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Hall Effect Thruster Plume Contamination and Erosion Study

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Abstract

The objective of the Hall effect thruster plume contamination and erosion study was to evaluate the impact of a xenon ion plume on various samples placed in the vicinity of a Hall effect thruster for a continuous 100 hour exposure. NASA Glenn Research Center was responsible for the pre- and post-test evaluation of three sample types placed around the thruster: solar cell cover glass, RTV silicone, and Kapton®. Mass and profilometry were used to identify the degree of deposition and/or erosion on the solar cell cover glass, RTV silicone, and Kapton® samples. Transmittance, reflectance, solar absorptance, and room temperature emittance were used to identify the degree of performance degradation of the solar cell cover glass samples alone. Auger spectroscopy was used to identify the chemical constituents found on the surface of the exposed solar cell cover glass samples. Chemical analysis indicated some boron nitride contamination on the samples, from boron nitride insulators used in the body of the thruster. However, erosion outweighed contamination. All samples exhibited some degree of erosion, with the most erosion occurring near the centerline of the plume and the least occurring at the ± 90° positions. For the solar cell cover glass samples, erosion progressed through the antireflective coating and into the microsheet glass itself. Erosion occurred in the solar cell cover glass, RTV silicone and Kapton® at different rates. All optical properties changed with the degree of erosion, with solar absorptance and room temperature emittance increasing with erosion. The transmittance of some samples decreased while the reflectance of some samples increased and others decreased. All results are consistent with an energetic plume of xenon ions serving as a source for erosion.

Introduction

A Hall effect thruster operates by accelerating xenon ions through an electrostatic potential. The thrust produced is useful for stationkeeping and orbit raising applications. Such systems are of interest to NASA and the commercial communications satellite industry. However, the impact of the xenon ion plume on spacecraft components in the vicinity of the Hall effect thruster must be understood. The objective of this study was to evaluate the impact of the xenon ion plume on various representative samples placed in the vicinity of a Hall effect thruster for a continuous 100 hours of operation in a test completed in September, 1999. This study was patterned after a previous Hall effect thruster contamination study.[1] Many features of the hardware used to hold samples in the previous study were utilized here. For example, the collimators used in this study to

diminish the contribution of contamination from the surrounding vacuum tank facility were similar to collimators used in the previous study. Placement of the samples around the Hall effect thruster was similar to the previous study. This study was conducted in conjunction with other performance and electromagnetic interference testing. Details of the performance and electromagnetic interference characterization may be found elsewhere.[2] However, it should be noted that the operation of the Hall effect thruster during this study represents a beginning of life operation, owing to the relatively few hours of operation placed on the thruster, at the time of this study.

The choice of samples and their location with respect to the thruster was provided by Space Systems/Loral. Of primary interest was solar cell cover glass. Other sample types included RTV silicone, Kapton®, and optical solar reflectors. NASA Glenn Research Center was responsible for the characterization of the solar cell cover glass, RTV silicone, and Kapton®, while Space Systems/Loral was responsible for the characterization of the optical solar reflectors. Mass and profilometry were used to identify the degree of deposition and/or erosion on the solar cell cover glass, RTV silicone, and Kapton® samples. Transmittance, reflectance, solar absorptance, and room temperature emittance were obtained on the solar cell cover glass samples alone. Auger spectroscopy was used to identify the chemical constituents found on the surface of the exposed solar cell cover glass samples.

This paper summarizes the results obtained from the pre- and post-exposure evaluation of the solar cell cover glass, RTV silicone, and Kapton® samples. Emphasis is placed on mass loss, profilometry, and changes in optical properties as a function of position around the thruster. Chemical analysis confirms the erosion mechanism responsible for the changes observed in mass, profilometry, and optical properties.

Materials and Methods

A large vacuum facility (approximately 8 meters in diameter and 21 meters long) was used for this study. The facility was recently upgraded to include twelve cryogenic pumps. The 4.5 kW Hall effect thruster, operated at 3 kW for this study, was placed approximately 1.2 meters below the centerline of the vacuum chamber, substantially away from any walls. Grafoil® flexible graphite was used to cover much of the wall area downstream of the thruster, and was also used to cover the mounting hardware needed to position and support the samples. Grafoil® flexible graphite was selected to provide this protection because of its low sputter yield.

Samples were placed one meter from the thruster. They were placed coplanar with the centerline of the plume, every 5°, from –90° to –30° and +30° to +90°, for a total of 26 positions. Sample placement is summarized in Table 1 and shown graphically in Figure 1. Samples in positions –90° to –50° and +50° to +90° were mounted in collimators, as shown in Figure 2. Samples in positions –45° to –30° and +30° to +45° were mounted in J-shaped brackets, as shown in Figure 3. Placement of samples at angles less than ± 30° was deemed unacceptable due to anticipated excessive erosion.

The collimators were equipped with molybdenum apertures and tantalum foil liners to keep material sputtered from the surroundings from depositing onto the samples. Aperture size and position was determined from a ray tracing analysis utilizing the diameter of the thruster, the size of the sample, and the distance between the thruster and sample.[1] Apertures located 5.72 and 15.24 cm in front of a sample were 2.69 and 3.83 cm in diameter, respectively. The manufacturing process for the collimators required vacuum brazing the molybdenum apertures to the collimators. A nickel braze was selected. The samples were held in place by tantalum foil. The tantalum foil around the perimeter of the sample also served as a mask to generate a step height for profilometry.

The solar cell cover glass samples, each 2 cm x 2 cm, were provided by Space Systems/Loral. The solar cell cover glass samples were microsheet glass, approximately 100 microns thick. One side of the microsheet glass was coated with a blue antireflective coating. It was this side that was exposed to the thruster plume. A second coating was applied to the opposite side. An orientation mark on each sample ensured that the blue antireflective coating side was facing the thruster.

The RTV silicone samples, on microsheet glass, were also provided by Space Systems/Loral. The RTV silicone samples were cut to size and held in place on their respective sample disks by tantalum foil. Again, the tantalum foil around the perimeter of the sample served as a mask to generate a step height for profilometry. Care was taken not to cut or gouge the RTV during assembly so as to not alter the mass. This was confirmed by mass measurements on one sample after completing the assembly process.

The Kapton® samples were also provided by Space Systems/Loral. Again, these samples were held in place by tantalum foil and the foil served as a mask to generate a step height for profilometry. Care was taken to dehydrate the Kapton® samples, under vacuum, prior to making any mass measurements.

Placement of the tantalum foil around the perimeter of each sample resulted in a unique exposure area for each sample. Hence, after each sample was installed on its respective sample disk, it was photographed, along with a calibration marker of known area, in order to identify the exact area of exposure, to approximately ± 2%. In this way, mass loss could be reported per unit area.

It should be noted that the tantalum foil mask was held in place by a combination of Torr Seal® epoxy and tantalum wire. For most of the samples, this assembly process worked well. However, for some of the solar cell cover glass samples, the Torr Seal® migrated to the edge of the glass causing a small part of the unexposed solar cell cover glass to break off upon de-integration, creating some concern over post-exposure mass measurements. There was no concern over post-exposure profilometry, optical measurements or chemical analysis as none of the exposed regions were affected. A photo documentation recovery effort was established to recover the lost mass information on these samples, by photographing the broken area, along with a calibration chip of known area, to obtain the missing area. The mass of the missing area was reinstated

mathematically using the as-measured areal density of the pristine solar cell cover glass. Selected samples were measured in triplicate, yielding an uncertainty less than ± 4%.

The collimators and J-shaped sample holders were affixed to a stainless steel bracket designed to surround the thruster in a semicircle. A laser was placed in the center of a spare collimator, the spare collimator was placed on each collimator bracket, and the laser beam was directed back to a point where the center of the thruster would be placed at the origin of the semicircle. Each collimator bracket was adjusted such that the laser illuminated the origin to within ± 1 mm. The J-shaped brackets were adjusted according to length only. All samples were set to a distance of 1 meter from the origin. Although most samples were tangential, it should be noted that some samples were placed in their collimator or J-shaped bracket at various angles of incidence, as indicated by Table 1.

Alignment with respect to the thruster was accomplished by placing the spare collimator containing the laser on aligned brackets at 0° and 90°. The laser light passed through the center of the thruster when placed in the 0° position and illuminated the edge of the thruster faceplate when placed in the 90° position.

Pre- and post-exposure evaluation was conducted according to the criteria set forth in Table 2. Mass was obtained before and after plume exposure to identify any deposit or erosion on the order of micrograms. Mass was obtained to the nearest ± 0.000001 g for the solar cell cover glass samples, and to the nearest ± 0.00001 g for the RTV and Kapton® samples.

Profilometry was used after plume exposure to identify contaminant thickness and/or erosion loss. Minimum thickness detected by this technique was on the order of 100 angstroms. The step height was measured at the edge of the exposed region, at the step established by the tantalum mask surrounding the sample. The step height on all samples was obtained with an estimated uncertainty of ± 2%.

Transmittance measurements were made on the solar cell cover glass samples to identify optical performance degradation as a result of plume exposure. Transmittance with respect to the air mass zero solar spectrum was obtained to the nearest ± 0.002 before and after plume exposure using a Perkin-Elmer Lambda-19 spectrophotometer equipped with a 15 cm diameter integrating sphere.

Reflectance measurements were also made on the solar cell cover glass samples to identify optical performance degradation as a result of plume exposure. Reflectance with respect to the air mass zero solar spectrum was obtained to the nearest ± 0.002 before and after plume exposure using a Perkin-Elmer Lambda-19 spectrophotometer equipped with a 15 cm diameter integrating sphere.

Solar absorptance measurements made on the solar cell cover glass samples to identify optical performance degradation as a result of plume exposure were obtained by difference. By definition, the sum of absorptance, reflectance, and transmittance must equal 1. Solar absorptance was obtained to the nearest ± 0.004.

Room temperature emittance measurements were made on the solar cell cover glass samples to identify degradation as a result of plume exposure. Emittance was obtained before and after plume exposure using a Gier Dunkle DB-100 infrared reflectometer and by subtracting infrared reflectance from 1. Quintuplet measurements were obtained and the average was reported to the nearest ± 0.004.

The solar cell cover glass samples were submitted for Auger analysis to identify chemical makeup. The Auger analysis is sensitive at the atomic percent level and identifies elements present in the first 30 angstroms of the surface.

One sample of each type was kept as a laboratory control, for evaluating mass, optical properties, and chemical analysis, as appropriate.

Results and Discussion

In the following discussion, the results are presented as a function of position around the thruster. In each case, the data are presented from –90° to +90°, where 0° nominally represents the centerline of the plume. Note: data plotted at the –100° position are results from the laboratory control. The in-tank controls will be discussed separately. It should be noted that 0° represents the centerline of the plume in name only. The results suggests that the plume is either asymmetrical or directed slightly to the south side of the tank. The latter is more likely.

Contamination

There is one result to suggest a contamination mechanism. The chemical analysis by Auger spectroscopy shown in Figure 4 reveals the presence of boron and nitrogen at levels above the control at all positions surrounding the thruster. The amount varies from 2 to 8 atomic percent. The likely source for the boron and nitrogen is boron nitride, a material of construction used in the body of the thruster. Noticeably absent from the chemical analysis are the elements iron, nickel, chromium, molybdenum, and tantalum, elements that represent the stainless steel and other materials of construction in the vacuum facility that could have come from sputtering. This absence suggests that the design of the collimators worked to diminish contamination from the surroundings, as planned.

Selected samples were subjected to subsequent depth profiling, at a sputter rate of approximately 80 angstroms/minute. Chemical analysis by Auger spectroscopy during depth profiling revealed that, in every case, the boron and nitrogen were removed within the first minute of sputtering, further suggesting that the amount of boron nitride contaminant is small.

The balance of the chemical results, and all other analyses, indicate various degrees of erosion of the solar cell cover glass, RTV silicone, and Kapton® samples, with the degree of erosion dependent upon location in the thruster plume.

Erosion

Figure 5 summarizes the atomic percent of sodium, potassium, and cerium, elements that could be constituents of the microsheet glass used to make the solar cell cover glass. Ceric oxide is commonly used for decolorizing glass.[3] These elements are uniformly absent from the first 30 angstroms of the control, the –90° to –60° positions, and the +75° position. The percentage of all three elements increases between –60° and +75, suggesting erosion into the microsheet glass.

Figure 6 summarizes the atomic percent of zirconium and silicon, elements that could be constituents of an antireflective coating on the solar cell cover glass. They are probably in their oxidized form, zirconia and silica. Zirconia is the outermost layer. When plotted together, it is interesting to note that as the zirconium decreases, the silicon increases. This cycle repeats three times suggesting that the antireflective coating is composed of at least three alternating layers of zirconia and silica, with the final increase in silicon representing the glass itself. Some erosion must be occurring in the –90° to –60° range, as well as the –60° to –30° range mentioned above, in order for the alternating layers to be seen. The same must be true on the opposite side of the plume. The degree of erosion increases for samples closer to the centerline of the plume.

Figure 7 summarizes the atomic percent of carbon and oxygen, the remaining elements found on the surface. Carbon is ubiquitous on samples exposed to the atmosphere. The oxygen is probably in the form of oxides. One solar cell cover glass sample, at the –50° position, had a trace of aluminum.

Erosion as a function of position is also indicated by mass loss and profilometry. All samples exhibited some erosion. Mass loss per unit area was found for all samples, and is summarized in Figure 8. Profilometry results are summarized in Figure 9. It is in these figures that the plume offset to the south of the vacuum facility is best seen. Mass loss varies from negligible to 9.1 mg/cm^2. Step height as measured by profilometry varies from 300 angstroms to 379,000 angstroms. Clearly, most erosion occurs near the center of the plume. The shape of the mass loss per unit area curve and the step height curve are quite similar, suggesting that the two completely independent measurement methods are tracking the same bell-shaped trend. This is confirmed by the linear relationship shown in Figure 10, where mass loss per unit area for solar cell cover glass is plotted as a function of step height.

Table 3 summarizes the surface roughness of the three sample types as measured by profilometry, as a result of the 100 hour xenon ion exposure. The erosion of the solar cell cover glass is fairly uniform, leaving little surface roughness, while the erosion of the RTV silicone leaves a roughened surface. The Kapton® samples are intermediate.

The chemical and physical evidence for erosion is overwhelming. The optical data support this conclusion. One anomaly was found in the optical data. The solar cell cover glass sample located at +50° appeared hazy. Figure 1 shows the high angle of incidence for this particular sample and the degree to which this sample was exposed to potential contamination sources from outside of its collimator. One possibility is that erosion from the adjacent J-shaped sample holder yielded a small number of seed particles that initiated seed texturing of the solar cell cover glass surface. Regardless of source, the texture caused the results from the optical analysis to be anomalous. It should be noted that the results from the chemical and physical analysis of this sample were not anomalous, suggesting that the contribution of the seed particles was negligible. The balance of the optical analysis data support the evidence for erosion.

Figure 11 summarizes the total transmittance of the solar cell cover glass samples, as a function of position. Starting from –90°, the total transmittance gradually decreases until reaching a minimum value near –65°, then increases as the curve moves to the –30° value. A mirror image of this trend can be envisioned on the opposite side of the plume, by omitting the anomalous +50° reading. The plume offset to the south can also be seen. Figure 12 summarizes the total reflectance, as a function of position. Starting from –90°, the total reflectance gradually increases until reaching a maximum value near –65°, then decreases as the curve moves to the –30° value. Again, a mirror image of this trend can be envisioned on the opposite side of the plume. These trends in transmittance and reflectance suggest that as more of the antireflective coating is eroded away, the impact of the antireflective coating decreases, causing greater reflectance at the expense of transmittance. Once through to the microsheet glass substrate, reflectance and transmittance remain nearly constant.

The sum of transmittance, reflectance, and absorptance must equal 1. Hence, solar absorptance was obtained by difference. Figure 13 summarizes the solar absorptance of the solar cell cover glass samples, as a function of position. Changes in solar absorptance are on the order of a few percentage points and are consistent with the erosion of the antireflective coating, through to the underlying microsheet glass. A mirror image of this trend can be envisioned on the opposite side of the plume, by omitting the anomalous +50° reading.

Figure 14 summarizes the emittance of the solar cell cover glass samples, as a function of position. Like the solar absorptance, the changes in emittance are on the order of a few percentage points. The changes coincide with the erosion of the antireflective coating, through to the underlying microsheet glass, suggesting that the emittance is surprisingly dependent on the presence or absence of the antireflective coating.

To confirm the presence of the three or more alternating layers of zirconia and silica suggested by the initial chemical analysis by Auger spectroscopy, one spare solar cell cover glass sample was subjected to depth profiling. Depth profiling was allowed to proceed to a depth of approximately 10,000 angstroms. Eight layers of zirconia were

revealed by this process. Figure 15 is a photograph of the sputter etched crater, and reveals the alternating layers of zirconia and silica , by contrast.

All of the data present an overwhelming case for erosion of the solar cell cover glass, RTV silicone, and Kapton® samples. This information should be useful for calculating erosion yields for the various materials and estimating the durability of various components place in the vicinity of the thruster.

Conclusions

Three types of samples were exposed to a xenon ion plume during a 100 hour test of a Hall effect thruster. The three types of samples were: solar cell cover glass, RTV silicone, and Kapton®. The samples were placed around the thruster at a distance of one meter. Many of the samples were held in collimators, successfully preventing contamination from the walls of the vacuum facility. The solar cell cover glass samples were subjected to chemical analysis by Auger spectroscopy, mass loss and profilometry, and optical properties analysis. The RTV silicone and Kapton® samples were subjected to mass loss and profilometry alone.

The chemical constituents of the samples suggested some contamination by boron nitride. However, most of the chemical constituents indicated erosion of the samples, with the degree of erosion becoming greatest toward the centerline of the plume. The erosion progressed through an antireflective layer and into the underlying microsheet glass substrate. The chemical analysis data suggested that the centerline of the plume was directed slightly to the south side of the vacuum tank.

Mass loss per unit area was found for all samples, with the greatest mass loss occurring near the centerline of the plume. Again, the data suggested that the centerline of the plume was directed slightly to the south side of the vacuum tank. The profilometry data agreed quite nicely with the mass loss per unit area data. Erosion of the solar cell cover glass samples yielded a fairly uniform surface, more so than RTV silicone and Kapton®.

The optical properties of the solar cell cover glass varied with the degree of erosion. Reflectance increased as erosion progressed through the antireflective coating, at the expense of transmittance. Both solar absorptance and emittance increased on the order of a few percent.

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2. L. Mason, R. Jankovsky, T. Haag, and L. Pinero, "SPT-140 Hall Effect Thruster Testing at Glenn Research Center," Submitted to Air Force Research Laboratory, 1999.
3. *The Merck Index, Tenth Edition*, M. Windholz, Ed., Merck & Company, Rahway, NJ, pp 278, 1983.

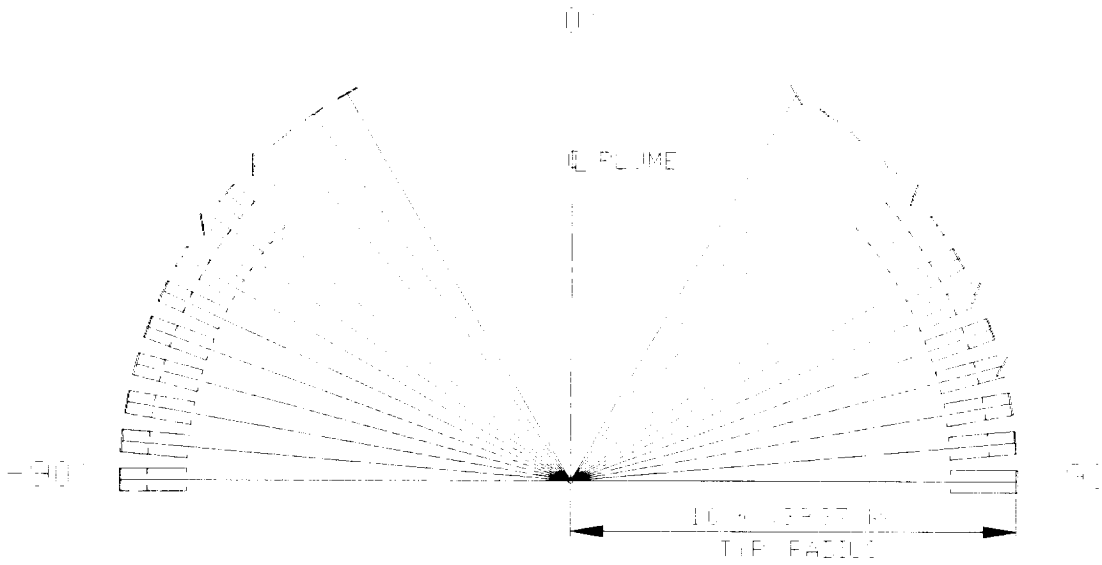

Figure 1. Schematic diagram showing the position of the collimators and samples with respect to the center line of the Hall thruster plume.

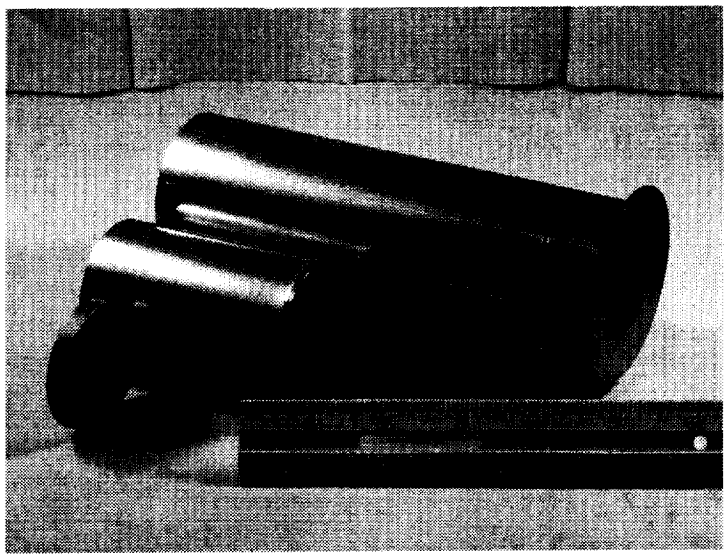

Figure 2. Photograph of one of the collimators used in the plume contamination and erosion study, exploded view.

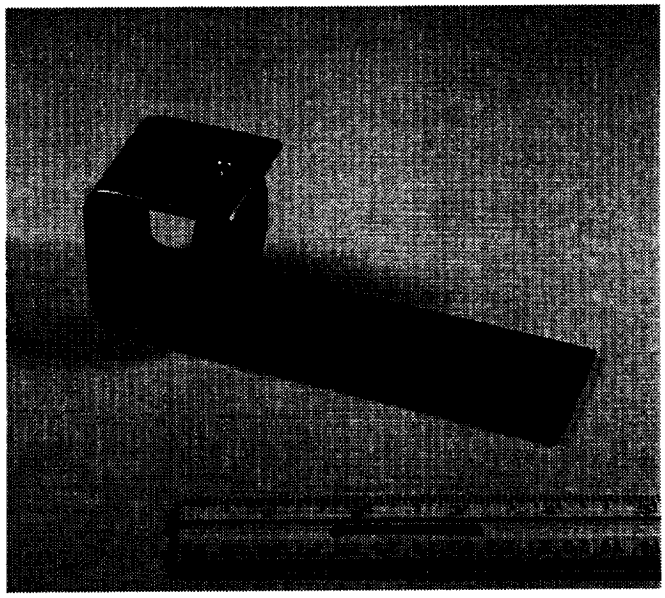

Figure 3. Photograph of one of the J-shaped sample holders used in the plume contamination and erosion study.

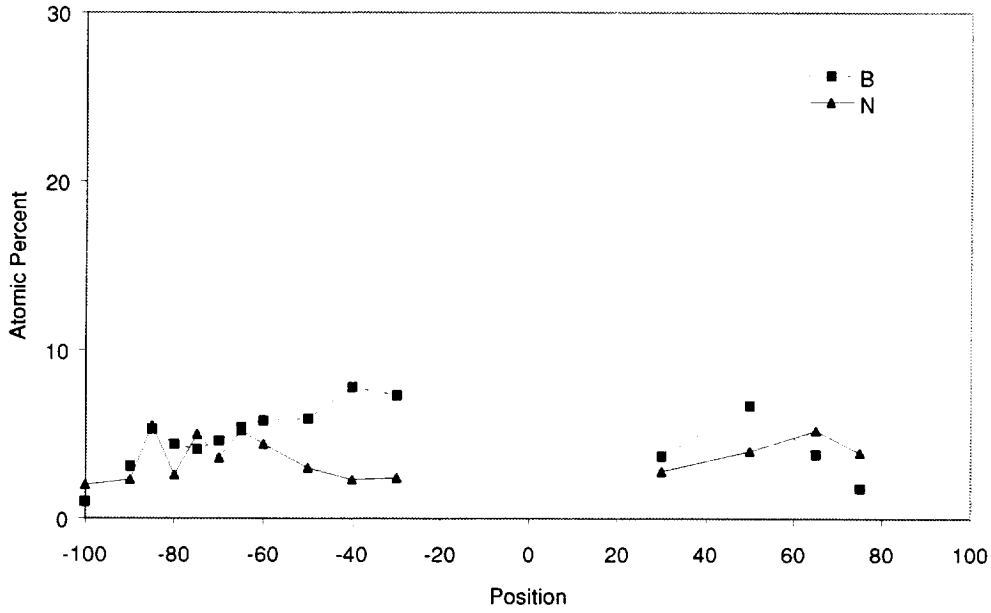

Figure 4. Boron and nitrogen, as a function of position.

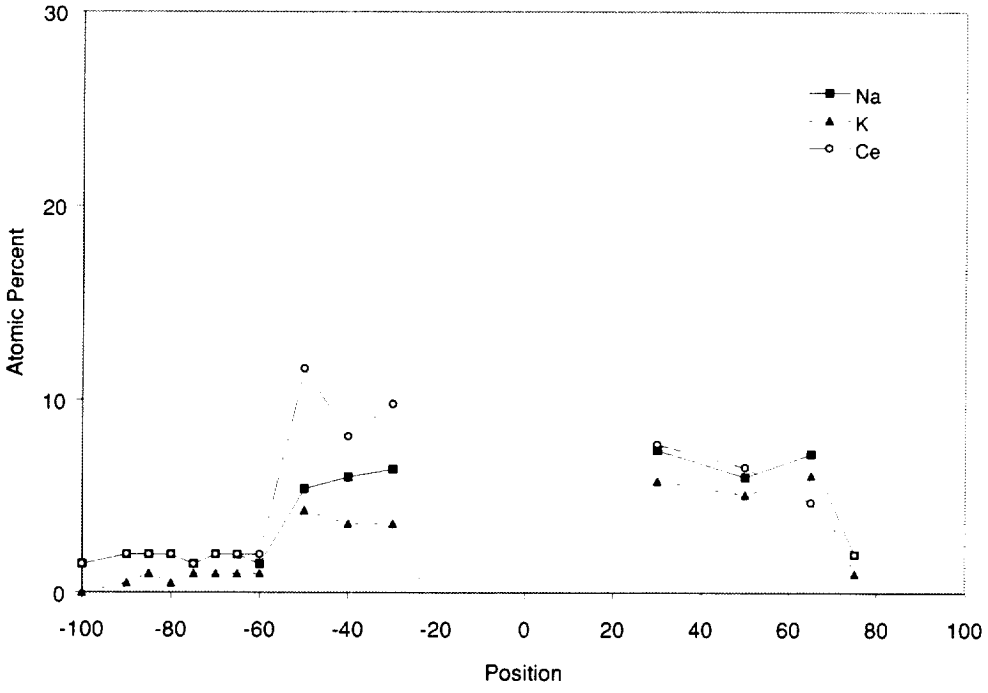

Figure 5. Sodium, potassium, and cerium, as a function of position.

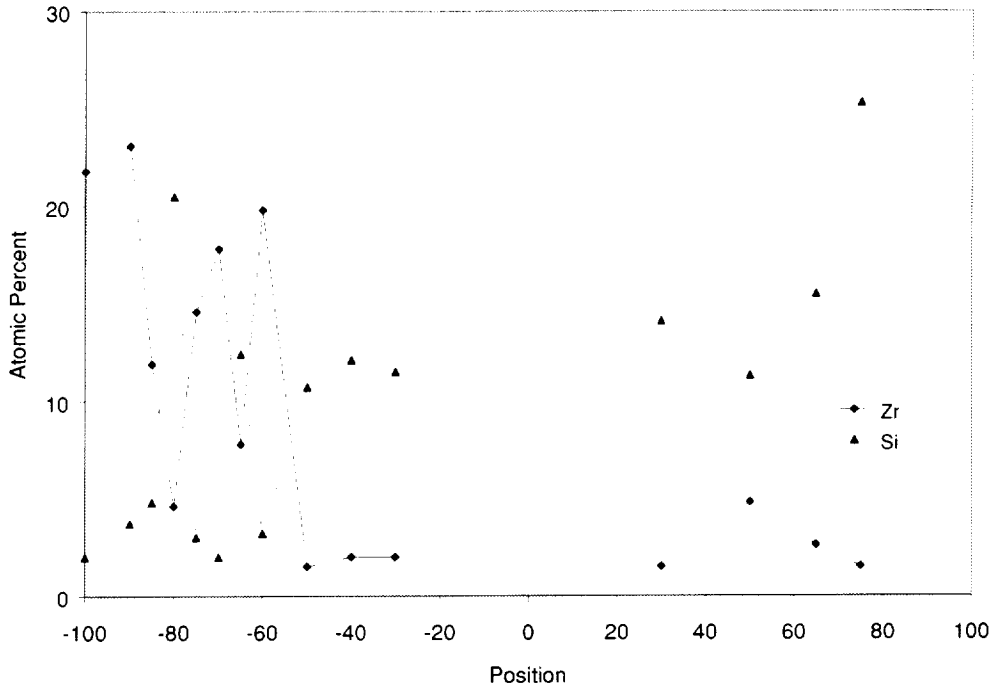

Figure 6. Zirconium and silicon, as a function of position.

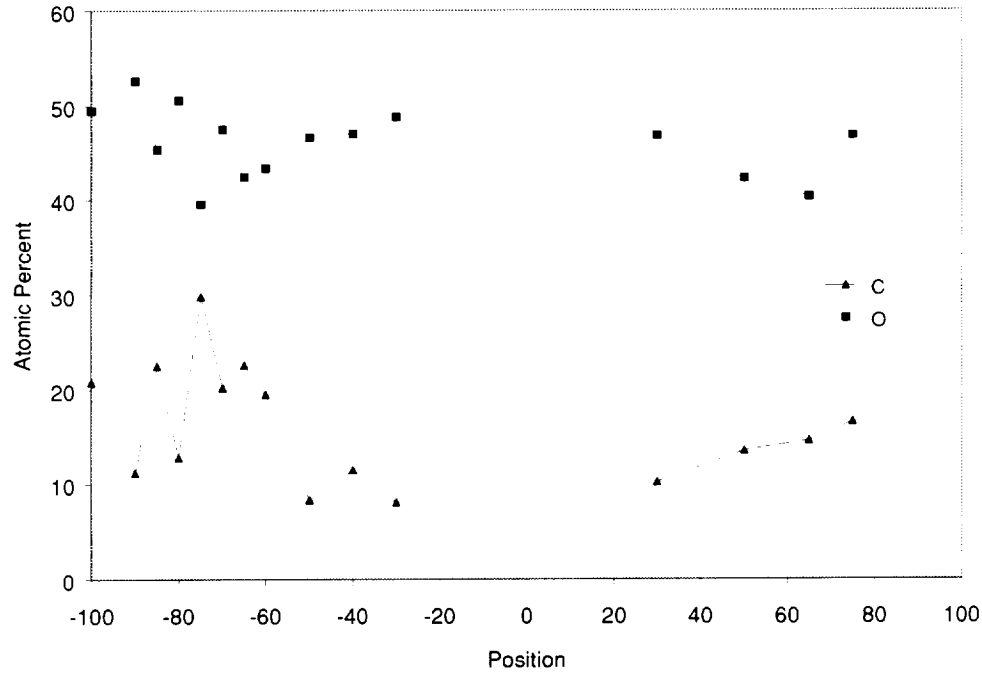

Figure 7. Carbon and oxygen, as a function of position.

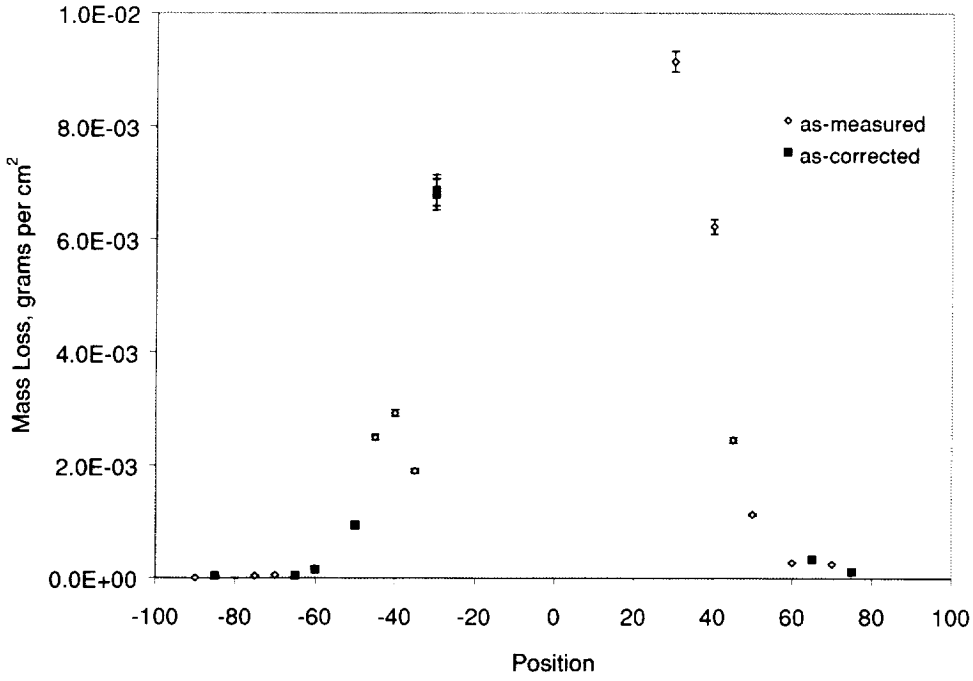

Figure 8. Mass loss per unit area, as a function of position.

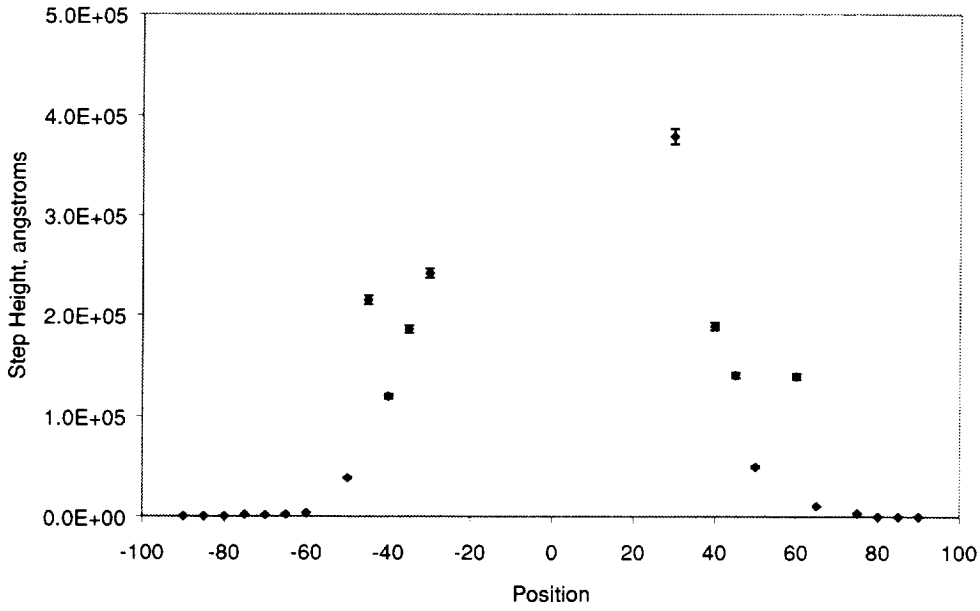

Figure 9. Step height, as a function of position.

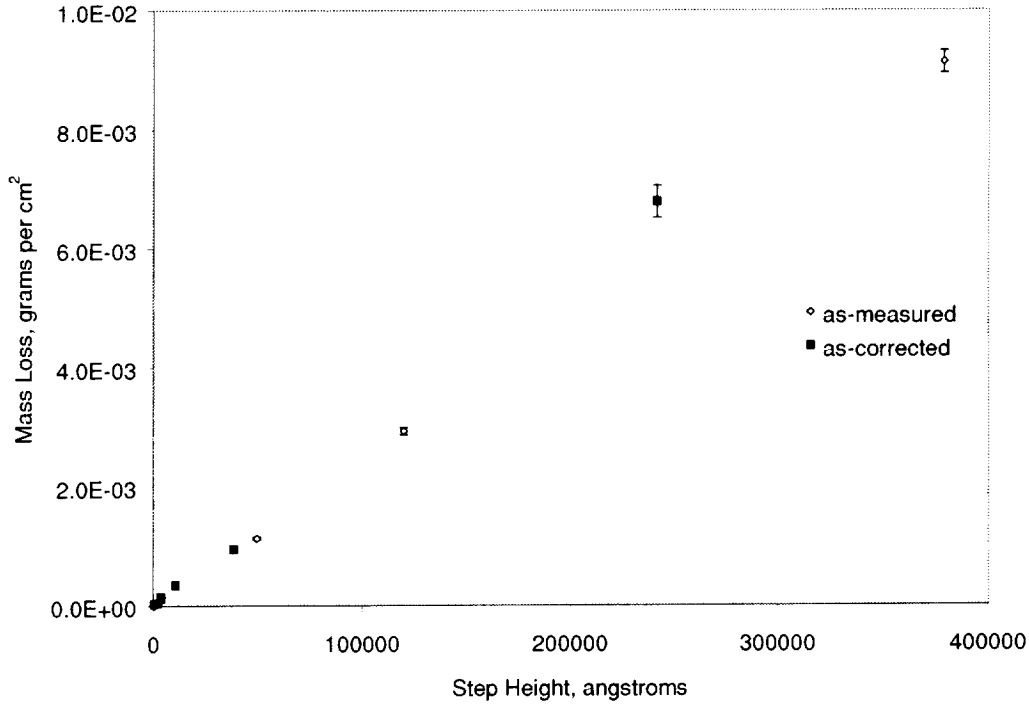

Figure 10. Mass loss per unit area versus step height for solar cell cover glass only.

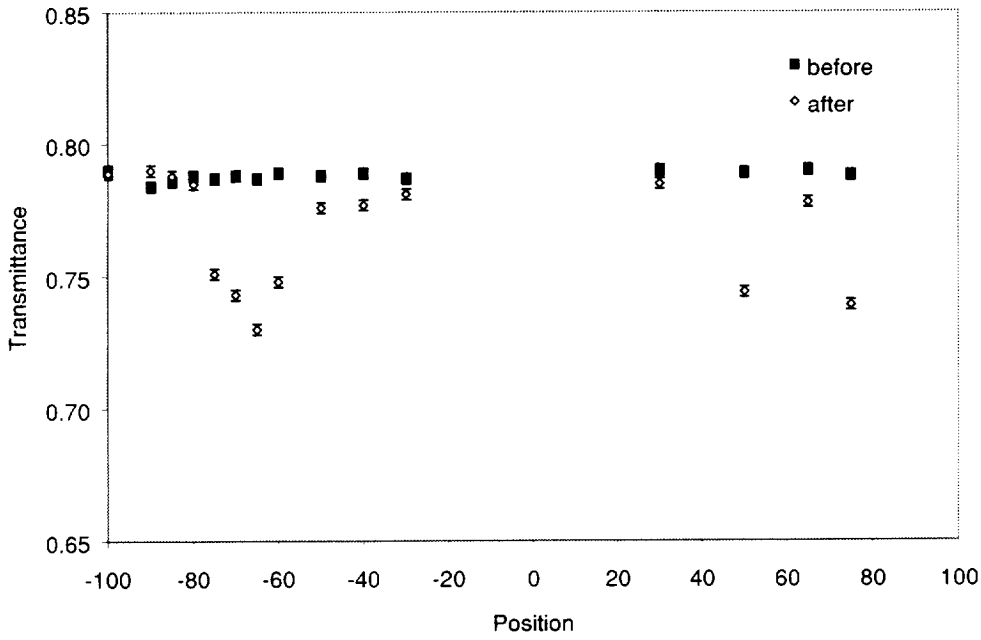

Figure 11. Total transmittance, as a function of position.

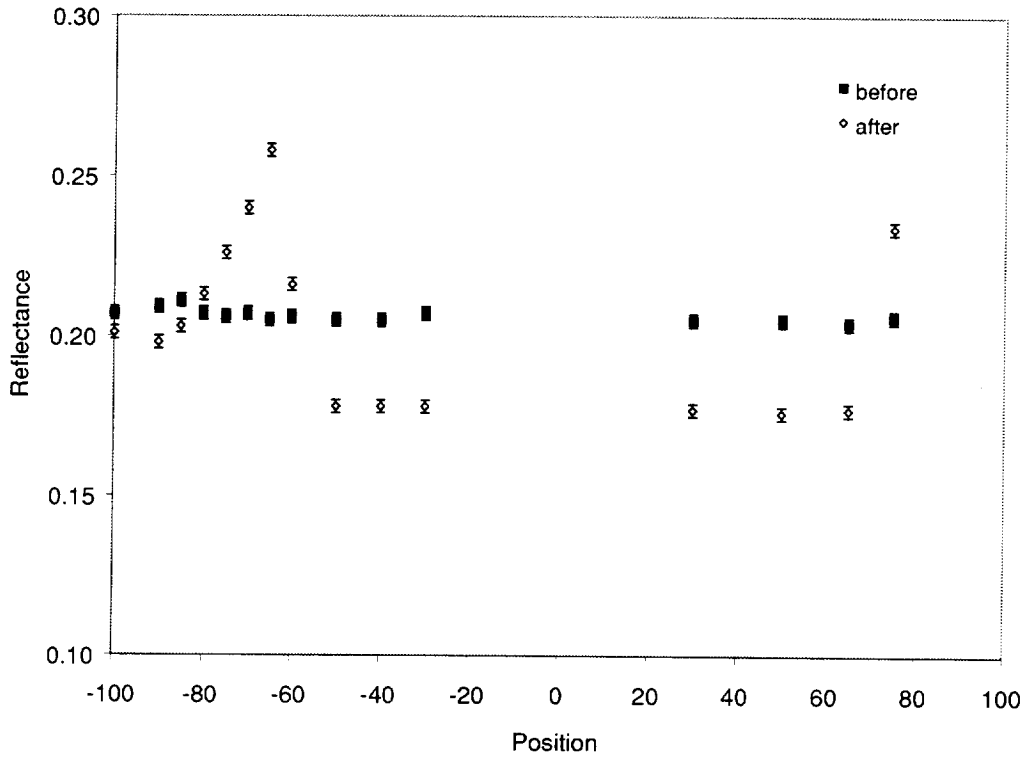

Figure 12. Total reflectance, as a function of position.

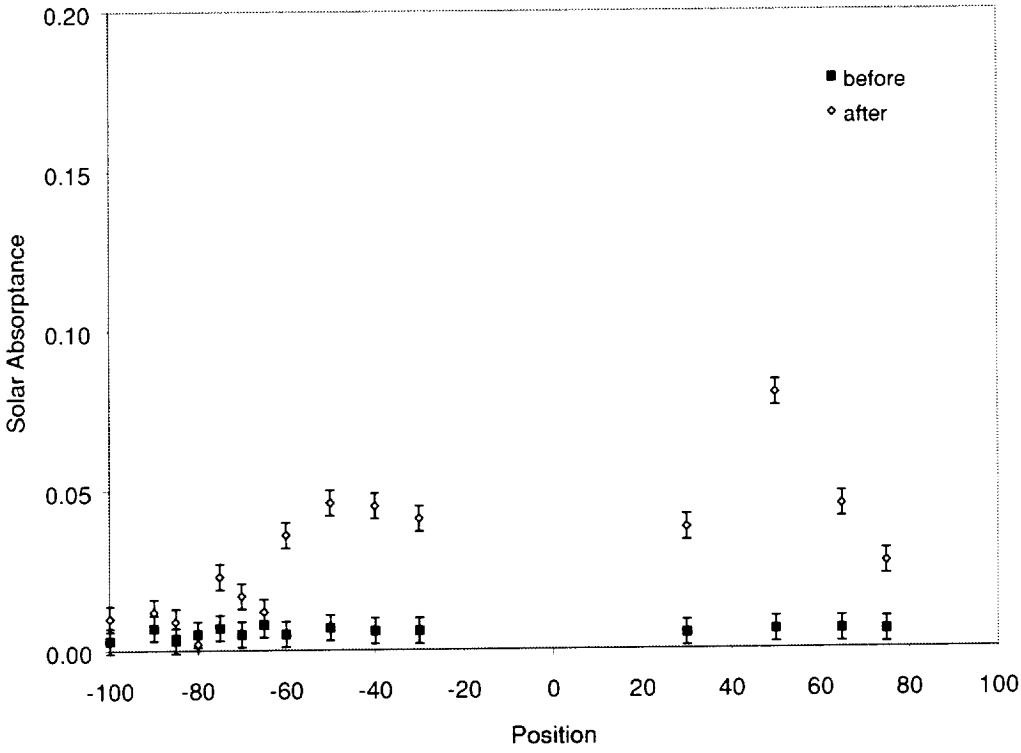

Figure 13. Solar absorptance, as a function of position.

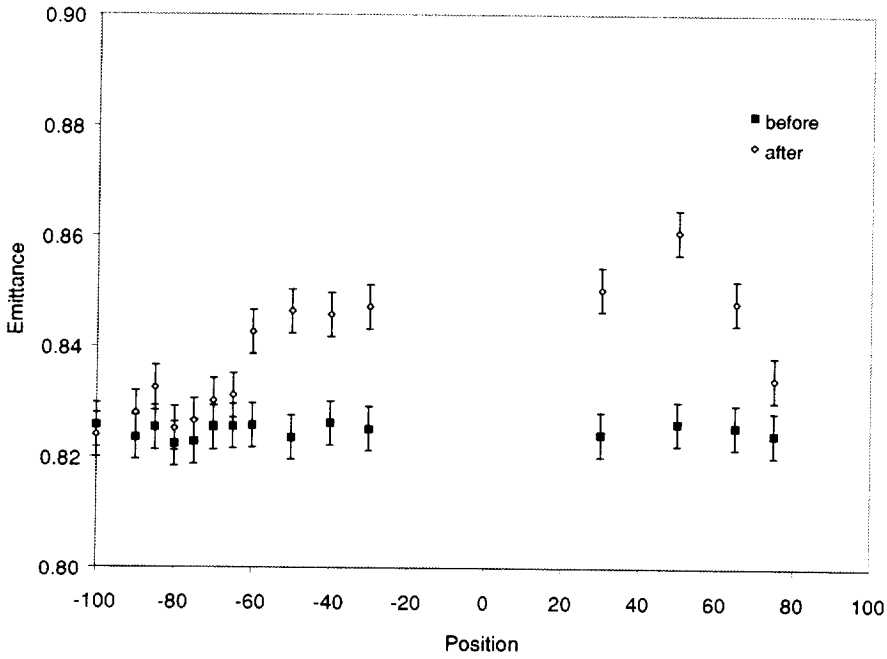

Figure 14. Emittance, as a function of position.

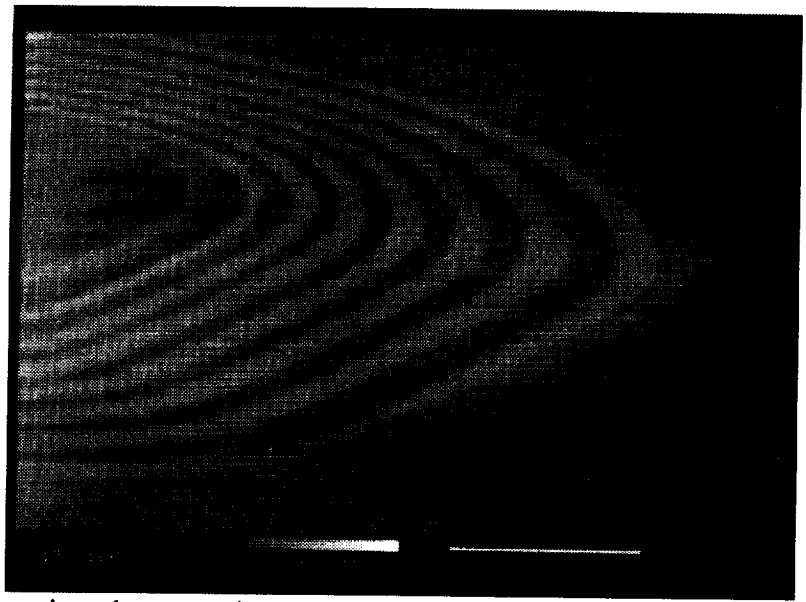

Figure 15. Scanning electron microscope photograph of alternating layers of zirconia and silica, after depth profiling.

Table 1. Sample placement with respect to the centerline of the plume (θ) and the angle of incidence (ϕ).

θ (deg)	ϕ (deg)	Solar Cell Cover Glass	Optical Solar Reflector	RTV Silicone	Kapton®
-90	0	X			
-85	0	X			
-80	0	X			
-75	0	X			
-70	0	X			
-65	0	X			
-60	0	X			
-55	45		X		
-50	0	X			
-45	45			X	
-40	0	X			
-35	0				X
-30	0	X			
30	30	X			
35	0		X		
40	0			X	
45	0			X	
50	60	X			
55	0		X		
60	0				X
65	45	X			
70	0			X	
75	45	X			
80	0		X		
85	0		X		
90	0		X		

Table 2. Measurement criteria for Solar Cell Cover Glass, RTV Silicone, and Kapton® samples.

Test	Solar Cell Cover Glass	RTV Silicone	Kapton®
Mass	X	X	X
Profilometry	X	X	X
Transmittance	X		
Reflectance	X		
Solar Absorptance	X		
Emittance	X		
Auger Chemical Analysis	X		

Table 2. Measurement criteria for Solar Cell Cover Glass, RTV Silicone, and Kapton® samples.

Test	Solar Cell Cover Glass	RTV Silicone	Kapton®
Mass	X	X	X
Profilometry	X	X	X
Transmittance	X		
Reflectance	X		
Solar Absorptance	X		
Emittance	X		
Auger Chemical Analysis	X		

Table 3. Average surface roughness of each sample type after exposure, as measured by profilometry.

Sample Type:	Roughness, angstroms
Solar Cell Cover Glass[1]	59
RTV Silicone	9945
Kapton®	1342
Anomalous Solar Cell Cover Glass Sample at +50°	1408

[1] Excluding anomalous sample at +50°

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13. ABSTRACT ***(Maximum 200 words)***

The objective of the Hall effect thruster plume contamination and erosion study was to evaluate the impact of a xenon ion plume on various samples placed in the vicinity of a Hall effect thruster for a continuous 100 hour exposure. NASA Glenn Research Center was responsible for the pre- and post-test evaluation of three sample types placed around the thruster: solar cell cover glass, RTV silicone, and Kapton®. Mass and profilometry were used to identify the degree of deposition and/or erosion on the solar cell cover glass, RTV silicone, and Kapton® samples. Transmittance, reflectance, solar absorptance, and room temperature emittance were used to identify the degree of performance degradation of the solar cell cover glass samples alone. Auger spectroscopy was used to identify the chemical constituents found on the surface of the exposed solar cell cover glass samples. Chemical analysis indicated some boron nitride contamination on the samples, from boron nitride insulators used in the body of the thruster. However, erosion outweighed contamination. All samples exhibited some degree of erosion, with the most erosion occurring near the centerline of the plume and the least occurring at the ± 90° positions. For the solar cell cover glass samples, erosion progressed through the antireflective coating and into the microsheet glass itself. Erosion occurred in the solar cell cover glass, RTV silicone and Kapton® at different rates. All optical properties changed with the degree of erosion, with solar absorptance and room temperature emittance increasing with erosion. The transmittance of some samples decreased while the reflectance of some samples increased and others decreased. All results are consistent with an energetic plume of xenon ions serving as a source for erosion.

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