# PFM Thermal balance-thermal cycling test of the ExoMars Entry Descent and Landing Demonstrator Module

M. Gottero[1], V. Perotto[2] and R. Martino.[3]
*Thales Alenia Space Italia, Torino, Italy*

C. Alary[4] and S. Lapensee[5]
*European Space Agency, ESA ESTEC, Noordwijk, the Nederlands*

**The PFM thermal vacuum test of the Entry Descent and Landing Demonstrator Module (EDM) for the ExoMars 2016 mission was successfully carried out in June-July 2015. It combined the thermal balance and thermal cycling verification of the module and was executed in the TAS testing facilities in Cannes, for a total effective duration of 32 days.**

**Due to the peculiar characteristics of the ExoMars mission, the test profile and objectives went well beyond the standard thermal verification of satellites. The heterogeneous environments encountered during the mission (leading to stringent and sometimes conflicting requirements), the extremely limited energy resources, the novelty of this design in the European scenario, the fact that no STM results were available, drove the decision to also implement in the test a realistic simulation of some of the most critical mission phases. The strong thermal insulation of the EDM bays, needed to survive in the harsh environment of the coasting phase and during on-Mars operations, made the time constants of the system quite large, with an additional challenge in terms of test schedule.**

**To meet such goals, a much optimized profile was conceived, based on detailed numerical simulation of the entire test in transient conditions. Besides the standard thermal balance phases (for model correlation and thermal design verification) and thermal cycling plateaus (for workmanship verification and functional checks), representative Thermal Boost and Coast phases were implemented, including the relevant functional operations.**

**This PFM-level test of EDM was the first experimental verification of a novel design that has been developed by TAS-I Torino since 2008, based on extensive numerical simulation and elementary testing of the basic technologies/materials. Insulating materials/solutions for vacuum conditions (conduction and radiation) and Mars atmosphere (convection), heat capacitors based on phase-change materials (developed in cooperation with a US supplier), proper operational profiles (e.g. thermal boosting before separation) and ablative TPS heat shields for the entry phase (TAS-F) are the cornerstones of such design. This complex test permitted the verification of a significant part of such solutions in a relevant environment.**

**This paper describes the test setup and plan, presents the main results with focus on key points and discusses the test evaluation campaign, including the thermal model correlation activity.**

[1] ExoMars thermal system engineer, Thermal Systems, Strada Antica di Collegno 253, 10100 Torino, Italy.
[2] Senior thermal engineer, Thermal Systems, Strada Antica di Collegno 253, 10100 Torino, Italy.
[3] Senior thermal engineer, Thermal Systems, Strada Antica di Collegno 253, 10100 Torino, Italy.
[4] Thermal Systems Engineer, Exomars Project, ESA ESTEC, Noordwijk, the Nederlands
[5] Thermal Engineer, TEC-MTT, ESA ESTEC, Noordwijk, the Nederlands

**Nomenclature**

BCV = Back Cover
BS = Back Shell
CB = Central Bay
CTPU = Central Terminal Power Unit
DAS = Data Acquisition System
DMTTA = DM Thermal Test Adapter
ECSS = European Cooperation for Space Standardization
EDL = Entry Descent and Landing
EDM = Entry Descent and Landing Demonstrator Module
EGSE = Electrical Ground Support Equipment
ESA = European Space Agency
FS = Front Shield
GAD = Ground Access Doors
IMU = Inertial Measurement Unit
MLI = Multi Layer Insulation
MSA = Main Separation Assembly
PCM = Phase Change Material
PFM = Proto Flight Model
RCS = Reaction Control Subsystem
RTG = Radioisotope Thermoelectric Generator
SCC = Spacecraft Composite
SLI = Single Layer Insulation
SP = Surface Platform
SS = Steady State
STM = Structure Thermal Model
S/C = Spacecraft
TB = Thermal Balance
TC = Thermocouple
TCS = Thermal Control Subsystem
TGO = Trace Gas Orbiter
TMM = Thermal Mathematical Model
TPS = Thermal Protection System
TV = Thermal Vacuum
TVTB = Thermal Vacuum Thermal Balance

## I. Introduction

The ExoMars program has been established with cooperation between the European Space Agency (ESA) and the Russian Space Agency (Roscosmos) to investigate the Martian environment and to demonstrate new technologies.

It consists of two missions: a 2016 launch of a carrier/orbiter releasing a demonstrator lander, and a 2018 launch of a rover carrying a drill and a suite of instruments dedicated to exobiology and geochemistry research.

With the 2016 mission, the Trace Gas Orbiter (TGO) carries scientific instruments to detect and study atmospheric trace gases, such as methane.
In addition, the TGO will act as a carrier, releasing the EDM three days prior to arriving on Mars.

The main objective of the lander EDM (ExoMars Entry Demonstrator) is to demonstrate the capability of landing a payload on the surface of Mars.
The EDM contains sensors to evaluate the EDM performance as it descends, and a small payload to study the environment at the landing site.


**Figure 1. ExoMars 2016 SpaceCraftSpacecraft Composite: Carrier-Orbiter (TGO) and Mars capsule (EDM).**

## II. EDM thermal design

The EDM is a capsule with four components:

- The Back Shell (BS) consists of a conical structure, covered with the Thermal Protection System (TPS) and holds the parachute system, the sun sensor, the HEPA filters and the mechanisms for the separation with the Front Shield and the Surface Platform.

- The Surface Platform (SP) consists of a honeycomb disc structure where the Back Shell separation mechanisms, the propulsion system, the radar assembly, the inertial measurement unit and two batteries are mounted. The remaining units, which are the main computer, the transponders and switches, the battery and a scientific payload are located inside the Central Bay (CB) specifically designed for the Martian surface environment.

- The Front Shield (FS) consists of a conical structure covered with TPS and it holds the passive part of Back Shell separation mechanisms.

- The Main Separation Assembly (MSA), (not shown in the picture) fixes the EDM onto the TGO.

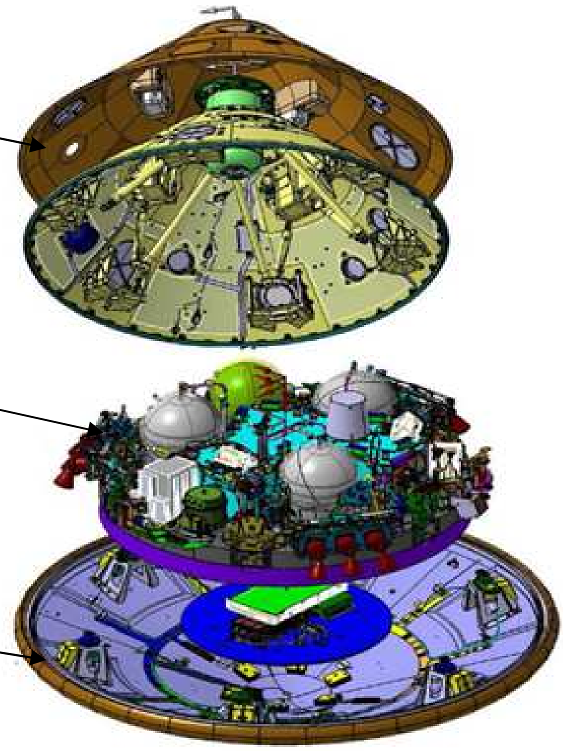


**Figure 2. EDM exploded view**

The mission consists of four main phases: Cruise, Coast, Entry and Mars Surface.

During the Interplanetary cruise, the EDM is dormant most of the time except during check-outs and prior to the separation from TGO. The TGO provides power to the EDM and communication with Earth during the Cruise phase.

After the separation, the EDM will coast for 72 hr. before entering the Mars atmosphere. The EDM is powered only by its own batteries and will remain dormant during the coast except for the last 2 hr. in preparation for the six minutes Entry, Descend and Landing (EDL) event.

The Entry starts with aerothermal loads and ends with the parachute opening. During the descent, the FS is jettisoned and the RADAR measures the distance to the ground. Once the desired altitude is reached, the SP separates from the BS and performs a soft landing using its guidance and propulsion subsystems. The EDL phase lasts roughly for 300 s.

Once on the Mars surface, the SP scientific payload operates while the lander transmits data to the orbiters during passes until the Central Bay battery is depleted. In a worst case scenario, the battery will be depleted after two Martian Days, or 2 SOLs.

The EDM thermal design was challenging because of the following main design drivers:

- First, the heater power of the propulsion sub-system needed to be minimized during the interplanetary cruise phase.
- Second, the total energy available in the coast and EDL is about 2000 Wh, and an additional 2000 Wh is available for the Mars Surface. The total energy is provided by dedicated batteries.

- Third, the TPS needs to be maintained above -100˚C in all phases in order to avoid degradation. In addition, the FS and BS TPS was sized assuming a temperature below -40˚C and -20˚C respectively at the start of the EDL. Therefore, various attitudes of the EDM versus sun angle needed to be accounted for in order to verify that TPS would remain within the allowable temperature. Moreover, during the cruise, the EDM is in the TGO's shadow while during coast, the EDM is spinning thus exposing the BS to the sun.
- Fourth, the thermal design needed to accommodate short duration unit power dissipations during check-outs, separation, and EDL. These power events will typically last for one hour for checks, 2 hour before separation and about 4 hours prior to landing. The total maximum dissipation of the electronics is 115W and just a few watts during hibernation.

The first three drivers impose a highly insulated design that consequently requires some form of heat removal and disposal. In summary, the thermal design of the EDM consists of the following:

1. The BS TPS is covered with SLI (Single Layer Insulation), an external layer of Kapton with a combination of aluminum and silicon oxide depositions, glued to the TPS. The low infrared emittance (0.3) conserves energy during cruise and coast while the low solar absorptance (0.14) maintains the TPS cold at start of EDL. An MLI covers all BS internal surfaces of the conical structure, to create a benign environment for the SP and to minimize the heat leaks of the SP. Heaters are used by the sun sensor, the mechanisms of separation from the FS and SP, and the parachute container.

2. The FS is a structure without any electronics or actuators for the separation mechanisms (the active parts of the mechanisms are on the BS). The sun never illuminates it, so it requires a different solution versus the BS: an MLI on both the external and internal surfaces. This combination minimizes the EDM heat leaks and guarantees the TPS temperature requirements.

3. The SP is completely wrapped in MLI. Local additional MLI is used on the propulsion components and on the electronics. The CB, in addition to the MLI, has a layer of polyimide foam to improve the insulation on Mars. Heaters are used on structure, electronics and propulsion components.

4. A thermal boost is performed before separation from the TGO in order to raise the temperature of the EDM and decrease heater use during the coast phase. Energy is stored in the SP components in particular the BC parachute, the SP structure and the fuel tanks. The TGO electronics control the EDM heaters in a way that maximizes the use of the TGO power while remaining within its maximum 240 W limit.

5. Thermal capacitors are mounted under three units: CTPU, TRANSCEIVER and IMU. The first two are inside the well-insulated CB. Without an effective external heat sink, the heat they produce is actually an important contribution to the CB heating on Mars. The MIMU is mounted directly on the SP main structure, which is a poor heat sink, the unit dissipation is large compared to its thermal capacitance, and its maximum operative temperature limit is only 50˚C. Thermal requirements for capacitors were identified through simulations.

   EDM thermal capacitors are PCM-based heat exchangers specifically designed for ExoMars and manufactured by the US company ERG Aerospace. They use phase change waxes that transition from solid to liquid at the desired control temperature and absorb considerable heat energy in the process. In order to effectively transmit the heat into the PCM wax, which has very low conductivity of its own, the wax is contained within an aluminum housings filled with an open-celled aluminum foam that acts both as a structural core material and provides a very large surface area for the wax to make contact with. For details, see Ref.1.

## III. EDM thermal verification

The thermal verification of the ExoMars 2016 spacecraft (SCC, Spacecraft Composite: TGO+EDM) relied on two separate but complementary test campaigns carried out in parallel at module level:

- EDM thermal cycling/thermal vacuum test
- TGO thermal cycling/thermal vacuum test.

A dedicated trade-off, taking into account the technical objectives as well as the programmatic constraints (schedule and costs), demonstrated that performing two separate tests was adequate to properly cover the full thermal verification of both the EDM and TGO. This is mainly due to the fact that the EDM and TGO are thermally decoupled and only a conductive interface sink as well as electrical/software interfaces needed to be represented during the tests using dedicated simulators.

The goal of the EDM TVTB, subject of this paper, was the system qualification of the EDM capsule under vacuum when subjected to the extreme hot and cold temperature limits, the validation of the Thermal Mathematical Model (TMM) and the verification of the adequacy of the thermal design in a PFM approach.

This test was the conclusion of a verification campaign that didn't foresee STM activities at module level but included a series of elementary tests at sample and component level: verification of CB insulations (including material performance in representative atmosphere), verification of heat shield sandwich samples (MLI+structure+TPS+SLI/MLI) in vacuum and under aerothermal fluxes (Simoun test), as well as full characterization and qualification of the thermal capacitors for the SP.

## IV. EDM test configuration and instrumentation

The EDM test configuration was representative to the flight configuration with the exception of:

- TPS tiles around the BCV access doors were missing and their SLI blankets were installed directly on the structure to assure the correct optical properties.
- Ground Access Doors (GADs) replaced the flight access doors and were used also as pass-through for the bundles of cables to the power supply, data handling and chamber Data Acquisition System (DAS).
- Propellant inside the tanks was replaced with propellant simulant (de-ionized water, reproducing the nominal heat capacitance of the propellant). Correctly simulating the heat capacitance of the tanks was very important in this test for the simulation of the thermal boost and of the temperature drop in coast.
- Helium tank was empty since the thermal capacitance of Helium is small.
- The Parachute flight Gas Generator was missing.
- Flight HEPA filter was replaced with a structural model.
- No Sun simulator was used. EDM remains for the entire cruise in the shadow of the TGO; in coast the Sun flux is not high (about 700 $W/m^2$) and the capsule is spinning. The decision to avoid Sun simulation was judged preferable to simplify the test and facilitate correlation.
- The EDM was fixed to the trolley, simulating the TGO and also for the phases, simulating the coast.

During the thermal test, there were no simulations of the Mars phase with the SP in a partial pressure $CO_2$ atmosphere. This limitation didn't allow some units inside the Central Bay to reach the minimum temperatures. In addition, the lander performance in $CO_2$ atmosphere was not verified. Such limitations didn't jeopardize the EDM verification since:

- Qualification/acceptance tests at unit level have been performed in a Mars-representative temperature range
- Full redundancy (4+4) has been implemented for CB thermostats not switching during the TVTB
- Tests at sample level have been conducted to verify the performance of the Central Bay insulation material in atmosphere
- Wide uncertainty was applied to estimations of on-Mars energy consumption to cover uncertainty on the convective heat-transfer coefficients.

The EDL phase with aerothermal fluxes was obviously not simulated in the frame of the TVTB even though that phase is the sizing case for the Heat Shield. Nevertheless, the following tests were performed in order to verify the Heat Shield:

- The qualification of the heat shield has been accomplished by analysis and Simoun tests at sample level.

- All structures have been subjected (already completely integrated) to the sterilization process at 125°C (which for the BS is even more demanding than flight loads from a thermal point of view). The mechanical tests (sine & acoustic) performed at spacecraft level after sterilization and integration have screened any workmanship errors at structural level.

The S/C was equipped with 252 thermocouples Type T on EDM and 75 on test adapter and cables. Heater power and total energy consumed in coast were measured by the test EGSE; they are important to verify the design of heaters and batteries. The test heaters were used to partially compensate the missing heat fluxes, to help create specific test conditions or to simulate/compensate the flight heater lines where constant power was preferred. The test harness was kept within its temperature limits by special heater lines. However, the overall test conditions were colder than in flight, mainly because the sun effect on BS was not simulated.

The EDM was installed with its support DMTTA inside the chamber ESP70 so that its +Y axis was installed along the length of the chamber. The figure below represents the position of the EDM inside the ESP70 seen from the door of the thermal vacuum chamber.

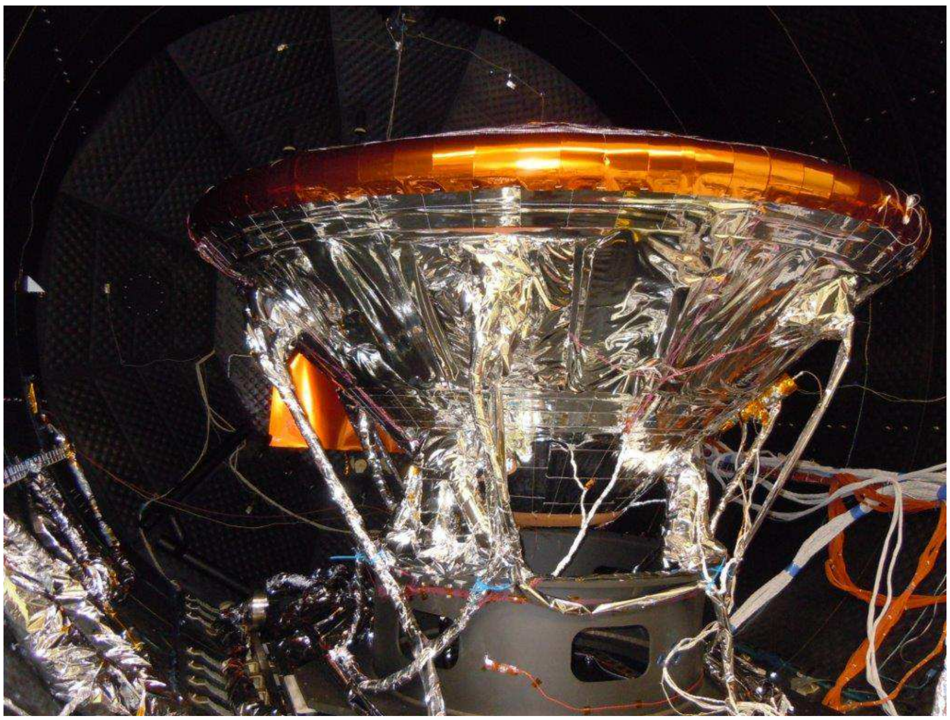


**Figure 3 EDM installed in the Thermal Vacuum Chamber**

## V. EDM test phases and main outcomes

The sequence of test phases is shown below with the expected indicative temperature of the SP plate. The thermal balance part consists of two steady states simulating the cold and hot phases of the cruise, the cruise thermal boost and the separation from TGO, followed by 72 hr. of coast. The thermal vacuum consists of a cold and hot plateau.

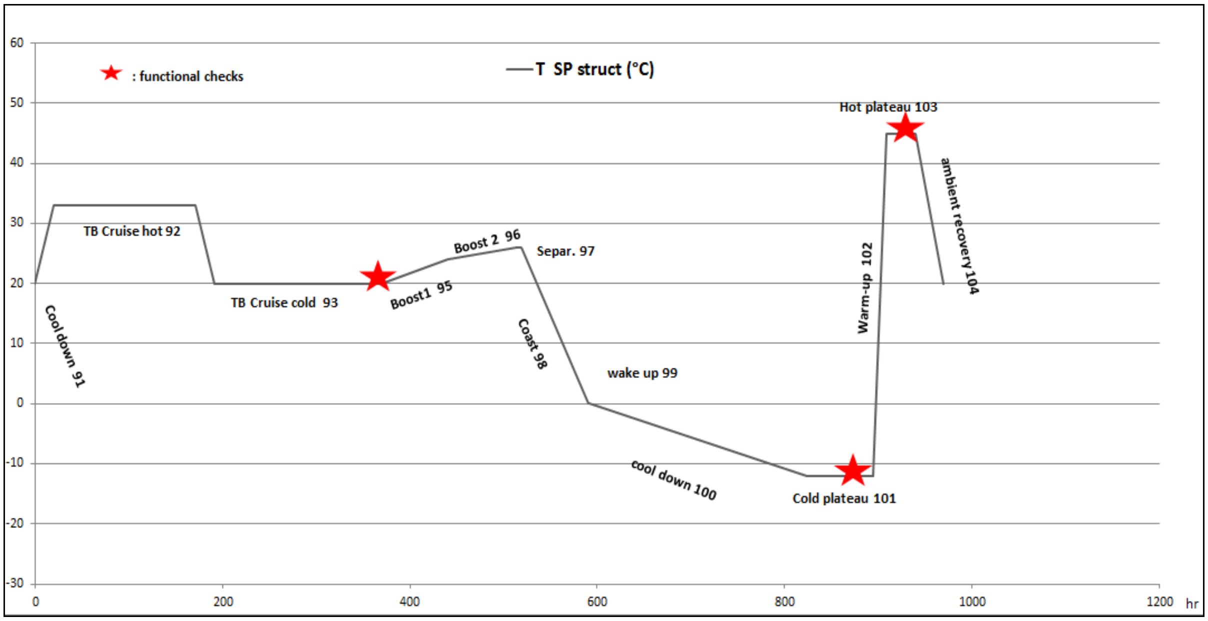



**Figure 4 TVTB test profile**

All TB steady states plateaus were dedicated to the verification of the thermal model conductors whereas the thermal boost and coast were focused on the thermal capacitances and time constants, which are fundamental in this mission since the dimensioning cases are transients.

The energy budget, in fact, is one of the most critical aspects of this mission. It is characterized by a relatively long coast (different from usual Mars missions, where the carrier is not an orbiter and can release the landing payload just before the injection point) and relies on batteries (neither solar arrays nor RTG devices). Besides permitting the verification of capacitances and time constants, a quite representative simulation of the boost and coast phases permitted to get an overall verification of the TCS approach and performance.

The TV phases were used to verify the proper operation of the equipment in their extreme cold and hot temperature limits.

Due to very large time constants of the system, the cool-down to the cold plateau is extremely long for EDM (order of one week). The overall test durations wouldn't have been compatible with the tight schedule of the project if the number of cycles requested by ECSS had been implemented. So, a reduced profile with just one cycle was agreed among parties and the related risks were judged acceptable based on testing at equipment/subsystem level, on analysis and on the fact that no real thermal cycling will be seen by EDM during its mission. This test relaxation affected only the EDM whereas the carrier/orbiter was submitted to the full thermal cycling in accordance to ECSS.

The test started on Tue June 9th 2015 and, despite minor anomalies that didn't prevent the achievement of the planned profile and objectives, ended Sat July 18th 2015.

The Analysis of results indicated that:

- All EDM temperatures remained all the time within the requirements.
- The temperatures of the SP were significantly colder than expected in TB Hot and TB Cold phases: the SP heaters were not able to maintain the SP at the planned temperature at TB Cold and the duty-cycle was 100%

at TB Hot. This issue originated partially from test conditions which are colder than the flight and due to the higher heat leak between the SP and the Heat Shield. Additional heater power was thus allocated after the test to counteract the unexpected heat leak.

- The propellant tanks did not fully stabilize in the steady states because of their high time constants. This would have required much longer phases which were not compatible with the schedule. Hence their asymptotic temperature was extrapolated.
- The algorithm for the thermal boost optimization (guaranteeing max boost efficacy compatibly with the max current deliverable by TGO) worked properly and the EDM maximum heater power was limited to 220W.
- Due to differences between the test and flight environments, the post-processing of the measured total energy consumption for the TCS in coast was extrapolated to the flight conditions. The TCS approach and performance was confirmed and the thermal-boost parameters (thresholds, priorities in heater activation) were re-optimized based on test data. Some minor post-test refinements of MLI blankets were implemented as well.
- As expected, only a partial achievement of the objective temperatures was obtained at Cold Plateau, due to the test setup. In the Hot plateau, all the relevant EDM items were brought at the objective temperature levels, except for the RTPU NL Battery due to a failed test heater.
- All functional checks performed in the TB and TV were successful.
- The performance of the thermal capacitors was tested at the Hot Plateau. One complete cycle of wax melting/solidification was observed, reproducing the test results at unit-level testing.

## VI. EDM TMM correlation

The EDM TMM was built in ESATAN-TMS r5 and runs on a Linux platform. It consists of 6737 thermal nodes and more than 1.5 million conductors. It simulates the entire mission from start of interplanetary cruise to the end of Martian phase in one analysis run. This was indispensable since no single phase was dimensioning case for the TCS.

The model was adapted for the TVTB, and three phases were correlated:

1. TB hot steady state. It is a steady state for most items except those whose heaters are switching (e.g. RCS wet components, RTPU 60V battery)
2. TB cold steady state. It is a steady state for most items except for heaters that are cycling (e.g. RCS wet components, RTPU 60V battery) but it is colder than TB hot. Also the transient between the two TB phases was simulated and used for a verification of the capacitances.
3. TB coast. It is a 72 hr. cooling down period and reproduces the flight coast long hibernation. The coast test phase is important for the verification of the capacitances. Unfortunately the exact predicted flight conditions at the start of the coast were not achieved due to the test conditions. Therefore, the measured temperatures were loaded into the TMM. This exercise required some extrapolations since the amount of TCs are much less than the TMM nodes. Nevertheless, due the existing symmetries in the EDM design, a small uncertainty of roughly < 2 K was achieved the initial coast temperatures.

The correlation objectives were to reproduce temperatures of equipment within 5 K, average and standard deviations less than 3 and 5 K respectively for all TC, and to calculate the energy consumed by the heaters in coast within 10%.

In a first run after the test (post-test predictions), with only an update of the test conditions and for only the steady states, the EDM average / standard deviations were: TB hot 1.94 / 7.78, TB cold 3.51 / 8.21 K. The equipment maximum error was 7 K. The large standard deviation originated from the BS structure, while the SP and FS temperatures were well reproduced.

The correlation consisted of two steps.

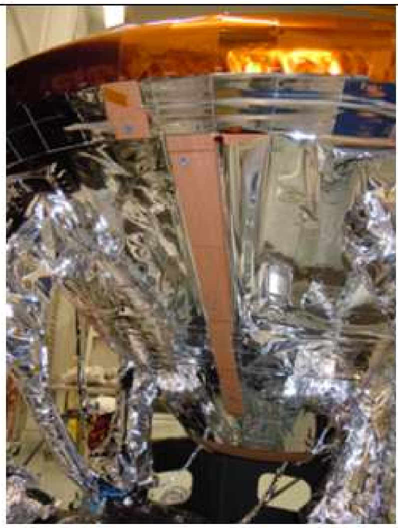
1. The first focused was on the temperatures of the steady states and on an analysis of the areas with the largest errors and on the correction of the thermal parameters with a global effect.
2. The second was applied to the coast phase and its heater energy consumption, focused also on local temperatures, in particular of the RCS. The correction of the thermal parameters was also made in a semi-automatic way with the stochastic optimization technique.

**Correlation phase1**

The modifications to the TMM were:

- Areas of the GADS without the TPS and covered by test SLI had to be re-modelled accurately, in particular the percentage of glued area of SLI which changes locally, the cables and harness passing through the GADs, the presence of MLI on the internal side of the GADs. The SLI was found less adherent to structure than to TPS. A strip bare TPS were no SLI could be installed to avoid interference with the EDL sensor originated a cold spot on the BS, and had to be modelled accurately.

Dark brown area is without TPS



Strip of bare TPS

**Figure 5. BS TPS and ground access door**

- Pressure gauge mounted on GAD-Z was erroneously insulated, when its heaters were powered the tubes to the GAD exceeded 160 °C, then one heater failed so the temperatures of the tubes remained at 120 °C throughout the test. The gauge did not fail, but a hot spot occurred on the BS around the GAD. The model was updated to simulate the gauge as a boundary.
- SP model was updated to simulate more accurately the separation mechanisms between the BS and the SP, as well as the MLI on the SP. The MLI is a complex tent that was made basically with a cut–to-fit approach. Therefore the MLI representation in the model was not known in detail before the test.
- The fuel tank model was not able to reproduce the test results in transients, because the model details for the shell and liquid were too coarse. In addition the liquid convection within the tank overcomes the conduction when testing in gravity. Another more detailed model was made which accounted for convection between the shell and liquid nodes.

After these modifications, the model was run also for the coast phase and the results were: EDM average / standard deviations: TB hot SS 1.53 / 4.45, TB cold SS 2.51 / 4.78 K, TB coast 2.51 / 4.78 K. The equipment maximum error was 6 K. The predicted energy used by heaters in coast was 2200 Wh vs 2570 Wh measured.

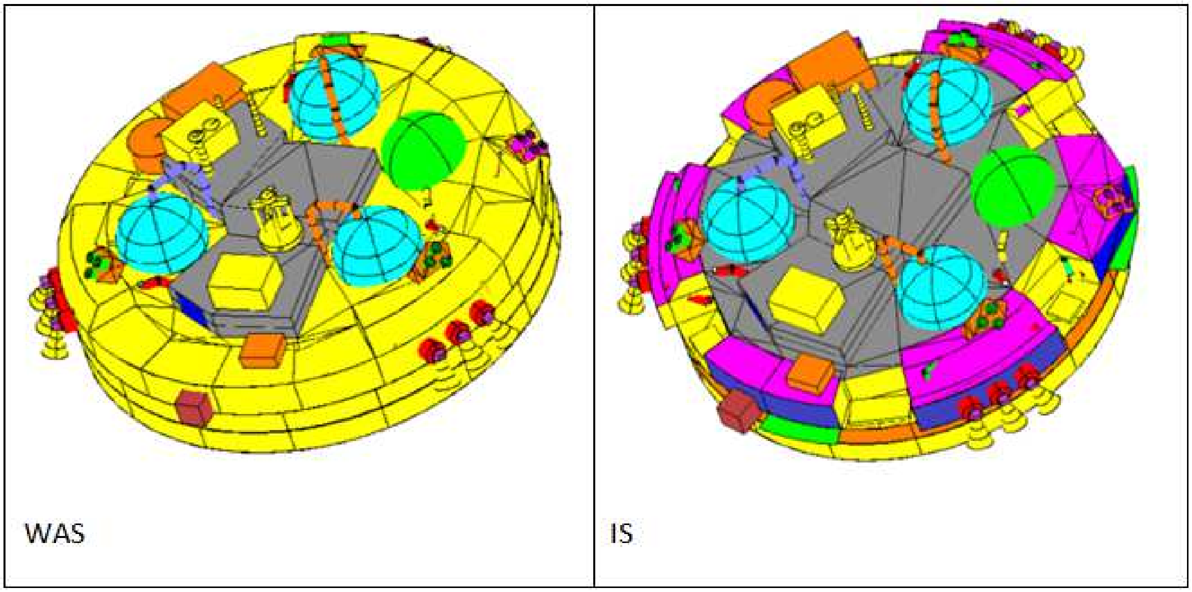



**Figure 6. Model of surface Platform MLI tent**

**Correlation phase2**

For the refinement phase of the correlation we adopted a stochastic approach which consists of several steps [2]. A single step consists of running the model many times, each time with a different combination of thermal parameters (input parameters), of observing the results stored in a set of output parameters and then to pick up the best combination of input parameters as a base for another step.

In detail N=82 input parameters were identified, they describe the global thermal parameters as the MLI efficiency and the conductance of the honeycombs, and local parameters as the contact conductance of individual units. Each input parameter i=1,N varies in a range according to a given Probability Distribution Function (PDF), e.g. flat, Gaussian. The range and distribution functions are generally obtained from measurements of the properties at sample level or from past thermal tests.

For each correlation step a set of j=1,M simulations was made to explore the N input parameters, the range of each parameter was divided in M intervals all having the same probability, and the median ave (i,j) was associated to interval j of input parameter i.

For each simulation j an integer random number k was generated between 1 and M for each parameter i, the parameter i was given the value ave(i,k), if ave(i,k) was already used in a previous simulation a new random number was generated until a not-used ave(i,k) was found. So, after M runs all the median values ave(i,j) of input parameter i were explored. Each simulation produced results for 2 steady states and for the transient cases.

The effect of the combinations of input parameters was calculated on a set of 36 output parameters, they were:

- The average deviation of all TC and of selected groups of TC (e.g. separation mechanisms, RCS, equipment) in all the correlated cases.
- The duty cycle and the heater energy consumed by all heaters and by selected groups of heaters (RCS, mechanisms, sun sensor, equipment) in the transient case.

Several sets of M=25 runs were made. At the end of each step the combination of input parameters that produced the best output results was then taken, the PDF were updated by centering them on the best values and another step was made.

The most significant changes identified in this process were:

- The BCV conductivity of the cone honeycomb in plane was increased about 3 times to account for inserts, harness etc.
- The conductivity of the BCV bars was increased from 2 to 4 times to account for bundles of cables running on them (bundles are different for each bar)
- The contact conductance between the MSA bracket and the BCV bars was multiplied by 0.16, and between the PAS ring and the BCV bars multiplied by 0.43.
- The contact conductance between the BCV bars and the separation mechanisms on the SP was multiplied by 2.2.
- The conductivity of the main honeycomb panels was multiplied: for the SP main panel by 1.42 (here the increase is due to cables running all over the panel), for the crushable structure by 3.11 and for the radar panel by 4.63 (for these last two items we did not have measures on samples, and cables were also present)
- The conductors between the equipment cover and the baseplate was multiplied from 1.5 to 4 depending on the unit, generally the contacts units-plane were better than expected, with and without thermal filler.

Final results were:

| | | | 92 TB HOT | | | | 93 TB COLD | | | | 98 TB coast | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EDM_ALL | nr.of | TC | = | 258 | | | = | 262 | | | = | 261 | | |
| EDM_ALL | average | deviation | = | 0.79 | | | = | -0.65 | | | = | 0.94 | | |
| EDM_ALL | standard | deviation | = | 2.97 | | | = | 2.62 | | | = | 3.93 | | |
| EDM_ALL | TC | with | max | error | = | 1015 | max | error | = | 981 | max | error | = | 510 |
| EDM_ALL | TC | with | min | error | = | 983 | min | error | = | 707 | min | error | = | 1309 |

The five rows of the table contain the number of TC used, the average and standard deviations of their errors $T_{calculated}$-$T_{test}$, and the TC with the maximum and minimum errors.

All electronics have an error < 5K, except one battery for which the 2-nodes model provided by the supplier came out to be too coarse.

The energy consumption in coast is captured within 8%.

An example of model correlation in transient (for most of the test phases) is shown in the following figure:

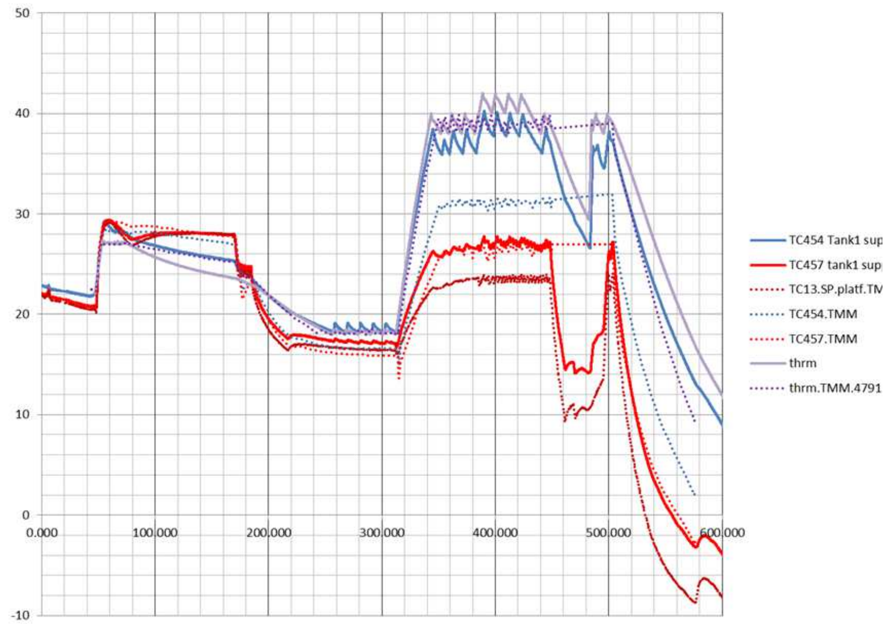



**Figure 7. Example of correlation in transient for propellant tanks (test temperatures - solid line – vs. predictions – dotted line).**

## VII. Conclusions

The ExoMars EDM thermal vacuum-thermal cycling verification was a challenging activity due to various reasons being peculiar to this mission:

- The strong thermal insulation of the system made the time constants very high. The test profile had to be strongly optimized based on accurate test predictions of the entire test campaign and compromises had to be found in the selection and arrangement of test phases.
- The critical energy budget made the transient phases very important to accurately verify time constants and to estimate the actual heat leak. Furthermore, in order to properly correlate the model, flight dedicated test phases such as the thermal boost and coast, were introduced.
- Considering that a unique spacecraft configuration was tested in a pure PFM approach (no STM) and that simulation of the on-Mars and EDL phases was not feasible in the TVTB, efforts had to be done to cover, as far as possible within the existing constraints, a wide range of test objectives related to the entire mission.

Accurate planning of the test using numerical simulation of the entire test profile came out to be a key element for the successful achievement of the project purposes.

Overall, the test was executed according to the plans and all the expected objectives were met. The requested success and stabilization criteria were achieved at each end-of-phase. The verification and functional checks of the thermal hardware and of the EDM equipment were successfully performed at the planned temperatures (coherently with the scope and possibilities of this test). The adequacy of the thermal design was verified during the test, with two open-points related to colder temperatures of the Surface Platform vs. pre-test predictions and uncertainty on the energy consumption during the coast phase. Such open points have then been solved during the post-processing and correlation activities and led to increasing the heater power allocated to the landing platform and re-optimize the parameters of the thermal boost. A fully satisfactory correlation of the thermal model was obtained, both in steady-state and in transient conditions.

Following the thermal test campaign, the EDM and TGO completed their preparation at TAS premises. In December 2015 they were transferred to the Baikonur Cosmodrome to be integrated and installed on the Proton launch vehicle. Launch has been successfully accomplished on March 14th 2016: the spacecraft is now on its way to Mars, all thermal parameters are nominal.

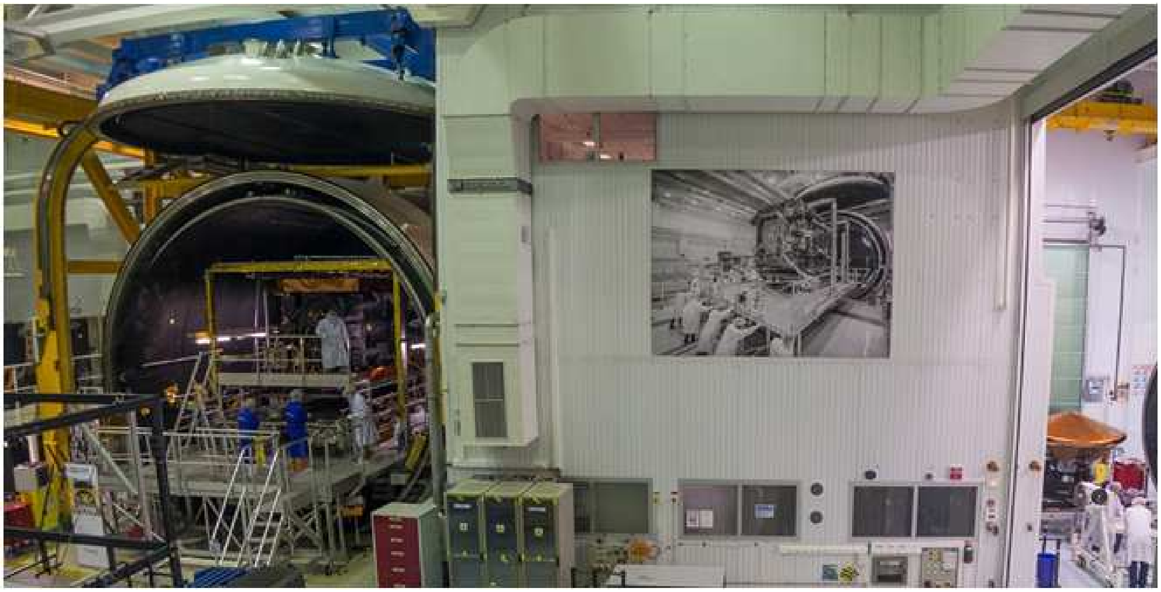


**Figure 8. ExoMars 2016 verification campaign: EDM (on the right) just removed from its 3-m test chamber while the TGO (on the left) is getting in the large space simulator of TAS facilities in Cannes (courtesy ESA/B.Bethge)**

## References


[1]Gottero, M. et al., “Phase-change thermal capacitors for ExoMars 2016 mission”, ICES-2014-147, *44th International Conference on Environmental Systems,* ,13-17 July 2014, Tucson, Arizona.

[2]Mareschi, V. et al., “Thermal Test Correlation with Stochastic Technique”, SAE paper 2005-01-2855.