Variable Emissivity Radiator Breadboard

ESTEC contract 4000119687/17/NL/KML

Executive Summary Report

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1. TERMINOLOGY

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

2. 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.

2.1 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, especially 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.

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 satellite with drastic constraints on cost and mass budget (eg. micro & nano satellites)

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.

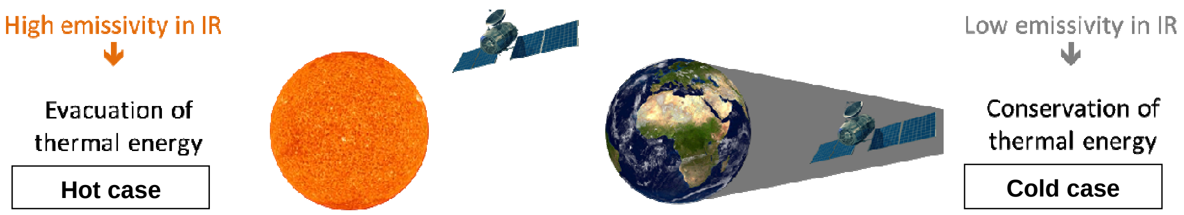


Figure 1 : Need of variable emissivity radiator for a spacecraft

2.2 Brief description of 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's, as Smart Radiator Devices (SRD) or Variable Emissivity Radiators (VER). 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 – 2.5µm) 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's.

2.3 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 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 0.8, 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 an 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 selected as a 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 with the aim to verify the compliance of their performances with functional and operational requirements. After this evaluation phase the most promising technology was 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.

3. TCH & ECH MATERIAL DESIGN & MANUFACTURING

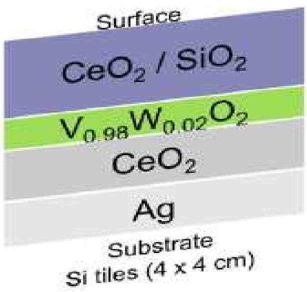
3.1 TCH material design & manufacturing

Since the 1990's the development of thermochromic coatings has been mainly progressed around two main materials : La1-xSrxMnO3 and VO2.

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'energie 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 expertize in VO2 material.

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



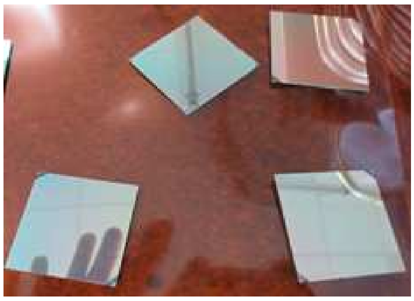


Figure 2 : TCH multilayer stack (patented) (left), 40x40mm² solar protected TCH tiles (right)

The aim of the doping of VO_2 by W material is to reduce the TCH transition temperature from 68°C (pure VO_2) 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 few adjustments. However, a specific development was necessary for VO_2 realization. After the implementation and control of two specific means such as an in-situ optical regulation of the Ar/ O_2 plasma and a vacuum chamber devoted to the annealing step under Ar/O_2 atmosphere, IREIS could synthesize functional thermochromic thin films in a repeatable manner for large surfaces. VO_2 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 VO_2 phase and composition was achieved by very accurately controlling the oxidation level during the coating process and also during the annealing step.

Tiles were fully manufactured at IREIS according to the process steps described in Figure 3. During the first part of the project (CCN1) the undoped tiles coated with the full TCH stack were characterized for thermo-optical validation on the required range of wavelength and then were used to cover the BB TCH radiator to be integrated and tested in task 5 and 6.

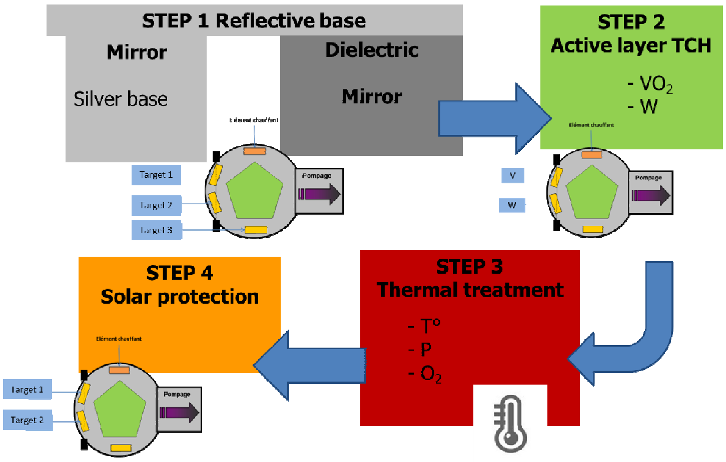


Figure 3: Process flow implementation in IREIS facilities

In a second phase of the project (CCN2) doped samples were produced by several processing way using different modes of mixing VO2 and W. The study was developed on several axis: doping rate, thickness control, processing mode, annealing time and reproducibility.

The final performances of tiles coated with full stack are listed in Table 7 below.

	Doping rate	**α**	**ε LT**	**ε HT**	**Δε**	**Tc**
Targets		<0.2	<0.2	>0.85	0.65	<30°C
CCN2 tile – TCH 60 nm	**3.7%**	**0.44**	**0.54**	**0.80**	**0.26**	**33°C**

Table 1 : Performances achieved on tiles with full stack at the end of CCN2

We also produced doped tiles with several W rate with a better reliability than obtained during CCN1. As expected, the Tc decreases with W increase to reach a switching temperature of 33°C with 3.7% of W.

The switching amplitude is also progressively reduced by W addition as reported in the litterature. The switching amplitude is higher without solar protection. Indeed, the contrast in emissivity is about 0.5 without SP and it becomes 0.32 with SP (Table 6).

The main parameter that still require a strong improvement at the end of this work is the level of solar absorption α which must be reduced.

3.2 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) 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).

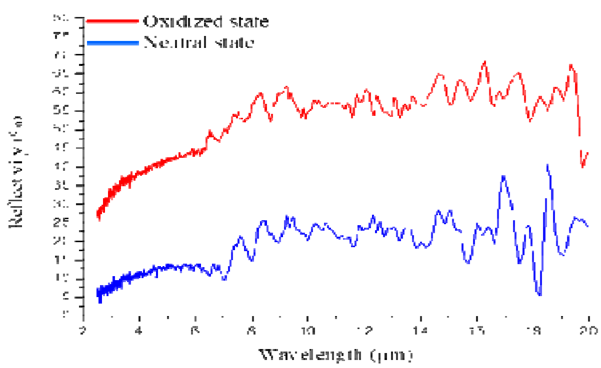


Figure 5 : Electro-emissive effect on LPPI IPN devices

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 satellite. 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 (SiO_2/CeO_2 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)

The figure below shows pictures of two 50x50mm² ECH samples. The left picture shows a bare EED sample and the right picture shows a sample with Germanium based coating.

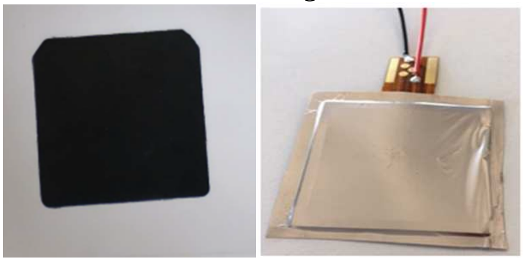


Figure 6 : EED sample bare (left), encapsulated with thin film coated with Germanium (right)

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 literature.

4. TCH & ECH MATERIAL TESTING

4.1 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 materials, before and after the following testing sequence in order to assess their possible degradation:

- TCH only :
  - Equivalent of 1 year of UV exposure for a satellite north or south panel
  - Hygrometry : 7 days, 45°C±3°C, 93% relative humidity ±5%
  - Handling and cleaning: adhesive test and isopropanol cleaning test representative of integration process on a radiator
- TCH and ECH :
  - 100 thermal cycles in the temperture range [-50°C; +100°C], of which 90 cycles were at ambient pressure under Nitrogen atmosphere and 10 cycles were conducted in vacuum
  - Long term thermal endurance (LTTE) test: 90°C for 600 hours (TCH) and 144 hours (ECH)
  - Outgasing test according to ECSS-Q-ST-70-02C[22].

4.2 Test results

4.2.1 TCH material test results

During the test, the best performance was observed on un-doped samples (pure VO_2) with solar protection. An emissivity of $\varepsilon = 0.76$ 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 $\Delta\varepsilon = 0.38$. Finally, the homogeneity and solar specularity were measured and it was found that they are similar to values measured in OSR tiles.

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. Moreover the solar protection also protects against environmental effects. In particular the solar protection coating protects VO_2 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 emissivty was identified, which requires further investigation.

The TCH tiles showed no major sign of degradation after the thermal cycling and endurance testing. The outgasing test results were compliant with ECSS-Q-ST-70-02C requirements (RML < 1%, CVCM < 0,1%). 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 performances of the TCH coupon as measured in the various phases of the project 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.

	TCH initial status (CEA/CNES)	TCH VO2 with SP (CEA, TAsk3)	TCH VO2 w/o SP (CEA, task3)	TCH VO2 with SP (IREIS,60nm, task8)	TCH VO2 doped with SP (IREIS, task8)	Requirements
High emissivity (εH)	0.75	0,75	0,5	0,81	0,82 (1.6%) 0.8 (3.7%)	>0,8
εH contrast	0.35	0,35	0,4	0,32	0,29 (1.6%) 0,26 (3.7%)	>0,3
Alpha S	0,59	0,45	0,53	0,40	0,45	<0,2 BOL
Tc / range	65°C+/-15°C	50°C+/-15°C	55°C+/-15°C	59°C / 13°C	47°C+/-15°C (1.6%) 33°C +/-15°C (3.7%)	25°C +/- 15°C
Hysteresis	+10°C on TC when T increase	+10°C on TC when T increase	+10°C on TC when T increase		+4°C on TC when T increase	εH maxi for T≤40°C heating
Specularity		specular limit = 40°	specular limit = 40°			Like OSR CMX
Homogeneity (@RT)		OK (delta <0.01)				Δα, Δε <0.02 on the tile
Area	25x25	40x40 mm²	40x40 mm²	40x40 mm²	40x40 mm²	40x40mm2
Mass		1200 g/m² (with 500µm Si substrate)	1200 g/m² (with 500µm Si substrate)	430 g/m² (150µm substrate)	430 g/m² (TBC)	< OSR CMX 150µm +10%
Electrical		OK (<100 ohm front/front; <10Kohm front/back)				Similar to OSR CMX 150µm +10%

Table 2 : Summary of TCH performances at the end of project

4.2.2 ECH material test results

The maximum emissivity for the Ge encapsulated EED was measured to be $\varepsilon = 0.75$. As such it is lower than for OSR standard tiles, which have a maximum emissivity of $\varepsilon = 0.84$. The ECH Ge tiles have a range of emissivity of $\Delta\varepsilon = 0.22$, 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 though 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
High emissivity (Hemispherical)	0.73 @RT Reduced at -20°C	0.75	>0.8
Emissivity contrast	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	Not tested	0°C ; +80°C
Power	steady : <5 w/m² (peak~10W/m² for less than 5 sec)	steady : <5 w/m² (peak~10W/m² for less than 5 sec)	<10W/m2
Area	40x40mm² and 50x50mm²	50x50mm²	50x50mm²
Memory	17h @ RT, At least 1h @-20°C & +50°C	Not tested	> 1 hour for T>0°C

Table 3 : ECH testing results vs. requirements

5. TCH & ECH RADIATOR BREADBOARD DESIGN & MANUFACTURING

The objectives of the test were to design, manufacture and test TCH and ECH small radiators mock up at different temperature under thermal vacuum. These tests were done in comparison to the reference element, an OSR radiator.

5.1 TCH radiator breadboard design & manufacturing

5.1.1 Design

The TCH radiator was tested with two other radiators : the ECH radiator and an OSR radiator. The test aimed at characterizing the behavior of TCH tiles under vacuum in temperature. This is done by comparison to the reference, the OSR radiator. The TCH radiator has then been designed to be easily compared to the OSR.
The design constraints were the following :

- Isolate the behavior of the tiles for thermal correlation
- Similar design to the OSR radiator for easy comparison
- Material representative of flight
- Applicability of Thales Alenia Space standard processes
- Compatibility with the test set up
- Compatibility with IREIS/CEA manufacturing capability

A design equivalent to previous test campaigns has been chosen. The radiator was an aluminum 2024PL plate treated TSA (representative of satellite panels) of 200mmx200mmx2mm. There are 16 TCH tiles bonded to the plate with a thermal joint.

For testing, the radiator was instrumented with heater at the back to control the heating power injected. The radiator was then equipped with an MLI protection from the back of the radiator up to the edge of the TCH. The only apparent components were the TCH. The same MLI was used on the OSR and the TCH radiator to have the same active surface.

5.1.2 Manufacturing

The tiles used for the fabrication of the TCH radiator were made by IREIS. They are with undoped VO2 and have on top a solar protection.
The main steps of the TCH radiator manufacturing were the surface treatment of the aluminum plate and the manual assembly of the TCH layout using space qualified process and adhesive. The assembly of the radiator was nominal and fully in accordance with a standard (proprietary) process of Thales Alenia Space for radiator integration.

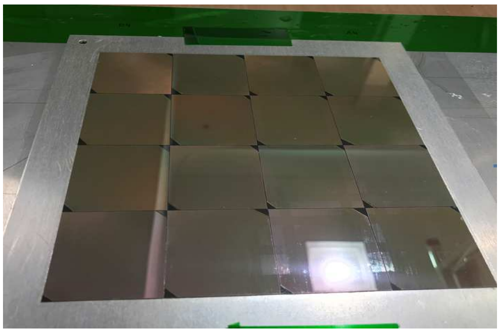


Figure 7 : **Assembly of the TCH radiator**

5.2 ECH radiator breadboard manufacturing and design

The electro-emissive radiator was composed of 16 EEDs, which are fixed with a conductive tape to a multilayer support, including a thick aluminum plate (1.5 mm) which has a high thermal conductivity (237 W.m-1.K-1). On the aluminum plate a thin layer of epoxy was coated to electrically insulate the samples from the aluminum. To maintain the samples and provide the electrical contacts to the active layers, the EEDs samples were covered by a frame-like element namely the “top support”. This plate covered with gold was composed of 4 windows. The configuration of this radiator allowed a large exposure of the active layer to the environment. A view of the ECH BB radiator is showed on the right of the Figure 9.

During testing, the radiator was instrumented with heaters on its back to control the injected heating power. The radiator was then equipped with an MLI protection from the back of the radiator up to the edge of the ECH and on the “top support”. The only apparent components are the ECH tiles. The same MLI is used on the OSR and the TCH radiator.

5.3 Instrumentation of the radiator breadboard

Each of the three radiators was equipped with a heating foil, bonded at the back of the plate. The voltage and current applied to the heaters was adapted to obtain the expected temperature, according to predictions. There were three type K thermocouples at the back of each radiator.

6. RADIATORS BREADBOARD TESTING

6.1 Test facility and configuration

We used a $1m^3$ chamber to run the test on the radiator. The chamber has a thermal range of [-180°C; +220°C] and can be operated with vacuum or a dedicated pressure.

Figure 8 : Thermal chamber

The samples were then placed in a radiative box made of copper with the inside covered in black paint (Z306). The outside and the bottom of the box were covered in the same MLI covering the radiators. The testing configuration is shown in the picture above.

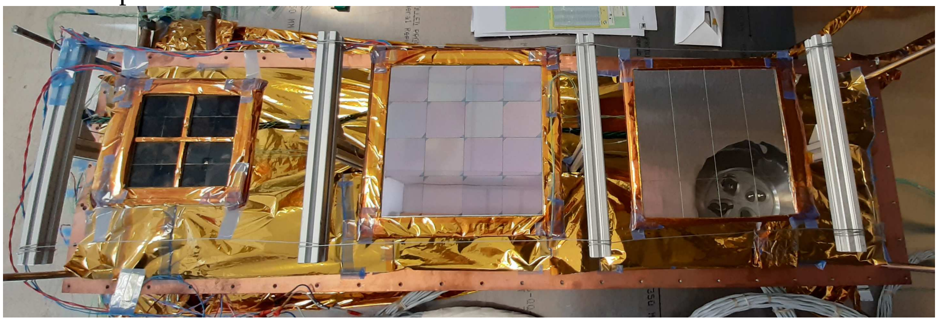


Figure 9 : Radiators before closure of the radiative box

6.2 Before-test emissivity measurements

Different emissivity measurements were made for the ECH, TCH and OSR tiles in order to predict the test performances and also to compare before and after test values and assess the impact of the thermal vacuum testing on tiles and radiator performances.

6.2.1 Influtherm

The thermo-optical measurements were made at Influtherm at room temperature and gave the following results :

Breadboard	Power	ε (mean)
TCH	N/A	0.48
ECH	-1.7V	0.61
	+1.2V	0.81

No emissivity transition were measured for the TCH radiator.

6.2.2 ESTEC

The ESTEC laboratory measured the emissivity profile of the TCH tiles in order to characterize the variation between high and low emissivity state. They measured a transition in emissivity that occurred between 60°C and 80°C. The emittance in stabilized states is given below.

Temperature	Emissivity ε
Below transition	0.57 to 0.58
Above transition	0.80 to 0.81

6.3 Test sequence

The test was divided in two periods. The breadboards were first passed through 8 different stages of heating power in order to compare and analyse their thermal behavior, with a particular effort to assess as reliably as possible the associated variation of the TCH and ECH emissivity. For each heating value, the emissivity of ECH radiator was changed from minimum to maximum value. Then the breadboards were put through 10 thermal cycles from -50°C to +60°C.The graph showing the evolution of temperature is given below.

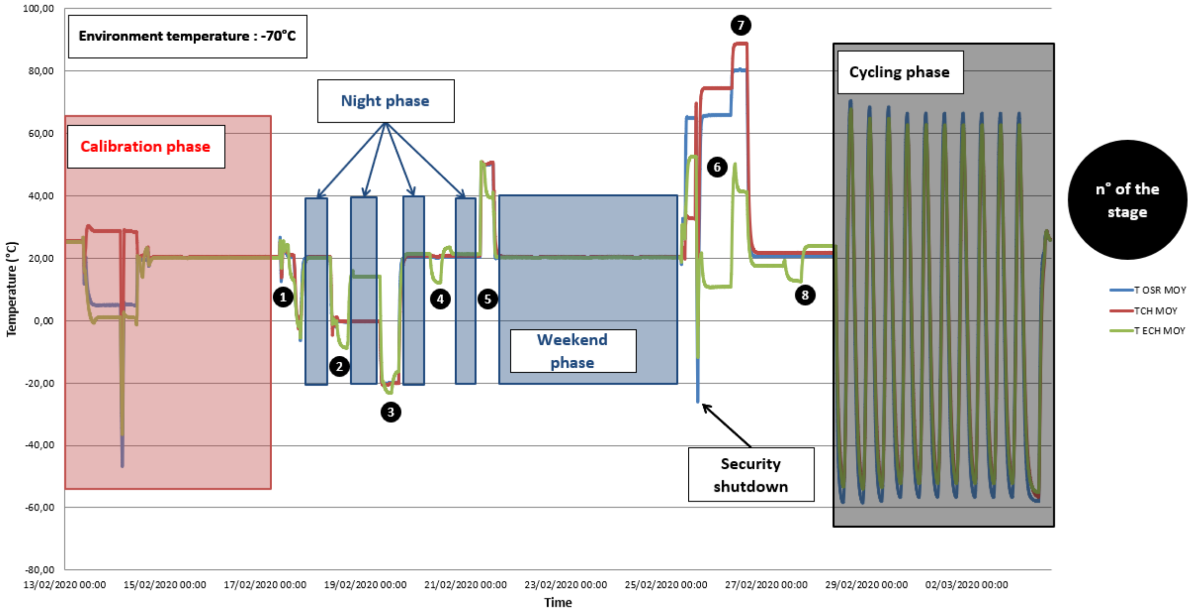


Figure 10 : Temperature recording on the radiators during the thermal balance and cycling

6.4 Results and discussion

6.4.1 TCH radiator

The temperature range of [+55°C,+76°C] led to a good fitting of the test results (< 0,5°C on each step) and was very close to the one measured by ESA of [+60°C,+80°C].

The TCH radiator showed valid and promising results all along the test. The emissivity variation was demonstrated and correlated through simulation as well as the temperature of commutation. In cold case, it was observed that TCH BB needs less heating power than an OSR radiator for the same equilibrium temperature.
On the figure below, we can see that the difference between calculated and measured temperature is very low (<0.5°C) with a slightly higher deviation at the -20°C stage (<1°C). A comparison between TCH and OSR for cold cases gives a saving in heating power of 35% at 0°C, which is significant.

However, due to the lower TCH emissivity in hot case the heat rejection with TCH is lower. For a same heat load above about 16W (corresponding to about 600W/m²) we stabilize with TCH about 7°C higher than with OSR. Of course this considers only the effect of the IR emissivity and does not take into account the impact of the solar absorption.

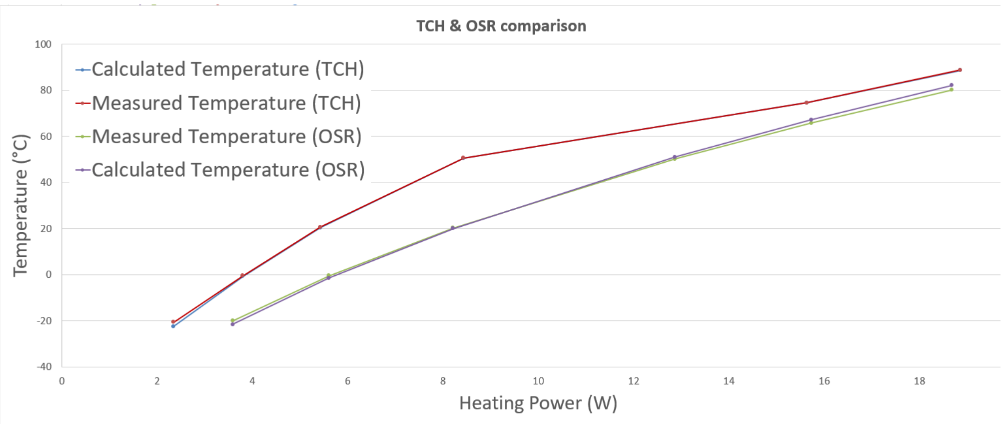


Figure 11 : TCH & OSR radiator temperature vs heating power

Finally, concerning the impact of the thermal vacuum balances and cycling on thermo-optical performances the test results are very promising since no relevant impact have been observed over all the test.

6.4.2 ECH radiator

The nominal value for the emissivity of the ECH radiator was taken from the measurement of Influtherm [0.61;0.81]. This value was confirmed by the correlation of the model vs experimental results.
Here below we present the graph T VS P for the various steps measured and simulated on the ECH BB (Figure 14).

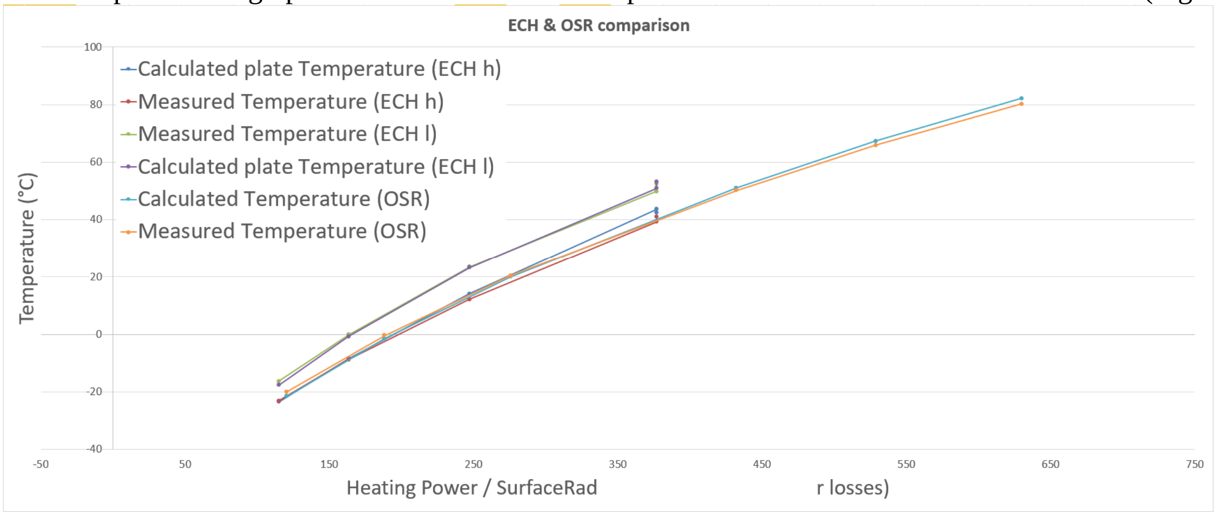


Figure 12 : ECH & OSR radiator temperature vs heating power

We can see that the difference between ECH calculated and measured temperature is low (<2.5°C), but higher than for OSR and TCH, as expected.

We can also observe clearly the thermal impact of the change in emissivity on the ECH temperature associated to the 10-12°C gap between the two curves : the upper curve giving the temperature when emissivity is low (+1.2V), the lower one giving the temperature when emissivity is high (-1.7V)

The heating power saving in cold case is of the order of 35% at 0°C, similar to the one brought by TCH. It is quite higher than the electrical power needed for the activation and the preserving of the radiator low emissivity. The ratio $P_{required}/P_{saved}$ is less than 20% during the first fractions of second after the commutation and less than 1% after

For hot cases, due to an ECH "high emissivity" (~0.8) slightly lower than OSR (0.84) one, the heat rejection capacity is slightly lower also. For a given heat load density (376 W/m², hottest case of our test for ECH) we stabilize with ECH about 1.5°C higher than the OSR in ECH high emissivity state. It would be worse for higher heating powers. Note that these encouraging results are without considering the solar absorptivity effect which would mitigate the ECH interest in hot case since α_S is still very high for non-encapsulated samples

During the test it was also observed that the ECH emissivity switch did not suffer from the thermal vacuum solicitation since we observed the same behavior on the three 20°C reference steps (beginning, middle and end of test).

Another important observation is that the ECH radiator is still operational at -20°C. It is not the case for all other ECH developments presented in the literature that stop commuting at higher temperature, near 0°C.

Concerning the "memory effect", no evolution of emissivity was observed for up to 17 hours in hot or cold case, without any power supplied to the device. This is really interesting since it allows to switch ON the device a few seconds two or three times per day to keep a stable emissivity, in both state and no continuous power is necessary to maintain a selected state.

Few leakage marks were observed on the ECH tiles of the radiator after the thermal balance and cycling test. This phenomena was also observed during the coupon level environmental tests in Task 4. This impacted the results of the after-test thermo-optical measurement but did visibly not impact the thermal performances of the ECH radiator during the thermal balances between the three reference 20°C balances, as observed.

7. CONCLUSION

This project has brought considerable advancement in the development of solutions for variable emissivity coatings for satellite surfaces, and in particular for thermal radiators. It took more time and effort than expected due to the great complexity and novelty of these technologies. But the results are promising and point to a follow-up to this study.

Two variable emissivity technologies have been developed: thermochromic coatings (TCH) based on W-doped VO2 and electrochromic devices (ECH) electro-emissive conducting polymer.

For the TCH materials, the major achievements can be summarized as follows :

- this work allowed for the transfer of the technology and knowledge from lab scale production at CEA to near-industrial means at IREIS,
- IREIS successfully manufactured quite many undoped and doped TCH tiles with an area of 40x40mm² and a good reproducibility. Promising trials on larger tiles were performed,
- the highest emissivity (hot case) was finally measured as high as 0.8 for 3.7% W doped tiles while the emissivity contrast was as high as 0.26 and the transition temperature was reduced from 65°C (task3) down to 33°C (task8),
- the solar absorptivity was slightly reduced from 0.55 down to 0.45 thanks to the deposition of a solar reflective multilayer on the TCH stack,
- in a preliminary environmental testing the TCH tiles showed good resistance to UV and thermal aggression,
- they were also demonstrated compliant with handling, cleaning and storage constraints,
- finally a small 16 tiles TCH radiator was successfully integrated and tested without specific problems in comparison with its equivalent covered with OSR tiles,
- the TRL for TCH at the end of the project is considered as 4.

At the end of the project, the main challenges identified for the usability of TCH on satellites are the following

- The solar absorptivity has to be reduced from 0.44 down to less than 0.2

- The transition temperature, in particular regarding the temperature giving the maximal emissivity, should be still slightly decreased from 33°C down to less than 25°C

Other axes of improvement, of interest but less critical for an applicability of the technology to space are a slight increase of the "hot case" emissivity from ~0.8 up to 0.84 and an increase of the emissivity contrast, as much as possible. With the reduction of the transition temperature it would be also interesting to reduce the hysteresis in order to get the transition as low as possible when heating.

These axes of improvement are to be developed in the follow up activity to this project.

For ECH the planned and spent efforts were lower than for TCH since the TRL was low at the beginning of the project. The achievements on this route can be summarized as follows :

- At tile level, the highest emissivity was kept as high as 0.8 while the solar absorptivity was reduced from 0.95 down to less than 0.45 thanks to an original encapsulation process and materials based on Ge deposition on HDPE film,
- however this encapsulation decreases the IR emissivity contrast from 0.3 down to 0.2,
- encapsulated tile has been tested in vacuum conditions at ambient temperature without relevant impact on its thermo-optical performances,
- we demonstrated the operating of a small radiator breadboard with 16 non-encapsulated tiles in thermal vacuum balances and cycles in a test with a duration of several weeks,
- electrical power and outgassing performances are compliant with expectations (with ECSS for outgassing),
- the TRL for TCH at the end of the project is considered as at most 3.

For ECH the TRL reached is still lower than TCH and the main challenges are the leakage of the electrolyte from the interpenetrated polymer matrix, the still too high absorptivity of the encapsulation, and the integration and control of a ECH radiator, that was not investigated in this study. A suitable future R&D project should address the study and development of an all-solid ECH device, including the electrolyte.

In brief all these achievements make the TCH and ECH technologies quite promising for possible application on spacecraft in order to reduce significantly the need in heating power and so to impact positively the cost and the mass budget of a spacecraft. At the end of this project TCH coating is more mature and more easy to integrate and operate on a spacecraft since it is a passive smart coating and it looks like a standard OSR tile.

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END OF THE DOCUMENT