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Development of Variable Emissivity Coatings for Thermal Radiator

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For years the use of variable emissivity devices and coatings has been envisaged by the academic and industrial space actors. The objective is to overcome the limitations of common optical coatings with constant thermo-optical properties. Variable emissivity devices and coatings allow designers to maximize heat rejection whilst minimizing the heater power demand. The most promising of these coatings are based on thermochromic (TCH) and electrochromic (ECH) materials. Thermochromic materials can be adjusted to behave as poor emitters at low temperature, and good emitters at high temperature. As such, they are proposed as smart elements capable of supporting thermal control on board spacecraft. TCH operate without the need of any electronic feedback or electromechanical actuation, and therefore, at zero power costs. Another promising material for variable emissivity devices is based on electrochromics. The advantage of ECH for space application is achieved by adapting the infrared emissivity of a surface by application of a low power electrical potential. In an ongoing research and development (R&D) activity funded by ESA and CNES the TCH multilayer tiles are based on VO₂ technology developed with industrial means and ECH devices are based on encapsulated conducting polymers. By now ECH and TCH emissivity contrast between cold and hot case has been measured up to 0.3 and 0.4 respectively, within a variation range as narrow as 20°C for thermochromic. In this presentation the various approaches in order to design, manufacture and test TCH and ECH

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materials as well as variable emissivity radiator breadboards will be discussed. Prototypes and final test results for both technologies will be presented.

Nomenclature

α	=	Solar absorptivity
<i>CC</i>	=	Cold Case
<i>CEA</i>	=	Commissariat à l'énergie Atomique (French Nuclear Agency)
<i>CNES</i>	=	Centre National d'études Spatiales
<i>CVCM</i>	=	Collected Volatile Condensable Material
<i>ECH</i>	=	Electrochromic
<i>ECP</i>	=	Electronic Conducting Polymer
<i>EED</i>	=	Electro Emissive Device
<i>EOL</i>	=	End Of Life
<i>EOR</i>	=	Electrical Orbit Raising
ε	=	Infrared emissivity
ε_H	=	Hemispherical infrared emissivity
<i>HC</i>	=	Hot Case
<i>HRC</i>	=	Heat Rejection Capacity
<i>ICMCB</i>	=	Institut de Chimie de la Matière Condensée de Bordeaux
<i>IREIS</i>	=	Institut de Recherche en Ingénierie des Surfaces (HEF Group)
<i>LTTE</i>	=	Long Term Thermal Endurance
<i>LPPI</i>	=	Laboratoire de Physico-Chimie des Polymères et Interfaces
<i>MLI</i>	=	Multi Layer Insulator
<i>PVD</i>	=	Plasma Vapor Deposition
<i>OSR</i>	=	Optical Solar Reflector
<i>R&D</i>	=	Research and Development
<i>RH</i>	=	Relative humidity
<i>RML</i>	=	Recovered mass loss
<i>RT</i>	=	Room Temperature
<i>SRD</i>	=	Smart Radiator Device
<i>TCH</i>	=	Thermochromic
<i>TRL</i>	=	Technology Readiness Level
<i>TRT</i>	=	Thales Research and Technology
<i>VEC</i>	=	Variable Emissivity Coating
<i>VER</i>	=	Variable Emissivity Radiator
<i>XRD</i>	=	X-Ray Diffraction

I. Introduction and context of the study

An efficient thermal control of a spacecraft guarantees the performance and longevity of the internal subsystems. The temperature of satellite components (e.g. payloads, avionics, structural elements) is set by the equilibrium between internal heat dissipation and external heat fluxes. The temperature of non-dissipating external components exposed to space, such as Multi-Layer Insulation (MLI) blankets and antenna, can vary in the range from about -150°C up to +150°C. However, for electronic units the temperatures must be maintained within a much smaller range. For example in telecommunication satellites qualification temperature ranges such as [-35°C to +65°C] and [-35°C to +90°C] are typical for the payload units.

A. Rationale of the study

A common design approach in satellite thermal control is to thermally insulate most of the satellite's external surfaces, while allowing certain areas (radiate windows or radiators) to reject heat to space. The radiator is sized for

the hot case. The hot case usually represents the combination of highest internal dissipation, external heat fluxes and degraded optical surface properties.

To operate most effectively the radiator emissivity has to be as close as possible to a perfect black body. At the same time the solar absorptivity needs to be as low as possible. The ratio between absorptivity and emissivity (α/ε -ratio) directly impacts the heat rejection capacity and/or the possible size of the satellite and eventually its competitiveness, specially with regard to the telecommunication satellite market.

Once the radiator area is determined, it is analysed whether it can also accommodate the cold case, when the satellite is subjected to the lowest external heat flux and reduced equipment dissipation. In the cold case, a high infrared emissivity is a disadvantage. Together with the radiator size, a high infrared emissivity can lead to units falling below their minimum operational temperature limits in cold case. To avoid that, heaters are usually used to warm up the equipment to compensate for the lack of internal dissipation and external heat fluxes. Although being a simple and efficient solution to overcome low temperatures in the cold case, heaters consume a significant part of the installed electrical power, which is a limited resource in any spacecraft. This is of particular importance for recent telecom satellites which use electrical orbit raising. The electrical orbit raising to geostationary orbit takes several months and is a cold case because the satellite is not fully operational. Hence the available electrical power is preferably dedicated to the electrical propulsion rather than for the heating of the satellite.

In these conditions the capability to reduce the radiative heat loss toward deep space by tuning the thermo optical properties of the radiator surfaces is of crucial interest. The most widely used technology for changing the thermo-optical properties is louvers or shutters. Louvers or shutters mechanically adjust the view factor between the radiator and the cold sink and with that the amount of heat that is rejected by the radiator. Specifically, the louver includes a bimetal or similar actuator for driving blades, depending on the temperature of the radiator. The blades are movable to increase or decrease the effective area and therefore the temperature of heat radiation surfaces, i.e., increases the amount of heat radiation at a high temperature or reduces it at a low temperature.

However, if thermally efficient, a louver is bulky, heavy and expensive. For all these reasons its use is not adapted for a telecom satellite with large radiators with an area of tens of square meters and/or with drastic constraints on cost and mass budget.

Hence it would be desirable to have a radiator covered with a coating with a high infrared emissivity and a low solar absorptivity in the hot phases of the mission; and a low infrared emissivity in the cold phases as schematized in Figure 1.

This study was thus launched in order to develop such a solution under the form of variable emissivity coatings (VEC), with a focus on thermochromic (TCH) and electrochromic (ECH) materials.



Figure 1 : Need of variable emissivity radiator for a spacecraft

B. Thermochromic and Electrochromic solutions

Thermochromic (TCH) materials can be adjusted to behave as poor emitters at low temperatures, and good emitters at high temperatures. They have been proposed and partially implemented since the early 2000, as Smart Radiator Devices (SRD) or Variable Emissivity Radiators (VER) ¹⁻⁶. These smart elements are capable of supporting thermal control on board of a spacecraft, without the need of any electronic feedback or electromechanical actuation, and therefore at zero power costs. There are several types of solutions proposed for smart radiators that range from sintered tiles, and sol-gel paints, to vacuum thin-films. Interestingly, the combination of variable emissivity and solar protection functionalities has been largely unexplored, so far. A solar protection will allow to lower the solar absorptivity of the radiator, which is an important parameter for coatings in space applications.

Another promising approach is based on electrochromic technology (ECH). Common ECH devices operate in the visible and the near-IR region (0.4 – 2.5 μ m) and modulate transmitted or reflected light intensities upon application of low voltage (1 to 4V). The advantage of ECH for space applications is thus achieved by adapting the

infrared emissivity of a surface. This potential was identified by the space community and the development of ECH solution was part of many technological road maps since the early 2000's⁷⁻¹⁰.

C. Objectives of performance for TCH and ECH materials

The impact of variable emissivity coatings on spacecraft systems and associated major requirements in terms of design and performance were first investigated through an internal system study. The main savings achieved by the use of VEC coatings concern in particular heating power, mass, size and cost of the overall system. For example, depending on thermo-optical coating performance assumptions, mission definition (LEO or GEO) and typical utilization (payload and/or platform) up to 50% of heating power could be saved. In our study this saving corresponds to a reduction of solar array surface (up to 20%), a reduction of hardware for active thermal control and batteries, and a reduction by up to 50 days of the Electrical Orbit Raising (EOR) duration. These advantages could be achieved if the change of the emissivity occurs within a suitable range of temperature, typically between 10°C and 40°C.

For this target TCH and ECH the high emissivity should be as close as possible to a perfect black body in order to optimize the heat rejection capacity of the satellite in hot case without enlarging the radiative areas, compared to the standard solutions such as optical solar reflectors (OSR) or Second Surface Mirrors (SSM). In consequence the emissivity of ECH and TCH should be similar to that of OSR or SSM, i.e higher than 0.8¹¹, in order to need the same radiator area in hot cases. Likewise the solar absorptivity at any temperature shall be as low as possible with a target of 0.20 EOL for the same reason.

The emissivity variation of both TCH and ECH has to be as high as possible in order to save a maximal amount of heating power in cold case. An emissivity variation of at least 0.3 was identified as minimal target for giving a relevant saving at satellite system level.

For TCH the emissivity transition temperature has to occur in the range 10°C-40°C in order to be useful for a large number of applications on various types of space missions. A transition temperature higher than 40°C leads to an overheating of the satellite in hot cases.

For ECH the emissivity transition is electrically controlled. For the same reason as above this transition has to be possible at least in the range 10°C-40°C. Yet, the power necessary to control the ECH has to be lower than the resulting saving in heating power. The related requirement for a large applicability range was control power lower than 10W/m² which is less than 10% of the heating power saved by the desired 0.3 emissivity change, to be induced by appropriate voltage application.

The integration of the variable emissivity coating is a relevant issue for design. For this a tile based approach was selected. The tiles have to be attached to the radiator with adhesive in a similar way as OSR, at least for TCH. A tile size of 40x40mm² was selected for TCH, which is similar to current OSR tiles. For ECH the target tile size of 50x50mm² was chosen as a good compromise between the limitations of integration, operating efforts and the optimization of electrical and thermo-optical performances of the device.

The logic of the experimental study was first to design and manufacture prototypes of TCH and ECH materials, and then to test them in aim to verify the compliance of their performances with functional and operational requirements. After this evaluation phase the most promising technology will be selected for the manufacturing and testing of a VEC radiator breadboard.

It should be noted that ECH is more complex than TCH with regard to its integration and control within the satellite system due to the fact that it is an active technology. Hence, besides the material and process development discussed in this paper, ECH requires further development on operational and system aspects. These issues are part of the technology road map but are out of the scope of this paper.

II. TCH & ECH material design & manufacturing

A. TCH material design & manufacturing

Since the 90's the development of thermochromic coatings has been mainly progressed around two main materials : La_{1-x}Sr_xMnO₃¹⁻³ and VO₂⁴⁻⁶.

The development step described in this paper concerns VO₂ based TCH material and was focused on optimizing performances, shifting the manufacturing from laboratory to more industrial facilities and performing environmental and functional testing on individual tile level. The TCH tiles were designed on the basis of a patent by CEA (Commissariat à l'énergie Atomique) and CNES (Centre National d'Etudes spatiales)⁵. This was done in a

collaboration with ICMCB (Institut de Chimie de la Matière Condensée de Bordeaux) for their expertise in VO₂ material¹².

Functional TCH devices on silicon substrate samples were first achieved and validated at a laboratory scale by CEA. Three initial functions are necessary to obtain a thermochromic stack (Figure 2, left) that is compliant with the requirements :

- W doped VO₂ thermochromic material
- Ag reflective base with CeO₂ dielectric material
- (CeO₂/SiO₂) Dielectric multilayer for solar protection



Figure 2 : TCH multilayer stacking (patented design⁵) (left), 40x40mm² solar protected TCH tiles (right)

The aim of the doping of VO₂ by W material is to reduce the TCH transition temperature from 68°C (pure VO₂) to 20-30°C, which would enable a larger application range. The first samples were realized at CEA in a multi-cathodic sputtering laboratory reactor. Process parameters were then transferred from CEA to IREIS (Institut de REcherche en Ingénierie des Surfaces, part of HEF Group) for an adaptation to industrial means. However CEA and IREIS means are significantly different on several points, especially regarding the chamber size, the coating mode and the target size. A higher production capability is provided by industrial processing, but it also leads to a longer coating time. Hence the process stability became a critical parameter in part due to the use of a larger sized target.

The full stack is made of 20 layers (many of them constituting the CeO₂/SiO₂ multilayer) using 5 different materials. In CEA and IREIS, the process flow was divided in 4 steps using a deposition machine and annealing equipment. During the first step, several target materials were used to create the reflective base. During the second step the thermo-active layer was made using V and W targets. The third step was a thermal treatment, required to obtain the thermochromic crystalline phase of vanadium oxide.

In order to reduce their solar absorptivity, the TCH tiles were covered during the 4th step by a solar protection coating. This thin multilayer coating acts as an interferential mirror and aims to decrease the solar absorptivity without degrading the emissivity of the tiles.

The deposition process of the reflective base and the solar protection initially developed on laboratory equipment at CEA, was successfully transferred to an industrial equipment at IREIS with only few adjustments. However, a specific development was necessary for VO₂ realization. After the implementation and control of two specific means such as an in-situ optical regulation of the Ar/ O₂ plasma and a vacuum chamber devoted to the annealing step under Ar/O₂ atmosphere, IREIS could synthesize functional thermochromic thin films in a repeatable manner for large surfaces. VO₂ characterization was done in a first approach at IREIS where a resistivity bench was specially improved to allow the observation of the switch from semi-conductive to metallic behavior after crossing the transition temperature (T_c). The thermo-optical response was validated on relevant samples in a reduced wavelength range (at Hubert Curien Laboratory near IREIS) while resistivity and X-ray diffraction (XRD) were performed at ICMCB for detailed characterizations.

A proper VO₂ phase and composition was achieved by very accurately controlling the oxidation level during the coating process and also during the annealing step.

Encouraging results were obtained with tungsten doped samples. Tiles were fully manufactured at IREIS according to the process steps described in Figure 3. The tiles coated with the full TCH stack were characterized for thermo-optical validation on the required range of wavelength.

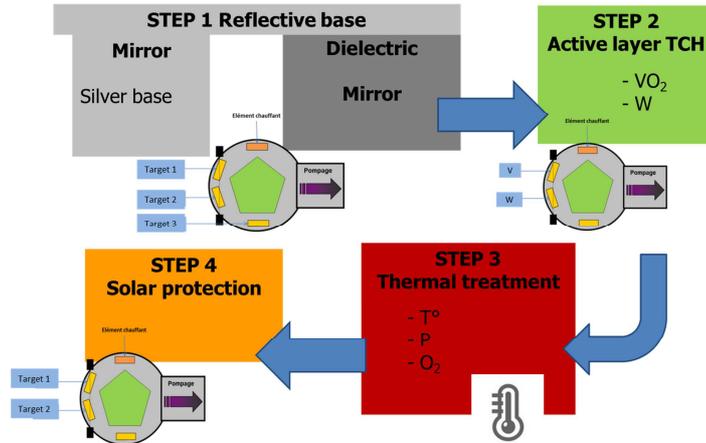


Figure 3 : Process flow implementation in IREIS facilities

B. ECH Material design & manufacturing

Organic materials and among them electronic conducting polymers (ECPs) have been studied as electrochromic materials and represent now an important class of electroactive materials investigated in academic and industrial laboratories. ECPs have promising electronic, optical and electro-chemical properties. Among the numerous applications with ECPs, the spectral electro-modulation in the infrared region opens possibilities to develop organic infrared (IR) electrochromic devices. The LPPI laboratory (Laboratoire de Physico-Chimie des Polymères et Interfaces, Cergy University) has developed since 2008 all polymer-based Electro-Emissive Devices (EEDs), made of inter-penetrating polymer network (IPN) of poly(ethyleneoxide), Nitrile-butadiene rubber and poly(3,4-ethylenedioxythiophene) (PEO/NBR/PEDOT)¹⁴⁻¹⁹ as shown on Figure 4. The emissivity variation of the active layer results from a modification of its IR-properties by applying a bias voltage. EEDs are similar to electrochemical cells with two electrodes separated by an electrolyte. The latter is necessary to ensure the ionic conduction within the electrochemical cell. One of the electrodes, on which the active layer is coated, is the working electrode, while the second electrode acts as a counter-electrode (see Figure 4).



Figure 4 : Schematic representation of the tri-layer NBR/PEO/PEDOT IPN (up) and its connexion frame (down)

By changing the bias voltage, a change in the oxidation degree of the ECP active layer is induced. For example, by applying a positive electrical voltage, the active layer can optically switch from a high emissive state to a low emissive state in the infrared (see figure 5). The originality of EED architecture made by LPPI is that ECP is interpenetrated on both sides of the host matrix during its formation (i.e. in two steps the device is fabricated and cannot delaminate).

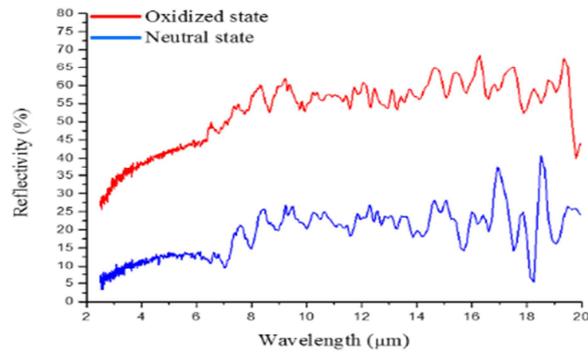


Figure 5 : Electro-emissive effect on LPPI IPN devices

The flexible polymer tiles are deep black in color and have a high solar absorptivity (>0.9). The solar absorptivity has to be strongly reduced to limit overheating in case of application on an illuminated surface of the satellite¹³. Hence some propositions for various encapsulation means or coatings for electro-emissive devices (EED) have been realized and tested :

- Thin film with solar reflective multilayer deposited (SiO₂/CeO₂ based Bragg mirror) (CEA and IREIS)
- Thin film painted with various thickness of space qualified white paint (CNES and Thales Alenia Space-F)
- Germanium based thin film (LPPI / Thales Research and Technology/ Thales Alenia Space-France)

Figure 6 shows the electro-emissive devices (EED) in their connection frame and covered with the various coatings. Figure 7 shows pictures of 50x50mm² ECH samples without connection frame. The left picture shows a bare EED sample and the right picture shows a sample with Germanium based coating.



Figure 6 : Images of single EED connected and covered with various coatings

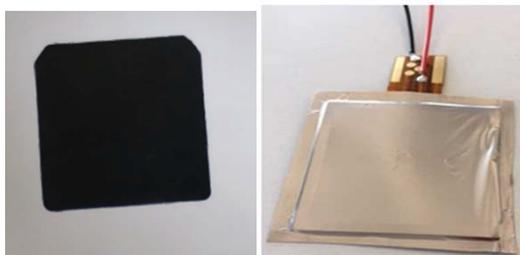


Figure 7 : EED sample bare (left), encapsulated with thin film coated with Germanium (right)

The best compromise between solar absorptivity reduction and IR transparency was found for the EED encapsulated in Ge coated thin film through numerical and experimental activity aiming to optimize the optical, electrical and mechanical design. This finding concurs with other studies found in the literature²⁰.

III. TCH & ECH material testing

A. Test plan

A test plan was defined and executed in order to check the functional performances of the TCH and ECH materials/devices and their resistance to space environment. Tests were conducted on coupons of various sizes. The TCH coupons had a size of 40x40 mm² and ECH coupons had sizes of 20x20mm² and 50x50mm². TCH and ECH coupons were put through a series of measurements and functional performance tests, which are detailed in the following list:

Measurement of functional performance

- Total hemispherical emissivity over a temperature range from 5°C to 80°C (TCH)
- Total hemispherical emissivity over a voltage range from -1.7V to +1.2V, at ambient temperature (ECH)
- Solar absorptivity and its dependence over the same temperature (TCH) and voltage (ECH) range
- Evaluation of emissivity hysteresis over temperature (TCH)
- Homogeneity of the emissivity across the tile surface (TCH and ECH)
- Mass and area specific density of the tile (TCH and ECH)
- Peak and steady control power (ECH)
- Stability of the emissivity versus time with and without power supply (ECH)

Environmental testing

Measurements of thermo-optical performance (IR spectral hemispherical emissivity, and total solar absorptivity) were performed in accordance to ECSS-Q-ST-70-09 on measurements of thermo-optical properties of thermal control materials²¹, before and after the following testing sequence in order to assess their possible degradation:

- TCH only :
 - o Equivalent of 1 year of UV exposure for a satellite north or south panel i.e. 1112 Equivalent Sun Hours (ESH))
 - o Hygrometry : 7 days, 45°C±3°C, 93% relative humidity ±5%
 - o Handling and cleaning: adhesive test and isopropanol cleaning test representative of integration process on a radiator
- TCH and ECH :
 - o 100 thermal cycles in the temperature range [-50°C; +100°C], of which 90 cycles were at ambient pressure under Nitrogen atmosphere and 10 cycles were conducted in vacuum
 - o Long term thermal endurance (LTTE) test: 90°C for 600 hours (TCH) and 144 hours (ECH)
 - o Outgasing test according to ECSS-Q-ST-70-02C²².

B. Test results

1. TCH material test results

During the test, the best performance was observed on un-doped samples (pure VO₂) with solar protection. An emissivity of $\epsilon = 0.76$ was measured. The solar absorptivity was measured to be $\alpha = 0.44$ and also to be independent of the temperature in the measured temperature interval.

The emissivity increased from 0.38 up to 0.76 over the measured temperature range. This means an emissivity contrast of $\Delta\epsilon = 0.38$.

As shown on Figure 8 the transition temperature of undoped tiles is in the temperature range 50°C to 70°C which was expected. Yet, also the W-doped samples, which are supposed to have a lower transition temperature, did not show clear evidence of this commutation in the temperature range from 0°C to 50°C. This point is the goal of a follow up of the project. Besides for undoped sample an hysteresis effect of +10°C on the commutation temperature when heating vs. cooling has been observed (not shown on Figure 8). Finally, the homogeneity and solar specularly were measured and it was found that they are similar to values measured in OSR tiles.

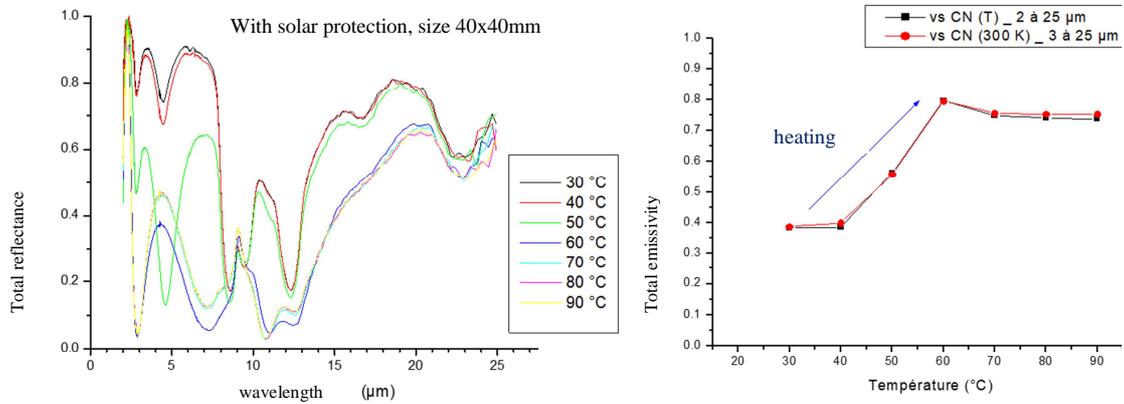


Figure 8 : Spectral IR reflectivity measurements (left), and total integrated IR emissivity variation vs temperature (right) for a TCH sample with solar protection and undoped VO2

Apart from the reduction of solar absorptivity, the solar protection coating showed two other positive effects. First, it increases the maximum emissivity by about 0.25. Without the solar protection coating TCH tiles show a maximum emissivity of $\epsilon = 0.5$, while TCH tiles with solar protection coatings show a maximum emissivity of $\epsilon = 0.76$. Moreover the solar protection also protects against environmental effects. In particular the solar protection coating protects VO2 physico-chemical properties against humidity. This finding was confirmed by an additional and dedicated hygrometry test.

No degradation of solar absorptivity was measured after the exposure of the solar protected TCH tiles to UV radiation. However, a small increase of the transition temperature for the change in emissivity was identified, which requires further investigation.

The TCH tiles showed no major sign of degradation after the thermal cycling and endurance testing. The outgassing test results were compliant with ECSS-Q-ST-70-02C requirements (RML < 1%, CVCM < 0,1%)²². Finally, all handling and cleaning tests performed on the TCH tiles confirmed the compliance with the industrial integration process for thermal radiators.

A summary of the results of the TCH coupon tests is given in Table 1. In brief, the testing of the TCH tiles revealed performance close to the requirements but there are still some improvements needed to enter a product phase. The most critical are the reduction of the solar absorptivity by at least 0.25 and the decrease of the transition temperature by at least 35°C.

	Testing/measurement	TCH VO2 with Solar protection	TCH VO2 w/o solar protection	Target/Requirement
Design & Functional	High emissivity ϵ_H	0.75	0.5	>0.8
	ϵ_H contrast	0.35	0.4	>0.3
	Solar absorptivity α	0.45	0.53	<0.2
	Transition temperature	50°C < Tc < 70°C	55°C < Tc < 75°C	10°C < Tc < 40°C
	Hysteresis	+10°C on Tc when T increase	+10°C on Tc when T increase	As low as possible
	Homogeneity (@RT)	Delta ϵ_H < 0.01	No tested	Delta ϵ_H < 0.01
	Area	40x40 mm ²	40x40 mm ²	40x40mm ²

Environment	N2 Gaseous thermal cycling TC [-50°C; +100°C]	No impact on ϵ_H and α	No impact on ϵ_H and α	[-50°C; +100°C]
	Long Term Thermal Endurance (600hours @ +90°C)	ϵ_H slight decrease @RT	Not tested	600hours @ 90°C
	UV exposure (1112 ESH)	No impact on ϵ_H +10°C impact on T_c	No impact on emissivity	1 year UV in GEO on north/south panel (1112 ESH)
	Outgassing	RML < 1%, CVCM < 0,1% OK with ECSS	Not tested	ECSS-Q-ST-70-02C
	Hygrometry (7 days, 45°C, 93% relative humidity)	No impact on ϵ_H and α	Not tested	ECSS-Q-ST-70-02C
	Handling & cleaning (adhesive, isopropanol)	No impact on ϵ_H and α	Not tested	adhesive, isopropanol

Table 1 : TCH testing results vs requirements

2. ECH material test results

The maximum emissivity for the Ge encapsulated EED was measured to be $\epsilon = 0.75$. As such it is lower than for OSR standard tiles, which have a maximum emissivity of $\epsilon = 0.84$. The ECH Ge tiles have a range of emissivity of $\Delta\epsilon = 0.22$, between high and low emissivity state. The Germanium layer on the encapsulated samples significantly reduced the solar absorptivity to $\alpha = 0.44$, compared to a bare “black” ECH tile with $\alpha > 0.9$.

During environmental resistance testing it was observed that after the 90 thermal cycles in Nitrogen [-50°C; +100°C] the ECH are still commuting but, their performance is slightly degraded due to damage of the tiles. Specifically, the ionic liquid leaked out which prevented the nominal commutation effect. Then, after the long term thermal endurance test (6 days at 90°C) the ECH thermo-optical properties showed no degradation even if ., a leakage of ionic liquid was detected again, as after the thermal cycling. The tile performance was measured after the test and the performance was found to be quite similar to the ones before test. ECH tiles are compliant with the ECSS outgasing requirements (RML<1%, CVCM<0.1%)²².

Electrical measurements were also performed on ECH tiles. A peak power consumption of less than 10W/m² was measured for the commutation control with an input voltage of -1.7V and +1.2V. In steady state the power consumption was less than 5 W/m². This value is compliant with expectation. It is less than the heating power needed to compensate for the emissivity change in cold case.

A summary of the results for the ECH coupon testing is given in Table 2. In brief, the testing of the ECH tiles showed promising results, especially for the Ge encapsulated samples. However, further improvements are necessary in order to compete with the performance of OSR based radiators, in particular for applications on large telecom satellites. At tile design level the major axes of development are related to the further reduction of the solar absorptivity and the prevention of electrolyte leakage in thermal vacuum environment. Additionally, for ECH significant work is necessary on system and integration aspects as it is a connected and active technology.

		ECH non encapsulated	ECH-Ge encapsulated	Requirements
Design & performance	High emissivity (Hemispherical)	0.73 @RT Reduced at -20°C	0.75	>0.8
	emissivitycontrast	0.3 (constant vs temperature above 0°C)	0.22	>0.3
	Solar absorptivity	0.95	0.44	<0.2
	Switch temperature range	-20°C ; +50°C	No tested	0°C ; +80°C

	Power	steady : <5 w/m ² (peak~10W/m ² for less than 5 sec)	steady : <5 w/m ² (peak~10W/m ² for less than 5 sec)	<10W/m ²
	Area	40x40mm ² and 50x50mm ²	50x50mm ²	50x50mm ²
	Memory	17h @ RT, At least 1h @-20°C & +50°C	Not tested	> 1 hour for T>0°C
Environment	N2 Gaseous thermal cycling	Slight impact on emissivity but visual degradation due to electrolyte leakage	TO properties BOT/EOT measurements likely impacted by the leakage	[-50°C; +100°C]
	Long Term Thermal Endurance	144 hours @90°C only No impact on emissivity	Not tested	600hours @ 90°C
	Outgassing	RML < 1%, CVCM < 0.1%	Not tested	ECSS-Q-ST-70-02C

Table 2 : ECH testing results vs. requirements

IV. Conclusion

For the TCH materials, this work allowed for the transfer of the technology and knowledge from lab scale production at CEA to near-industrial means at IREIS-HEF, leading to larger tiles and full TCH stacks. IREIS successfully manufactured more than 20 TCH tiles with an area of 40x40mm² and a good reproducibility on these 20 tiles.

Promising functional performance was observed compared with the defined requirements, in particular for the emissivity profile of the undoped tiles. The samples showed a maximum emissivity of $\epsilon = 0.76$ and a transition in emissivity of $\Delta\epsilon = 0.38$. The solar absorptivity was reduced to $\alpha_s = 0.45$ with a solar protection coating. This is a significant improvement but it is still higher than required. The doping trials with tungsten did not provide the desired results since the transition temperature was 65°C rather than the target of 25°C.

The testing campaign also revealed a resistance of the TCH tiles to the space environment that is similar to that of common OSR. However, further life testing must be performed on future generations of tiles to consolidate these findings.

Future improvement steps identified by the testing phase of TCH tiles will be focused on the further reduction of the thermochromic transition temperature (T_c) through a maturation of the doping process, and the reduction of the solar absorptivity through a further R&D activity on the solar protection optical design.

The work on ECH tiles showed promising results especially for the infrared emissivity and its contrast. The main development efforts were spent on the encapsulation of the tiles with the aim of reducing the solar absorptivity. The solar absorptivity was reduced by a factor of two from initially $\alpha > 0.9$ to $\alpha = 0.44$. Although this is a significant reduction, the value is still too high for a space application and has to be further reduced with future R&D activities. For the emissivity the results are quite promising with a maximum emissivity of $\epsilon = 0.76$ and change in emissivity of $\Delta\epsilon = 0.22$. Yet also for the emissivity further improvements are necessary in order to compete with a radiator based on OSR.

The resistance of ECH tiles to space environment was partially assessed. The tests indicated a suitable resistance of electro-chemical and optical performances to the thermal and vacuum degradation but also identified a major area of improvement which is the electrolyte containment. Further tests such as UV exposure on encapsulated samples also still have to be conducted.

Finally, the issue of the implementation and operating of ECH in a satellite system is also to be investigated.

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References

- ¹S. Tachikawa, A. Ohnishi, Y. Nakamura, A. Okamoto, "Design and Optical Performances Evaluation of Smart radiation Device with Multilayer Coating", ICES 2008-01-2152
- ²S. Tachikawa, A. Ohnishi, K. Matsumoto, Y. Nakamura, A. Okamoto, "Multi-layer Coating for Smart Radiation Device with Solar Absorbance 0.13", ICES 2009-01-2574
- ³S. Tachikawa, A. Ohnishi, Y. Nakamura, A. Okamoto, "In-Orbit Thermal Performance of a Smart Radiation Device" ICES 2007-01-3125
- ⁴E. Haddad, R. Kruzelecky et al., "Multi-Function Tuneable Emittance Smart Coatings For Thermal Control In Harsh Space Environment"; ICES, 36th International Conference On Environmental Systems, July 11-14, 2006, Norfolk, Virginia, USA; Paper 2006-01-2263, October 21-24, 2001 San Francisco, USA.
- ⁵R. V. Kruzelecky, E. Haddad, W. Jamroz, M. Soltani, M. Chaker, D. Nikanpour, X. Jiang, and G. Colangelo, "Thin-film Smart Radiator Tiles with Dynamically Tuneable Thermal Emittance"; SAE, Inc. Proceeding, Paper # 2005-01-2996; 35-ICES, July 11-14, 2005, Rome, Italy.
- ⁶Xiao Wang, Yunzhen Cao, Yuzhi Zhang, Lu Yan, Ying L "Fabrication of VO₂-based multilayer structure with variable emittance", Applied Surface Science 344 (2015) 230-235
- ⁷J. G. Metts, J. A. Nability, D. M. Klaus, "Theoretical performance analysis of electrochromic radiators for space suit thermal control", Advances in Space Research 47 (2011) 1256-1264.
- ⁸Hannah Goldberg, Juergen Mueller, and Leon Alkalai Jet Propulsion Laboratory, "Micro-Inspector Spacecraft: An Overview", 20th AIAA/USU Conference on Small Satellites, 2006
- ⁹Hulya Demiryont et al., "Emissivity-modulating electrochromic device for satellite thermal control", STAIF 2008
- ¹⁰K. Shannon, Spacecraft Thermal Control Workshop, "Variable Emittance Electrochromic Thermal Control Space Testing", Aerospace Corporation, El Segundo, March 2009
- ¹¹Qioptiq Space Technology, Optical Solar Reflector data sheet, Qioptiq Space A4-0002 02.06
- ¹²Victor, J.L., Marcel, C., Sauques, L., Labrugère C., Amiard F., Gibaud, A., Rougier, A., "From multilayers to V1-xWxO₂±δ films elaborated by magnetron sputtering for decreasing thermochromic transition temperature", Journal of Alloys and Compounds, 2021, 858, 157658
- ¹³C. Marcel, F. Sabary, X. Verdalet Guardiola, S. Remaury*, "Solid state thermochromic device, and method for producing said device". CEA/CNES* patent US 2019 243036 (A1)
- ¹⁴P. Verge, P.H. Aubert, F. Vidal, L. Sauques, F. Tran-Van, S. Péralta, D. Teyssié, C. Chevrot, "New Prospects in the Conception of IR Electro-Tunable Devices: The Use of Conducting Semi-Interpenetrating Polymer Network Architecture", Chem. Mater., 22 (2010) 4539-4547.
- ¹⁵Teissier, A., Dudon, J.-P., Aubert, P.-H., Vidal, F., Remaury, S., Crouzet, J., & Chevrot, C. (2012). *Feasibility of conducting semi-IPN with variable electro-emissivity: A promising way for spacecraft thermal control*. Solar Energy Materials and Solar Cells, 99, 116–122.
- ¹⁶L.J. Goujon, A. Khaldi, A. Maziz, G.T.M. Nguyen, P. Aubert, C. Chevrot, D. Teyssié, C. Plesse, G.T.M. Nguyen, P. Aubert, F. Vidal, C. Chevrot, D. Teyssié, *Macromolecules* 44 (2011) 9683
- ¹⁷Goujon, L. J., Aubert, P.-H., Sauques, L., Vidal, F., Teyssié, D., & Chevrot, C. (2014). *Soft and flexible Interpenetrating Polymer Networks hosting electroreflective poly(3,4-ethylenedioxythiophene)*. Solar Energy Materials and Solar Cells, 127, 33–42. <http://doi.org/10.1016/j.solmat.2014.03.036>
- ¹⁸Louet, C., Cantin, S., Dudon, J.-P., Aubert, P.-H., Vidal, F., & Chevrot, C. (2015). *A comprehensive study of infrared reflectivity of poly(3,4-ethylenedioxythiophene) model layers with different morphologies and conductivities*. Solar Energy Materials and Solar Cells, 143, 141–151.
- ¹⁹G. Petroffe, *Active Thermal Control of Satellites by Self-supported Devices with Organic Electro-active Materials*, PhD thesis, Cergy-Pontoise, 2018.
- ²⁰P. Chandrasekhar et al., "Variable-Emittance Infrared Electrochromic Skins Combining Unique Conducting Polymers, Ionic Liquid Electrolytes, Microporous Polymer Membranes, and Semiconductor/Polymer Coatings, for Spacecraft Thermal Control", J. Appl. Polym. Sci. 2014.
- ²¹ECSS-Q-ST-70-09C, 31 July 2008, Measurements of thermo-optical properties of thermal control materials
- ²²ECSS-Q-ST-70-02C, Thermal vacuum outgassing test for the screening of space materials (15 November 2008)