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Semi-Automated Bonding of OSR – Qualification of a novel Process

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Optical Solar Reflectors (OSR) are efficient thermal emitter glass tiles with a typical size of 40x40mm. They cover spacecraft radiator panels to reduce absorption of solar radiation and to dissipate internally generated heat into space. On modern high-power telecom satellites total radiator areas reach sizes of more than 20m². State-of-the-art processes to apply such OSR tiles are labour intensive and involve application of two-component adhesives, manual placing of tiles and long duration temperature controlled adhesive curing cycles. This paper presents the qualification campaign of a sophisticated OSR application method using electrically conductive pressure sensitive adhesive (PSA) and a semi-automated OSR pick-and-place facility. Compared to standard OSR application using electrically conductive filled silicone resins, the new process is resulting in radiator surfaces with up to 27% lower mass. After manual application of the PSA the panel is placed in the 3-axis controlled gantry system, where a precise manipulator takes each tile and places it on the CAD pre-defined position on the panel. When the panel is covered with OSR an automated rolling process applies the required pressure to activate tape adhesion. The application process in the pick-and-place system guarantees high degree of reproducibility and increased precision at decreased radiator through-put durations. For qualification, samples prepared with the automated process were subjected to a thorough space environmental test campaign. This campaign involved vacuum thermal-cycling and exposures to electrons, protons and UV-radiation simulating a 15 year GEO mission, followed by tile pull-off testing. Since successful completion of the qualification campaign a number of spacecraft radiators have been equipped with single sizes up to 2,1 x 2,2 meters including radiators of the SmallGEO, Exomars and EDRS-C programs.

Nomenclature

α_S	=	Solar Absorptance
ε_{IR}	=	Infrared Emittance
ρ	=	Reflectance
<i>BOT</i>	=	Beginning of Test
<i>CAD</i>	=	Computer Aided Design
<i>e-</i>	=	Electron
<i>EOT</i>	=	End of Test
<i>ESH</i>	=	Equivalent Sun Hour
<i>GEO</i>	=	Geostationary Orbit
<i>ITO</i>	=	Indium Tin Oxide conductive coating

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<i>MOS</i>	=	Margin of safety
<i>OSR</i>	=	Optical Solar Reflector
<i>p+</i>	=	Proton
<i>PSA</i>	=	Pressure Sensitive Adhesive
<i>UV</i>	=	Ultra-Violet part of the electromagnetic spectrum

I. Introduction

OSR tiles, are made of cerium dioxide doped borosilicate glass coated with a silver second-surface and a thin, transparent, and electrically conductive Indium Tin Oxide (ITO) space facing layer, which is applied optionally by the tile supplier.

Tiles are attached on spacecraft radiators to reflect incident solar energy of wavelengths between 200nm and 2500nm, and to emit in the infrared spectrum the waste heat energy produced within the spacecraft.¹

An effective radiator must thus have a low ratio of absorption to emissivity. This ratio is defined α/ϵ , where α is the solar absorption coefficient and ϵ the infrared emissivity of the material, and is typically in the order of 0.06 to 0.12 depending on the OSR type.^{2,3}

On modern high-power telecom satellites, total radiator areas can reach sizes of more than 20 m² requiring the application of a large number – i.e. several thousand – of OSR tiles which are typically supplied in sizes of 40x40mm. These tiles have to be placed and spaced apart precisely to cope with differential expansion and contraction between spacecraft structure and OSR glass.

Bonding of tiles to spacecraft panels is in common practice performed manually and involves processes such as the application of two component silicon adhesives, placement of OSR tiles, filling of interstices between tiles with conductive resin to prevent electrostatic charging and a low pressure temperature controlled adhesive curing cycle. After application often a cleaning step has to be performed to remove excess adhesive from OSR surfaces.⁴

Accordingly, this construction technique results in high radiator cost due to the extensive labor involved and considerable risk for breakage of tiles due to manual handling and cleaning.

In order to improve the state-of-the-art technique a new process has been developed. OSR tiles are automatically bonded using a computer controlled pick-and-place facility on radiator panels equipped with electrically conductive pressure sensitive adhesive tape.

This paper provides in a first part an introduction into the new process and presentation of the pick-and-place facility (Figure 1). The second part of the paper describes the qualification program and tests performed to verify end of life process reliability.

II. Application Process

The OSR application process applied at RUAG Space consists of three main steps:

- 1) Cleaning of radiator surfaces and application of PSA tape
- 2) Precise placement of OSR tiles using the automated pick-and-place facility
- 3) Activation of tape adhesion by an automated rolling process

A. Application of tape

After cleaning of radiator facesheet surfaces an electrically conductive tape is manually applied in strips of 1 inch width separated by 1mm from each other. This gap enables venting of tape intrinsic air and of residual air pockets from tape application.

Electrical conductivity from OSR surfaces to the aluminium facesheets is guaranteed via ITO coated OSR lateral faces.

The tape applied and qualified has long heritage in MLI manufacturing and application of second surface mirror foils. By providing a contact resistance of $<10 \Omega/\text{cm}^2$, the tape has a thickness of 50 μm and a mass of only ~80 grams/m².

With the given weight of the OSR tiles the low mass of the adhesive results in major mass savings compared to standard application processes. While techniques using two component silicon resins might weight more than

650 g/m², radiator surfaces on panels equipped with the herein described process weight ~470 g/m², which corresponds to a considerable mass saving of ~27%.

In addition, the new process does not result in lump adhesive resin material at OSR interstices which has to be manually removed and requires delicate cleaning processes in standard techniques.

B. Automated OSR placement

During tape application radiator panels are fixed on a tilting trolley equipped with a facility interface table which provides an M6 threaded inserts attachment array of 150x150mm. The table has a size of 2500x2700mm, which corresponds to the maximum size of panels that can be automatically equipped with OSR using the RUAG Space developed pick-and-place facility presented in Figure 1.

After tape application the table with the radiator panel attached is inserted into the OSR pick-and-place facility and accurately aligned to the machine main axes. The facility is a 3-axis controlled gantry system, where a precise manipulator takes tiles from a 100 OSR depot, which is manually fed by the operator, and places them on the CAD pre-defined positions on the panel at a precision of ± 0.05 mm.

The machine is equipped with a number of interchangeable manipulator tools which allow placing between one and 100 OSR tiles of 40x40mm at a time. Independent from the selected tool, tiles are placed in a cadence of less than 30 seconds anywhere within the traversing range of the facility manipulator arm.

Apart from restocking of tiles in the OSR depot the pick-and-place process is fully automated and does not require manual interaction.



Figure 1. OSR Pick-and-Place facility at RUAG Space

C. Activation of tape adhesion

To achieve full adhesion of OSR tiles to the underlying tape and panel, pressure has to be applied to the film. By outfitting the facility with a flexible rolling tool a predefined force is applied with a constant velocity rolling process. Subject to radiator complexity rolling is done fully automated or remote controlled by the facility operator.

After activation of tape adhesion the OSR equipped radiator panel is removed from the facility and cleared for product assurance inspection.

III. Qualification Program

Qualification of the new process was a multistep program starting with an entirely manual process which was then transferred to the semi-automated approach detailed herein.

A. Test Campaign

The qualification campaign, as presented in the flowchart Figure 2, is based on thermal- and space environmental exposures followed by electrical, thermo-optical and mechanical material qualification testing.

Samples were thermally cycled in accordance to the requirements of spacecraft development programs between -70°C and +90°C in two exposure campaigns -see paragraph IV. Thermo-optical properties, electrical conductance and OSR tile adhesion were measured of test coupons before and after exposure.

In addition two space environmental exposure campaigns were performed. The first consisted of only electron irradiation selected to test the OSR tile adhesion after intense 15 year GEO representative radiation bombardment.

The second environmental test campaign included 8 year representative GEO exposure with UV, electrons and protons and a subsequent 7 year exposure to electrons and protons. This campaign was intended to test the interaction of OSR tiles with the environment and measure stability of thermo-optical properties and electrical conductance.

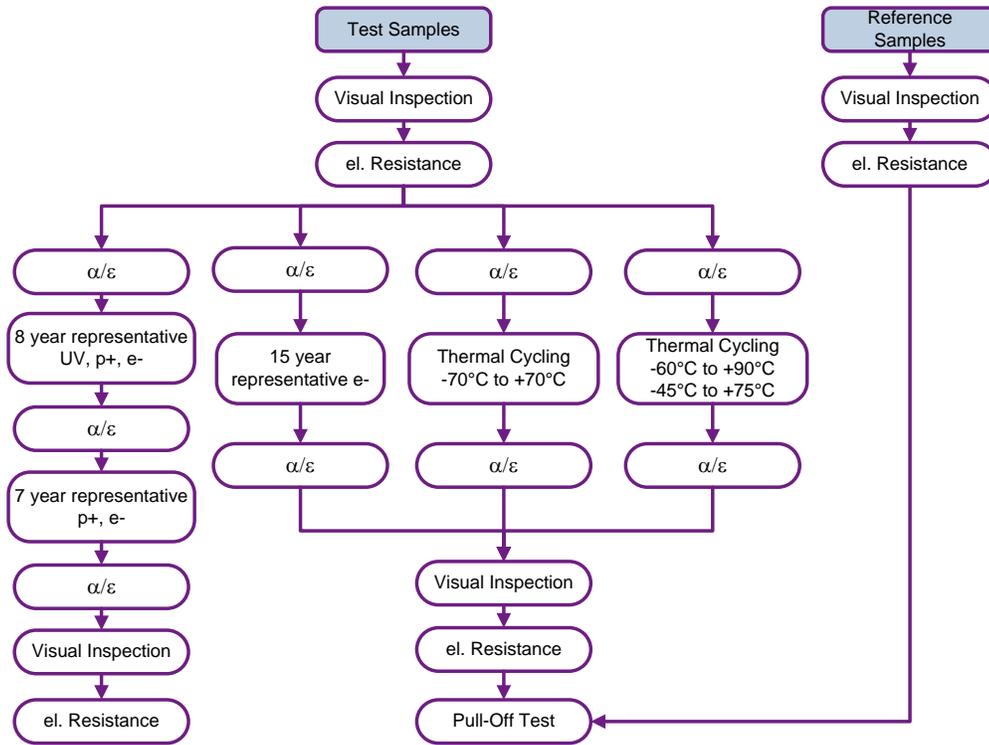


Figure 2. Qualification Test Program

B. Test Materials

All tests were performed with OSR type PS344 of thickness 150µm supplied by QIOPTIQ Space Technology. The OSR type PS344 has a typical solar absorptance of ≤ 0.010 and infrared emittance of ≥ 0.80 . Front-to-back electrical resistance is defined $< 200\text{k}\Omega$.³

Samples were bonded to aluminium facesheets in sizes as required by the testing facility.

IV. Exposures

A. Thermal Cycling

Thermal cycling tests were performed in accordance with ECSS-Q-70-04 –see Ref. 5– at the ESA certified space materials test house Aerospace & Advanced Composites GmbH, Austria.

Two exposure runs were performed in vacuum $< 1 \times 10^{-5}$ mbar. The first covered the spectrum of the low Earth orbit GOCE mission with a temperature cycling envelope between -70°C to $+70^\circ\text{C}$. 100 cycles were performed with a dwell time of 10min.

The second test was performed for the SmallGEO geostationary satellite bus. The temperature program consisted of 100 cycles between -60°C and $+90^\circ\text{C}$ followed by 60 cycles between -45°C and $+75^\circ\text{C}$. The first 100 high temperature cycles were intended to cover possible loss of attitude cases during the nominal 15 year mission, the second 60 cycles were added to cover the nominal temperature environment.

B. Space Environmental Exposures

1. Facility

The facilities named SEMIRAMIS and GEODUR were designed at ONERA for the evaluation of thermal control coatings in a simulated space environment, especially GEO orbits. Their main characteristics are cleanliness -very low organic residual partial pressures in vacuum- and reliability allowing to keep samples in vacuum for several months.

The proton and electron beams are supplied, respectively, by 2.5 and 2.7MV Van-de-Graaff accelerators. The protons are obtained from plasma of pure hydrogen and separated from other charged species by a magnetic mass analysis after acceleration. In order to irradiate the samples, protons are swept across the sample holder surface. In the case of electrons, the beam is diffused through a thin aluminium window.

The solar UV generator is based on 6.5kW short arc Xenon sources, whose spectral distribution in UV is close to that of the sun.

In both facilities, vacuum lower than 1×10^{-6} mbar was obtained after a 1-day pump-down period and 3×10^{-7} mbar at the end of the test.

The sample holder temperature was maintained at 40°C for the duration of the test. Both exposures were conducted in accordance with the relevant standards Refs. 6, 7.

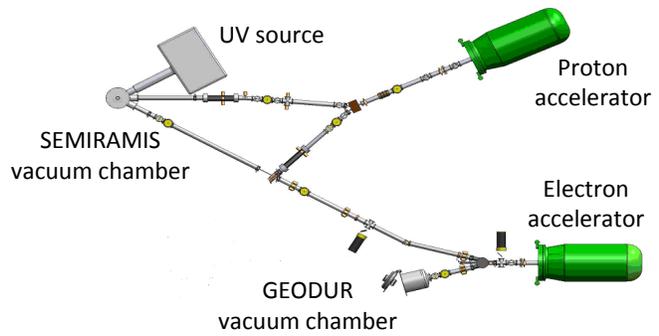


Figure 3. ONERA space environmental exposure facilities

2. Test Conditions

1.1 15-year GEO representative electrons

15-year GEO representative electron irradiation was performed in the GEODUR facility. A dose of 620Mrad was deposited on OSRs with a mean current of $30\text{nA}/\text{cm}^2$ using a 1MeV electron beam with a fluency of $2 \times 10^{16} \text{e}/\text{cm}^2$.

Thermo-optical measurements were performed in air before and after electron irradiation. As 1 MeV electron irradiation mainly affects OSR material thickness of $10 - 1000\mu\text{m}$ this test was intended to measure degradation of the PSA interface and tile adhesion.

1.2 8-year full GEO irradiation and 7-years representative protons and electrons

The test was divided in two steps; 8-years equivalent irradiation with UV, electrons and protons and 7-years equivalent in particles only resulting in a total accumulated irradiation dose of 219.8Grad.

The first step was the UV exposure under 8897 Equivalent Solar Hours (ESH) with solar constants varying between 7 and 9.

On GEO, the dose profile inside a material due to the interaction with trapped electrons and protons decreases rapidly versus the material thickness. Figure 4 shows the space-dose profile calculation (based on trapped particles evaluated with AE8 and AP8 models) corresponding to 15-year in GEO inside a reference material of OSR density $2.7 \text{g}/\text{cm}^3$. Simulation of this profile was performed with one electron energy affecting the material bulk and with two proton energies, which mainly interact with the mirror surfaces.

8-year GEO corresponding electron exposure was conducted at a fluency of $8 \times 10^{15} \text{e}/\text{cm}^2$ of 400keV electrons with a mean current of $13\text{nA}/\text{cm}^2$.

Irradiation with 240keV and 45keV protons was performed at fluencies of $1.6 \times 10^{15} \text{p}/\text{cm}^2$ and $1.6 \times 10^{16} \text{p}/\text{cm}^2$, respectively, corresponding to 8-year GEO proton exposure with a mean current of $25\text{nA}/\text{cm}^2$.

After each of the irradiation steps, solar reflectance measurements were performed in-situ under vacuum.

In the second part of the test, samples were exposed to the following 7 year GEO representative particle environment:

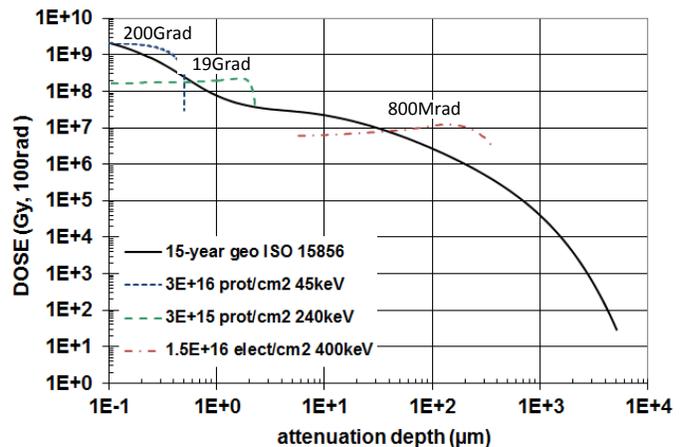


Figure 4. Total dose of 15 year in particles

- 7×10^{15} electrons/cm² of energy 400keV at a mean current of 22nA/cm².
- 1.4×10^{15} protons/cm² of energy of 240keV at a mean current of 25nA/cm².
- 1.4×10^{16} protons/cm² of energy of 45keV at a mean current of 28nA/cm².

Again, solar reflectance measurements were performed in-situ under vacuum after electron and proton irradiations.

V. Electrical Conductivity

Resistance between OSR front surface and sample panel aluminium facesheet was measured using a FLUKE 77 digital multimeter.

In accordance with the OSR specifications the success criteria for front to structure electrical resistance was set <200k Ω .³

BOT measurements revealed considerably better conductance than specified with front to structure resistance values ranging from app. 50 Ω to 5k Ω .

No significant degradation in electrical resistance was measured after thermal or environmental exposures and all data stayed well within the requirement. EOT front to structure resistance values were measured ranging from approximately 50 Ω to 6.5k Ω .

VI. Thermo-Optical Properties

A. Test Set-Up

Reflectance measurements were performed ex-situ in air, with a Perkin Elmer Lambda 1050 spectrophotometer associated with a 150mm integrated sphere. Reflection measurements are corrected by a specular aluminium etalon and balanced with the ASTM E490 solar spectrum. Absorptance α_s was determined by subtracting the integrated reflectance spectrum from unity.

During the 15year exposure program involving UV and particles, solar absorptance was measured in-situ without breaking the vacuum, using a Perkin Elmer Lambda 1050 spectrophotometer with a 60mm integrating sphere. Solar absorptance values were measured with an accuracy of ± 0.005 .

Normal infrared emissivity ϵ_{IR} was measured with an accuracy of ± 0.010 ex-situ with an AZ Technology TEMP 2000A.

All Thermo-optical measurements were performed in accordance to ECSS-Q-ST-70-09C.⁸

B. Measurement Results

1. Solar Absorptance

The variation of solar absorptance α_s of OSR type PS344 due to thermal and environmental exposures is presented in Figure 5.

The BOT value of the pristine material of 0.079 \pm 0.002 is an average calculated from 8 sample measurements taken throughout the test campaign.

Thermal cycling exposure did not reveal significant changes in absorptance with an average of 0.080 \pm 0.002 tested after cycling to -70 $^{\circ}$ C/+70 $^{\circ}$ C.

However, exposure to simulated space environment with electrons, protons and UV leads to increases in solar absorptance. After 15 year GEO equivalent electron exposure an increase of 13% to 0.089 \pm 0.001 was measured.

In-situ measurements of absorptance performed without breaking vacuum during the 8 year GEO irradiation including UV and 7 year GEO representative electron and proton radiation allows distinguishing the influence of radiation types.

An increase of 15% to 0.091 \pm 0.001 was measured after 8897 ESH UV exposure. After the full 8 year equivalent GEO radiation dose, including protons and electrons, absorptance has increased significantly by 63% to

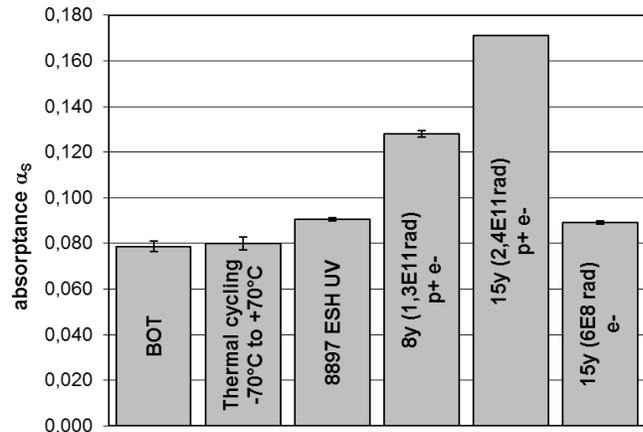


Figure 5. Variation of solar absorptance due to environmental exposure

$\alpha_s=0.128\pm0.002$. Further exposure to additional 7 year GEO representative electron and proton radiation results in an absorbance of 0.171 ± 0.001 , which corresponds to an increase of 117% from BOT.

In summary the above data indicates that both, UV and electron exposures increase absorbance of the tested OSR type. The most significant degradation is however measured after combined electron and proton irradiation, where, after 15 year equivalent GEO exposure, a more than doubling of α_s was observed.

Further, the importance of in-situ testing was underlined by recovery effects that were found to take place in reflectance properties between measurements taken in vacuum and those taken ex-situ in air, where absorbance has recovered to 0.151 ± 0.001 . Absorbance data of the pristine, BOT OSR tiles was not different in in-situ and ex-situ measurements.

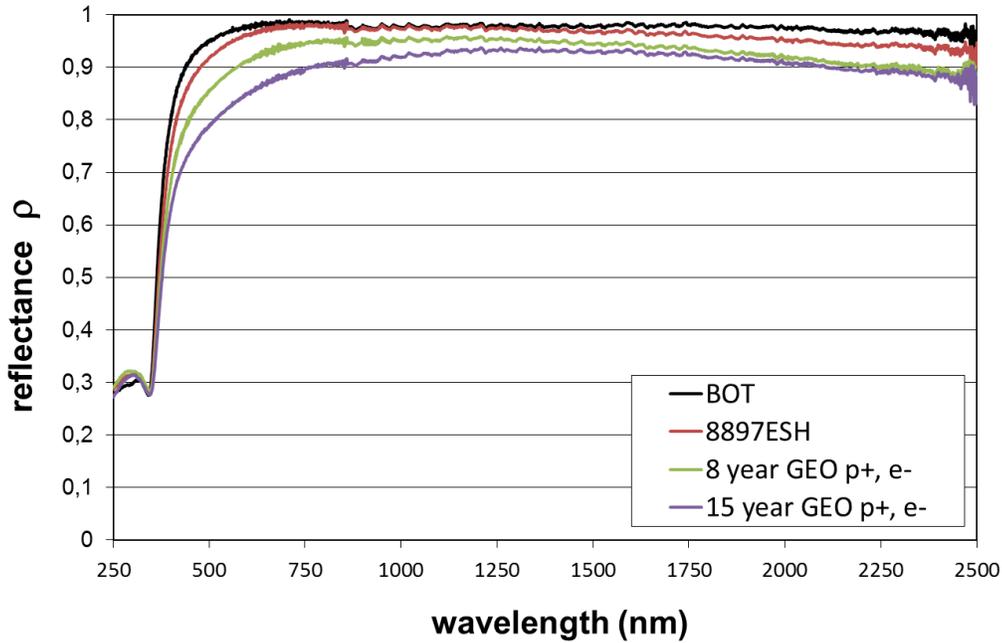


Figure 6. In-situ taken reflectance spectra

Reflectance spectra taken during the 8 year full GEO irradiation and 7 year GEO representative electron and proton radiation are presented in Figure 6.

Decreases are measured in the visible wavelength range between app. 350 and 800nm. Also in the infrared, decreases are observed in reflectance from approximately 0.97 to 0.90 between 800 and 2500nm.

Comparable degradation of OSR absorptivity after environmental exposures are reported in literature. Marco et. al. [Ref. 9] describe an increase in α_s from ~ 0.085 to ~ 0.108 of an ITO coated OSR after 3 year simulated GEO environment including 3336ESH UV, proton and electron irradiation. An increase in absorbance by 0.021 was published by Ding et. al. after irradiation with 15 year GEO representative low energy electrons. Both reports consider a degradation of the ITO top coating as main source for the increase in absorbance.

2. Infrared Emittance

Results of the thermal emittance measurements before and after exposures are presented in Table 1.

While changes in emittance after thermal cycling were within the error of measurement, small increases of 0.003, above the standard deviation of the test, were found after 15 year GEO representative electron exposure. Still this change is also within the measurement uncertainty.

A significant increase of 0.018, even above the measurement accuracy of the equipment, is measured in ϵ_{IR} after exposure to 8 year full GEO irradiation followed by 7 year GEO representative electron and proton radiation.

No literature reports were found for this phenomenon. Possible explanations could range from microscopic surface roughening by proton sputtering, oxidation in air after vacuum exposure or surface contamination during testing.

Table 1. Evolution of infrared emissivity

Test	ϵ_{IR} BOT	ϵ_{IR} EOT	$\Delta\epsilon_{IR}$
Cycling -70°C/+70°C	0.797±0.004	0.800±0.006	0.003
15y GEO e-	0.815±0.001	0.818±0.001	0.003
15y GEO UV, e-, p+	0.795±0.001	0.813±0.001	0.018

VII. Pull-Off Testing

A. Test Set-Up

Pull-off testing was performed in ambient conditions using a custom made tensile test facility equipped with a 500N load cell. After exposure 5mm aluminum interface plates of size 40x40mm were bonded on each OSR using 966PSA. By connecting a steel wire to the center of the plate the pull-off force was applied.

B. Success Requirement

Including margin the mass of one OSR with conductive PSA is 1 gram. With the assumption of a maximum acceleration of 200g including tolerances and safety margins the minimum pull-off strength required to withstand launch loads is 2N.

C. Test Results

Pull-off test results of pristine, BOT, samples are compared to data measured after thermal- and environmental exposure and presented in Figure 7. A minimum of three samples were tested.

The average force for OSR pull-off is 75N at BOT, which corresponds to a margin of safety of 37 to the required minimum strength of 2N.

After thermal cycling to -70°C/+70°C or -60°C/+90°C and -45°C/+75°C pull-off forces measured were 67N and 69N, respectively. This corresponds to a decrease of ~10% but a residual MOS of approximately 34.

Pull-off strength after exposure to 6×10^8 rad electron irradiation was measured 64N, which still corresponds to a MOS of 32 after full 15year GEO mission duration.

The data show that a large margin of safety is given even after exposures to loads which exceed launch forces. Considerably lower forces are to be expected in orbit during nominal satellite operation.

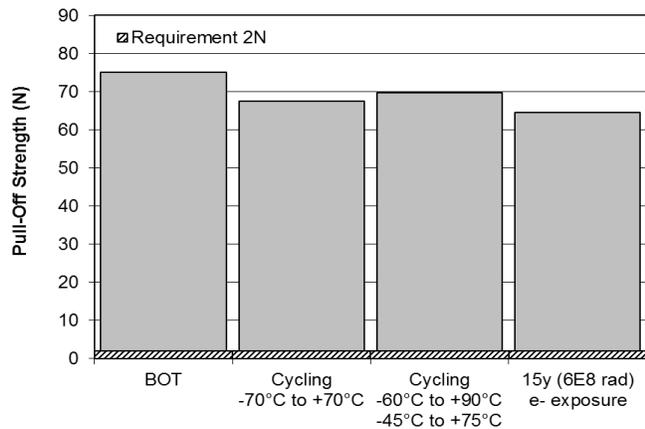


Figure 7. Variation of pull-off strength in dependence of environmental exposure

VIII. Conclusion

A sophisticated process for OSR application has been developed at RUAG Space, which combines bonding of tiles with electrically conductive PSA and precise placement using an automated pick-and-place facility.

After manual application of PSA, up to 100 OSR tiles at a time are automatically applied on radiator panels of sizes up to 2500x2700mm in a 3-axis controlled gantry system and at a cadence of less than 30 seconds. A force controlled automated rolling process is employed to activate the adhesive and achieve final adhesion of OSR.

Qualification of the process was performed by thermal cycling tests and 15 year GEO representative space environmental exposures.

While thermal cycling tests triggered no changes, thermo-optical property measurements revealed an influence of UV or electron irradiation and considerable increase of absorptance by 117% after 15 year GEO representative proton and electron exposure.

Pull-off tests showed that an average force of 75N has to be applied to detach automatically bonded OSR, which corresponds to a margin of safety of 37 to the required minimum strength of 2N. Small decreases in pull-off forces are measured after thermal and environmental exposures but safety margins are still above 30. No influence of exposures on OSR electrical conductivity was measured.

Since successful completion of the qualification campaign a number of spacecraft have been equipped with OSR using the new process. OSR bonded with conductive PSA by RUAG Space have gained flight heritage on GOCE, VenusExpress and GAIA missions, and the automated application facility has been proven efficiency when radiators were equipped for the SmallGEO and Exomars programs.

Acknowledgments

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