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# TESTING AND QUALIFICATION OF A SEMI-AUTOMATED BONDING PROCESS FOR OPTICAL SOLAR REFLECTORS

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## ABSTRACT

Optical Solar Reflectors (OSR) are highly efficient thermal emitter tiles with a typical size of 40x40mm. Spacecraft radiator panels are covered with these tiles to reduce absorption of solar radiation and to dissipate heat of internal payloads into deep space.

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 test and qualification campaign of a new 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 filled silicone resins, the new process is resulting in radiator surfaces with up to 27% lower mass.

The pick-and-place facility will be introduced, the process qualification campaign discussed. Results of tensile- and thermo-optical testing of exposed samples compared to pristine materials will be shown.

## 1. 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.

They 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  $\alpha/\epsilon$ , where  $\alpha$  is the solar absorption coefficient and  $\epsilon$  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 m<sup>2</sup> requiring the application of a large number – i.e. several thousand – of 40x40mm OSR tiles. 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 labour involved and a 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.

## 2. APPLICATION PROCESS

The RUAG Space OSR application process 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



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

## 2.1. Application of tape

After cleaning of radiator facesheet surfaces the electrically conductive tape is manually applied in strips of a width of 1 inch 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  $50\mu\text{m}$  and a mass of only  $\sim 80 \text{ grams}/\text{m}^2$ .

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  $650 \text{ gram}/\text{m}^2$ , radiator surfaces on panels equipped with the herein described process weight  $\sim 470 \text{ gram}/\text{m}^2$ , which corresponds to a considerable mass saving of  $\sim 27\%$ .

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.

## 2.2. Automated placement of OSR

During tape application radiator panels are fixed on a tilting trolley equipped with a facility interface table which provides an attachment array of  $150 \times 150 \text{ mm}$  of M6 threaded inserts. The table has a size of  $2500 \times 2700 \text{ mm}$ , 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 and places them on the CAD pre-defined positions on the panel at a precision of  $\pm 0.05 \text{ mm}$ .

The machine is equipped with a number of interchangeable manipulator tools which allow placing between one and 100 OSR tiles at a time. In dependence of 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.

## 2.3. 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.

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

## 3. QUALIFICATION PROGRAMM

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

### 3.1. Test Campaign

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

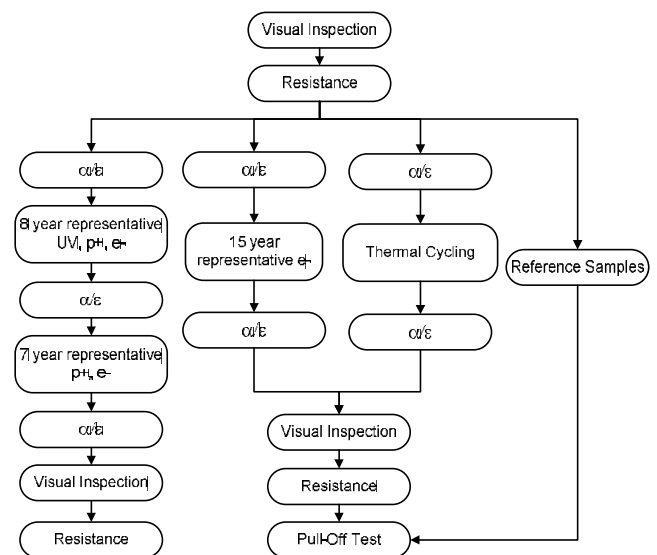


Figure 2. Qualification Test Flow

Samples were thermally cycled in accordance to the requirements of spacecraft development programs (see chapter 4). Thermo-optical properties, electrical conductance and OSR tile adhesion were measured of pristine (beginning of test, BOT) test coupons and after exposure (end of test, EOT).

In addition two space environmental exposure campaigns were performed. The first consisted of solely 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.

### 3.2. Test Materials

All tests were performed with OSR type PS344 of thickness  $150\mu\text{m}$  supplied by QIOPTIQ Space Technology.

The OSR type PS344 has a typical solar absorptance of  $\leq 0.010$  and infrared emittance of  $\geq 0.80$ . 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.

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

The second test was performed for the SmallGEO geostationary (GEO) satellite bus. The temperature program consisted of 100 cycles between  $-60^\circ\text{C}$  and  $+90^\circ\text{C}$  followed by 60 cycles between  $-45^\circ\text{C}$  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.

## 5. SPACE ENVIRONMENTAL EXPOSURES

### 5.1. 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 (samples in vacuum for several months).

The proton and electron beams are supplied, respectively, by 2.5 and 2.7 MeV 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  $1 \times 10^{-6}$  mbar was obtained after a 1-day pump-down period and  $3 \times 10^{-7}$  mbar at the end of the test. The sample holder temperature was maintained at  $40^\circ\text{C}$  for the duration of the test.

Both exposures were conducted in accordance with the relevant standards Ref [6] and Ref [7].

### 5.2. Test Conditions

#### 5.2.1 15-year GEO representative electrons

15-year GEO representative electron irradiation was performed in the GEODUR facility. A dose of 6.2MGray was deposited on OSRs with a mean current of  $30\text{nA}/\text{cm}^2$  (Figure 3).

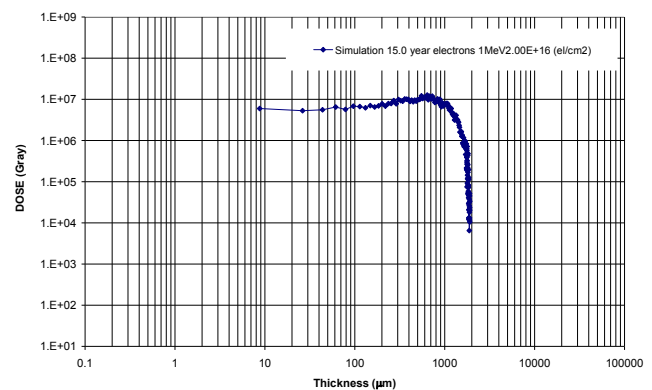


Figure 3. 6.2MGray obtained with 1MeV electron beam with a fluency of  $2 \times 10^{16} \text{ e}/\text{cm}^2$ .

Thermo-optical measurements were performed in air before and after electron irradiation.

As electron irradiation mainly affects material thickness of 10 – 1000  $\mu\text{m}$  (see Figure 3) this test was intended to measure degradation of the PSA interface and tile adhesion.

#### 5.2.2 8-year full GEO irradiation and 7-years representative protons and electrons

The test was divided in two steps; 8-years UV, electrons and protons and 7-years in particles only.

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

On GEO, the dose profile inside a material due to the absorption of 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 density of OSR of  $2.7 \text{ g}/\text{cm}^3$ . Simulation of this profile was performed with one electron energy affecting the material bulk and with two proton energies which mainly interact with the surface of the OSR.

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 13nA/cm<sup>2</sup>.

Irradiation with 240keV and 45keV protons was performed at fluencies of 1.6x10<sup>15</sup> p+/cm<sup>2</sup> and 1.6x10<sup>16</sup> p+/cm<sup>2</sup>, respectively, corresponding to 8-year GEO proton exposure with a mean current of 25nA/cm<sup>2</sup>.

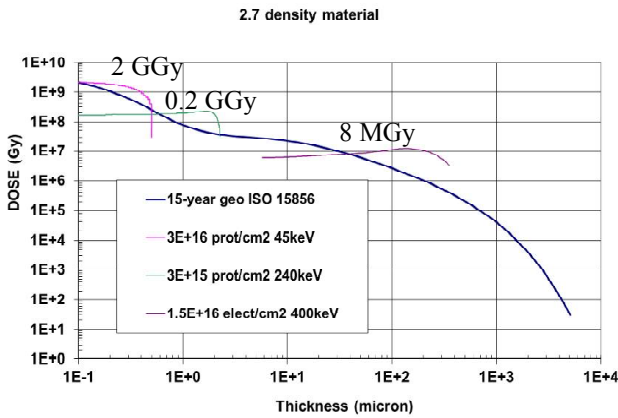


Figure 4. Total dose of 15-year in particles.

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:

- 7x10<sup>15</sup> electrons/cm<sup>2</sup> of energy 400keV at a mean current of 22nA/cm<sup>2</sup>.
- 1.4x10<sup>15</sup> protons/cm<sup>2</sup> of energy of 240keV at a mean current of 25nA/cm<sup>2</sup>.
- 1.4x10<sup>16</sup> protons/cm<sup>2</sup> of energy of 45keV at a mean current of 28nA/cm<sup>2</sup>.

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

## 6. ELECTRICAL RESISTANCE

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

In accordance with the OSR specifications a success criteria was defined of front to structure electrical resistance <200kΩ [3].

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

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 found ranging from approximately 50Ω to 6.5kΩ.

## 7. THERMO-OPTICAL PROPERTIES

### 7.1. Test Set-Up

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

Solar absorptance was tested ex-situ in air, with a Perkin Elmer Lambda 1050 spectrophotometer associated with a 150mm integrated sphere. Reflexion measurements are corrected by a specular aluminium etalon and balanced with the ASTM E490 solar spectrum. Absorptance  $\alpha_S$  is 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  $\pm 0.005$ .

Normal infrared emissivity  $\epsilon_{IR}$  was measured ex-situ with an AZ Technology TEMP 2000A with an accuracy of  $\pm 0.010$ .

### 7.2. Test Results

#### 7.2.1 Solar Absorptance

The stability of solar absorptance  $\alpha_S$  of OSR type PS344 in dependence of thermal and environmental exposures is presented in Figure 5.

The BOT value 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°C/+70°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 full GEO irradiation 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 exposure, including protons and electrons, absorptance has increased significantly by 63% to  $\alpha_S=0.128\pm0.002$ . Further exposure to additional 7 year GEO representative electron and proton radiation results in  $\alpha_S=0.171\pm0.001$ , which corresponds to an increase of 117% from BOT.

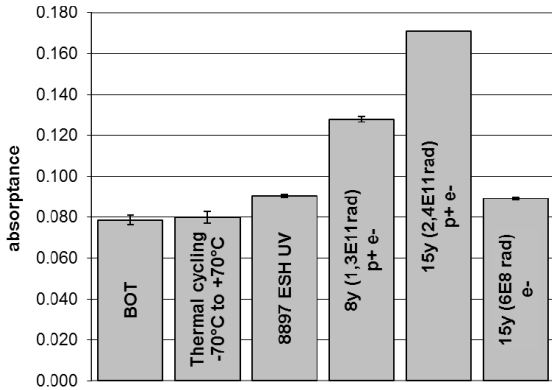


Figure 5. Variation of solar absorptance in dependence of environmental exposure

In summary the above data indicates that both, UV and electron exposures increase absorptance 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  $\alpha_s$  was observed.

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.

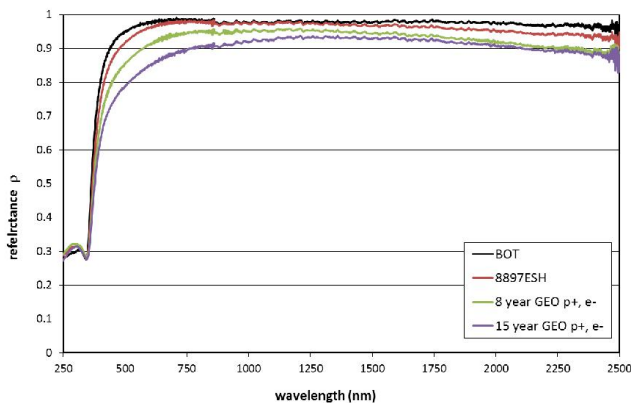


Figure 6. Reflectance spectra degradation

Increases in absorptance after environmental exposures are also reported in literature. Marco et. al. [9] describe an increase in  $\alpha_s$  from  $\sim 0.085$  to  $\sim 0.108$  of an ITO coated OSR after 3 year simulated GEO environment including 3336ESH UV, proton and electron irradiation. An increase in absorptance of  $\Delta\alpha_s=0.021$  was published by Ding et. al. [10] after irradiation with 15 year GEO representative low energy electrons. Both papers consider degradation of the ITO top coating as main source for the increase in absorptance.

## 7.2.2 Infrared Emittance

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

While no changes in emittance were found after thermal cycling, small increases of 0.003, above the standard deviation of the test, were found after 15 year GEO representative electron exposure.

A significant increase of 0.018, even above the measurement accuracy of the equipment, is measured in  $\epsilon_{IR}$  after exposure to 8 year full GEO irradiation and 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	$\epsilon_{IR}$ BOT	$\epsilon_{IR}$ 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

## 8. Pull-Off TESTING

### 8.1. 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 aluminium interface plates of size 40x40mm were bonded on each OSR using 966PSA. By connecting a steel wire to the centre of the plate the pull-off force was applied.

### 8.2. 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.

### 8.3. 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.

The average BOT force for OSR pull-off is 75N, which corresponds to a margin of safety (MOS) 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  $\sim 10\%$  but a residual MOS of approximately 34.

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

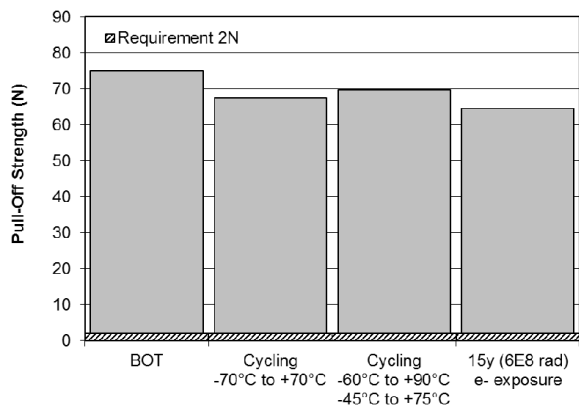


Figure 7. Variation of pull-off strength in dependence of environmental exposure

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.

## 9. SUMMARY and CONCLUSIONS

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 was measured on the electrical conductivity between ITO coated OSR surface and structure.

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.

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