CHANGES IN OPTICAL AND THERMAL PROPERTIES
OF THE MISSE 2 PEACE POLYMERS AND SPACECRAFT SILICONES

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ABSTRACT

This paper documents optical and thermal properties of polymers and silicones from the Materials International Space Station Experiment 2 (MISSE 2) Polymer Erosion and Contamination Experiment (PEACE) Polymers experiment and from the MISSE 4 Spacecraft Silicones experiment. PEACE included forty-one polymer samples that were exposed to the low Earth orbit (LEO) environment on the exterior of the International Space Station (ISS) for almost four years. The Spacecraft Silicones experiment is comprised of eight DC 93-500® silicone samples manufactured by Dow Corning, four of which were flown as part of MISSE 2, and four of which were flown as part of MISSE 4. MISSE 4 was exposed to the space environment on the exterior of ISS for 1 year. Both the PEACE Polymers and the Spacecraft Silicone experiments were exposed to atomic oxygen (AO) along with solar and charged particle radiation while in LEO. The majority of the PEACE samples are comprised of numerous thin film layers stacked together. Because many of the PEACE polymers are commonly used for spacecraft applications, their optical and thermal properties are very important. DC 93-500® silicone is a popular spacecraft optical adhesive, often used for photovoltaic applications, hence changes in optical properties, particularly transmittance, due to LEO exposure is very important. Changes in optical and thermal properties due to LEO environmental exposure have been analyzed for all of the materials that could be measured. Due to the long duration space exposure, several of the MISSE 2 samples were too degraded for their properties to be measured. Total and diffuse reflectance, and total and diffuse transmittance, were measured as a function of wavelength and compared with non-exposed control samples. Specular reflectance and specular transmittance were then computed. Thermal emittance data was also generated for numerous samples. For most samples, specular and diffuse reflectance characteristics changed greatly upon directed LEO atomic oxygen exposure. Typically, there is a decrease in specular reflectance with an increase in diffuse reflectance. These optical property changes are relevant to glare issues, Fresnel lens photovoltaic concentrator power loss issues and issues with spatial variations in the thermal load on a spacecraft. The wavelength dependant data also allows computation of the change in solar absorptance (α_s) and thermal emittance, which is critical for predicting thermal control characteristics of a spacecraft. A summary of the MISSE 2 PEACE Polymers and Spacecraft Silicones experiments, the specific materials flown, optical and thermal property measurement procedures, and the optical and thermal property data are presented.

1. INTRODUCTION

Functional materials used on the exterior of spacecraft are subject to many environmental threats that can cause degradation in material properties which can potentially threaten spacecraft mission success. In LEO these threats include AO, photon radiation, charged particle radiation, temperature effects and thermal cycling, impacts from micrometeoroids and debris, and contamination. Atomic oxygen is the predominant gas species in LEO and is present in other planetary orbital environments. At spacecraft velocities, LEO AO is energetic enough (~4.5 eV) to cause bond breakage and subsequent oxidation. The oxidation products of most polymers are gas species, therefore material erosion occurs. Atomic oxygen can produce serious structural, thermal or optical degradation of spacecraft components. [1]

The Materials International Space Station Experiment (MISSE) missions consist of a series of flight experiment trays exposed for long durations to the LEO environment on the exterior of the International Space Station (ISS). Various materials, components and devices have been placed in the space environment to determine durability in space. These experiments have yielded very important materials knowledge for current and future spacecraft performance. Numerous MISSE experiment materials are analyzed in this paper to access the optical and thermal properties after long term LEO exposure. Unforeseen changes in either the optical properties or the thermal properties could have devastating effects to the spacecraft.

2. POLYMER EROSION AND CONTAMINATION EXPERIMENT (PEACE)

Forty-one different polymer samples, collectively called the Polymer Erosion and Contamination Experiment (PEACE) Polymers, have been exposed to the LEO space environment on the exterior of the ISS for nearly four years as part of Materials International Space Station Experiment 2 (MISSE 2). The purpose of the MISSE 2 PEACE Polymers experiment was to determine the AO erosion yield of a wide variety of polymeric materials exposed for an extended period of time to the LEO space environment. The polymers range from those commonly used for spacecraft applications, such as Teflon® FEP, to more recently developed polymers. Additional polymers were included to explore erosion yield dependence upon chemical composition to enable the development of an erosion yield predictive model. The majority of samples were comprised of thin film polymers, with numerous layers stacked together to last a minimum of three years in LEO. Figure 1 shows pre-flight, and Figure 2 shows post-flight photographs of the MISSE 2 PEACE Polymers experiment in sample tray E5. The MISSE 2 PEACE Polymers experiment is unique because it contains the widest variety of well-documented polymers exposed to identical long duration LEO AO conditions. [2] Table 1 lists the various polymers included in the PEACE polymers experiment. Several samples were vacuum heat-treated to reduce outgassing contamination prior to inclusion on the MISSE 2 experiment and are listed in detail by de Groh. [2]

Fig. 1. Photograph of MISSE 2 PEACE Polymer experiment tray before exposure

Fig. 2. Photograph of MISSE 2 PEACE Polymer experiment tray after exposure

Although MISSE 2 was supposed to be a 1.5-year mission, planning for a three-year mission exposure was crucial in the success of this experiment, as it was exposed to LEO AO for almost four years. The AO fluence for the experiment was determined to be 8.43 x 10^{21} atoms/cm^2 based on mass loss of the two polyimide Kapton H witness samples. Estimated environmental conditions of solar exposure, tray temperatures, and ionizing radiation doses on MISSE 2 are described in detail by Pippin. [3] The PEACE Polymers tray (E5) received approximately 6,300 Equivalent Sun Hours (ESH) of solar radiation. The base plate thermal cycling temperature range for MISSE 2 was nominally between +40 °C and -30 °C with occasional short-term excursions to more extreme temperatures. [3] The 3.95-year exposure duration in LEO resulted in approximately 22,800 thermal cycles. [3] The thermo-luminescent dosimeters (TLD) data indicated that MISSE 2 received approximately 26 krads (Si) through 0.005 cm aluminum. [3] Black light inspection of the trays showed minimal to no contamination on the MISSE surfaces. [3] Results of x-ray photoelectron spectroscopy (XPS) contamination analysis of two MISSE 2 sapphire witness samples in sample tray E6 (located next to tray E5) indicated an extremely thin silica contaminant layer (1.3 and 1.4 nm on each slide, respectively). [4] A small amount of fluorine was also detected. [4] The MISSE 2 environment was found to be an unusually clean environment with very low spacecraft induced molecular contamination. This is due to low outgassing of other MISSE 2 Tray 1 materials and also due to the position of MISSE 2 on ISS. Therefore, the flight data are not affected by contamination. This further increases the importance of this long duration flight data.

Table 1. MISSE 2 PEACE polymers

Material	Abbreviation
Acrylonitrile butadiene styrene	ABS
Cellulose acetate	CA
Poly-(p-phenylene terephthalamide)	PPD-T, Kevlar
Polyethylene	PE
Polyvinyl fluoride	PVF, Tedlar
Crystalline polyvinylfluoride w/white pigment	PVF, Wh Tedlar
Polyoxymethylene; acetal; polyformaldehyde	POM, Delrin
Polyacrylonitrile	PAN
Allyl diglycol carbonate	ADC, CR-39
Polystyrene	PS
Polymethyl methacrylate	PMMA
Polyethylene oxide	PEO
Poly(p-phenylene-2 6-benzobisoxazole)	PBO
Epoxide or epoxy	EP
Polypropylene	PP
Polybutylene terephthalate	PBT
Polysulphone	PSU
Polyeurethane	PU
Polyphenylene isophthalate	PPPA, Nomex
Pyrolytic graphite	PG
Polyetherimide	PEI
Polyamide 6	PA 6
Polyamide 66	PA 66
Polyimide	PI
Polyimide (PMDA)	PI, Kapton H
Polyimide (PMDA)	PI, Kapton HN
Polyimide (BPDA)	PI, Upilex-S
Polyimide (PMDA)	PI, Kapton H
High temperature polyimide resin	PI, PMR-15
Polybenzimidazole	PBI
Polycarbonate	PC
Polyetheretherketone	PEEK
Polyethylene terephthalate	PET
Chlorotrifluoroethylene	CTFE
Ethylene-chlorotrifluoroethylene	ECTFE, Halar
Tetrafluorethylene-ethylene copolymer	ETFE
Fluorinated ethylene propylene	FEP
Polytetrafluoroethylene	PTFE
Perfluoroalkoxy copolymer resin	PFA
Amorphous Fluoropolymer	AF
Polyvinylidene fluoride	PVDF, Kynar

3. SPACECRAFT SILICONES EXPERIMENT (MISSE 2 and 4)

The objective of the Spacecraft Silicones Experiment was to determine changes in optical properties and nanomechanical surface hardness of silicones exposed to various LEO AO and UV radiation fluence levels. Silicones are widely used on spacecraft, such as the use of DC 93-500® to bond cover glasses to solar cells for the ISS photovoltaic array blankets or as protective coatings on the back of solar arrays. Silicones have previously been thought of as being AO durable because they typically do not lose weight in an AO environment and the surface converts to a glassy SiO_x layer. Unfortunately, the oxidized glassy layer eventually shrinks as it densifies and cracks, exposing the underlying silicone or the substrate material to AO. The MISSE 2 and MISSE 4 Spacecraft Silicones experiments each included four DC 93-500® silicone samples. Three of the four samples were covered with different thickness layers of Kapton H (0.3 mil (8 µm), 0.5 mil (13 µm) and 0.8 mil (20 µm)) in order for each of the samples in the same experiment to receive different AO fluences, as the AO erodes through the over-laying Kapton before attacking the underlying silicone. Because the 10 mil (254 µm) thick silicone samples are rubbery and can stick to smooth surfaces, they were placed on 1/16" (0.16 cm) thick fused silica slides to allow post-flight optical properties to be made without the samples bending and hence inducing cracking in the glassy oxidized layer. Silicones can darken with AO and UV radiation exposure increasing the solar absorptance of the material, and hence knowledge of the degree of darkening on-orbit is desired. The MISSE 2 Spacecraft Silicones experiment samples were flown in PEC 2 sample tray E5 (samples 2-E5-1 to 2-E5-4), along with the MISSE 2 PEACE Polymers experiment, and were exposed to ram exposure for 4 years. The MISSE 4 Spacecraft Silicones experiment samples were exposed to ram exposure for 1 year in MISSE 4 sample tray E22 (samples 2-E22-2 to 2-E22-5). The MISSE 2 samples all crazed as the AO exposure caused surface shrinking. Figure 3 shows the "mud-tile" surface that developed due to conversion of the silicone surface to a silicate glassy layer. The AO fluence for the MISSE 2 samples ranged from 8.43×10^{21} atoms/cm^2 (no cover) to 7.08×10^{21} atoms/cm^2 (0.8 mil thick Kapton cover). [1] The AO fluence for the MISSE 4 samples ranged from $2.1 \times 10^{21} \pm 0.3 \times 10^{21}$ atoms/cm^2 (no cover) to $1.4 \times 10^{21} \pm 0.3 \times 10^{21}$ atoms/cm^2 (0.8 mil thick Kapton cover). [5]

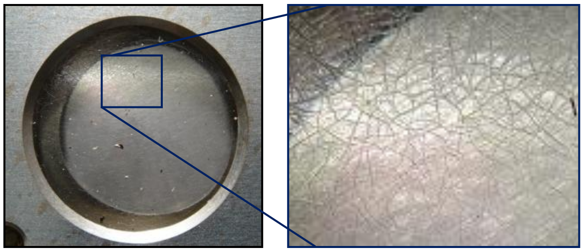

Fig. 3. Photo of MISSE 2 DC 93-500 Silicone sample (2-E5-1) showing “mud-tile” crazing

4. PROCEDURE

As noted above, many of the MISSE PEACE polymer samples were comprised of enough polymer thin films stacked together to survive a 3-year LEO exposure. Because the mission was ultimately four years in duration, many of the polymers lost numerous layers, one sample was completely eroded away and several of the polymers were eroded through all layers in at least a portion of the exposed area. It was determined that the best way to measure the optical and thermal properties of the flight samples was to determine which layers should be measured, and then compare the same number of layers from control samples (prepared as back-up flight samples). If a sample was partially eroded, that layer, along with the one beneath it was analyzed and the control sample was made up with the same number of layers. If there was a question of AO erosion occurring on multiple layers, all partially eroded layers were used along with one solid layer beneath it. If the top layers could be damaged by pulling the layers apart, the samples were left as a whole and an equal number of control sample layers were used for analysis. Several samples consisted of only one flight layer such as pyrolytic graphite, and the silicone samples of MISSE 2 and 4. The DC 93-500® samples were kept on the fused silica base as to not induce any further cracking related to handling. The properties of the silicone samples compared with the average of two control DC 93-500® samples on fused silica.

In order to handle the samples without damaging their fragile erosion morphology, the samples were loaded into a holder that mimicked the flight hardware mounting plate (see Figure 4). This allowed the sample to be placed in the optical and thermal equipment without touching any of the delicate surfaces. Only the holder would touch the equipment. The front of the sample holder recessed the sample by 0.013 cm. The back of the holder allowed a cavity of up to 0.305 cm dependent on the individual sample thickness.

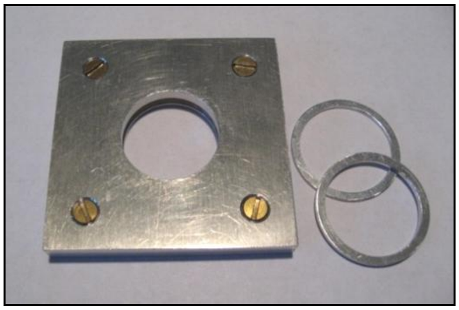

Fig. 4. Photograph of sample holder for optical and thermal measurements

4.1 Spectrophotometer Used For Optical Characterization

A Perkin Elmer Lambda-19 spectrophotometer was used to measure total reflectance (TR), diffuse reflectance (DR), total transmittance (TT) and diffuse transmittance (DT) from 250 nm to 2500 nm. The instrument is equipped with a 15 cm Spectralon integrating sphere. Specular reflectance (SR) and specular transmittance (ST) are calculated from the difference between total and diffuse values. Absorptivity data (1-reflectivity-transmissivity) can be integrated with respect to the air mass zero solar spectrum to obtain solar absorptance (A). A Labsphere certified Spectralon standard was used for calibration. Beam size was checked on each of the samples to verify that correct optical alignment was good.

4.2 Reflectometer Used For Thermal Characterization

The Surface Optics Corporation Model SOC 400T can accurately measure the directional reflectance of surfaces over a large spectral range, 2 to 25 microns, to obtain the directional thermal emittance over a large temperature range. The unit provides a sample aperture of 1.27 cm (0.5 in.). Automatic integration of reflectivity data in the infrared with respect to blackbody curves is used to calculate total emittance for a user selectable temperature range. Data were obtained at 200K, 300K, 400K, 500K and 573K. The samples were placed in the sample holder shown in Figure 5 and were backed by a Gier Dunkle gold standard. The samples analyzed had to be placed upside-down on the instrument, thus they needed to be mechanically stable enough to remain stationary for the 3.5-minute scan. Several samples could not be analyzed due to the potential of the fragile layers falling into the instrument.

Before thermally measuring all of the samples, Kapton (254 μm) was first measured by being placed directly on the instrument backed with a gold standard and was also measured in the sample holder with the gold standard backing. Table 2 shows the results of those measurements. There is a slight increase in emittance due to use of the sample holder, although necessary to use due to the surface texture on the flight samples. This difference will be especially more noticeable with the thin film, transparent samples and to a lesser degree with the thicker or opaque samples. Thus, the thermal emittance values will be more of a comparison tool instead of absolute emittance values.

Table 2. Thermal Emittance Values Comparing Measurement With and Without a Holder - Kapton

Sample	200K	300K	400K	500K	573K
Kapton – Direct	0.88	0.88	0.88	0.87	0.85
Kapton - Holder	0.91	0.91	0.91	0.90	0.89

5. RESULTS AND DISCUSSION

As noted above, one of the materials was completely eroded and others were eroded enough that optical and thermal measurements were not taken. Materials too damaged to measure optical and thermal properties included PE (2-E5-9), PMMA (2-E5-16), PA 66 (2-E5-28), PI CP1 (2-E5-29), PBI (2-E5-35), and PET (2-E5-38). Due to the top sample position of the SOC 400T (hence, the samples are mounted upside down over the sensitive equipment), PS (2-E5-15), PBO (2-E5-18) and PPPA (2-E5-24) could not have their thermal properties measured for fear of losing the fragile samples in the instrument.

Post retrieval and control optical measurements, including total and diffuse reflectance and total and diffuse transmittance (TR, DR, TT, and DT respectively), were taken of the remaining samples and are listed below in Table 3. The calculated values of the specular reflectance, specular transmittance, and solar absorptance (SR, ST, and A respectively), are also listed in Table 3. The number of layers measured is also shown for each sample.

Several trends were noted in the optical and thermal data. For example, total reflectance generally increased at least slightly with exposure, exceptions noted were mainly the fluorinated polymers and pyrolytic graphite. Diffuse reflectance showed great increases with most materials (due to surface texturing), the exceptions being PBO, PBT, Nomex, pyrolytic graphite and PTFE. Specular reflectance decreased in every sample measured (also due to surface texturing) with the exception of PMR-15. PMR-15 had an eroded hole on the sample and this may have affected its value. Total transmittance decreased in most samples measured with the exception of PBO, Nomex, and PTFE. Diffuse transmittance showed great increases with most materials but had many exceptions (White Tedlar, Delrin, PEO, EP, PBT, PU, PC, PEEK). Specular transmittance decreased in every sample with the exception of Nomex and PTFE. Solar absorptance increased in most cases with the exception of Kevlar, PMR-15, PTFE and two of the MISSE 4 silicone samples.

Table 4 lists the calculated thermal emittance data over the wavelength range of 2 to 25 microns at various temperatures as well as the number of layers measured. Many of the emittance values remained very similar before and after space exposure. Several materials experienced a decrease in the emittance including a large decrease with space exposure for PU and smaller decreases for FEP and PTFE, possibly due differences in thickness between the flight sample and control. Quite a few materials showed an increase in emittance values most likely due to the development of cone structures on the surface of the materials. PG showed the largest increase in emittance with the development of a black velvet appearance after space exposure. Other samples that experienced increased emittance values included POM, PAN, PEO, EP, PP, PSU, PEI, Upilex-S, Kapton H, and PEEK. It should be noted that the samples were all measured in the sample holder, which was not flush with the SOC 400T face in an effort to not damage the surface morphology (0.013 cm away). The gold standard used as a backing material for the measurements was also not flush with the sample and had the thickness of the sample holder between the sample and the gold standard. Therefore, the values obtained ought to be used as a comparison and not as absolute values for these materials.

Table 3. Post Retrieval and Control Optical Properties Integrated from 250 nm to 2500 nm

MISSE 2 Samples	Film Thickness (µm)	# Layers Measured	TR	DR	SR	TT	DT	ST	A
-01 DC 93-500 on Fused Silica Flight	254	1	0.074	0.039	0.036	0.893	0.249	0.644	0.033
-02 DC 93-500 w/0.3 mil Kapton Flight	254	1	0.072	0.038	0.034	0.892	0.237	0.655	0.037
-03 DC 93-500 w/0.5 mil Kapton Flight	254	1	0.070	0.035	0.035	0.894	0.228	0.666	0.037
-04 DC 93-500 w/0.8 mil Kapton Flight	254	1	0.071	0.036	0.035	0.894	0.230	0.664	0.035
DC 93-500 on Fused Silica (Average of 2 Controls)	254	1	0.071	0.012	0.059	0.924	0.013	0.911	0.005
-06 ABS Flight	127	2	0.279	0.279	0.000	0.401	0.399	0.001	0.321
-06 ABS Control	127	2	0.258	0.212	0.046	0.538	0.391	0.146	0.204
-07 CA Flight	51	2	0.203	0.148	0.055	0.642	0.236	0.406	0.155
-07 CA Control	51	2	0.140	0.018	0.123	0.789	0.069	0.721	0.070
-08 PPD-T Kevlar Flight	56	3	0.622	0.621	0.001	NA	NA	NA	0.378
-08 PPD-T Kevlar Control	56	3	0.609	0.607	0.003	NA	NA	NA	0.391
-10 PVF Tedlar Flight	51	3	0.197	0.188	0.009	0.701	0.508	0.193	0.102
-10 PVF Tedlar Control	51	3	0.242	0.155	0.087	0.753	0.295	0.457	0.006
-11 PVF White Tedlar Flight	25	2	0.732	0.729	0.003	0.045	0.045	0.000	0.223
-11 PVF White Tedlar Control	25	2	0.813	0.626	0.186	0.047	0.047	0.000	0.140
-12 POM Delrin Flight	254	1	0.350	0.349	0.001	0.459	0.456	0.002	0.191
-12 POM Delrin Control	254	1	0.270	0.265	0.005	0.581	0.579	0.003	0.149
-13 PAN Flight	51	4	0.254	0.236	0.018	0.447	0.374	0.073	0.299
-13 PAN Control	51	4	0.251	0.186	0.065	0.696	0.149	0.546	0.053
-14 ADC CR-29 Flight	787	1	0.194	0.186	0.008	0.465	0.460	0.005	0.341
-14 ADC CR-39 Control	787	1	0.119	0.043	0.076	0.829	0.035	0.795	0.052
-15 PS Flight	51	3	0.306	0.256	0.050	0.610	0.359	0.251	0.085
-15 PS Control	51	3	0.254	0.019	0.235	0.720	0.020	0.700	0.026
-17 PEO Flight	~740	1	0.302	0.302	0.001	0.449	0.447	0.003	0.249
-17 PEO Control	~740	1	0.210	0.189	0.021	0.609	0.596	0.013	0.181
-18 PBO Flight	25	3	0.438	0.419	0.019	0.123	0.122	0.001	0.439
-18 PBO Control	25	3	0.530	0.449	0.081	0.104	0.103	0.001	0.366
-19 EP Flight	~2300	1	0.087	0.084	0.002	0.382	0.381	0.001	0.531
-19 EP Control	~2300	1	0.094	0.049	0.045	0.641	0.629	0.012	0.265
-20 PP Flight	508	1	0.194	0.193	0.001	0.616	0.613	0.003	0.190
-20 PP Control	508	1	0.089	0.037	0.052	0.866	0.403	0.462	0.045
-21 PBT Flight	76	4	0.649	0.620	0.029	0.150	0.150	0.000	0.201
-21 PBT Control	76	4	0.706	0.669	0.037	0.159	0.160	-0.000	0.135
-22 PSU Flight	51	1	0.107	0.103	0.004	0.746	0.684	0.063	0.147
-22 PSU Control	51	1	0.125	0.063	0.062	0.853	0.454	0.399	0.022
-23 PU Flight	51	7	0.411	0.402	0.009	0.389	0.314	0.075	0.199
-23 PU Control	51	7	0.356	0.278	0.078	0.546	0.467	0.079	0.098
-24 PPPA Nomex Flight	51	2	0.506	0.497	0.009	0.301	0.290	0.011	0.193
-24 PPPA Nomex Control	51	2	0.647	0.635	0.012	0.200	0.198	0.002	0.153
-25 PG Flight	2030	1	0.017	0.014	0.003	NA	NA	NA	0.983
-25 PG Control	2030	1	0.268	0.253	0.015	NA	NA	NA	0.732

-26 PEI Flight	254	1	0.151	0.152	-0.000	0.625	0.570	0.055	0.224
-26 PEI Control	254	1	0.110	0.080	0.030	0.757	0.267	0.490	0.133
-27 PA 6 Flight	51	2	0.155	0.136	0.020	0.743	0.478	0.265	0.102
-27 PA 6 Control	51	2	0.162	0.115	0.047	0.790	0.365	0.425	0.047
-30 PI Kapton H Flight	127	2	0.212	0.211	0.001	0.404	0.391	0.013	0.384
-30 PI Kapton H Control	127	2	0.173	0.043	0.130	0.445	0.030	0.415	0.382
-31 PI Kapton HN Flight	127	2	0.223	0.223	0.000	0.312	0.302	0.010	0.465
-31 PI Kapton HN Control	127	2	0.171	0.044	0.127	0.403	0.117	0.286	0.426
-32 PI Upilex-S Flight	25	2	0.293	0.293	-0.000	0.362	0.338	0.025	0.345
-32 PI Upilex-S Control	25	2	0.218	0.034	0.184	0.444	0.020	0.424	0.338
-33 PI Kapton H Flight	127	1	0.078	0.075	0.003	0.515	0.495	0.019	0.407
-33 PI Kapton H Control	127	1	0.117	0.013	0.104	0.554	0.019	0.534	0.330
-34 PI PMR-15 Flight	305	1	0.160	0.133	0.027	0.347	0.344	0.003	0.493
-34 PI PMR-15 Control	305	1	0.099	0.078	0.021	0.332	0.257	0.075	0.568
-36 PC Flight	254	1	0.178	0.178	0.000	0.591	0.590	0.001	0.231
-36 PC Control	254	1	0.099	0.094	0.005	0.835	0.754	0.081	0.066
-37 PEEK Flight	76	3	0.278	0.276	0.002	0.369	0.365	0.005	0.353
-37 PEEK Control	76	3	0.249	0.173	0.075	0.563	0.522	0.040	0.189
-39 CTFE Kel-F Flight	127	4	0.124	0.121	0.003	0.770	0.770	-0.000	0.106
-39 CTFE Kel-F Control	127	4	0.069	0.011	0.058	0.931	0.014	0.917	0.001
-40 ECTFE Halar Flight	76	1	0.058	0.041	0.016	0.795	0.166	0.629	0.148
-40 ECTFE Halar Control	76	1	0.082	0.033	0.049	0.885	0.064	0.822	0.032
-41 ETFE Tefzel Flight	76	1	0.066	0.066	-0.000	0.840	0.835	0.005	0.094
-41 ETFE Tefzel Control	76	1	0.062	0.015	0.047	0.939	0.021	0.919	-0.001
-42 FEP Teflon Flight	51	1	0.051	0.025	0.025	0.944	0.017	0.928	0.005
-42 FEP Teflon Control	51	1	0.051	0.011	0.040	0.948	0.015	0.933	0.001
-43 PTFE Flight	51	1	0.085	0.071	0.014	0.886	0.234	0.652	0.029
-43 PTFE Control	51	1	0.095	0.074	0.020	0.865	0.218	0.647	0.040
-44 PFA Flight	51	2	0.088	0.060	0.029	0.904	0.046	0.858	0.008
-44 PFA Control	51	2	0.088	0.018	0.070	0.911	0.026	0.885	0.001
-45 AF Flight	51	1	0.052	0.044	0.008	0.932	0.073	0.859	0.016
-45 AF Control	51	1	0.054	0.021	0.033	0.944	0.030	0.914	0.002
-46 PVDF Kynar Flight	76	1	0.088	0.085	0.003	0.759	0.733	0.025	0.154
-46 PVDF Kynar Control	76	1	0.078	0.064	0.014	0.921	0.629	0.292	0.001

MISSE 4 Samples	**Film Thickness (µm)**	**# Layers Measured**	**TR**	**DR**	**SR**	**TT**	**DT**	**ST**	**A**
-02 DC 93-500 on Fused Silica Flight	254	1	0.086	0.031	0.055	0.915	0.050	0.864	-0.001
-03 DC 93-500 w/0.3 mil Kapton Flight	254	1	0.082	0.035	0.047	0.907	0.107	0.800	0.011
-04 DC 93-500 w/0.5 mil Kapton Flight	254	1	0.080	0.031	0.049	0.916	0.105	0.811	0.004
-05 DC 93-500 w/0.8 mil Kapton Flight	254	1	0.085	0.040	0.045	0.898	0.110	0.788	0.017
DC 93-500 on Fused Silica (Average of 2 Controls)	254	1	0.071	0.012	0.059	0.924	0.013	0.911	0.005

Table 4. Post Retrieval and Control Thermal Properties – Emittance

MISSE 2 Samples	**Layers Measured**	**200K**	**300K**	**400K**	**500K**	**573K**
-01 DC 93-500 on Fused Silica Flight	1	0.93	0.93	0.93	0.93	0.93
-02 DC 93-500 w/0.3 mil Kapton Flight	1	0.93	0.94	0.94	0.94	0.93
-03 DC 93-500 w/0.5 mil Kapton Flight	1	0.94	0.94	0.94	0.94	0.93
-04 DC 93-500 w/0.8 mil Kapton Flight	1	0.93	0.94	0.94	0.94	0.93
DC 93-500 on Fused Silica (Average of 2 Controls)	1	0.96	0.96	0.96	0.95	0.94
-06 ABS Flight	2	0.95	0.95	0.94	0.91	0.90
-06 ABS Control	2	0.94	0.94	0.93	0.91	0.89
-07 CA Flight	2	0.96	0.95	0.94	0.92	0.91
-07 CA Control	2	0.95	0.94	0.93	0.93	0.90
-08 PPD-T Kevlar Flight	3	0.91	0.91	0.90	0.88	0.86
-08 PPD-T Kevlar Control	3	0.91	0.91	0.89	0.87	0.85
-10 PVF Tedlar Flight	3	0.86	0.86	0.83	0.78	0.75
-10 PVF Tedlar Control	3	0.87	0.87	0.83	0.78	0.75
-11 PVF White Tedlar Flight	2	0.99	0.96	0.92	0.87	0.84
-11 PVF White Tedlar Control	2	0.95	0.94	0.90	0.87	0.84
-12 POM Delrin Flight	1	1.00	1.00	1.00	0.99	0.99
-12 POM Delrin Control	1	0.94	0.94	0.94	0.95	0.95
-13 PAN Flight	4	1.00	1.00	1.00	0.99	0.99
-13 PAN Control	4	0.92	0.92	0.91	0.89	0.87
-14 ADC CR-29 Flight	1	0.98	0.98	0.97	0.95	0.95
-14 ADC CR-39 Control	1	0.94	0.94	0.94	0.94	0.94
-17 PEO Flight	1	1.00	1.00	1.00	1.00	1.00
-17 PEO Control	1	0.96	0.96	0.96	0.96	0.96
-19 EP Flight	1	1.00	1.00	1.00	1.00	1.00
-19 EP Control	1	0.96	0.96	0.96	0.96	0.96
-20 PP Flight	1	0.88	0.91	0.92	0.92	0.91
-20 PP Control	1	0.76	0.82	0.85	0.85	0.86
-21 PBT Flight	4	0.94	0.95	0.95	0.94	0.94
-21 PBT Control	4	0.92	0.93	0.93	0.93	0.92
-22 PSU Flight	1	0.89	0.89	0.88	0.86	0.84
-22 PSU Control	1	0.86	0.86	0.84	0.82	0.79
-23 PU Flight	7	0.42	0.42	0.42	0.41	0.40
-23 PU Control	7	0.94	0.94	0.94	0.93	0.93
-25 PG Flight	1	0.99	0.99	0.99	0.99	1.00
-25 PG Control	1	0.45	0.47	0.49	0.50	0.51
-26 PEI Flight	1	1.00	1.00	1.00	0.99	0.99
-26 PEI Control	1	0.95	0.95	0.95	0.94	0.93
-27 PA 6 Flight	2	0.92	0.92	0.90	0.88	0.87
-27 PA 6 Control	2	0.94	0.93	0.92	0.90	0.89
-30 PI Kapton H Flight	2	0.94	0.94	0.94	0.93	0.92
-30 PI Kapton H Control	2	0.93	0.93	0.93	0.92	0.92
-31 PI Kapton HN Flight	2	0.95	0.96	0.95	0.94	0.93
-31 PI Kapton HN Control	2	0.93	0.93	0.93	0.93	0.92
-32 PI Upilex-S Flight	2	0.85	0.87	0.87	0.85	0.83
-32 PI Upilex-S Control	2	0.81	0.83	0.83	0.80	0.78
-33 PI Kapton H Flight	1	0.96	0.96	0.96	0.95	0.95
-33 PI Kapton H Control	1	0.92	0.92	0.92	0.91	0.90

-34 PI PMR-15 Flight	1	0.98	0.97	0.96	0.94	0.93
-34 PI PMR-15 Control	1	0.93	0.93	0.93	0.93	0.92
-36 PC Flight	1	0.91	0.92	0.93	0.92	0.91
-36 PC Control	1	0.94	0.95	0.94	0.93	0.92
-37 PEEK Flight	3	0.97	0.97	0.97	0.95	0.94
-37 PEEK Control	3	0.93	0.93	0.92	0.91	0.90
-39 CTFE Kel-F Flight	4	0.96	0.94	0.88	0.81	0.76
-39 CTFE Kel-F Control	4	0.94	0.92	0.87	0.81	0.77
-40 ECTFE Halar Flight	1	0.91	0.90	0.86	0.80	0.76
-40 ECTFE Halar Control	1	0.90	0.89	0.85	0.79	0.75
-41 ETFE Tefzel Flight	1	0.85	0.87	0.84	0.78	0.75
-41 ETFE Tefzel Control	1	0.87	0.88	0.84	0.78	0.74
-42 FEP Teflon Flight	1	0.82	0.80	0.74	0.69	0.65
-42 FEP Teflon Control	1	0.86	0.85	0.79	0.73	0.69
-43 PTFE Flight	1	0.79	0.76	0.71	0.65	0.61
-43 PTFE Control	1	0.83	0.80	0.75	0.69	0.65
-44 PFA Flight	2	0.89	0.88	0.83	0.77	0.73
-44 PFA Control	2	0.91	0.90	0.85	0.79	0.75
-45 AF Flight	1	0.92	0.90	0.86	0.81	0.77
-45 AF Control	1	0.93	0.92	0.88	0.83	0.79
-46 PVDF Kynar Flight	1	0.92	0.92	0.88	0.83	0.78
-46 PVDF Kynar Control	1	0.94	0.94	0.91	0.88	0.86
MISSE 4 Samples	**Layers Measured**	**200K**	**300K**	**400K**	**500K**	**573K**
-02 DC 93-500 on fused silica Flight	1	0.96	0.96	0.95	0.95	0.94
-03 DC 93-500 w/0.3 mil Kapton Flight	1	0.95	0.95	0.95	0.95	0.94
-04 DC 93-500 w/0.5 mil Kapton Flight	1	0.95	0.95	0.95	0.94	0.93
-05 DC 93-500 w/0.8 mil Kapton Flight	1	0.96	0.96	0.96	0.95	0.94
DC 93-500 on fused silica (Average of 2 Controls)	1	0.96	0.96	0.96	0.95	0.94

6. SUMMARY

Optical and thermal properties were measured for the MISSE 2 PEACE Polymers experiment samples, and the MISSE 2 & 4 Spacecraft Silicone experiment samples, after long-term space exposure on the ISS. The majority of the PEACE Polymer samples were comprised of numerous thin film layers stacked together. Because the MISSE 2 mission was much longer (3.95 years) than planned (1.5 years), one sample was completely eroded away (PBI) and numerous other samples were severely degraded. Therefore, optical and thermal measurements could not be obtained on all samples. The optical properties of 43 samples, and thermal properties of 40 samples, were obtained and compared to control samples. Several trends were observed in the data. For most samples, specular and diffuse reflectance characteristics changed greatly upon directed LEO atomic oxygen exposure. Typically, there is a decrease in specular reflectance with an increase in diffuse reflectance. Because many of the PEACE polymers, and the DC 93-500® silicone, are commonly used for spacecraft applications, knowledge of potential changes in their optical and thermal properties with long term space exposure is very important. A summary of the MISSE 2 PEACE Polymers and Spacecraft Silicones experiments, the specific materials flown, optical and thermal property measurement procedures, and the optical and thermal property data is provided.

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