JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 39, No. 2, March–April 2002

Mir Solar-Array Return Experiment: Power Performance Measurements and Molecular Contamination Analysis Results

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In 1997 a solar-array segment was removed from the Space Station Mir core module and returned for ground-based analysis. The segment, which is similar to the ones the Russians have provided for the Functional Cargo Block and Service Module, was microscopically examined and disassembled by U.S. and Russian science teams. Laboratory analyses by the International Space Station program 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 caused by 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 nonarticulating photovoltaic (PV) array on the Space Station Mir core module by suited Russian cosmonauts. This segment, which had been exposed to the orbital space environment for a period of over 10 years, was very similar in its design and construction to the International Space Station (ISS) solar arrays that Russia is providing for the Functional Cargo Block (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 U.S. Spacehab module for return to Earth, where detailed laboratory studies of the effects of prolonged space exposure could be conducted. After the orbiter was returned to its processing facility at the Kennedy Space Center, the Spacehab module was removed and taken to the Spacehab Laboratory outside the Kennedy Space Complex for postflight 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 U.S. and Russian investigators. The U.S. team consisted of scientists and engineers from NASA John H. Glenn Research Center at Lewis Field, NASA Langley Research Center, NASA Marshall Space Flight Center, NASA Johnson Space Center, Boeing, Motorola, Lockheed Martin, and AlliedSignal. The Russian team consisted of scientists and engineers from Rocket-Space Corporation Energia (RSC Energia).

The segment consisted of eight panels. One panel was removed by the Russian specialists and given to the U.S. 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 nonarticulating PV array on the Mir core module from which the Russian segment was removed is shown in Fig. 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 Fig. 1) was deployed during a Russian extravehicular activity (EVA) on 16 June 1987. This particular segment, which has experienced prolonged (125 months) exposure to the orbital space environment, was later removed from the Mir core module by Russian cosmonauts on 3 November 1997.

Mir PV Array and 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. Array panels 1 and 8 each contain 306 large silicon cells and 103 small silicon cells for a total of 409 cells per panel. Panels 2–7 each contain 360 large silicon cells. These cells are protected by an cover glass cover and an optical solar reflector (OSR), which are each bonded to a layer of fabric mesh that is 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.

Presented as Paper 2001-0684 at the AIAA 39th Aerospace Sciences Meeting, Reno, NV, 8–11 January 2001; received 1 February 2001; revision received 10 October 2001; accepted for publication 2 November 2001.

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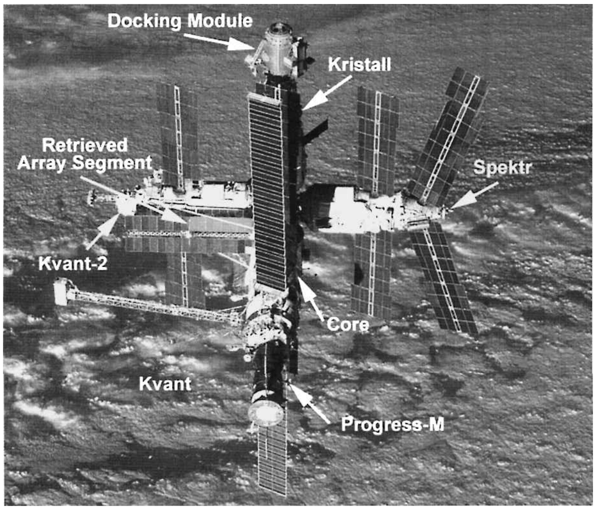

Fig. 1 Photograph of Space Station Mir taken During STS-79 mission showing location of solar-array segment retrieved during STS-89.

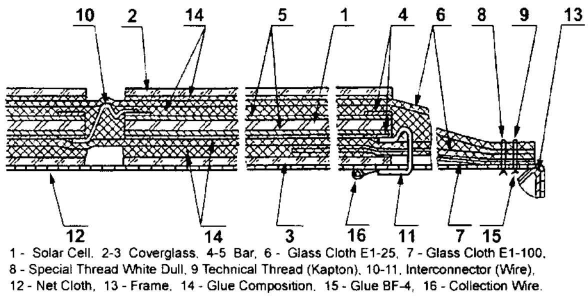

Fig. 2 Configuration and components of the Russian BSD 37KE solar-array design.

As shown in Fig. 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 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 polymer, is physically attached to the solar-array assembly with organic threads (items 8 and 9) between the cells, which penetrate and tie all three interior fabric layers together to enhance their mechanical strength properties. The BF-4 polymer, which is used to rigidify the fabric, is a mixture of poly(vinyl butyral) polymer resin, solvents, and phthalate plasticizers.

The electrical wires (item 16), which 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 stretched and bonded to the solar panel outer support frame (item 13) with an organic silicone adhesive.

Preliminary Visual Examinations

A visual examination of the array segment after it was returned by the space shuttle for postflight inspection revealed it

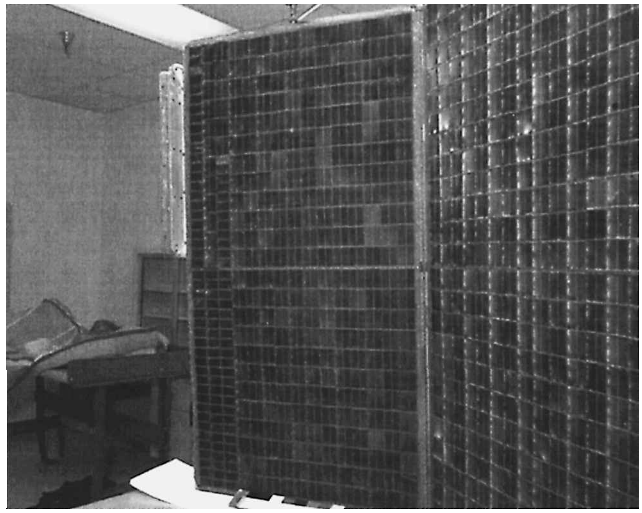

Fig. 3 Photograph of the front side of panels 1 and 2 showing the opaque, white silicate film that coated the surfaces of the solar-cell cover slides.

Fig. 4 Photograph of the backside of the array showing the opaque, white silicate film that coated the surfaces of the optical solar reflectors.

was contaminated[1] by a diffusely reflecting, transparent white film, which was deposited nonuniformly along the length of the panel on both the cover slides and the OSRs. The visual effects of these contaminant films on the front side and back side of the array are shown in Figs. 3 and 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 Fig. 3, when viewed obliquely, these deposits are observed as a series of white individual flashes along the vertical edges of the solar cells. The sources of this contaminant film appear 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 contaminant surface film originated at the suture penetration sites. The silicone contaminants produced by the potting material were most likely oxidized[2] by arriving atomic oxygen in the low Earth orbit (LEO) environment to produce silicon oxide deposits on the front and back side of the solar cells.

As observed in Fig. 4, the contaminant films, which condensed on the back side of the array, are optically diffuse and more concentrated near the edges of the OSRs. Visually, these films appear less concentrated near the centers of the OSRs. 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-cell surfaces. Organic constituents that were outgassed from this sealant also formed heavy deposits on the large open-weave fabric that covered the OSRs. This net cloth and the OSRs that it covered are each visible in the photograph of Fig. 4. Figures 5 and 6 include 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

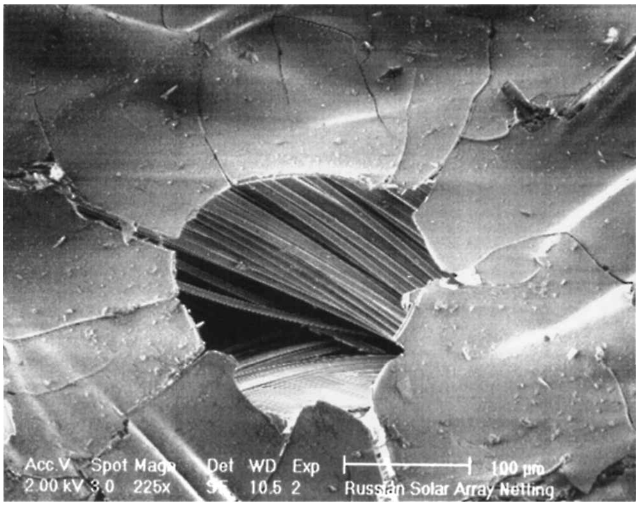

Fig. 5 SEM image of silicate contaminant film on backside of net cloth.

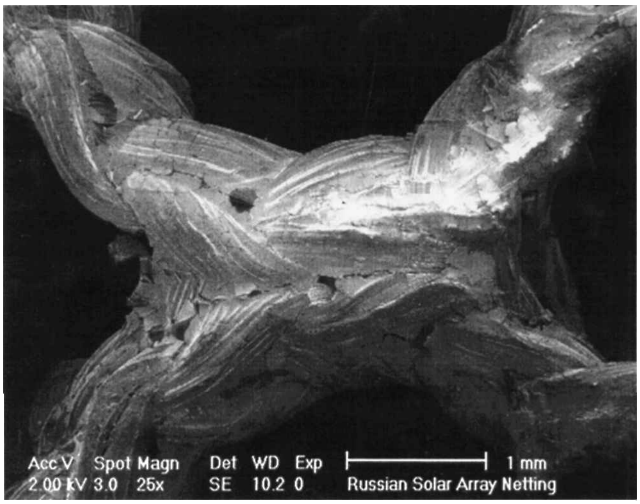

Fig. 6 SEM image of silicate contaminant film over organic fibers of the backside net cloth.

silicate crust. The individual fibers that comprise the fabric can easily be seen in Fig. 5 through an opening in the silicate crust, which has coated the surface of the net cloth.

The metal support frame and handrails for the array 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 in physical appearance, and its color had changed from a bright white to various hues of light and dark tan as a result of exposure to the same contaminant. An analysis of the chemical composition of this paint has revealed it contains the elements 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.[3]

Silica contamination measurements made on the flexible hand hold tape[4] indicate a surface film thickness of 1.6 μm. Energy dispersive spectroscopy was performed on the contaminant film, which indicated it was almost completely composed of silicon and oxygen with very little carbon present.

The nonuniform colorations of the previously white handrail and a power diode box cover are easily visible in Figs. 7 and 8, respectively. The shadow pattern on this cover was produced by the protective grid cover (see the section on the right in Fig. 4), which was mechanically attached to the backside of the panel. During LEO exposure, this cover shielded the white regions of the diode box from solar ultraviolet radiation and direct impingement of atomic oxygen atoms. Previous studies have identified similar clear areas on Long Duration Exposure Facility (LDEF) experiment surfaces in regions, where the arriving silicone contaminants were shadowed from atomic oxygen and solar UV exposure.

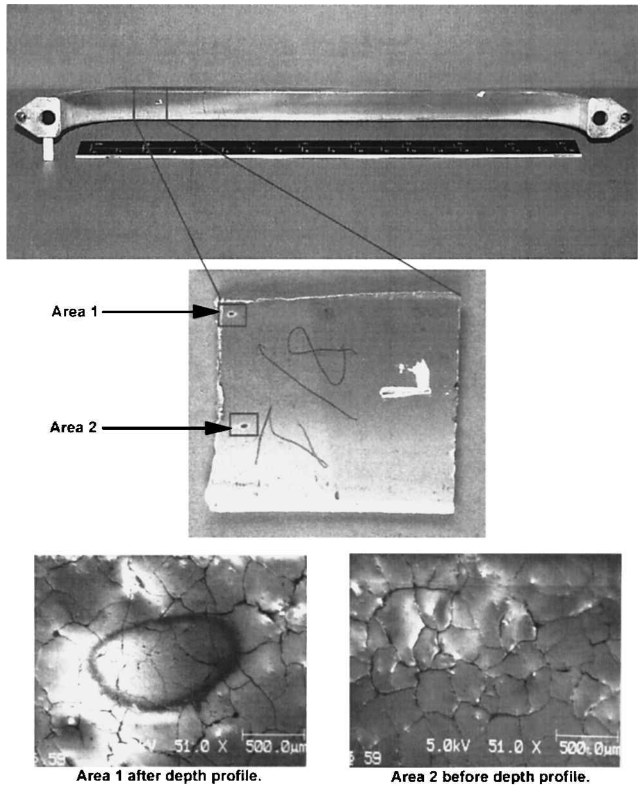

Fig. 7 Mir solar-array handrail showing analysis areas and SEM surface images.

Fig. 8 Power diode box cover on back of solar array showing shadow pattern produced by the protective grid cover.

Optical Property Measurements

To evaluate the optical performance of the solar-array components, solar absorptance measurements were obtained of the solar cells, handrail, diode box, and other structural components of the returned Russian solar array using a laboratory spectroreflectometer. The results of these measurements are summarized in Figs. 9 and 10 for the solar-array handrail and a typical silicon solar cell from the array, respectively. These figures represent the total hemispherical reflectance of the handrail and solar-cell surfaces plotted as a function of wavelength over the range 250–2500 nm.

The optical properties of the AK-573 paint used on the handrail and the power diode box cover degraded significantly during its exposure to silicone contamination, atomic oxygen, and solar UV radiation. The solar absorptance of this coating (Fig. 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 in solar absorptance of 80% during the 10-year period of orbital exposure.

The optical performance of the cover slides for the Russian solar cells were, however, much less degraded than those of the AK-573

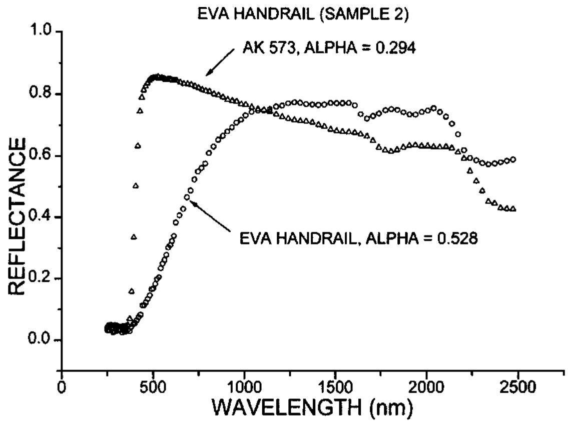

Fig. 9 Spectroreflectrometer measurements of the Mir solar-array handrail.

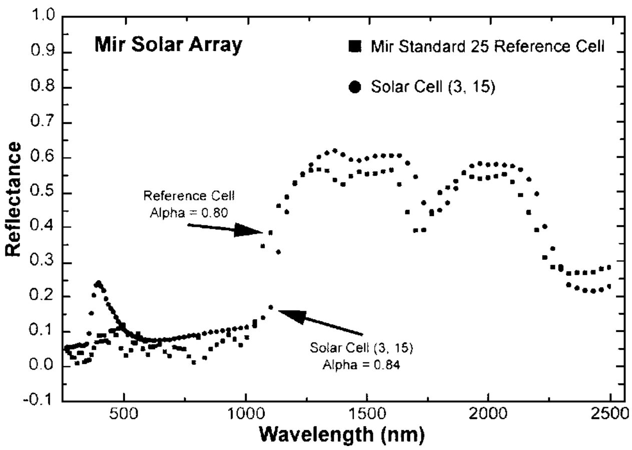

Fig. 10 Spectroreflectrometer measurements of standard (unflown) and contaminated Mir photovolatic solar cells.

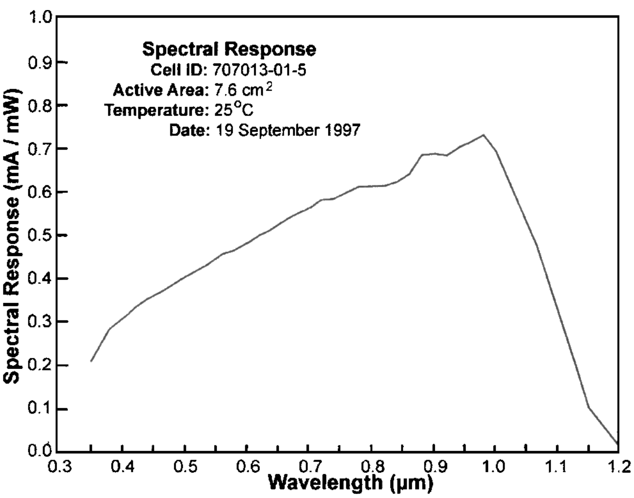

Fig. 11 Spectral response of a typical silicon solar cell.

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 (0.35–1.0 μm) to efficiently convert solar energy into electrical power.

The spectral response of a typical solar cell is shown in Fig. 11 as a function of wavelength over the wavelength range 0.35–1.20 μm. From Fig. 11 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 to 1.20 μm.

From the reflectance data given in Fig. 10, it can be concluded that the optical transmittance (1.0-optical reflectance) of the cover glass remained very close to 90% over the wavelength range 0.35–1.0 μm. These measurements also show the solar reflectance of the cell increases appreciably in the wavelength range 1.0–2.0 μm, which is representative of the near-infrared portion of the solar spectrum.

Thus, the silicate contaminant layers, which formed on the surface of the cover slides, do not appear to have appreciably backscattered the incident solar radiation, which 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 (space-exposed) side of the cover slides. The thickness of this film varied from 0.2 to 5.0 μm across each surface, with thicker layers around the edges of the cell and thinner layers near the center of the cell. The ISS contamination control requirement for sensitive surfaces from all molecular sources is 0.13 μm (1300 Å) for 10 years of on-orbit lifetime.

The chemical composition and thickness of the contaminant film were analyzed[5] using x-ray photoelectron spectroscopy (XPS). Composition chemistry and depth profiles of two different regions (edge and center) of a typical contaminated solar cell are shown in Figs. 12a and 12b. The interface between the contaminant film and the solar-cell cover slide is indicated by the presence of cerium and sodium at 4.2 and 2.1 μm in these figures, respectively.

The XPS depth profiles for the solar-cell cover slides reveal 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 film. The 65/35 concentrations of the oxygen and silicon constituents are indicative of SiO_x, an inorganic amorphous silicate.

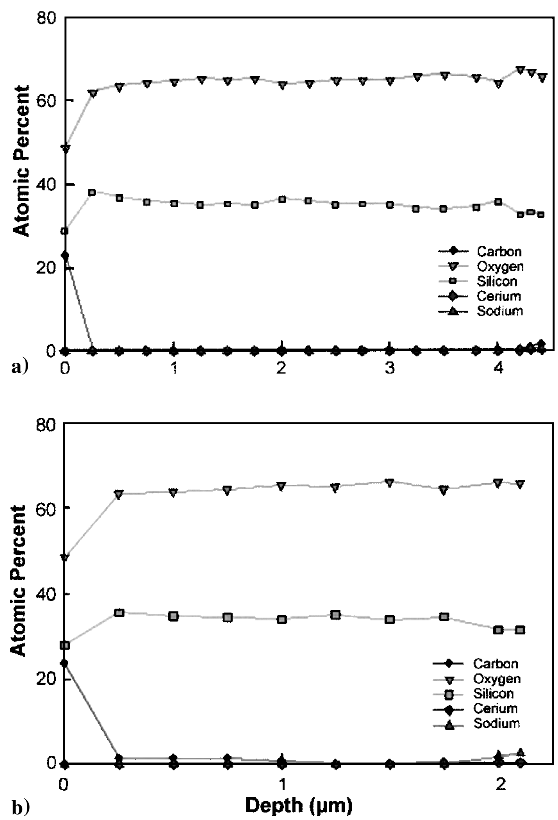

Fig. 12 XPS depth profile analysis of a contaminated edge and the center region of a Mir solar-cell cover slide.

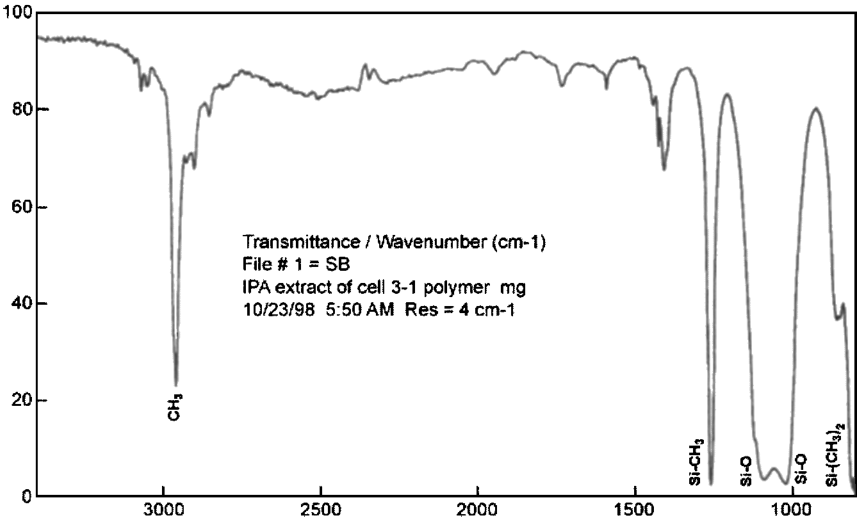

Fig. 13 Infrared transmission spectrum of the Mir solar-cell silicone polymer adhesive.

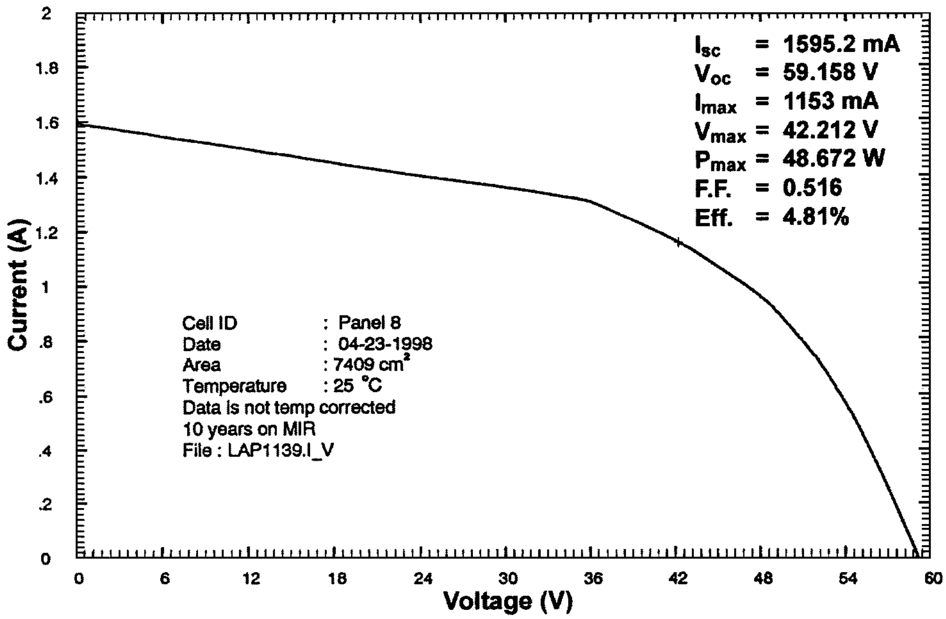

Fig. 14 Current-voltage characteristics for panel 8 of the returned Mir solar-array segment.

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

Studies[2–4] have shown that these types of silicones include varying amounts of volatile condensable constituents. The surface films produced by these 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 reevaporation. This exposure 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 U.S. 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. The current-voltage (I-V) characteristics of the PV panel are summarized in Fig. 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%.

Recently, the U.S. team received three pristine, unflown Mir standard solar cells from the Russian 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 then carefully removed from the solar-array panel, and current-voltage and power efficiency measurements were obtained from all six cells. 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 Fig. 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

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	Unflown silicon solar cell	11.43	——
Mir Standard 26	Unflown silicon solar cell	11.80	——
Mir Standard 27	Unflown silicon solar cell	11.64	——
8-07-19 (1)	Contaminated cell, with cover glass	11.11	0.40–2.50
8-07-19 (2)	Contaminated cell, without cover glass	11.41	——
8-09-18 (1)	Contaminated cell,with cover glass	11.06	0.35–5.00
8-09-18 (2)	Contaminated cell, without cover glass	11.09	——
8-10-12 (1)	Contaminated cell, with cover glass	10.97	0.20–1.40
8-10-12 (2)	Contaminated cell, without cover glass	10.90	——

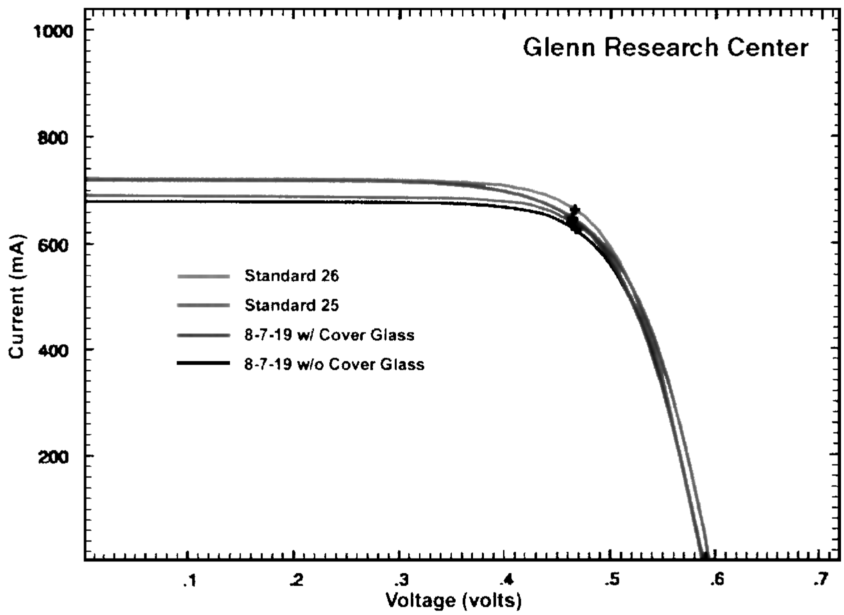

Fig. 15 Current-voltage comparisons of two Mir standard cells and a contaminated solar cell with and without its cover glass.

degradation in solar-cell performance as a result of contamination (with film thicknesses varying from 0.2 to 5.0 μm) was negligible (~0.58% during an orbital exposure of 10 years).

Conclusions

This study by the U.S. 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, which is very similar in design and construction to the ISS solar arrays that Russia is providing for the FGB Module and the Service Module, 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, which heavily coated the array handrail, hand holds, backside netting, and solar-cell surfaces. Atomic oxygen and solar violet–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 cover. For ISS mechanical hardware and electrical enclosures exposed directly to incident solar radiation, these kinds of increases would cause their surfaces to overheat and possibly fail or become too warm for a suited crewperson to grasp or touch with his or her pressurized gloves.

During its use aboard the Mir station, the solar-array panel examined by the U.S. 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% (0.58/12.0 = 4.8%) 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 have shown that very little degradation in solar-array performance was caused by the presence of the inorganic silicate contaminants on the solar-cell surfaces.

Acknowledgments

The authors wish to gratefully acknowledge the dedicated work, professional skills, and exceptional contributions of the following persons, without which these results and this report would not have been possible: Kim DeGroh, NASA Glenn Research Center, Molecular Contamination Analysis; Sharon Rutledge, NASA Glenn Research Center, Molecular Contamination Analysis; Thomas See, Lockheed Martin, MM/OD Impact Studies; James Zwiener, AZ Technology, Optical Property Measurements; Miria Finckenor, NASA Marshall Space Flight Center, Molecular Contamination Analysis; Rachel Kamenezky, NASA Marshall Space Flight Center, Molecular Contamination Analysis; Steve Hornung, Allied Signal, Molecular Contamination Analysis; Robert Pinkerton, Motorola, Power Degradation Studies; Alexander Markov, Rocket-Science Corporation "Energia," RSC-E Project Manager; Dmitriy Surin, Rocket-Science Corporation "Energia," Power Degradation Studies; Viktor Konoshenko, Rocket-Science Corporation "Energia," MM/OD Impact Studies; Artur Azarelov,

Rocket-Science Corporation "Energia," Molecular Contamination Analysis; and Stanislav Naumov, Rocket-Science Corporation "Energia," Molecular Contamination Analysis.

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