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Assembly and Testing of a Thermal Control Component Developed in Brazil

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ABSTRACT: The optical solar reflector is basically a mirror of second surface with low absorptivity/emissivity ratio and negligible degradation in the space environment, which makes it an excellent coating for thermal control of satellites. It works as a radiator and is used in particular parts of the external surfaces of the satellites in order to reject the undesirable heat to the deep space. In the Brazilian Space Programs, the radiators of the satellites are generally painted with special white paints in order to reject heat instead of the use of optical solar reflector. The problem of white-ink radiators is the high degradation of the thermo-optical properties that happen over the useful lives. Thus, a process of manufacturing and assembly of optical solar reflector was developed in Brazil. To validate this process in terms of mechanical and thermal properties, 3 types of optical solar reflector radiators were manufactured, and their absorptivity and emissivity properties at the temperature of 23 °C were measured. Optical solar reflector coupons were mounted on aluminum plates to perform vibration, thermal vacuum and thermal-shock tests. A study was also done to optimize the thickness of the glue to fix the structure of the satellite on the optical solar reflector. It showed an excellent environmental stability and maintained its thermo-optical characteristics after the tests.

KEYWORDS: Solar radiator, Satellite thermal control, Solar absorptivity, Emissivity.

INTRODUCTION

Artificial satellites are equipment sent into space in order to perform a certain task, such as: meteorological studies, telecommunications, data collection for scientific studies, etc. In the space environment, the satellite is exposed to extreme thermal conditions such as solar radiation, radiation that comes from the Earth (albedo and infrared), and a strong heat sink that is deep space, where the fund temperature is 4 K. Therefore, the satellites are supposed to be protected from all thermal loads from space.

To protect the satellites, they are externally coated with thermal-control materials in order to isolate themselves of the external environment. Due to the absence of convective medium, heat exchange between the satellite and the space environment is made exclusively by radiation. One of the materials commonly used to coat the satellite is the thermal blanket known as multi-layer insulation (MLI) (Nagano *et al.* 2011). However, this coating cannot completely insulate the satellite, because of several devices which, by Joule effect, generate heat inside of the satellite. This heat raises the internal temperature, reaching above the acceptable limits, and it is necessary to eliminate the excess of heat through openings in the blanket. These openings act as their heat rejection areas, radiating the heat of the equipment into deep space. Figure 1 shows the satellite CBERS-2B and the MLI with the respective openings for rejection of heat to deep space.

As all environments in satellites, the interaction is by radiation, and there is a high dependency of the thermal coating properties as a function of temperature. Thus, these heat rejection areas, known as radiators, are coated with a material which has

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good properties of emissivity and absorptivity (when exposed to direct solar radiation and albedo).

The Instituto Nacional de Pesquisas Espaciais (INPE) and the Instituto Tecnológico de Aeronáutica (ITA) have developed, manufactured, and qualified an optical solar reflector (OSR) to be used for thermal control of satellites. The OSR is a coating to be used as radiator for certain external surfaces of satellites. The aim is to reject heat that occurs in positions where it appears the incidence of solar radiation (direct and/or albedo).

In the design, thermal control coatings have to be resistant to the degradation effects of the space environment. Due to this degradation, there is an increase in the solar absorptivity and, thus, an increase occurs in the internal temperature of the satellite along its orbital life. The temperatures may exceed acceptable values, which can cause serious damage for equipment pieces in the satellite, consequently reducing the life of the mission.

The OSR-type heat radiators, as well as the white-ink radiators, are passive and used for thermal control of satellites. One of their characteristics is to have a lower absorptivity (α_s) in the solar band if compared to the white-ink radiators, as well as a high emissivity (ε), which means that they can reject heat from the interior of the satellite to the deep space. The main feature is to present an extreme low degradation of thermo-optical properties if compared to other thermal control coatings (Gilmore 1994; Marshall and Breuch 1968).

As previously mentioned, the OSR is basically a mirror of second surface. It consists of a layer of thin silver film that is deposited on a surface of high-quality glass coverslip. A high ε in the infrared spectrum is related to the glass coverslip, which is transparent in solar band and substantially opaque in the infrared (spectrum of wave length below 4.5 μm) (Marshall and Breuch 1968). Furthermore, the thickness of the glass layer also influences the ε value. The low $\boldsymbol{\alpha}_s$ in the solar spectrum is related to the thin silver film deposited on the glass coverslip (Greenberg *et al.* 1967).

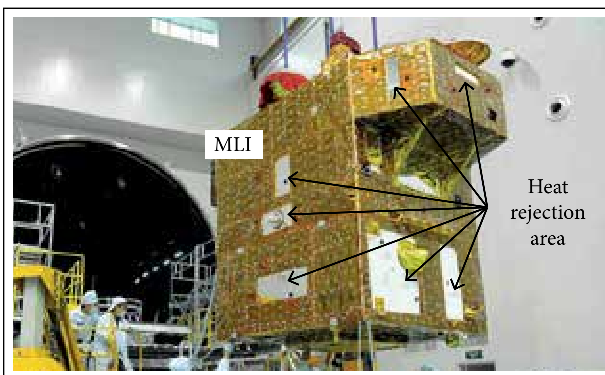

Figure 1. Satellite CBERS-2B and its heat rejection areas in the MLI.

What differs the OSR from other passive radiators is its negligible thermo-optical degradation of properties in relation to: atomic oxygen, protons, free electrons, and ultraviolet radiation. In addition, the OSR has a low degradation factor in relation to volatile organic photo-depositions that are generated by the outgassing from the satellite's internal components and products of the satellite's thrusters. that are generated by the outgassing from the satellite's internal components and products of the satellite's thrusters.

In this study, it was used a borosilicate glass with a thickness of 120 μm and dimension of 20 × 40 mm, supplied by the Shanghai Institute of Space Power Sources, in China. This material is doped with Cerium to avoid the appearance of color center in the glass surface due to ultraviolet radiation. These coverslips were originally used as a protective coating of the Brazilian satellite solar cells, and this material has demonstrated a good environmental stability in space flight.

EXPERIMENT

Silver has low adhesion to glass due to its lack of interaction with the active oxygen in the substrate (Benjamin and Weaver 1961). For greater adhesion between the substrate and the silver film, it was deposited an interface layer to increase this adhesion. As the metal interface might change the OSR of the α_s, 3 kinds of sample sets were made, each one with different interfaces. Thus, there was the possibility to analyze which of the 3 interfaces might have the best adhesion for the thin film of silver and the best a_s/ε relation. Then, the adopted interface materials were: chromium (Iacovangelo *et al.* 2003), aluminum, and magnesium fluoride (MgF_2) (Tanzilli and Gebhardt 1996). In order to avoid the oxidation of silver in the terrestrial environment, a layer of Cr was deposited to protect the silver layer. Thus, the final mirror was composed of 3 layers (Fig. 2).

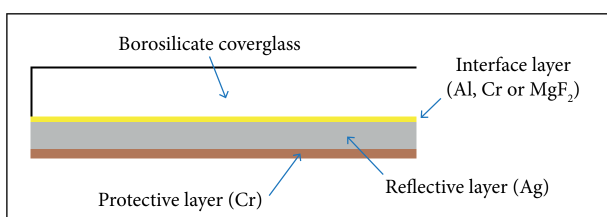

Figure 2. Representation of the layers deposited on the substrate.

Table 1. Borosilicate samples with their respective interfaces.

Substrate	Quantity	Interface material	Reflective metal	Metal protection
Borosilicate SiO_xN_y	14	MgF_2 (100 Å)	Ag (3,000 Å)	Cr (200 Å)
Borosilicate SiO_xN_y	14	Al (60 Å)	Ag (3,000 Å)	Cr (200 Å)
Borosilicate SiO_xN_y	14	Cr (60 Å)	Ag (3,000 Å)	Cr (200 Å)

To conduct the proposed experiment, 3 series of deposits were made on the borosilicate coverslip glass. The study about the deposits was based on the verification of optical and thermo-mechanical properties of the OSR for different interfaces. Therefore, it was deposited on each set of substrates (Fig. 2; the thicknesses are described in Table 1) The layers of the films on the substrate surfaces were made with an apparatus which deposits thin films, called electron beam.

THERMO-OPTICAL PROPERTY MEASUREMENTS

For a thermo-optical surface to be considered a good passive radiator, its emissivity in the infrared spectrum has to be the highest as possible, and its absorption in the solar spectrum, the lowest. In this paper, the data from α_s and ε were obtained from samples of OSR with different interfaces; so, it was possible to identify which sample had the best α_s/ε ratio. To measure these properties, a Gier Dunkle Device was used for: a) normal solar absorptivity α_s, which was done by the MS251 Solar Reflectometer; b) hemispherical emissivity ε, by DB100 Infrared Reflectometer. Table 2 shows the measurements for the 3 types of interfaces in the OSR. Initial measures have highlighted the differences among the values of the α_s for different samples.

Table 3 shows the ε values. In all 3 cases, no significant differences were detected among the samples. What could be observed is the following: the interface layer deposited has high influence on α_s values, but it has low influence on the values of emissivity in infrared spectrum (ε_{IR}). In this test, it can be concluded that the OSR with the best $\alpha_s/\varepsilon_{IR}$ ratio was the aluminum interface, with a value of $\varepsilon_{IR} = 0.810$ and $\alpha_s = 0.026$.

Table 2. Solar absorptivity for 3 interface types on the OSR.

Cover slip interface	Normal solar absorptivity (α_s)
MgF_2	0.051 ± 0.005
Al	0.026 ± 0.005
Cr	0.237 ± 0.006

Table 3. Data emissivity of 3 types of OSR.

Cover slip interface	Hemispherical emissivity (ε)
MgF_2	0.812 ± 0.005
Al	0.810 ± 0.006
Cr	0.814 ± 0.005

APPLICATION METHODS FOR MATERIAL EVALUATIONS

The OSR with each interface type was glued on 3 aluminum plates, each one with dimensions of 150 × 150 × 10 mm and mass of 800 g. Each plate contained 6 coverslips with different types of interface (Fig. 3). The total mass of the 3 coupons was 2.4 kg, approximately.

For the OSR to be fixed on the aluminum plates, it was used the Dow Corning® glue RTV566, a qualified resin-based silicon for space. This glue was used for having a high elasticity, keeping its mechanical properties at high temperature gradients, and presenting low rates of outgassing at low pressures.

Each thickness of the glue, used to join the OSR to the aluminum plates, was calculated. The development of an equation was based on Volkersen's formulation, which was expanded to Goland and Reissner (Chen and Nelson 1979). This equation takes into account the thermal expansion, elastic modulus of each material (glass and aluminum), and the shear modulus of the adhesive.

Another important consideration is that the shear stress is equal to 0 at the center of the assembly and increases gradually to the edge. Typically, the maximum shear stress occurs at the end of the bond and it is the item of most concern. Figure 4 shows how the expansion of the materials joined by bonded joints would be studied.

Equation 1 provides the maximum tension applied to the glue due to the thermal expansion of the materials (glass + aluminum). If this stress is higher or equal to the shear stress of the adhesive, it can break.

$$\tau_{máx} = \frac{(\omega_2 - \omega_1)\Delta TG}{a \cdot \left[\frac{G}{a}\left(\frac{1}{E_1 b_1} + \frac{1}{E_2 b_2}\right)\right]^{\frac{1}{2}}} \cdot \tanh\left\{x\left[\frac{G}{a}\left(\frac{1}{E_1 b_1} + \frac{1}{E_2 b_2}\right)\right]^{\frac{1}{2}}\right\} \quad (1)$$

where: τ_{max} is the glue maximum stress; ω is the linear dilatation coefficient; ΔT represents the temperature gradient; G is the glue shear module; a means glue thickness; E_1 is the Young's modulus for glass; b_1 is the glass thickness; E_2 is the Young's modulus for aluminum; b_2 is the plate thickness; x is the maximum distance from the center to the edge (where the diagonal of the square center is).

Figure 5 shows the curve that relates the maximum stresses for each thickness of imposed glue. It was obtained by a Matlab program, developed in this study by using the shear strength data from the manufacturer. In the case of RTV566 glue, the limit pressure of maximum rupture is up to 3 MPa (provided by theoretical calculation). Therefore, in Fig. 5, it is observed that, for borosilicate, the theoretical thickness is extremely small, which shows to be highly-elastic adhesive, suitable for the space requirements.

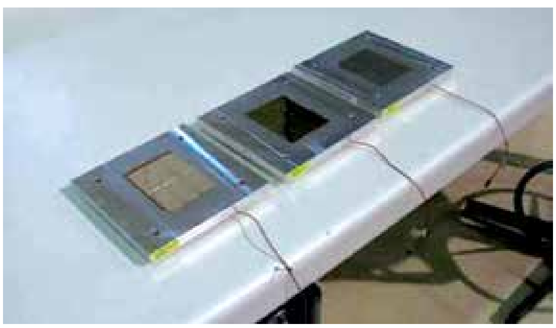

Figure 3. OSR coupons used in the environmental tests.

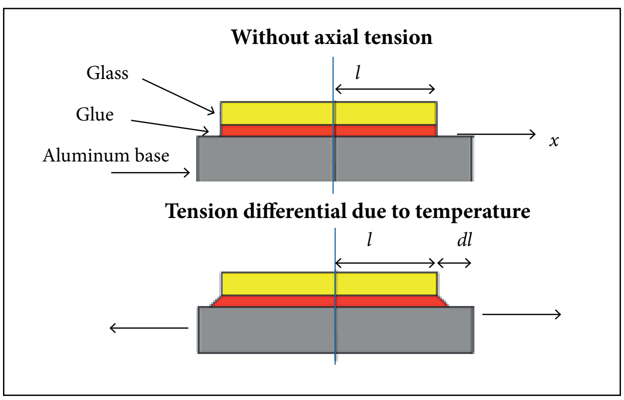

Figure 4. Differential expansion in plates. *dl*: gap relative to the distance *l* for dilations between the glass and the aluminum base.

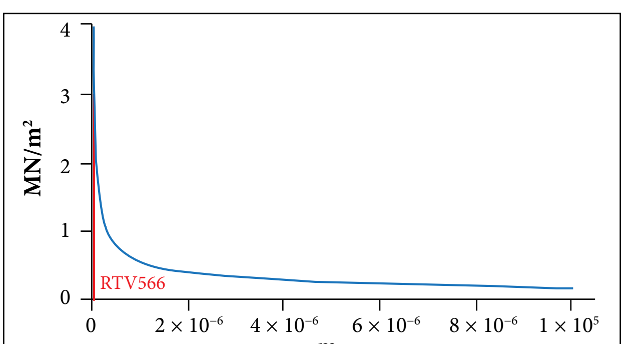

Figure 5. Maximum tension to which the glue was requested in relation to its thickness.

The thickness of adhesive used was between 0.04 and 0.06 mm (measurement made through a device, with ±0.01 mm of error). In order to ensure uniformity in the glue thickness, a fabric screen of 44 wires/cm was used. Figure 6 illustrates the bonding process that ensures the glue thickness. To ensure a good uniformity of the glue under OSR, a weight was evenly placed on the OSR after gluing.

Figure 6. Printing screen being used to apply the RTV566 on aluminum plates.

ENVIRONMENTAL TESTS

RANDOM VIBRATION TEST

The samples were subjected to random vibration according to the levels specified by the MIL-STD 883 — Method 2026 — K condition (Table 4). This test is intended to check the performance and mechanical strength of the bonding of the coverslips on OSR aluminum plate as well as the strength of adhesion of thin films of metal deposited on the borosilicate. This level was imposed for qualification of the OSR as a component.

The sets of sample (OSR + aluminum plate) were installed on the electromechanical shaker (Fig. 7). To monitor the test, acceleration sensors were installed. One sensor was installed on the underside of the center of each coupon, 3 in total, focused on measuring the direction normal to the OSR. An additional sensor was installed in the circular adapter plate test of the set to the head of the electromechanical vibrator which belongs to

Table 4. Specification of random vibration test for the OSR.

Frequency range (Hz)	Level
5 to 100	+6 dB/ILO
100 to 1,000	1.5 g^2/Hz
1,000 to 2,000	−6 dB/ILO
Effective acceleration	44.8 g_{rms}
Duration	15 min
Direction	Normal to the ORSs plane

the Laboratório de Integração e Testes (LIT) at INPE in order to control the applied excitation function.

The maximum excitation applied was 46.2 g_{rms}. The responses have reached in 53.1 g_{rms} for Cu; 55.5 g_{rms} for Al and 56.6 g_{rms} for MgF_2, considering from the bottom plate. It is possible to verify that the 3 interface layers showed excellent adhesion of the silver film to the borosilicate glass after the vibration tests. There was no delaminating of the silver from the glass surface. Furthermore, visual inspection was done, and it was found that there were no other damages, neither in the OSR, nor in the bonding.

Figure 7. Set of coupons installed for vibration testing.

THERMAL-VACUUM TEST

The test in the thermal-vacuum chamber simulates the space environment, in which the satellite will be exposed. For this test, it was used the 250 L # 1 thermal-vacuum chamber, which has a thermal shroud with temperature control operating from −180 to +150 °C and vacuum up to 10^{-7} Torr. This chamber is part of the Thermal-Vacuum Laboratory (TVL) at the LIT/INPE. The infrastructure and test setup are presented in Fig. 8.

The boundary conditions of the test were taken from the specification for the solar cells, from the classification of the AMAZON satellite program (Nagano *et al.* 2011). These conditions present the exposure time to the maximum and minimum pressure levels as well as the quantity of temperature cycles. The specification of the test is shown in Table 5.

Figure 8. Coupons inside the LIT Thermal-Vacuum Chamber #1.

Table 5. Parameters for the test in thermal-vacuum chamber.

Test parameters	Data
Number of cycles	4
Soak time	4 h
Maximum temperature	90 ± 5 °C
Minimum temperature	−90 ± 5 °C
Vacuum chamber pressure	Below 10^{-5} Torr

The use of these coupons previously used in vibration tests served as a method to check for potential problems that could arise from the vibration test (satellite launch simulation). Thus, any problem could be magnified during the thermal vacuum test and then could be checked after this.

This test aimed to verify possible cracks caused by OSR differential thermo-dilation, delamination of thin films of the metal borosilicate coverslip glass, as well as problems related to assembly with air bubbles in the glue, which could expand due vacuum and damage the radiator.

As the thermal-vacuum test setup, 2 thermocouples (type T) were installed on each coupon in order to provide the individual temperatures. These thermocouples worked to guaranty the parameters for the temperature control system of the chamber during the test. After installation of the thermocouples, coupons were installed inside the thermal-vacuum chamber.

What differs the OSR from other passive radiators is its negligible thermo-optical degradation of properties in relation to: atomic oxygen, protons, free electrons, and ultraviolet radiation. In addition, the OSR has a low degradation factor in relation to volatile organic photo-depositions

Figure 9 shows the simulated curve profile during the thermal-vacuum test. The test began at the hot level in order to take advantage of the temperature of the coupons. This procedure aimed at reducing the duration of the test, facilitating the chamber operation (Almeida *et al.* 2006).

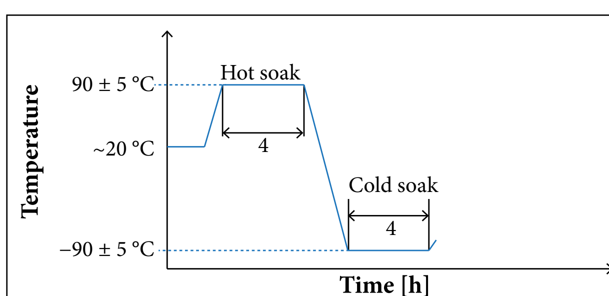

Figure 9. Theoretical curve for test in thermal-vacuum chamber.

Figure 10 shows the graph of the temperature in each specimen during the hot and cold cycles. At the end of each cycle, only a merely operational stop occurred in the thermal cycling, without compromising the vacuum pressure.

At the end of the thermal vacuum test, a visual inspection was performed, and no damage was observed, neither in the OSRs, nor in the bonding. With this test, one can conclude that the OSR was successfully qualified according to the AMAZON program.

THERMAL-SHOCK TEST

The thermal-shock test is an experimental method to check possible cracks on the glass and/or delaminating problems on the metal film due to high gradients of temperature imposed in the samples. For this test, it was used a thermal-shock chamber Thermotron Model ATS-320-V-10-705 LIT/INPE.

The minimum and maximum thermal-shock limits were imposed according to predicted temperature levels for the OSR, once in orbit. Temperatures about 90 °C were set for the hot cases and −90 °C for the cold ones. The number of cycles for test was 80 thermal profiles. These cycles were based on the qualification process for solar cells of the AMAZON satellite program (Instituto Nacional de Pesquisas Espaciais 2013) as well as on MIL-STD-1540B military standard. The qualification parameters for the thermal-shock test are presented in Table 6.

For the thermal-shock test, all thermocouples of the thermal-vacuum test described before were used. With these thermocouples, it was possible to measure the extreme temperatures and thermal transients of the coupons during the test.

The control of the thermal-shock chamber was directly connected with the measurements of the thermocouples. Thus, such temperatures were utilized to monitor the operation of the thermal-shock chamber elevator. When the coupons reached in a determined temperature level, the elevator was activated to take the coupons to the next compartment, and so on. Figure 11 shows the thermal-shock chamber with the coupons exposed in its elevator.

Figure 12 shows the 80 cycles performed in the coupon qualification test. In this figure, the developed temperature profile in the coupons is presented. After testing, visual inspection was performed on the samples, and no failure was observed.

Furthermore, visual inspections were done. It was observed there was not any damage, neither in the OSR, nor in the bonding.

Table 6. Parameters of the thermal-shock test.

Test parameters	Data
Number of cycles	80
Maximum temperature	90 ± 5 °C
Minimum temperature	−90 ± 5 °C

Figure 11. Coupons placed in the thermal-shock chamber elevator.

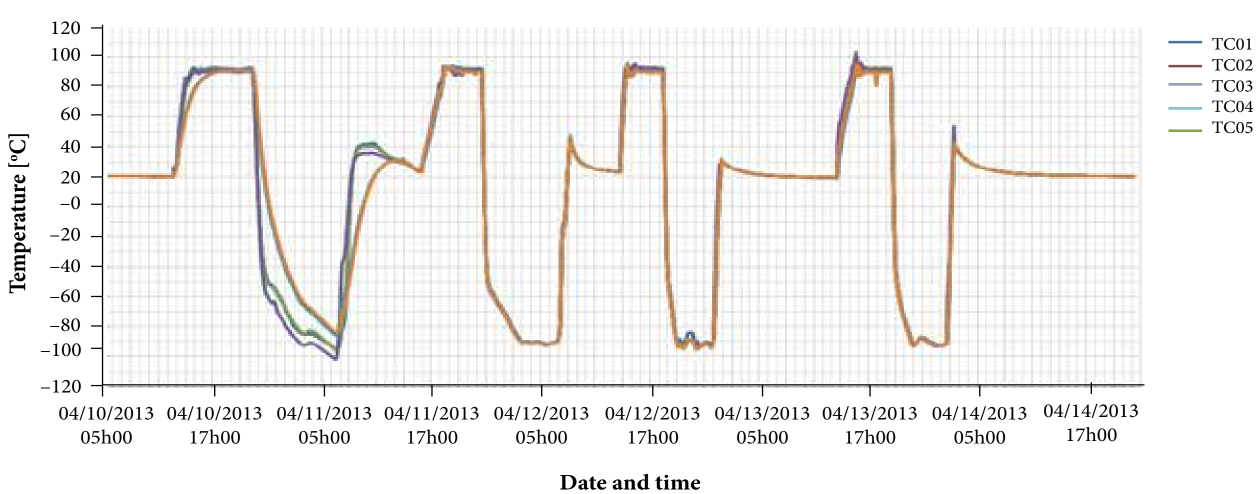

Figure 10. Developed temperature profiles of the coupons in the thermal-vacuum test.

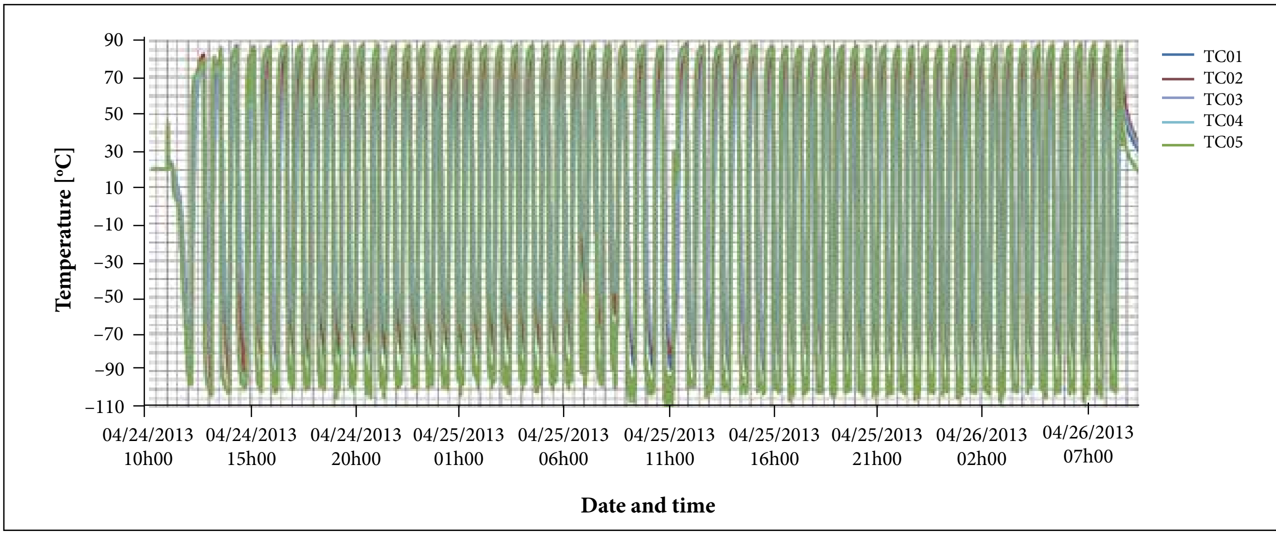

Figure 12. Results of the developed temperature profile in one of the coupons during the thermal-shock test.

By this test, it was concluded that the OSR has supported thermal-shock transient of 200 °C/min, and no damage was verified in its structure.

RESULT ANALYSIS

Once completed the package of environmental and mechanical tests, the final visual inspection and measurements of IR emissivity and solar absorptivity were made. For the final qualification, 3 main topics were considered:

Evaluation of the bonding process for OSR adhesion on base: it was taken into consideration the detachment of OSR aluminum plate in environmental and mechanical testing, and no damage was observed.

Evaluation of the process of films deposited on glass cover slip: aspects of delamination of the silver film from the glass surface were taken into consideration. For this case, no damage was observed too.

Evaluation of measurements of α_s and ε, before and after the environmental and mechanical tests: there were not significant changes in the measurements.

CONCLUSION

The OSR, manufactured and tested at the LIT/INPE, proved to be an excellent tool for thermal control of satellites, due to its characteristics of low degradation and excellent α_s/ε ratio if compared with white-ink radiators.

Other kinds of OSR, such as substrate of kapton or polytetrafluoroethylene, currently used by the Brazilian Space Program, could be developed too. In terms of mass, or maybe cost, these might be better; however, certainly in terms of degradation and α_s/ε relation, the OSR developed in this study is one of the best.

The developed manufacturing process was very reliable: the glass was already qualified for space flight, and the deposition process has maintained the same characteristics during the manufacturing of each unit.

The interface layers showed the adhesion needed to withstand the stresses that the space environment demands. In addition, the manufacturing process has been studied to improve the adhesion of the silver film on the surface of borosilicate, introducing 3 kinds of interfaces among them. The 3 interface layers showed an improvement in the silver film adhesion on the glass, as could be seen in the vibration and climate tests: there was not delamination of the silver in glass surface. All thermo-optical measurements applied to the OSR showed the aluminum interface layer to have the lowest solar absorptivity; the others have resisted to all environmental tests.

The OSR coupons have demonstrated good stability of the thermo-optical properties after being tested in the vibration, thermal-vacuum, and thermal-shock experiments. The stability in the large temperature range ensures their use in space vehicles, once predicted for conditions similar to the AMAZON Project.

The chosen adhesive (RTV566) has demonstrated mechanical and thermal stability due to differential expansion that occurred between the OSR and aluminum. The thermo-optical tests have shown that the deposited adhesion layer interferes with the values of α_s: the best option is the aluminum interface, which provides the best α_s/ε relation.

Thus, it can be concluded that the process of OSR development can be a good option in the manufacture of thermal radiators, being used as a tool for the thermal control of satellites. This qualification process has been well done at the LIT/INPE.

AUTHOR'S CONTRIBUTION

Boato MG and Garcia EC conceived the idea and co-wrote the main text; Beloto AF, Boato MG, and Santos MB performed the experiments. All authors discussed the results and commented on the manuscript.

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