

MIR SOLAR ARRAY RETURN EXPERIMENT: POWER PERFORMANCE MEASUREMENTS & MOLECULAR CONTAMINATION ANALYSIS RESULTS

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ABSTRACT

A solar array segment was recently removed from the Mir core module and returned for ground-based analysis. The segment, which is similar to the ones the Russians have provided for the FGB and Service Modules, was microscopically examined and disassembled by US and Russian science teams. Laboratory analyses have shown the segment to be heavily contaminated by an organic silicone coating, which was converted to an organic silicate film by reactions with atomic oxygen within the orbital flight environment. The source of the contaminant was a silicone polymer used by the Russians as an adhesive and bonding agent during segment construction. During its life cycle, the array experienced a reduction in power performance from ~12%, when it was new and first deployed, to ~5%, when it was taken out of service. However, current-voltage measurements of three contaminated cells and three pristine, Russian standard cells have shown that very little degradation in solar array performance was due to the silicate contaminants on the solar cell surfaces. The primary sources of performance degradation is attributed to "thermal hot-spotting" or electrical arcing; orbital debris and micrometeoroid impacts; and possibly to the degradation of the solar cells and interconnects caused by radiation damage from high-energy protons and electrons.

INTRODUCTION

During November 1997, one of four segments was removed from the non-articulating PV (Photo Voltaic) array on the Mir core module by suited Russian cosmonauts. This segment, which had been exposed to the orbital space environment for a period of over ten years, was very similar in its design and

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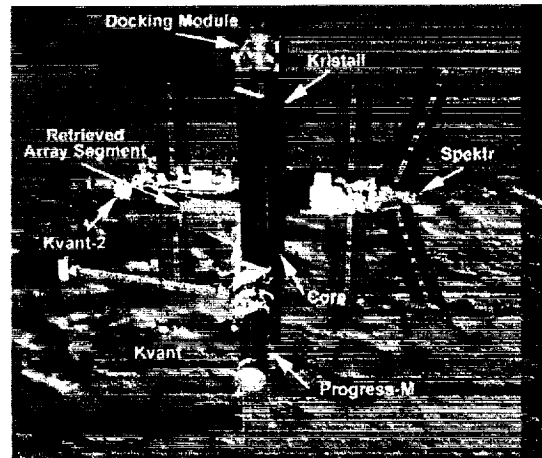


Figure 1. Photograph of Mir Space Station taken during the STS-79 mission showing the location of the solar segment that was retrieved during STS-89.

construction to the ISS solar arrays that Russia is providing for the FGB Module and the Service Module.

The solar array segment was placed in a protective bag, sealed, and stowed within the Mir core module. During the STS-89 mission to the Mir Orbital Space Complex in January 1998, the solar array segment was removed from the Mir core module and stowed aboard the US Spacehab module for return to Earth where detailed laboratory studies of the effects of prolonged space exposure could be conducted. After the Orbiter returned to its processing facility at the Kennedy Space Center (KSC), the Spacehab module was removed and taken to the Spacehab Laboratory outside the Kennedy Space Complex for post-flight processing. The solar array segment was subsequently removed from the Spacehab module and placed in an adjacent clean room for visual and microscopic examinations. During these examinations, the intact segment underwent scientific inspections and preliminary tests by a joint team of US and Russian investigators. The US team consisted of scientists and engineers from NASA GRC, NASA LaRC, NASA MSFC, NASA JSC, Boeing, Motorola, Lockheed-Martin, and Allied Signal. The Russian team consisted of scientists and engineers from RSC-Energia.

The segment consisted of eight panels. One panel was removed by the Russian specialists and given to the US investigators for further inspection, study, and laboratory

analysis. The remaining seven panels were returned to RSC Energia for inspection, study, and power performance analysis by the Russian team.

MIR PV ARRAY LOCATION

The location of the non-articulating PV array on the Mir core module from which the Russian segment was removed is shown in Figure 1. This array is located directly above the Kvant-2 module and is extended outward from the Mir core module in a direction parallel to the "Sofora" truss on the Kvant-1 module. The returned segment (see Figure 1) was deployed during a Russian EVA on June 16, 1987. Following 125 months of exposure to the orbital space environment, the array was removed from the Mir core module by Russian cosmonauts on November 03, 1997.

MIR PV ARRAY & SOLAR CELL CONFIGURATION

The Russian solar array panels consist of series and parallel combinations of individual solar cells that are supported within an expandable scissor metal frame. For identification purposes, the foldable panels were labeled by the inspection team as Panels 1-8, with Panel 1 being the panel closest to the Mir core module's outer surface. Each of the eight panel contained 306 large silicon cells and 103 small silicon, yielding a total of 409 cells per panel. These cells are protected by a cover glass and an OSR (Optical Solar Reflector), which were each bonded to a layer of fabric mesh that was tightly woven and impregnated with adhesive. Altogether, three interior fabric layers and one exterior layer are used by the Russians to provide structural rigidity and improve the mechanical strength of the solar array assembly, both during launch and later during deployment on orbit.

As shown in Figure 2, the front side of the solar cell (item 1) is bonded to a layer of glass cloth, which is tightly woven and impregnated with a silicone

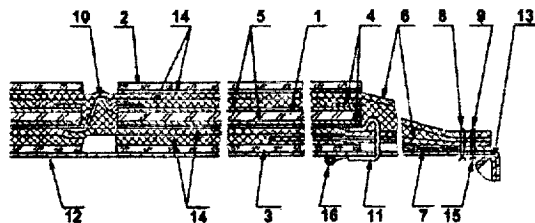


Figure 2. Fragment of the photoelectric part of Russian BSD 37KE Solar Array design.

adhesive. The glass cloth is, in turn, bonded to the backside of the cover glass (item 2) with this adhesive. The rear side of the solar cell is bonded to second layer of glass cloth, which is also tightly woven and impregnated with the same adhesive. The glass cloth is, in turn, bonded to the backside of the OSR (item 3) with the silicone adhesive. The purpose of the OSR is to reject heat from the solar cell attached to its surface and to minimize heat input from the backside of the solar panel when it is exposed to reflected or direct sunlight. A third layer of fabric mesh (item 7) extends beyond the outside perimeter of the array assembly. This last layer of tightly woven glass fabric, which is used to provide additional stiffness, is located between the second layer of glass cloth (item 6) and the OSR. This layer of reinforcement cloth is stretched and bonded to the solar panel outer support frame (item 13) with an organic silicone adhesive.

The polymer backside net cloth (item 12) consists of a large open-weave organic fabric that covers and protects the optical solar reflectors. This fabric, which is coated with a BF-4 organic adhesive (item 15), is physically attached to the solar array assembly with organic threads (items 8 and 9) between the cells that penetrate and tie all three interior fabric layers together to enhance their mechanical strength properties. The electrical wires (item 16) that connect the cells are located in gaps between the cells which are filled with an organic silicone potting compound. The polymer backside net cloth, which supports the array assembly during ground tests and deployment operations, is also stretched and bonded to the solar panel outer support frame (item 13) with the same organic silicone adhesive.

PRELIMINARY VISUAL EXAMINATIONS

A visual examination of the array during post-flight inspection revealed it was contaminated¹ by a diffusely reflecting, transparent white film that was deposited non-uniformly along the length of the panel on both the cover slides and the optical solar reflectors. The visual effects of these contaminants on the front- and back side of the array can be seen in Figures 3 & 4, respectively. Light rays that are diffusely scattered from deposits on the front side of the solar cells give rise to the white appearance of the surface film. As seen in Figure 3, when viewed obliquely, these deposits are observed as a series of white individual flashes along the vertical edges of the solar cells. The source(s) of this contaminant appears to have originated at vent locations where the reinforcement threads for the polymer backside netting penetrated the silicone potting material between the cells. Optical microscopy studies verified that the predominant source of the diffusely reflecting silica contaminant originated at these suture



Figure 3. Photograph of the front side of panels 1 & 2 showing the opaque white material that coated the edges of the Solar Array cover slides.

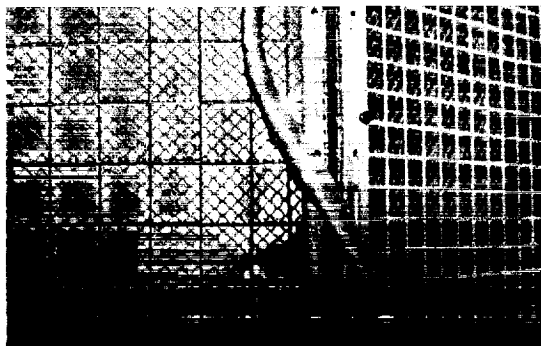


Figure 4. Photograph of the back side of the array showing the opaque white film that coated the Optical Solar Reflector.

penetration sites. The silicone contaminants were most likely oxidized² by arriving atomic oxygen in the LEO (low-Earth orbit) environment to produce the silicon oxide deposits on the front and back side of the solar cells.

As observed in Figure 4, the contaminant films that condensed on the backside of the array are optically diffuse and more concentrated near the edges of the OSR's (i.e., visually, these films appear less concentrated near the centers of the OSR's). The source of these contaminant films appear to be the organic silicone polymer that was used to seal the gaps between the solar cells and to attach the cover glass and OSR to the solar cell surfaces. Organic constituents that were outgassed from this sealant also formed heavy deposits on the large open-weave fabric that covered the OSR's. This net cloth and the OSR's are visible in the photograph of Figure 4. Figures 5 and 6 include high-resolution Scanning Electron Microscope (SEM) images of this fabric after it was

removed from the solar array panel. As indicated by these images, it was heavily coated with a brittle silicate crust. The individual fibers that comprise the fabric can easily be seen in Figure 6 through an opening in the silicate crust that has coated the surface of the net cloth.

The metal support frame and handrails were originally coated with a Russian, white, thermal-control paint. As a result of prolonged exposure to the Mir orbital space environment, this paint was highly degraded and had changed in color from a bright white, to various hues of light- and dark tan. Chemical analysis revealed the paint to contain zinc, oxygen, silicon, and carbon, and is probably Russian AK-573 paint, whose components consists of silicone and acrylic binders with a ZnO white pigment.

Silica contamination measurements made on the flexible handhold tape³ indicate a surface film thickness of 1.6 μm . EDS (Energy Dispersive Spectroscopy) analysis of the contaminant film showed it was almost completely

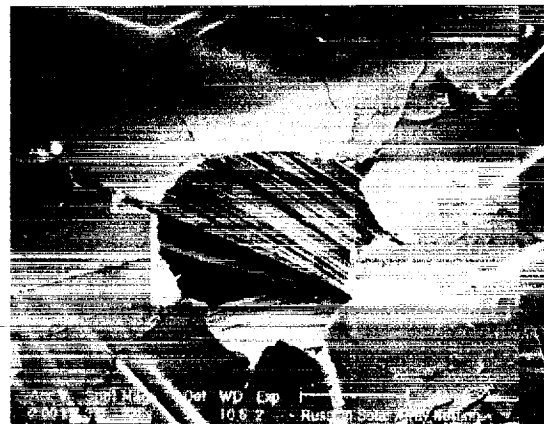


Figure 5. Scanning Electron Microscope image of silicate contaminate film on backside of net cloth.

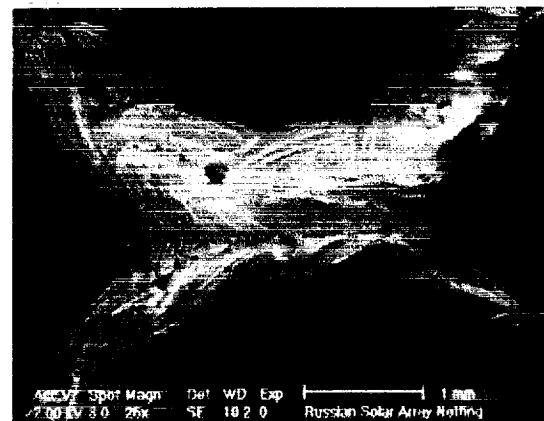


Figure 6. High-resolution SEM image of silicate contaminate film over organic fibers on backside of net cloth.

composed of silicon and oxygen with very little carbon present.

The non-uniform colorations of the handrail and power diode box are easily visible in Figures 7 and 8, respectively. The shadow pattern resulted from the protective grid cover (see Figure 5) that was mechanically attached to the backside of the panel and shielded areas of box from ultraviolet radiation and direct impingement of atomic oxygen. Previous studies² have identified similar shadowing phenomenon on LDEF surfaces where silicone contaminants were shadowed from atomic oxygen and UV exposure.

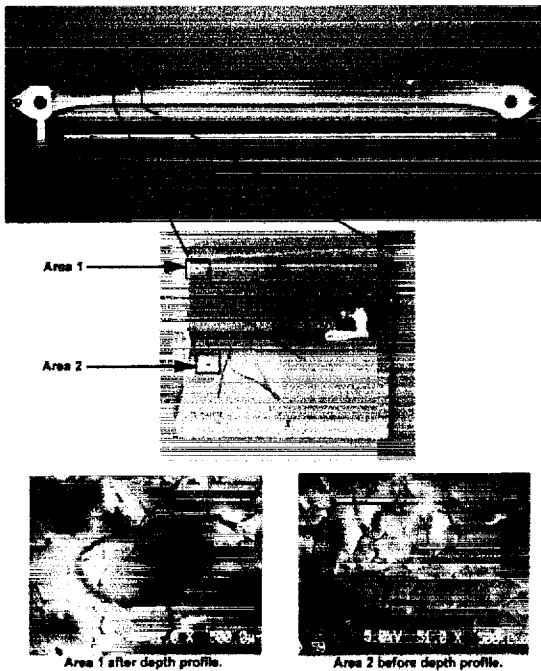


Figure 7. Mir Solar Array Handrail showing analysis areas and SEM images.

OPTICAL PROPERTY MEASUREMENTS

To evaluate the optical performance of the solar array components, solar absorptance measurements were obtained from the solar cells, handrail, diode box, and other structural components of the array using a laboratory spectrophotometer. The results of these measurements are summarized in Figures 9 and 10 for the handrail and a solar cell comprising the array, respectively.

The optical properties of the AK-573 paint degraded significantly during its exposure to silicone contamination, atomic oxygen, and UV radiation.



Figure 8. Over diode box cover on back of Solar Array showing shadowing pattern resulting from the overlying grid cover.

The solar absorptance of this coating (Figure 9) increased from an initial value of 0.294 when it was new, to a final value of 0.528 when the ground-based measurements were made. This change represents an increase of 80% over the 10-year period of orbital exposure.

The optical performance of the cover slides for the solar cells were, however, much less degraded than those of the AK-573 surfaces. Whereas the AK-573 white surfaces must be highly reflective when exposed to direct sunlight, the solar cells must be highly absorptive within the visible and near-infrared wavelength regions of the solar spectrum (0.35 μm to 1.0 μm) to efficiently convert solar energy into electrical power.

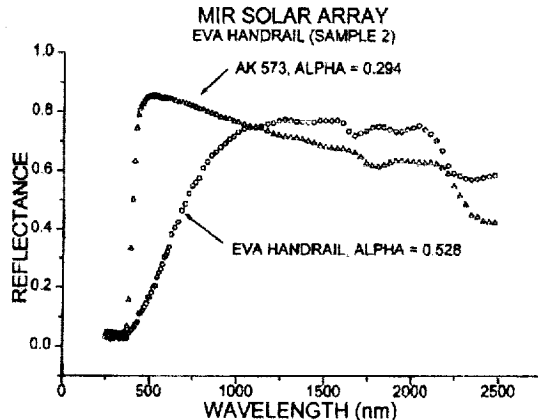


Figure 9. Spectrophotometer measurements of the Mir Solar Array Handrail.

The spectral response of a typical solar cell is shown in Figure 11 as a function of wavelength over the wavelength range 0.35 - 1.20 μm . Note from this Figure that the spectral response of a typical silicon solar cell begins at 0.35 μm and continues to increase linearly until it peaks at 1.00 μm . The cell response to solar radiation (sunlight) then falls off dramatically from 1.0 - 1.20 μm .

From the reflectance data given in Figure 10, it may be concluded that the optical transmittance (1.0 - optical reflectance) of the cover glass remained very

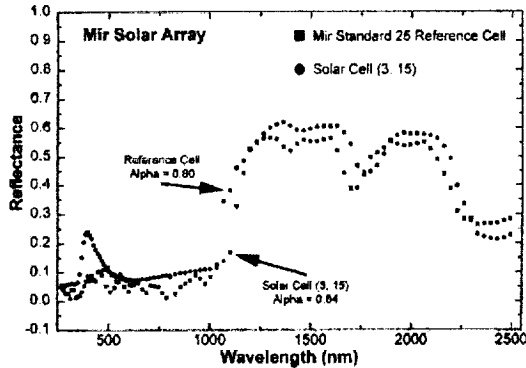


Figure 10. Spectroreflectometer measurements of a MIR photovoltaic cell.

close to 90% over the wavelength range 0.35 - 1.0 μm (350 - 1000 nm). These measurements also show the solar reflectance of the cell increases appreciably in the wavelength range 1.0 - 2.0 μm (1000 - 2000 nm), which is representative of the far "infrared" portion of the solar spectrum.

Thus, the silicate contaminant layers on the surface of the cover slides do not appear to have appreciably backscattered the incident solar radiation, which

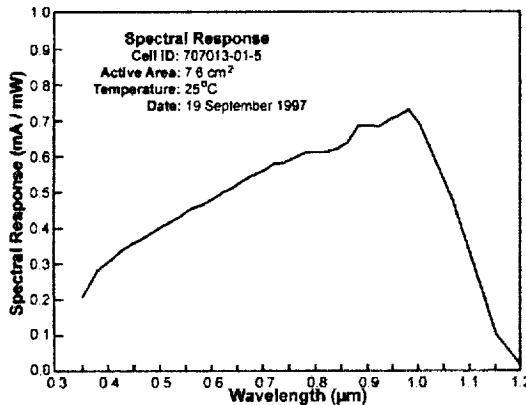


Figure 11. Spectral response of a typical solar cell.

would have degraded the optical performance of the solar cell. These measurements indicate these cells continue to absorb well in the visible and near infrared wavelength regions, and to reflect well within the far infrared region of the solar spectrum.

MOLECULAR CONTAMINATION MEASUREMENTS

Measurements were made of the composition and thickness of the contaminant film on the active side of

the cover slides. The thickness of this film varied from 0.2 - 5.0 μm ¹ across each surface, with thicker layers around the edges of the cell and thinner layers near the center of the cell.

The chemical composition and thickness of the contaminant film were analyzed⁴ using XPS (X-Ray Photoelectron Spectroscopy). A typical depth profile is shown in Figure 12, which shows a lack of carbon throughout the contaminant layer. Only oxygen (O), and silicon (Si) were detected by XPS below the immediate surface of the contaminant film. As indicated by the data in this Figure, these constituents are uniform in concentration throughout the film². The 65/35 concentrations of the oxygen and silicon constituents are indicative of SiO_x, an inorganic amorphous silicate.

The source of these contaminant films appears to be the organic silicone polymer that was used to seal the gaps between the solar cells and to attach the cover glass and OSR to the solar cells. An infrared transmission spectrum

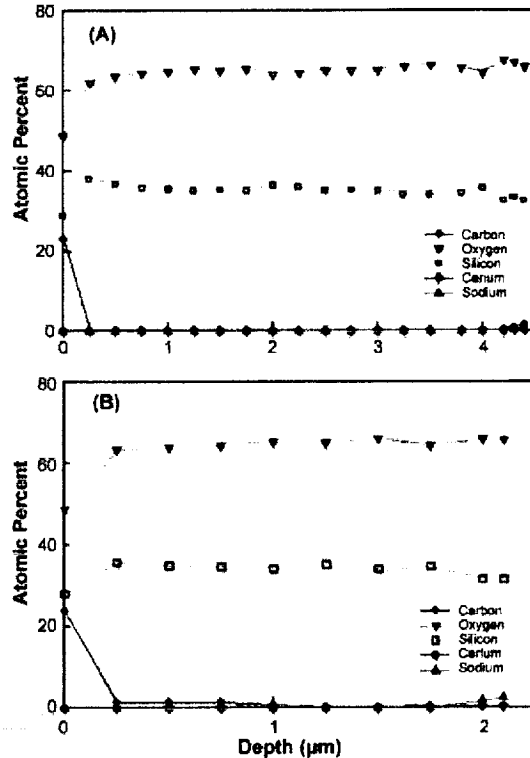


Figure 12. XPS depth profile of a contaminated edge of a Mir solar-cell cover slide. The interface between the contaminant layer and the cover slide is indicated by the presence of cerium and sodium in (A) at 4.2 μm , and in (B) at 2.1 μm .

¹ The ISS contamination control requirement is 0.13 μm (1300 Å) for 10 years of on-orbit lifetime.

² The cover glass interface in this figure is indicated by the presence of cerium and sodium.

of this adhesive polymer is shown in Figure 13. The position and depth of the absorption bands in this spectrum indicate that this material is an organic methyl silicone.

Studies^{2,3} have shown that these types of silicones include varying amounts of volatile condensable constituents. The surface films produced by these

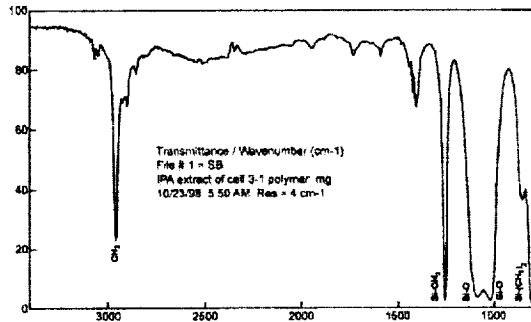


Figure 13. Infrared transmission spectrum of the solar cell silicon polymer adhesive.

constituents can easily be converted to an inorganic silicate by means of atomic oxygen attack in LEO, thus fixing the contaminant film to the surface and preventing its re-evaporation. This would explain the absence of carbon and the presence of the silicate coatings that formed on the front and back surfaces of the Mir solar cells, and on the handrail, hand holds, and backside netting during extended periods of atomic oxygen exposure.

POWER DEGRADATION MEASUREMENTS

The Russian PV panel that the US team retained for its investigations was sent to the NASA Glenn Research Center for visual examination, electrical continuity tests, and power performance measurements. During these evaluations, the orbital space performance of the PV panel and its solar cells were determined using a Spectrolab Large Area Pulsed Solar Simulator (LAPSS). The current-voltage (I-V) characteristics of the PV panel are summarized in Figure 14. From these tests, the overall power conversion efficiency of this panel was determined to be 4.8% at an operating temperature of 25° C. The Russian science team has estimated that the efficiency of the panel when it was new and first deployed was ~12 percent.

Recently, the US team received three pristine, unflown Mir standard solar cells from the Russian

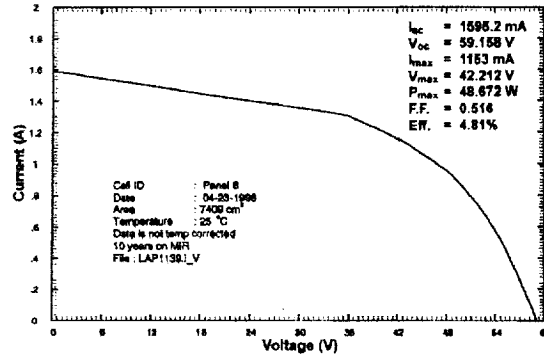


Figure 14. Current-voltage characteristics for Panel 8 of the Mir solar array.

team. These cells were of the same age, vintage, and design as the cells used for the Mir solar array segment. Three solar cells not damaged by micrometeoroid and orbital debris impacts or thermal degradation were carefully removed from the solar array panel and current-voltage and power efficiency measurements were obtained from all six specimen. Measurements were also obtained on the contaminated cells both with and without their cover glasses.

The current-voltage measurements for two Mir standard cells and one contaminated flight cell (Cell 8-7-19) with and without its cover glass are shown plotted against each other in Figure 15. As indicated by measurement values in this Figure and the values summarized in Table 1, the power conversion efficiencies of the cells with their cover slides removed (10.90%-11.41%) and with their cover slides intact (10.97%-11.11%) compare very favorably with the efficiencies (11.43%-11.80%) of the pristine, uncontaminated (unflown) Russian standard cells. It was determined from these measurements that the degradation in solar cell performance due to contamination (with film thicknesses varying from 0.2 - 5.0 μm) was negligible (~0.58% during an orbital exposure of 10 years).

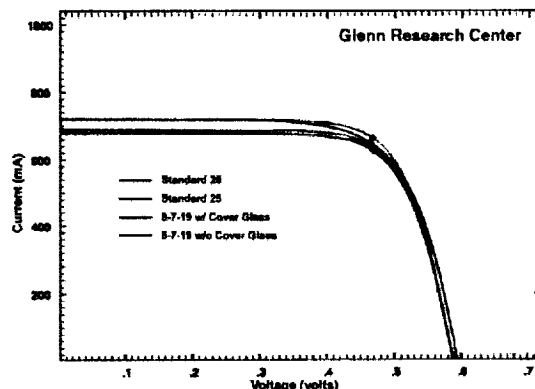


Figure 15. Current-voltage comparison of two Mir standard cells and a contaminated solar cell with and without its cover slide.

Table 1. Mir Solar Cell Test Configurations, Power Conversion Efficiencies, and Contaminant (Silicate) Layer Thickness.

Cell Identification	Cell Configuration	Power Efficiency (%)	Silicate Film Thickness (μm)
Mir Standard 25	Unflowed Silicon Solar Cell	11.43	--
Mir Standard 26	Unflowed Silicon Solar Cell	11.80	--
Mir Standard 27	Unflowed Silicon Solar Cell	11.64	--
8-07-19 (1)	Contaminated Cell, w/ Cover Glass	11.11	0.40-2.50
8-07-19 (2)	Contaminated Cell, w/o Cover Glass	11.41	--
8-09-18 (1)	Contaminated Cell, w/ Cover Glass	11.06	0.35-5.00
8-09-18 (2)	Contaminated Cell, w/o Cover Glass	11.09	--
8-10-12 (1)	Contaminated Cell, w/ Cover Glass	10.97	0.20-1.40
8-10-12 (2)	Contaminated Cell, w/o Cover Glass	10.90	--

STUDY RESULTS

This study by the US and Russian teams has provided a unique opportunity for the scientific community to analyze and characterize the effects of prolonged space exposure on operational spaceflight hardware. Laboratory analyses of a panel removed from a returned Mir solar array segment have shown the PV panel, during its operation aboard the Mir station, was heavily contaminated by an organic silicone coating which was converted to a heavy silicate film by reactions with atomic oxygen in the LEO environment.

The source of this coating was probably a silicone polymer that was used as an adhesive and bonding agent, and as a gap filler during array construction. During its exposure to the LEO environment, this polymer released volatile condensable contaminants that heavily coated the array handrail, hand holds, backside netting, and solar cell surfaces. Atomic oxygen and solar UV interactions with these contaminant films produced a significant increase (80%) in the solar absorptance of the AK-573 white thermal control paint applied to the handrail and power diode box.

During its use aboard the Mir station, the solar array panel examined by the US team experienced a reduction in power performance. Its power conversion efficiency degraded from ~12%, when it was new and first deployed, to ~5%, when it was removed from Mir and returned for laboratory analyses. This change represents a degradation in performance over the lifetime of the panel of 58%, or an average degradation rate of 5.8% per year. Of this 58% degradation in electrical performance, 5% is attributed to contamination.

A comparison of the current-voltage characteristics of three contaminated cells, both with and without their

cover slides, to the characteristics of three pristine, Russian standard cells, has shown there to be very little degradation in solar array performance due to the presence of the inorganic silicate contaminants on the solar cell surfaces. The principal sources of the remaining degradation (53%) in performance is attributed to either "thermal hot spotting" or electrical arcing, orbital debris and micrometeoroid impacts, and possibly to degradation of the solar cells and their interconnects by radiation damage from high-energy protons and electrons.

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