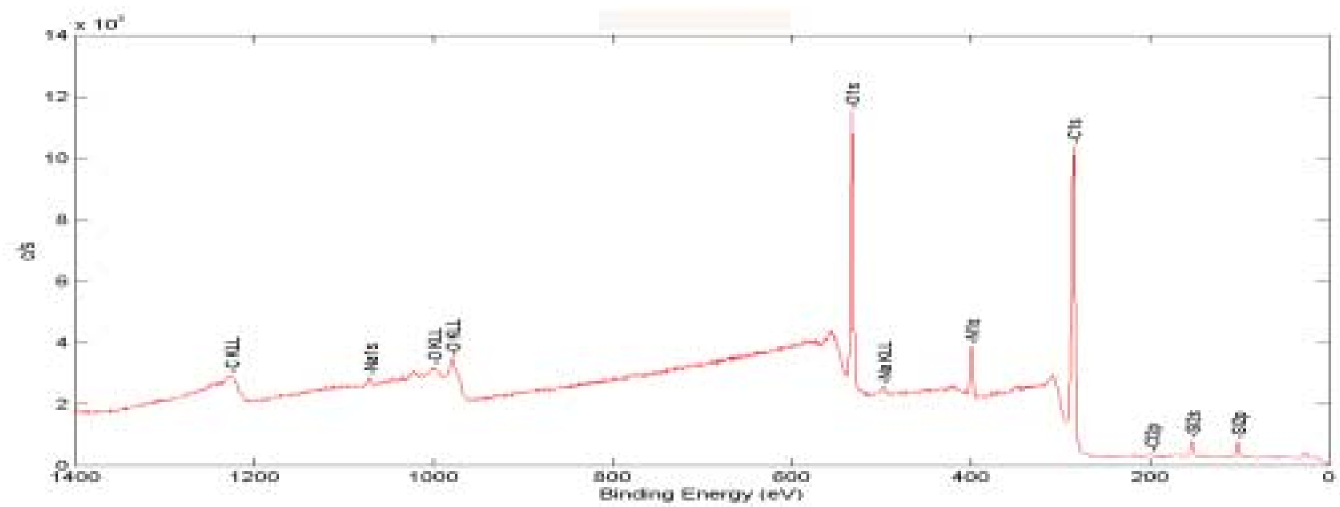

Figure 13. XPS survey of as-received mirror paint.

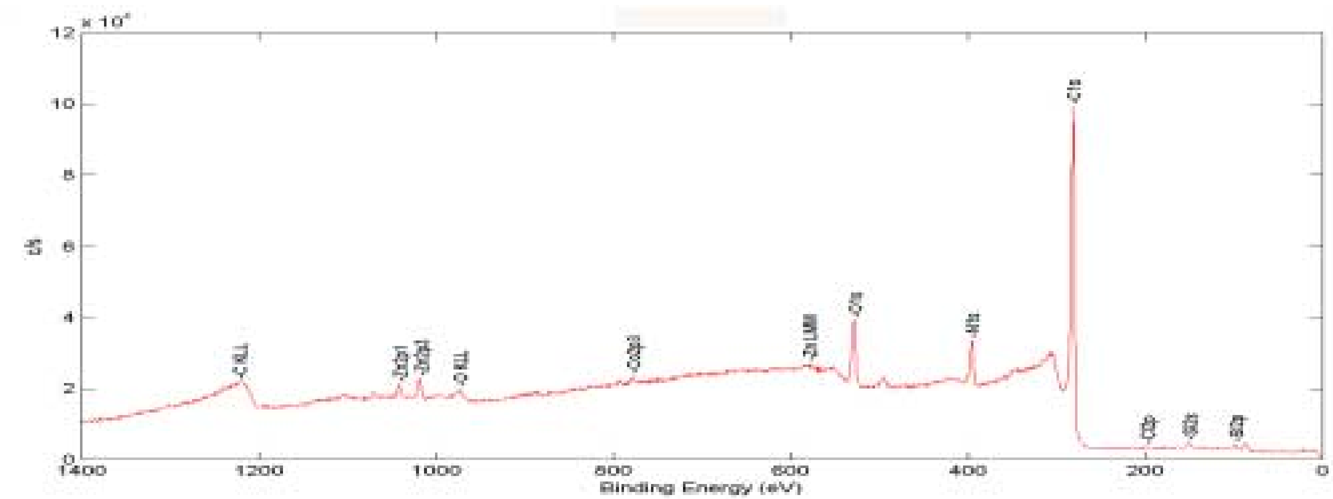

Figure 14. XPS survey of Ar^+ sputtered mirror paint.