The Challenges of the Thermal Design of BepiColombo Mercury Planetary Orbiter

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BepiColombo is the first European mission to Mercury. It will send in orbit around the planet two separate spacecraft: Mercury Magnetosphaeric Orbiter (MMO), provided by the Japanese Space Agency, and Mercury Planetary Orbiter (MPO), provided by the European Space Agency. The transfer from Earth to Mercury will be ensured by a dedicated module, Mercury Transport Module (MTM), which will provide. MPO, the subject of this paper, is the European scientific contribution to the BepiColombo mission. Its orbit around Mercury will be 3-axis stabilized, planet oriented, with a planned lifetime of 1 year, and a possible 1-year extension. The mission will perform a comprehensive study on Mercury, by means of several instruments, including a laser altimeter, different types of spectrometers, a magnetometer and radio science experiments. The subject of this paper are the complex challenged faced by the thermal design of MPO. The very harsh thermal environment experienced by the Module changes from a relatively cold condition after the launch (1.15AU distance from Sun) to a very hot condition orbiting Mercury (0.3AU distance from Sun at aphelion plus the infrared heat load from the Planet). The TCS is based on the shielding effect of a High Temperature High Performance MLI and on the particular radiator design, capable of reflecting most of the infrared flux coming from the Planet. The equipment are mounted on the internal structural panels which are connected to the radiator by a complex network of Heat Pipes. The Payloads typically have a dedicated thermal control, based on low temperature sub-radiators, which have to be highly decoupled from the internal spacecraft environment. Pointing stability requirements are satisfied mounting the instrument on dedicated Optical Bench.

Nomenclature

AOCS	=	Attitude and Orbital Control System
AU	=	Astronomical Unit (= 149.60×10^6 km)
CPS	=	Chemical Propulsion System
ESA	=	European Space Agency
ESH	=	Equivalent Sun Hours
GFRP	=	Glass Fiber Reinforced Polymer
HP	=	Heat Pipe
HT-MLI	=	High Temperature Multi Layer Insulation
JAXA	=	Japan Aerospace Exploration Agency
MCS	=	Mercury Composite Spacecraft (stack of MOSIF, MMO, MPO and MTM)
MTM	=	Mercury Transfer Module
PFM	=	Proto-Flight Model
RCS	=	Reaction Control System
RSA	=	Ruag Space Austria GmbH
S/C	=	SpaceCraft
STM	=	Structural Thermal Model
TAS-I	=	Thales Alenia Space Italia
TCS	=	Thermal Control System
UV	=	UltraViolet
VDA	=	Vapor Deposited Aluminum

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MMO	=	Mercury Magnetosphere Orbiter	VUV	=	Vacuum UltraViolet
MOSIF	=	Magnetospheric Orbiter Sunshade and Interface	α_S	=	Solar Absorptance
MPO	=	Mercury Planetary Orbiter	ε_{IR}	=	Infrared Emissivity

I. Introduction

BEPICOLOMBO is ESA's cornerstone mission to Mercury in collaboration with JAXA. With reference to fig. 1, it consists of a spinning satellite, "Mercury Magnetospheric Orbiter" (MMO) provided by JAXA, a module designed to protect the MMO, by the intense sun radiation during the cruise to Mercury[6] (MOSIF) and a 3-axis stabilized orbiter (MPO) both provided by ESA. Finally, the propulsion module (MTM), also provided by ESA, completes the composite spacecraft (MCS) that will cruise from Earth to Mercury orbit. The MTM houses the solar electric propulsion system that is needed to propel the MCS during its cruise. During the 6 years of cruise, the MCS stack is 3-axis stabilized and Sun-oriented to ensure sufficient electric power from the MTM solar arrays for the electric propulsion and protection from the Sun.

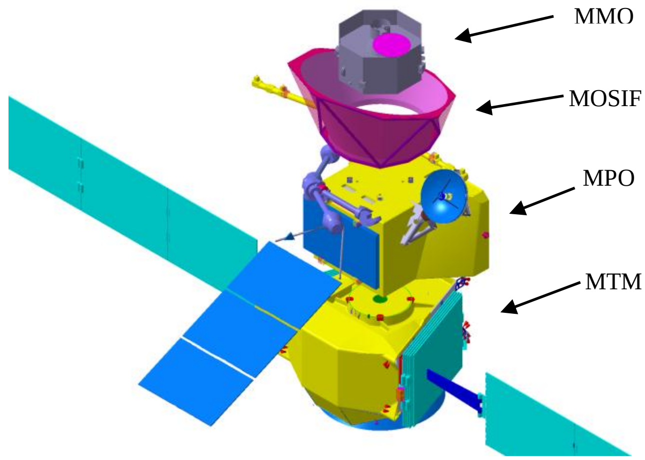

Figure 1. Mercury Composite Spacecraft composed of MTM, MPO and MMO inside its sunshade MOSIF.

The Mission is led by Airbus Deutschland Friedrichshafen (ASD), with Thales Alenia Space Italia Turin (TAS-I) responsible for the MPO and MOSIF thermal design. Ruag Space Austria GmbH (RSA) developed and provided the MLI.

The MPO carries fifteen payloads (P/L) for Mercury planet observation and remote sensing. It will provide a complete mapping of the entire planet surface with unprecedented resolution and will perform also other experiments of radioscience and fundamental physics[7].

The specific challenges of the thermal design of this mission and, in particular, of the mercury orbiter (MPO) stem clearly from the demanding natural thermal environment in combination with the chosen orbit and with the nadir pointing attitude of the spacecraft as will be explained in the following.

II. Mission

The BepiColombo mission will go through the following phases, with considerable changes of composite spacecraft configuration and thermal environment:

- Launch and Early Orbit Phase (MCS);
- Near-Earth Commissioning Phase, lasting 3-4 months and including commissioning (MCS).
- Interplanetary Cruise Phase (MCS), with min/max distances from sun 0.298/1.16 AU, and including Earth, Venus, Mercury fly-by's. The solar irradiance will correspondently range from 1,020 to 15,400 W/m^2.
- Mercury approach Phase:
    - Mercury capture (jettisoning of MTM);
    - Mercury Orbit Insertion;
    - MMO Orbit Acquisition, potentially including a Mercury Aphelion passage in nominal MMO orbit (jettisoning of MMO in its final orbit followed by jettisoning of MOSIF);
    - MPO Orbit Acquisition (MPO alone).
- Mercury Orbit Phase (MPO).

III. Thermal design drivers for the MPO

The thermal design drivers for the MPO are to be found in connection with the Mercury approach phase and with the Mercury orbit phase where extremely high solar and planetary fluxes will occur. Being the orbit of Mercury

[6] The MMO cannot withstand the sun irradiation when it is not spinning. Hence, the MOSIF is designed to keep it in shadow during the cruise to Mercury.
[7] For a description of the scientific mission, see ref. 7.

quite elliptic, the solar irradiance is a function of the Mercury true anomaly varying from 6,290 W/ m^2 at Mercury aphelion to 14,500 W/ m^2 at Mercury perihelion. Because of the slow rotation of Mercury around its axis and due to the properties of its surface, similar to those of the Moon with a superficial layer of regolith with low thermal conductivity, the surface of the sunlit face is essentially in equilibrium with the solar flux, and radiates as IR all the absorbed solar flux.

From the point of view of the orbital planetary fluxes, the selected orbit and the planet oriented attitude of the MPO represent a great challenge. The orbit is a 400 x 1500 km[8] polar orbit whose plane is inertially fixed (i.e. non-sun-sincronous). The orbital plane is oriented so that the angle between it and the sun (i.e. the β-angle) is zero at Mercury perihelion[9] with the major axis of the orbit close to the Mercury equatorial plane. The most critical phase is when flying over the sub-solar point region of the planet. To reduce the intensity of the orbital fluxes in such phase, the MPO orbit apocentre is positioned nominally above the sub-solar point at Mercury Perihelion, so to fly at the maximum altitude from the planet surface. Hence, in this case, the planetary fluxes are minimized when the solar irradiance is at its maximum. The opposite happens at aphelion and, consequently, the planetary fluxes are relatively constant between Aphelion and Perihelion, but naturally very different between day side and night side of the planet.

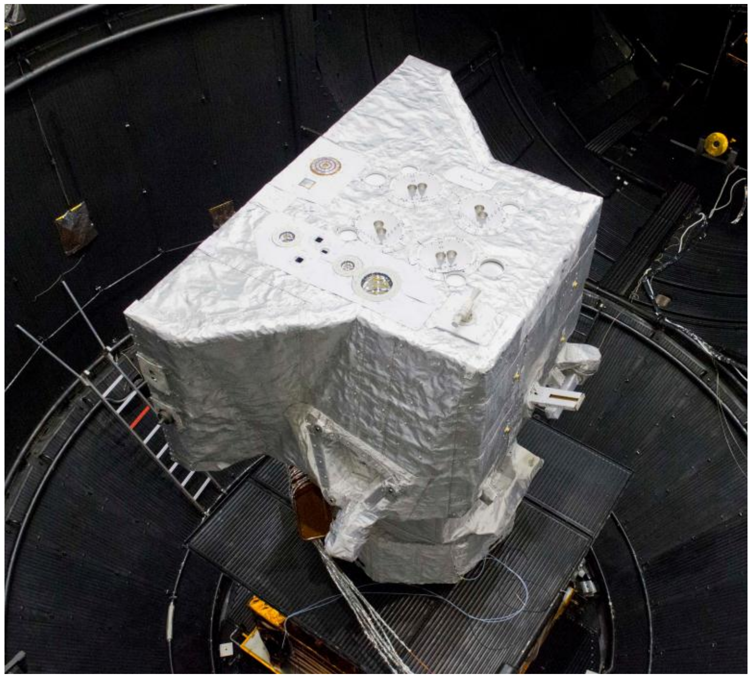

Figure 2. MPO inside the LSS chamber.

In such environments, the only selection of proper optical properties for the exposed surfaces of the S/C is not sufficient to maintain comfortable internal temperatures, while at the same time rejecting to space the internal dissipation. In particular, the high emissivity which is necessary for the radiators would cause an unbearable absorption of infrared energy from the planet; also the low solar absorptance of the classical radiators would still be too high with the Mercury solar irradiance and albedo. Consequently, the choice of a surface where to locate the S/C radiators was not an obvious one and the S/C is configured to accommodate the radiator surface according to the following criteria:

- the radiators are positioned only on one side of the spacecraft (-Y). During cruise this surface is oriented towards the anti-sun direction, whereas in Mercury orbit, the MPO is three axes stabilized with the side containing the radiators always parallel to the orbit plane.
- During half of a Mercury year, the β-angle ranges from 0° (at perihelion) to 180° (at aphelion) and the sun is always in the half-space opposite to the radiator. A flip-over maneuver keeps the radiator always in shadow of the S/C: at each perihelion or aphelion, the MPO is turned 180° along the local vertical so to keep the radiator face away from the sun.
- All the surfaces of the S/C but the radiator side are insulated from the external environment using an efficient High Temperature MLI which is able to endure the environmental fluxes and the corresponding high temperatures.
- The radiator is protected from direct view to the planet (and thus possible exposure to albedo and IR) by means of a system of high reflective louvre blades that will be described in the following.

As a consequence of the above features, it was not possible to define design worst cases that could envelope all conditions at the same time. The design driving hot cases are:

- cruise for parts of the solar array and the MGA
- perihelion nominal orbit for the overall structure
- orbit around Mercury, true anomaly 45° (spring season) for solar array cells

[8] These are nominal altitude figures. They will vary sensibly during the course of the mission.
[9] Because the orbit plane is inertially fixed, the β-angle will continuously vary along the Mercury year from 0° to 360°.

The design driving cold case is:

- cruise for most elements
- orbit insertion for SIXS instrument and magnetometers

A survival mode which is common on most of S/C's, where a spin stabilized attitude avoids the need of active control by reation wheels, thrusters etc., was not feasible on BC. The MPO radiator could not tolerate an arbitrary pointing towards the planet surface and the spin rate and clocking needed to be synchronized with the orbit position and duration.

IV. MPO Thermal Design

The MPO thermal design must provide acceptable internal temperatures with standard temperature ranges for both payload and spacecraft equipment, despite the harsh thermal environment experienced both during cruise and in the Mercury orbit, and, as far as possible be based on consolidate technologies.

The compact shape of the MPO is dominated by the size of the radiator surface. All the other surfaces are completely covered by a complex system of MLI insulation blankets. Starting from the external surface, there is a first sun-blocking blanket, followed by several layers of high-temperature MLI (HT-MLI) and finally a standard MLI as innermost blanket. Materials are graded according to their resistance to temperature across the various sets.

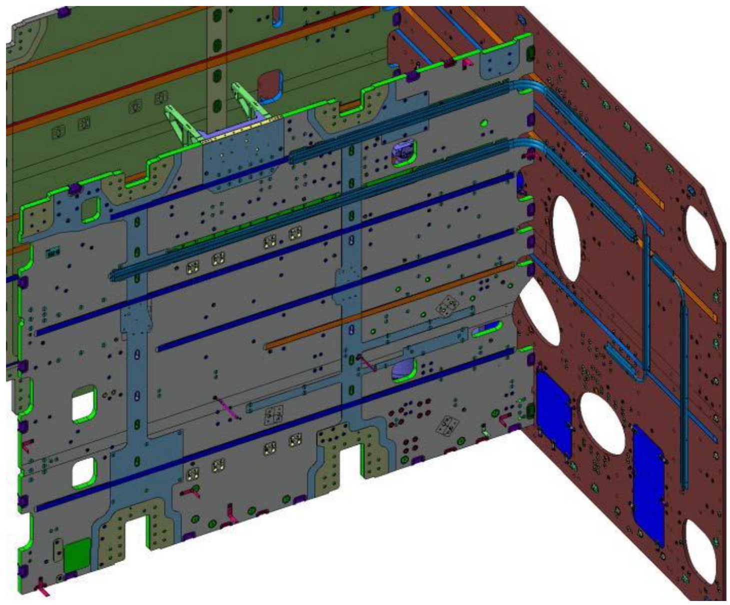

Figure 3. Heat Pipes Network.

As said, the MPO radiator is located on the only satellite side which is never sun exposed (–Y face). However, this side has a significant view to Mercury and consequently the radiator has to be shielded from the Mercury IR.

Most of the equipment are mounted on the internal +X and –X panels and then connected to the radiator with a network of heat pipes: embedded heat pipes on +/–X panels to distribute the heat; high capacity heat pipes that run on top of the +/–X panels and that, after a 90° turn, are clamped on the heat pipes of the radiator; heat pipes embedded in the radiator panel and on its surface for final heat spreading.

Payloads with strict pointing stability requirements are mounted on an optical bench and are cooled by heat pipes linking the units either to the radiator or to MPO main structure.

MPO battery and instrument cold detectors are linked to dedicated local radiators, mounted within cut-outs of the main radiator and thermally decoupled from it and from the S/C main structure, to be able to stay at lower temperatures.

Specific coatings had to be developed to limit and to withstand the high temperatures of external items (see ref. 3 and ref. 5 for details on the employed materials).

Also the high temperature High Gain Antenna has a dedicated thermal control, able to handle over 550 °C whilst providing the demanding performance required by the Radio Science Experiment. The high temperature Solar Array is able to survive up to 220 °C operational limit (achieved by design solutions which are not described in this paper).

The passive design is completed by a computer controlled heater system that keeps the temperatures above the minimum requirements during the cold cases of the cruise and the eclipses.

The overall mass of the MPO thermal control is around 130 kg, most of which is the MLI mass.

The MPO thermal control system is based on an extensive program of development and verification tests that started in the early phase of mission definition and culminated with the PFM thermal vacuum test:

- Radiator reflector blades (see ref. 1)
    - Breadboard test for proof of the concept
    - Breadboard test for verification of the selected design
- HT MLI (see ref. 2)
    - 2-D calorimetric tests for selection of blanket composition

- Sun illumination tests for the selection of the sun-blocking external layers
- 3-D calorimetric tests for derivation of preliminary performance data

- STM thermal balance test for qualification of the MPO thermal design
- Big size test of the improved HT MLI and its fixation method (see ref. 5)
- Sun illumination test for improvement verification of the sun-blocking external layers
- PFM thermal vacuum and thermal balance test for delta-qualification of the thermal control design and acceptance of the MPO module

These tests and their outcomes are recalled in the following.

V. Radiator Reflector Design

The MPO radiator has to reject to space the waste heat produced by internal equipment but, at the same time, it must also be efficiently shielded from the planetary heat fluxes. To this end, the radiator surface is covered by parallel fins that are thermally decoupled from the radiator panel structure.

The fins are of cylindrical shape[10], which, beside accomplishing the required shielding function, also enhances their stiffness. The fins reflect away the incident Mercury fluxes while not blocking the view of the radiator to space.

The fins are made of polished titanium and are silver coated on both sides to ensure high specular reflections. Measured emissivity of the fins is 0.01, with 0.98 of specular reflectivity. The external side of the radiator is white painted.

Fins are organized into different fields, due to the fact that on the radiator there are apertures for star trackers baffles, local radiators, thruster heat shields, an area covered with MLI and constraints due to the embedded heat pipes of the radiator plate. The fields are attached to the radiator plate by means of support walls that are thermally decoupled from the radiator with Vespel® thermal washers so to minimize the heat transfer from the fins to the radiator.

Adequacy of fins from thermal point of view has been demonstrated by performance tests done at radiator breadboard level and then again during the tests at system level.

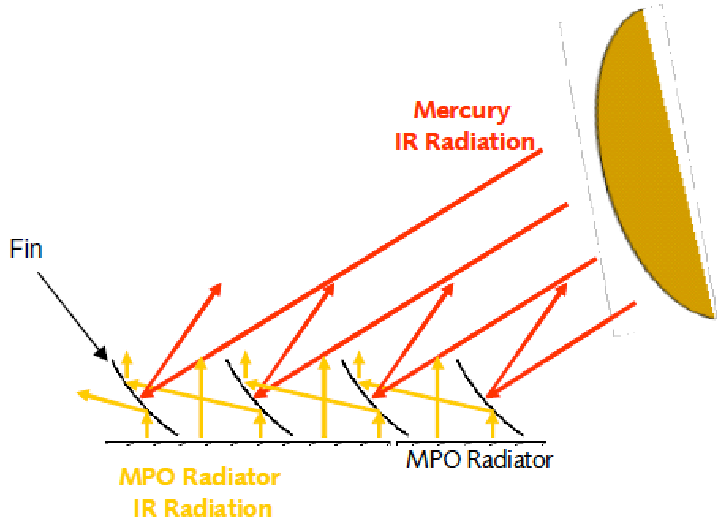

Figure 4. Radiator Reflector concept.

VI. Payload Radiator Design

The MPO radiator features several cut-outs which host local radiators that provide adequately low temperature levels to the instruments and to the battery. During the thermal balance test on the MPO STM, problems were detected with the cold interfaces at MIXS and SIMBIO-SYS. While the heat rejection capability was as expected, parasitic heat loads were significantly too high. Therefore the following improvements were implemented in the PFM to reduce the parasitic heat into the chain instrument thermal strap-heat pipe-local radiator plate:

- Wrapping in MLI of cold HPs and relevant thermal straps at the Instruments I/Fs
- Replacement of local radiator plates by thicker plates to have a better heat spreading.
- Implementation of MLI on the rear side of all local radiators (on some of them it had been omitted for easier installation of the instruments)
- Increased washer thickness for the cold HP fixations (not implemented in the MPO STM for schedule reasons)
- Electrical grounding of the local radiator plates by dedicated wires instead of sheet metal and reduced contact area between local radiator GFRP mounting brackets and main radiator surface.
- Recession of local radiator plates behind the main radiator level is reduced as much as possible to increase the view factor to space.

[10] The theoretical optimal shape would be parabolic, but because of the limited chord of the fins, a cylinder is a good enough an approximation of the ideal shape.

However, during the thermal balance test on the MPO PFM the reduction of parasitic heat fluxes from the S/C to the local radiator was found to be less than expected. The lesson learnt from this problem was that even very small couplings, which lead to thermal fluxes of fractions of watts and that are normally negligible, in this case could not be neglected and had to be accounted for both in the modeling and in the design.

After the PFM test a very thorough investigation on all the possible sources of heat into the local radiators was carried out and further improvements were implemented, such as:

- Removal of the white paint from the cold radiator edges;
- Replacing of the Kapton tape that seals the exposed core of the main radiator edges and that faces the local radiators with low emissivity tape;
- Application of low emissivity tape (cho-foil) on the heaters located on the back side of the cold radiators;
- Sealing of the even smallest gaps in the MLI on the back of the local radiators, including the slits for accessibility to alignment cubes;
- Application of low emissivity tape on the space side of the main radiator around the local radiators, to prevent indirect coupling by radiation between the warm main radiator and the local radiators through reflections on the highly reflective fins;

After the PFM system test, a breadboard test at local radiator was performed in order to verfy the benefit of such very small design changes.

VII. MLI

The purpose of the MLI is to protect the S/C from the harsh Mercury thermal environment. In addition to high solar flux, which includs extreme UV, also a high charged particle radiation flux needed to be considered.

MLI outer layer has been selected accounting account for the following requirements:

- low solar absorptance and high infrared emittance, to reduce the temperature when directly exposed to sun;
- capability to withstand up to 450 °C on its outermost layers;
- limited degradation of thermo-optical properties due to the orbital environment during the Mercury phase of the mission (UV exposure), to avoid excessive temperature increase of the MLI outer layer;
- limited emission of particulate (which, for contamination control reason, is particularly important for the optics and the exposed instruments);
- Minimum sunlight or IR transmittance of the outermost layers;

The MLI blankets design had to be mass efficient but without compromising its very high performances that are necessary to minimize the heat leaks into the satellite.

The MLI was a critical development because the existing and consolidated technology used until now in space programs is not completely applicable to BepiColombo due to the high temperatures expected on its outer layers, therefore a dedicated development and qualification program had been necessary.

The MPO insulation consists of a triple MLI concept:

- an external HT-MLI, able to protect the spacecraft from high temperature on the surface exposed to solar and planetary radiation, mounted to a dedicated lightweight support structure
- an intermediate MLI, not exposed to the environment, but made of materials capable to sustain 250°C
- a standard MLI (with a typical distance of 20mm from the HT-MLI for micro-meteoroid protection purpose) installed also on the support structure or used to cover internal items or external parts not exposed to solar and infrared fluxes

The blankets are spaced by 20mm. The spacing increases the protection against micro-meteorites. Also discontinuity in one layer is distributed over larger areas in other layers, reducing local hot spots on the structure

A. MLI Design Evolution

The initial MLI performance estimates were based on calorimetric samples, 2D blanket measurements and 3D cubes. While overlaps were present in the cube tests, other elements that ensured its fixation to the structure were missing. When those fixations were designed, emphasis was put on avoidance of holes in the outer blankets and on holding the outer blanket at distance from the mounting structure to create a bumper shield for micrometeoroids protection. This was done with a system of rails running on the inner side of the blankets and fixed to it by means of sewing lines.

The thermal balance test performed at system level on the STM of MPO showed that the heat leaks through the MLI was not compatible with the TCS requirements.

The main reasons for the insufficient MLI performance was identified as:

- Green house effect caused by the not fully opaque Nextel fabric used as outer layer;

- excessive compression of the HT-MLI layers due to the numerous sewing lines used for the fixation of the rails.

The following improvements have been identified:

- Reduction of greenhouse effect of Nextel (either with double layer of Nextel or with additional layer of white coated titanium, depending on contamination requirements);
- Increase in the number of separator layers in the HT-MLI behind the outer Nextel layer;
- Change of MLI mounting concept that eliminated the rails with associated sewing lines, hence reducing the compression effects;
- Inclusion of an additional innermost 10 layers blanket wrt the STM MLI system.

The enhanced design was then been validated with two different tests. First an illumination test at sample level has been carried out in the VTC1.5 chamber at ESTEC. This test demonstrated that one of the key elements – the transparency leading to green house effects – was improved significantly. Then a Thermal Balance test at blanket assembly level was carried out in the LSS chamber at ESTEC[11]. As it was not possible to repeat the STM system test because of cost and schedule reasons, the insulation performance of the complete improved package of MLI blankets was verified in a S/C representative configuration, accounting for representative blanket size, overlaps, mounting pattern and distances of sewing lines/standoffs. For this tests a complete S/C side wall was simulated, comparing in the same test the old STM design and the new improved design.

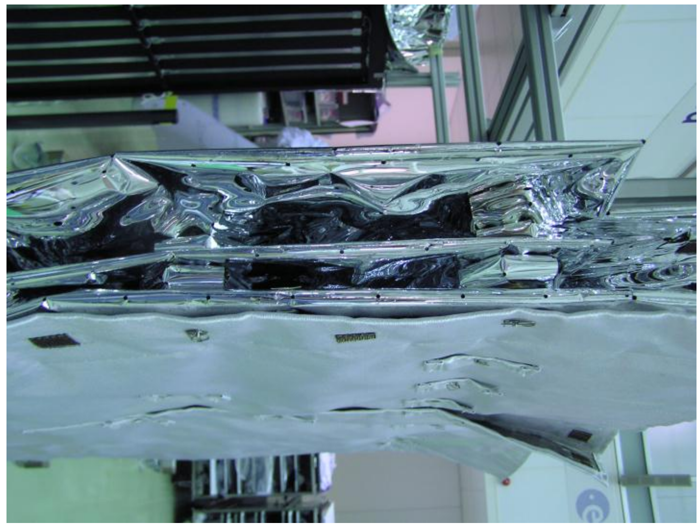

Figure 5. Flight MLI Configuration.

The two tests confirmed that the new improved MLI design performed significantly better than the previous one, as it was expected. The HT-MLI can be thought of being modeled with a linear conductor and a radiative conductor in parallel: the new design allowed to more than halve the linear contribution to the overall MLI conductance.

VIII. Propulsion Thermal Control

A. Tanks

The MPO propulsion system includes 1 Oxidizer Tank, 1 Pressure Tank, 1 large Fuel Tank and 2 Auxiliary Fuel Tanks. All tanks are made of titanium. The pipe work is equipped with wire heaters and wrapped by low-emissivity foil (Cho-foil).

The tanks are wrapped in standard MLI to decouple them thermally from the external environment. The propellant tanks are located centrally within the MPO, thus giving them the additional benefit of insulation from the external HT MLI and the structural panels and internal equipment. The structure runs at approximately room temperature, and so this combination of standard MLI plus local heaters is adequate for temperature maintenance. Special arrangement of heaters were necessary to provide heat density that matched the distribution of heat losses through conduction and radiation. (see 5).

B. 5N RCS Thrusters

Four pairs of 5N monopropellant thrusters used for RCS maneuvers are situated on the anti-sun side of the MPO, protected by titanium alloy heat shield and pointing in such a way that their nozzles are never directly sun-illuminated under nominal conditions (MPO radiator panel edges). These thrusters are thermally linked to the MPO radiator via the standard mounting of their brackets – no additional measures are required to increase coupling, since they are located in this cool, radiator region. The radiator also provides thermal mass in case of loss of attitude.

MPO internal environment is decoupled from each thruster by dedicated MLI located on the rear side of the shield.

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[11] See ref. 5.

C. 22N AOCS Thrusters

Four pairs of bi-propellant[12] 22N thrusters are used to reduce the orbit altitude from Mercury capture down to MMO orbit and then to MPO orbit. The 22N thrusters are not longer needed once the final altitude is achieved. These thrusters are located on the Nadir side of the MPO and their temperature is consequently driven by the Mercury IR flux focused at the nozzles during day time passages and by the sun illumination at eclipse entry or exit. The fact that they are not needed once the MPO is on orbit about Mercury is an important consideration in selecting an appropriate thermal design. The 22N thrusters have solenoid valves that have to be kept within their non-operating temperature limit of 121°C when non operating. To this end, thick copper straps link the thruster flanges to the mounting structure that acts as a thermal sink during the above mentioned hot passages.

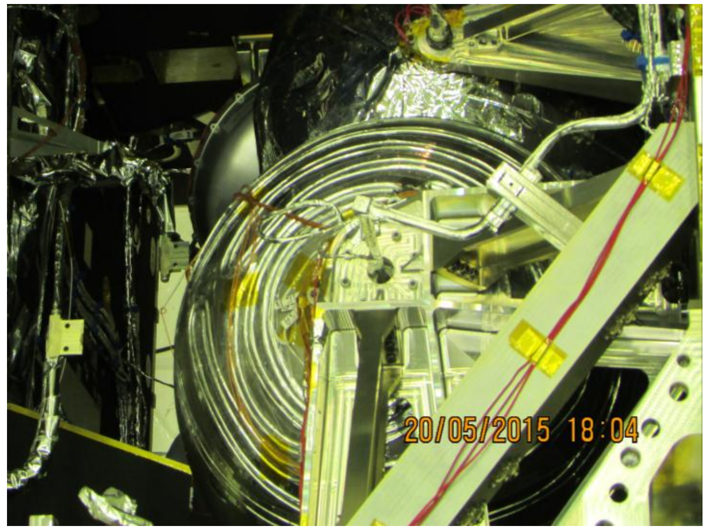

Figure 6. Wire Heaters layout on tank –Y.

IX. Conclusion

The extreme thermal environment in the vicinity of the Mercury planet experienced by Bepi Colombo imposed several challenges to the development of the MPO thermal design. It was necessary to develop and qualify new materials, such as the MLI coatings, and new technological solutions, such as the radiator reflector design. It was also necessary to change the verification approach, with dedicated tests for the verification of the performance of the MLI and of the insulation of the local radiators. The system verification program, based on a STM and followed by a PFM was the right option for a program with so many technological challenges. Infact, it allowed to discover several shortcomings in the thermal design of the MPO that were successfully corrected on the final PFM design.

In the end the verification of the thermal design has been successfully completed and the MPO thermal design is considered capable of satisfactorily accomplish the Bepi Colombo mission.

Acknowledgments

The development of a thermal design able to satisfy such challenging requirements as those of MPO was made possible by the excellent teamwork realized among the different teams involved: the BepiColombo final customer ESA, the spacecraft contractor Astrium Germany (Friedrichshafen) and the Thermal Control subcontractor Thales Alenia Space Italia (Torino), the MLI manufacturer RUAG (Vienna), ESA-TEC division who performed sample tests and performed a lot of in-situ measurements. Finally, we would like to thank the test facility responsible ETS (European Test Services).

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[12] The propulsion system of the MPO is a "Dual mode" system. It uses pure Hydrazine as fuel and NTO as oxidiser. Once the 22N bi-propellant thrusters are not needed anymore, the system gets re-configured into a mono-propellant one.

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