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Environmental Testing of Thermal Control Materials at Elevated Temperature and Intense Ultraviolet Radiation

S. Heltzel,* C. O. A. Semprimoschnig, and M. R. J. van Eesbeek
ESA, 2200 AG Noordwijk, The Netherlands.

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This paper presents two test campaigns in the frame of the ongoing program for the European Space Agency's mission to Mercury. Improvements on the experimental setup are presented that enable ground-based simulation of such a harsh space environment. The thermal endurance of white ceramic paints is investigated at 350°C. The solar absorptance of all paints increased significantly. Two types of ceramic woven fabrics were irradiated by 17 solar constants of ultraviolet light at an elevated temperature. The available data from the solar absorptance as a function of an ultraviolet dose up to 52,000 equivalent sun hours was extrapolated to the mission's end-of-life dose of 100,000 equivalent sun hours. The custom-baked Astroquartz 2 was the best performing material with an estimated end-of-life solar absorptance of 0.35.

Nomenclature

a, b, c	=	fitted constants
P	=	pressure
t	=	UV dose in equivalent sun hours
α_S	=	solar absorptance
$\alpha(t)$	=	solar absorptance as a function of UV dose

I. Introduction

THE European Space Agency, in collaboration with the Japan Aerospace Exploration Agency (JAXA), is preparing a mission to the planet Mercury to be launched in 2013. This inner-solar-system planetary mission, named BepiColombo, is one of the cornerstones of ESA's long-term science program. Because of its close proximity to the sun, the Mercury environment poses great challenges on this mission. External thermal control materials need to withstand, among other things, UV radiation up to 11 solar constants (SC) and heat loads up to 17 kW/m^2, which can drive up external temperatures to 350°C. Previous work (see [1,2]) on the recently launched Venus Express mission has shown that UV radiation and elevated material temperature play an important role in the degradation of thermo-optical properties. Therefore the need for environmental testing evolved, combining high-intensity UV radiation and elevated sample temperature, which is named Synergistic Irradiation Test (SIT).

This paper presents results of the ongoing critical materials technology (CMT) test program [3]. For simulating the Mercury environment in ground-based test facilities [4], major technical and experimental challenges had to be overcome. This paper describes some of the improvements that were performed on the test facilities as well as some detailed results of two test campaigns. First, the assessment of the thermal endurance of various white ceramic paints is presented. Second, the change in thermo-optical properties of ceramic woven fabrics is shown as a function of UV irradiation.

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*European Space Research and Technology Center, Materials Physics and Chemistry Section, PO Box 299. Phone: 31-71-5653675. Fax: 31-71-5654992. stan.heltzel@esa.int.

II. Thermal Endurance of Paints

Various white ceramic (silicate) paints from different suppliers have been assessed for their thermal endurance, for which two methods were used. Thermogravimetric analysis (TGA) is a fast method that is routinely used for the screening of materials by measuring mass loss as a function of temperature and, by that, determining the decomposition profile. A more comprehensive method is the isothermal aging under high vacuum conditions of samples on which thermo-optical properties are periodically determined. The paints are candidate materials to be used as thermal control coating up to 350°C, depending on the stability of the thermo-optical properties. A list of all paint types, which were obtained from MAP, AZ Technology, and Alion, is shown in Table 1.

A. Thermogravimetric Analysis

1. Procedures

The thermogravimetric analyzer, type TGA/SDTA851 from Mettler-Toledo, measures the mass of a sample while going through a temperature scan, determining mass loss as a function of temperature. The apparatus is purged with dry nitrogen gas to prevent unwanted reactions with the atmosphere, such as oxidation. The used heating rate is 2°C/ min from room temperature to 1000°C. The tests are performed in accordance with [5].

2. TGA Results

The decomposition profile of all paints under investigation has been determined. A typical example is shown in Fig. 1 for the paint AZ-2000-IECW. The graph consists of the TG curve (thermogravimetric curve, top trace) that shows mass as a function of temperature and the DTG curve (derivative TG, bottom trace) that shows the mass loss rate as function of temperature. The decomposition profiles of the other paints are comparable to the that shown in Fig. 1, and identical analysis provides a means to compare, which is done in Table 1.

The ceramic paints are hygroscopic, and desorption of water is observed as a stepwise change in mass. In the example of Fig. 1 a broad mass loss can be seen below 100°C, which is attributed to the off-gassing of absorbed humidity. The activation energy for desorption of water that is bonded to the crystal structure is higher than in the case of absorbed water. This is deemed to dominantly cause the sharp mass loss between 100°C and 200°C. To compare all tested paints, the off-gassing of humidity is determined on the TG curve as a horizontal mass loss step with limits between room temperature and 200°C, as can be seen on the analysis of Fig. 1. The quantification of this mass loss and the temperature with the maximum mass loss rate is summarized in Table 1. Off-gassing of

Table 1 Mass loss due to off-gassing of water and decomposition of organics. Favorable results are indicated in bold font

	Water 0–200°C		Organics 200–400°C	
	ΔM	Peak temperature	ΔM	Peak temperature
AZ70-WIZT	3.1%	150°C	0.6%	340°C
AZ93	3.4%	140°C	1.3%	330°C
AZ100-51	3.0%	140°C	0.9%	320°C
AZW/11-LA	2.9%	60°C	**0.3%**	330°C
AZ2000-IECW	3.4%	140°C	**0.3%**	320°C
AZ2100-IECW	2.7%	140°C	0.6%	320°C
Z93-P	2.1%	140°C	**0.2%**	330°C
Z93-C55	4.8%	80°C	0.7%	280°C
Z93-SC55	8.0%	100°C	0.7%	290°C
YB71P	0.5%	50°C	**0.2%**	290°C
PSB	3.7%	150°C	**0.3%**	360°C
PSBN	4.6%	150°C	**0.2%**	360°C

humidity is not a concern for the thermal endurance of these paints, although other related effects, such as cracking, could be a concern.

The mass loss steps at temperatures higher than 200°C are likely to be caused by (partial) decomposition of organic components, which could, for instance, be additives or contamination of the ceramic paint. In Fig. 1 this decomposition is seen clearly as a broad peak in the DTG curve, corresponding to a shallow stepwise mass change in the TG curve. Comparing all tested paints, this mass loss is quantified by integration of the peak in the DTG curve with limits from 200°C to 400°C, which is 50°C above the planned maximum service temperature. Both quantifications are summarized in Table 1 for all paints. Small or total absence of mass loss above 200°C is favorable for the thermal stability of these paints. The temperature at which the loss rate is at maximum provides information about the activation energy of the decomposition process. A paint is deemed thermally more stable in case that decomposition occurs at higher temperature.

3. Discussion

In Table 1 the first 6 paints are from AZ Technology, the following 4 paints are from Alion, and the last 2 paints are from MAP. The latter two paints need an aluminum substrate to stimulate the adhesion. The paints from Alion and AZ Technology do not require application on aluminum substrates. It is possible that the bonding of some paints to nonaluminium substrates is stimulated by organic additives. Organics that are possibly present in the paints could decompose at elevated temperatures.

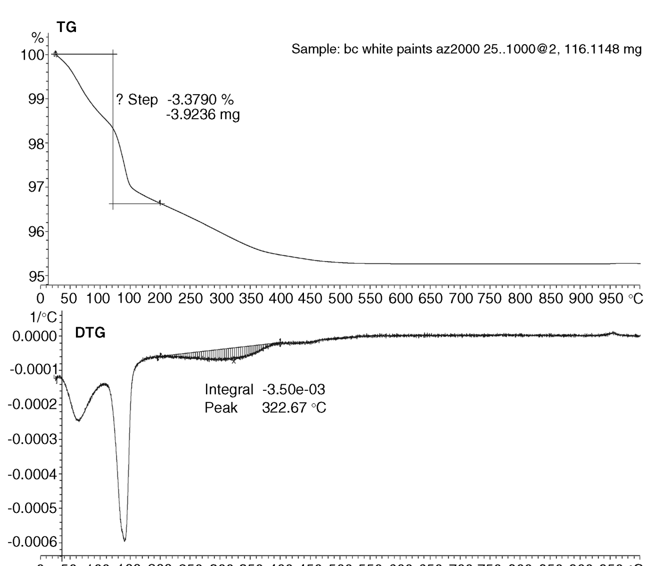

Fig. 1 Mass (top) and mass loss rate (bottom) as a function of temperature of AZ-2000-IECW.

Mass loss above 200°C is of concern for the use of the paint at elevated an temperature (i.e., 350°C) because it is likely to indicate decomposition of organic additives. In addition, outgassing of organic decomposition products may be a source of condensable contamination. Based on the quantification of the decomposition at the planned service temperature, a classification has been made in Table 1. The paints with a low mass loss at elevated temperature are indicated in bold font. The results presented here depend on the sample history, the quality of the bare materials, the specific application process, and the applied test method, and therefore they may only be used as a means to compare the materials, rather than an absolute characterization.

B. Isothermal Aging in High Temperature Exposure System

1. Procedures

The High Temperature Exposure System (HITES) is a small vacuum furnace that has been especially developed in the frame of the CMT for BepiColombo for the assessment of thermal endurance. The facility consists of a high vacuum chamber that can be heated to 450°C by three external heaters. The sample temperature is monitored by 3 in situ thermocouples. Rigid aluminum (99.5% pure) masking of the samples enables sliding of the samples to a vertically orientated position in a sample table with grooves at regular distance (see Fig. 2). In this way, more samples can be loaded into the facility, and every sample is facing the aluminum backside of the mask in front. This ensures equal view factors for every sample and reduces the chance of possible cross contamination.

After loading the sample table into the facility, the chamber is closed and evacuated. The chamber is heated to 350°C at a controlled slow heating rate of 0.1°C/ min. The TGA experiments have shown that large amounts of water desorbs from the hygroscopic ceramic paints when heated and evacuated. Additionally, if organic volatiles outgas from the paints they can cause cross contamination, especially if they are burned in due to high sample temperatures. The idea behind the slow heating rate is that any volatiles are pumped out of the chamber as soon as they outgas before the temperature increases much further. The cleanliness is verified according to [6,7] using witness windows (CaF_2) that were present during the exposure and that were afterwards analyzed by Fourier transformed infrared spectroscopy. In approximately 55 hours the temperature of the vacuum chamber increased to the set-point temperature of 350°C. For the first exposure (EXP1) isothermal aging at this temperature is performed for 12 hours and for the second exposure (EXP2) for another 506 hours. After the exposures the chamber is cooled down to room temperature and vented with dry nitrogen gas before opening and analyzing the samples.

Samples were prepared for assessment of the thermo-optical properties after exposures in the HITES for 12 hours and 518 (506 + 12 hours) at 350°C. The solar absorptance (α_S) is determined by measuring the reflectance spectra on a UV-VIS-IR spectrophotometer type Cary 500 of Varian, equipped with an integrating sphere. The thermal emittance is determined using the IR reflectometer, type TEMP 2000A of AZ Technology. These measurements are performed in accordance with [8].

2. Visual Inspection of Aged Samples

Most samples darkened significantly during the thermal aging compared with the beginning of life (BOL) samples, as can be seen in Fig. 3 for AZ-2000-IECW. Most samples show cracks in the paint

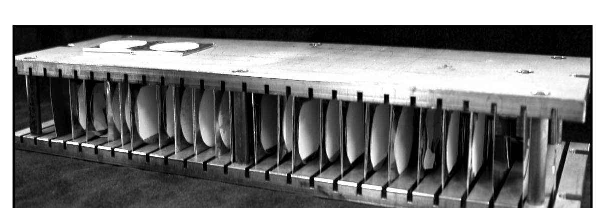

Fig. 2 Sample setup for thermal aging in the HITES.

surface after the thermal aging as is shown in the microscopic image in Fig. 4 and to a greater extent in Fig. 5. Some samples get a blue appearance, which is caused by absorption in the red part of the spectrum. This can be seen on the spectra of YB71P in Fig. 6 and in case of Z93-C55 on the local blue spots in Fig. 5.

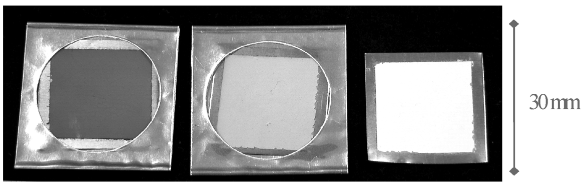

Fig. 3 Samples of AZ-2000-IECW at BOL (unmasked, right), after EXP1 (middle) and, after EXP2 (left).

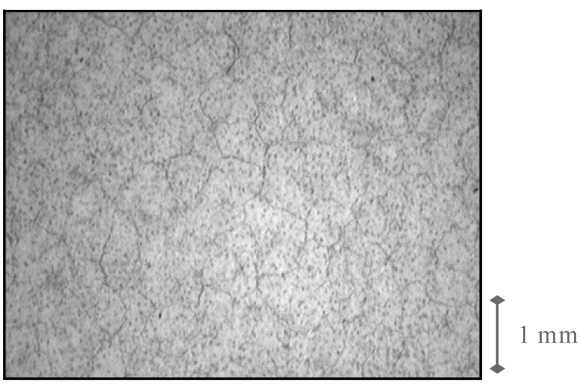

Fig. 4 Magnification of the surface of PSBN after EXP2.

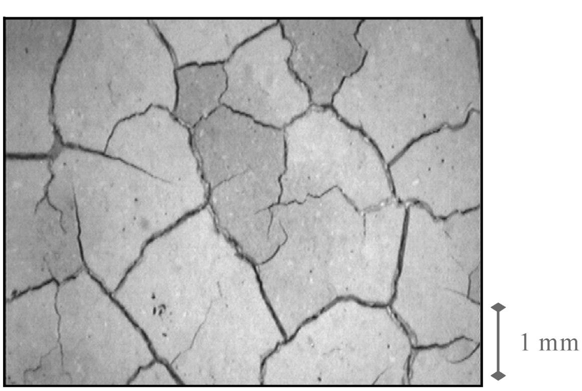

Fig. 5 Magnification of the surface of Z93-C55 after EXP2.

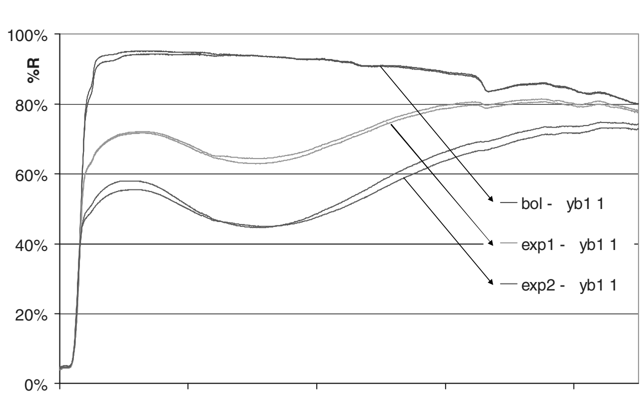

Fig. 6 Reflectance spectra of YB71P.

3. Solar Absorptance as Function of Thermal Aging

The degradation of the reflectance is illustrated for YB71P, PSBN, and AZW/11-LA in Figs. 6–8 respectively. At each inspection point, two samples were measured. All paints show large decreases in the reflectance. All BOL spectra show distinct absorption bands at approximately 1410 nm and 1908 nm. The first is likely to be an overtone of water absorption whereas the second peak is probably caused by an organic component. Reduction or absence of this absorption peak after thermal aging indicates the loss of these organics, as was also observed by TGA.

The reflectance spectra are weighed by the solar spectrum [9] and integrated to calculate the solar absorptance, which provides a means to quantify the observed degradation. The average solar absorptance at BOL and after both exposures are summarized in Table 2. In some instances the absorptance value is missing because the samples degraded such that analysis was not possible (due to flaking) or because samples were excluded for the second exposure.

4. Discussion

The thermal emittance of all samples has also been measured. After the exposures no differences compared with BOL were resolved. The emittance of all samples is in the range of 0.88 to 0.92.

In Table 2 it can be seen that the absorptance of all paints degrades significantly. The baseline thermal model of the BepiColombo mission uses a preliminary target value of 0.35 for the solar absorptance of thermal control materials at end of life (EOL). The best performing silicate paint is AZW/11-LA (indicated with bold font in Table 2), which has a favorably low absorptance at BOL and with an increase of 0.21 it remains below the target value after the second exposure. However, it should be noted that this aging campaign comprises only a fraction of the total exposure time to such heat loads for the mission and does not assess other degrading radiation such as UV. Therefore, it is not expected that these paints provide suitable means of thermal control for the whole of the

Fig. 7 Reflectance spectra of PSBN.

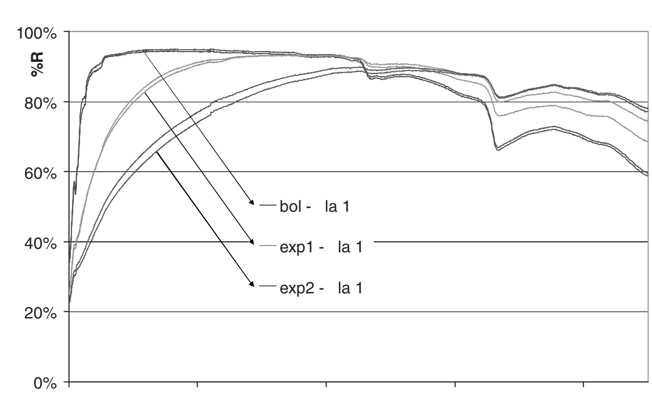

Fig. 8 Reflectance spectra of AZW/11-LA.

Table 2 Solar absorptance as a function of isothermal aging

	BOL 0 h	EXP1 12 h	EXP2 518 h
AZ70-WIZT	0.09	0.48	-
AZ93	0.14	0.25	0.41
AZ100-51	0.14	0.24	0.45
AZW/11-LA	**0.08**	**0.16**	**0.29**
AZ2000-IECW	0.25	0.48	0.71
AZ2100-IECW	0.18	-	-
Z93-P	0.13	0.22	0.39
Z93-C55	0.17	0.52	-
Z93-SC55	0.14	0.31	0.47
YB71P	0.10	0.32	0.45
PSB	0.12	0.25	0.49
PSBN	0.15	0.24	0.40

mission. On the other hand this first screening at 350°C was a worst-case exposure, and other aging campaigns are foreseen on some of these paints at a lower temperature.

This test campaign is an ongoing effort, and future tests are planned to focus on other types of thermal control coatings and other exposure levels. Environmental testing of thermal control coatings is not limited to thermal aging. Thermal control materials that prove to be thermally stable are then included in test campaigns that assess resistance to other forms of radiation, such as high-intensity UV radiation. An example of such test campaign is presented in the following chapter.

III. UV Irradiation of Multilayer Insulation Fabrics

Two types of ceramic woven fabrics are candidate materials for the external layer on the multilayer insulation (MLI) of BepiColombo. To assess the resistance of these and other external materials to the Mercury radiation environment, major improvements on the existing capabilities of the environmental testing facilities were necessary.

A. Design and Procedures for Environmental Testing in the Bake Out Facility

The vacuum facility in which environmental testing to high-intensity UV radiation is performed is traditionally called BOF (bake out facility), as shown in Fig. 9. It consists of a high vacuum ($P < 10^{-6}$ mbar) chamber in which samples can be exposed to UV radiation. The samples are surrounded by a cold shroud (see Fig. 10) that is purged with liquid nitrogen to condense possible contaminants and, by that, maintain a high level of cleanliness during the test.

1. UV Sources

The BOF is equipped with two types of UV sources. Eight halogen discharge lamps produce UV radiation in the range of 200 to 400 nm, besides visible and infrared (IR) radiation. The lamp house is positioned outside the vacuum chamber in front of a fused-silica window. The power output or the lamps can be varied by stabilized power supplies, providing a UV intensity of 5 to 20 SC.

In addition, four deuterium lamps each illuminate a quadrant of the base plate. These lamps are located on four positions on the main flange (see Fig. 10) such that the apertures of the lamps are positioned inside the vacuum chamber. These lamps produce vacuum UV (VUV) radiation in the range of 115 to 200 nm. The power output of these lamps is fixed. The highly energetic VUV radiation polymerizes small amounts of contamination on the lamp aperture, which strongly reduces the intensity at the sample level. Therefore these lamps are periodically dismounted, polished, and cleaned, without interrupting the vacuum of the sample chamber. In this way an intense beam of 16 SC of VUV radiation is available. The solar spectrum consists of approximately 1000 times more UV radiation above 200 nm than VUV radiation (see [9]). Therefore this part of the spectrum is often discarded, and no deuterium lamps are used in standard UV tests. However, for BepiColombo and other missions in close proximity to the sun, this part of highly energetic UV radiation is expected to contribute significantly to the degradation of thermo-optical properties.

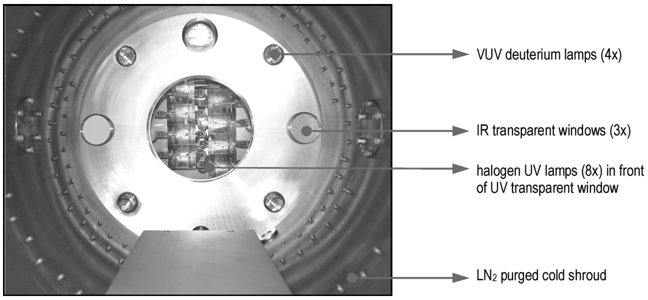

Fig. 10 Interior of BOF vacuum chamber.

2. Temperature Control and Measurement

The samples are mounted on heated sample holders. For assessment of the effect of temperature-accelerated UV testing, typically identical batches of samples are simultaneously exposed at different temperatures. To improve the thermal contact of thin films and woven fabrics to the sample holder, a curved fixture has been designed, as seen in the schematic drawing in Fig. 11. The samples are clamped on the top end, guided along the curvature of the fixture, and the bottom end of the sample is hanging freely but stressed by a small weight. The sample holders can be heated to a maximum of 450°C.

The temperature of the samples during UV radiation depends on the thermal contact to the sample holder, the radiative environment,

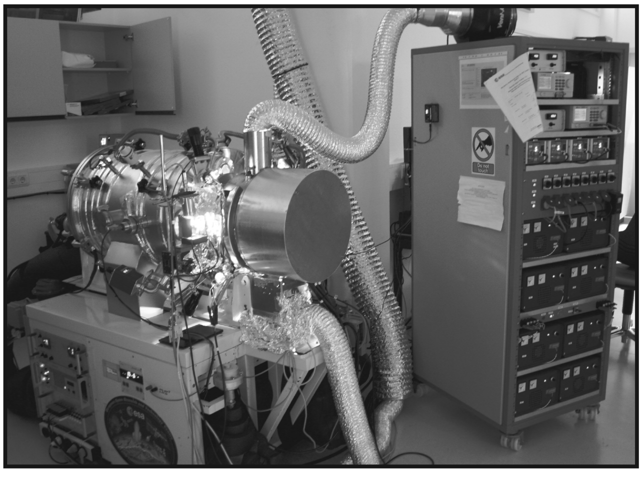

Fig. 9 Environmental test facility overview.

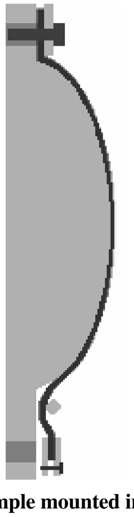

Fig. 11 Schematic of sample mounted in curved sample fixture.

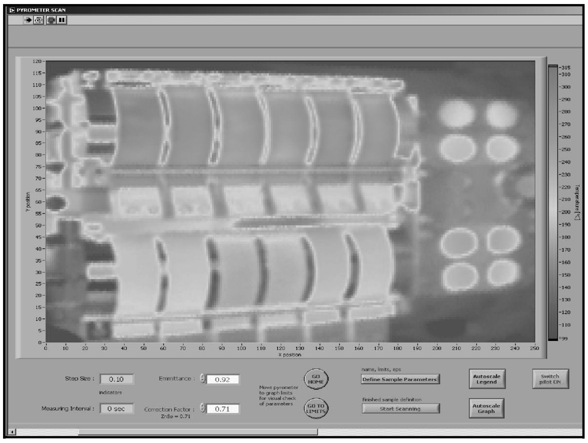

Fig. 12 Thermal image of sample area during UV irradiation.

Table 3 Overview of sample materials and designation

Material and heat treatment	Sample designation
Astroquartz 2 Custom baked by QMC at 700°C	A2Q
Astroquartz 3 Custom baked by QMC at 700°C	A3Q
Nextel Refrex 1210 Custombaked by QMC at 700°C	NCQ
Nextel Refrex 1210 Heat cleaned by Insulcon at 700°C	NCI
Nextel Refrex 1210 Heat treated by Insulcon at 900°C	NTI

and the thermo-optical properties of the sample. In high vacuum it is inaccurate to determine the temperature of thin or woven samples under radiation with a contact sensor due to its thermal mass and different thermo-optical properties. Therefore, a system has been developed that allows continuous registration of the surface temperatures of all samples in a contactless manner by measuring the IR radiation. The measurements are logged with a computer and custom-made software enables to plot a false-color image of the sample area, as seen in Fig. 12. The emitted infrared radiation is corrected for the thermal emittance of individual samples to determine the correct value of the sample surface temperature.

3. *Test Specifications*

The tested white ceramic woven fabrics are Nextel Refrex 1210, Astroquartz 2, and Astroquartz 3. Nextel (alumina-boria-silica) is supplied by Insulcon and Astroquartz (SiO_2) by JPS Glass. Nextel is commercially available with bake out procedures called "heat cleaned" and "heat treated," which involves baking the material at 700°C and 900°C, respectively. Astroquartz is not available with such treatment. Therefore, samples of Astroquartz 2 and 3, as well as samples of Nextel were additionally treated by a customized in-house (at QMC) heat cleaning procedure at 700°C. This adds to a total of five sample types, as indicated in Table 3. For this test campaign it was not considered to include unbaked samples. Previous work has shown that the organic binder that is applied on these woven fabrics for manufacturing purposes degrades significantly under UV irradiation. The samples are prepared with an aluminum (99.5% pure) foil mask and backing in order to make opaque samples that are representative to the current baseline design of the MLI.

The test matrix in Table 4 summarizes the set-point temperatures of the sample holders and the measured sample surface temperature. A single batch comprises all five samples indicated in Table 3. For EXP3, batch 4 was added on a sample holder at 450°C, comprising fresh, as received samples (see Fig. 13).

The average UV intensity was 17 SC, whereas the average VUV intensity was 16 SC. The UV dose in equivalent sun hours (esh) refers to the radiation between 200 and 400 nm. That quantity defines the duration in which a sample is irradiated by UV equivalent to the intensity in earth orbit. The third exposure had the longest duration of approximately 38,000 esh. The samples included in all three exposures accumulated a UV dose of approximately 52,000 esh. The total UV dose for the BepiColombo mission is estimated to be in the range of 100,000 esh. It is the aim of this test campaign to perform reliable extrapolation of the available absorptance data to the dose at EOL of the mission. The equivalent VUV dose is also shown in Table 4.

B. Results and Discussion

1. *Solar Absorptance*

The BOL reflectance spectra of Astroquartz and Nextel are shown in Fig. 14. The spectra are comparable with the exception that Nextel absorbs UV radiation lower than 400 nm. In Table 4 it can be seen that the differences in sample holder temperature do not result in such a large difference in sample surface temperature. For future work with even higher sample temperatures it is planned to improve this experimental setup. For this investigation it is not expected (and proven by the results) that UV degradation is much accelerated by sample temperature because during the pretreatment the samples were exposed to much higher temperatures than during the UV test. This paper further focuses on the results obtained from the samples exposed at 450°C.

In Fig. 15 the reflectance spectra are shown from the samples of batch 4 after EXP3. It can be seen that all samples degraded in comparable manner, but still (custom-baked) Astroquartz is not absorbing as much UV radiation as Nextel. Also in the visible range, the reflectance of Astroquartz and the custom-baked Nextel is somewhat higher than the commercially baked Nextel.

The spectra of Fig. 15 are used to calculate the solar absorptance at 38,000 esh. This is indicated in bold font in Table 5 because this data set is the most significant. The data derived from accumulated UV doses during multiple UV exposures (EXP1 + 2 and EXP1 + 2 + 3 in Table 5) are deemed less trustworthy than data obtained from a single exposure (e.g., EXP3).

The solar absorptance as a function of UV dose shown in Table 5 is graphically shown in Fig. 16. It can be seen that (custom-baked) Astroquartz has a lower solar absorptance throughout the test campaign than Nextel. The custom-baked Nextel has a lower

Table 4 Test matrix

	Thermal environment			Exposures		
	Sample holder (see Fig. 13)	Sample holder temperature	Sample surface temperature	EXP1 UV: 5,700 esh VUV: 5,800 esh	EXP2 UV: 8,300 esh VUV: 6,600 esh	EXP3 UV: 38,000 esh VUV: 31,000 esh
Batch 1	Top	450°C	240–280°C	X	X	X
Batch 2	Right	150°C	180–230°C	X	X	X
Batch 4	Bottom	450°C	270–290°C	-	-	X
Batch 3		References		-	-	-

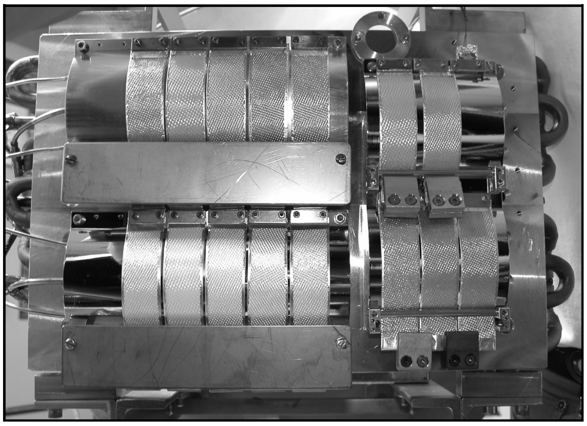

Fig. 13 Sample setup before EXP3.

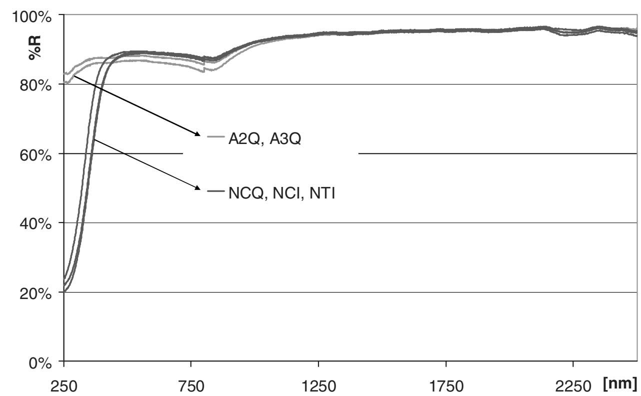

Fig. 14 Reflectance at BOL.

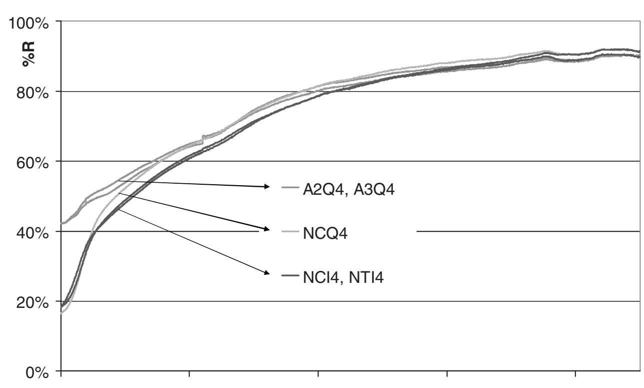

Fig. 15 Reflectance of batch 4 samples after EXP3.

absorptance than the commercially baked Nextel. The discontinuity for the data at 52,000 esh is related to the fact that the UV dose is accumulated during three exposures whereas the point at 38,000 esh is derived from a single exposure. Nevertheless a consistent trend is observed for all samples throughout the test campaign.

Table 5 Solar absorptance as a function of UV dose of samples exposed at 450°C

	BOL 0 esh	EXP1 5800 esh	EXP1 + 2 14,000 esh	EXP3 38,000 esh	EXP1 + 2 + 3 52,000 esh
A2Q	0.10	0.20	0.30	**0.34**	0.41
A3Q	0.12	0.21	0.30	**0.35**	0.44
NCQ	0.14	0.25	0.33	**0.36**	0.45
NCI	0.13	0.28	0.35	**0.39**	0.46
NTI	0.13	0.27	0.35	**0.39**	0.46

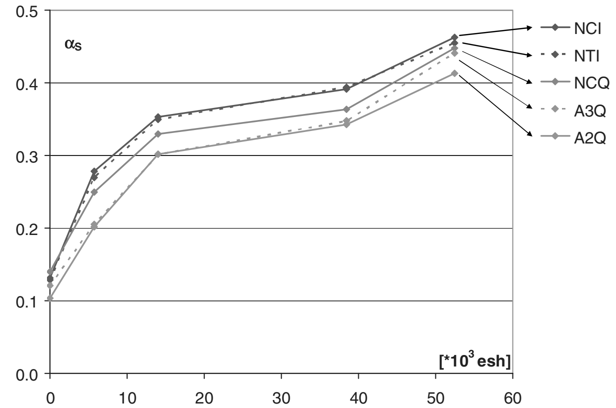

Fig. 16 Solar absorptance as function of UV dose at 450°C.

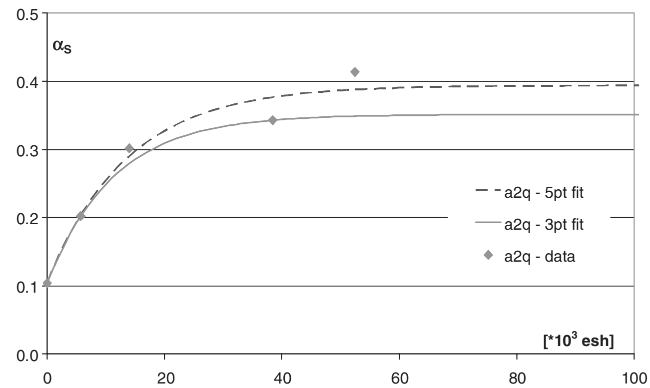

Fig. 17 Extrapolation of absorptance of A2Q based on 3-point (solid) and 5-point (dashed) curve fitting.

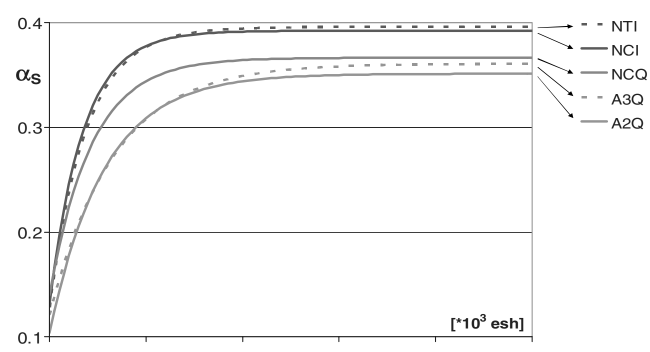

Fig. 18 Extrapolation based on 3-point fit of all samples.

2. Fitting and Extrapolation

The data points in Fig. 16 are used for curve fitting by a first order exponential decay function:

$$\alpha(t) = a - b \cdot e^{-t/c} \tag{1}$$

Curve fitting has been performed on the 3 data points derived from single UV exposures and on all 5 data points, obtained by accumulation over multiple exposures. Figure 17 shows the fitting and an extrapolation to 100,000 esh for Astroquartz 2. The 3-point fitting is deemed a "realistic" estimation, whereas the 5-point fitting is more "conservative."

In Fig. 18 the realistic curve fittings are shown for all sample materials, and Table 6 summarizes the extrapolations to 100,000 esh for both fittings. In all cases the trend shows that the degradation levels off after approximately the first 40,000 esh. Therefore, the absorptance data at 38,000 esh provide a good indication for the EOL

Table 6 Prediction of EOL absorptance at 100,000 esh

	3-point fit "realistic"	5-point fit "conservative"
A2Q	0.35	0.39
A3Q	0.36	0.43
NCQ	0.37	0.42
NCI	0.39	0.43
NTI	0.40	0.43

absorptance. The realistic fitting of Astroquartz 2 predicts an EOL absorptance of 0.35, which is just on the preliminary target value for the EOL absorptance of thermal control materials for the BepiColombo mission. The other materials do not meet this requirement but are not far above. Also in the conservative fitting A2Q performs the best.

IV. Conclusions

Missions to the inner part of the solar system impose unprecedented requirements on external thermal control materials. Ground-based simulation of such a harsh space environment is technically challenging but of paramount importance for the success of these missions. It has been shown that development of new facilities as well as improvements on those existing extend the capabilities of the European Space Research and Technology Center's materials laboratories for assessment of thermal endurance up to 450°C and stability of thermo-optical properties to UV radiation up to 20 SC.

The thermal endurance of white ceramic paints has been investigated. At 350°C it is not expected that any of the tested paints provide a suitable means of thermal control. It is planned to test at lower temperatures and to include other materials in future work.

Woven ceramic fabrics were exposed at elevated temperature to UV and VUV radiation of approximately 17 SC, accumulating a total UV dose of 52,000 esh. The longest individual exposure lasted 100 days (i.e., 38'000 esh). The available data on solar absorptance as a function of UV dose was extrapolated to 100,000 esh, which is the EOL dose of the BepiColombo mission. Custom-baked Astroquartz 2 has the lowest absolute absorptance as well as the lowest increase. The realistic extrapolation to the EOL dose predicts an absorptance of 0.35, which is just on the target EOL value of the current baseline design.

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J. Minow
Associate Editor