

Thermal Design of the Mercury Transfer Module

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ABSTRACT

This paper will describe the Thermal Control Subsystem of the Mercury Transfer Module of the BepiColombo mission. BepiColombo is an Interdisciplinary Cornerstone Mission to the planet Mercury, in collaboration between ESA and ISAS/JAXA of Japan, due for launch in 2014. The mission will be undertaken by a stack of three distinct spacecraft modules, including two scientific orbiters, the Mercury Planetary Orbiter (MPO) and the Mercury Magnetospheric Orbiter (MMO). The third entity, the subject of this paper, is the Mercury Transfer Module (MTM).

INTRODUCTION

The BepiColombo programme represents Europe's first mission to the planet Mercury. The two orbiters plus the propulsion module and sun shield are to be launched on an Ariane 5 launch vehicle from the Kourou spaceport. The project is approaching the end of "Phase B", with the Preliminary Design Review currently underway. Most of the major procurements having been kicked off and the manufacture of the first hardware has commenced. The first system-level tests (mechanical and thermal) will be performed on Structure Thermal Models (STMs) of the different modules from the middle of 2010 onwards.

The MTM is essentially the propulsion and power module for the cruise to Mercury phase mission and is the lower of three modules in the launch configuration. This can be seen in Figure 1.

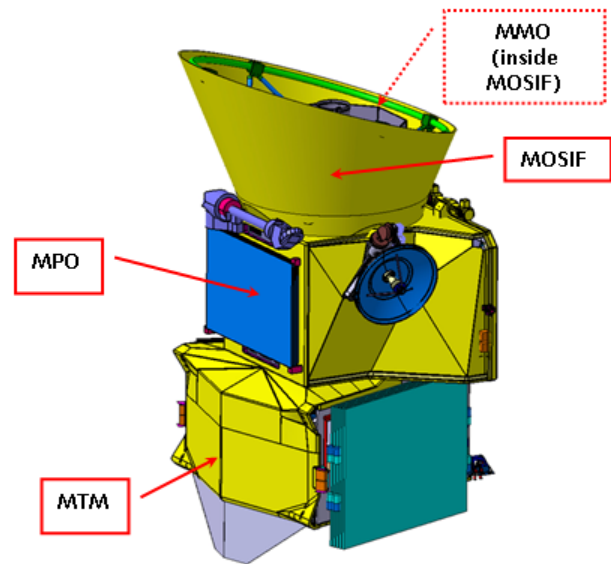


Figure 1- the BepiColombo "stack" of 3 spacecraft in launch configuration

THE MERCURY TRANSFER MODULE

Figure 2 below shows the principle elements of the MTM. On the lower, +Z side, there are four solar electric thrusters (SEPTs) and 12 pairs of 10N bi-propellant thrusters. Beneath the high temperature MLI (not shown in the figure) is the "engine bay", where the thruster pointing mechanisms for the SEPTs are located. On the left in the figure the main sun shield can be seen - this is on the +Y and nominally sun-pointing side of the module. The top (-Z) side is also covered with high temperature MLI and carries the MPO, the first of the

two orbiters in the BepiColombo stack. The three remaining sides are used as radiators. The main radiators ($\pm X$) are angled 20° away from the sun direction in order to give some tolerance to errors in the maintenance of the stack pointing throughout the mission.

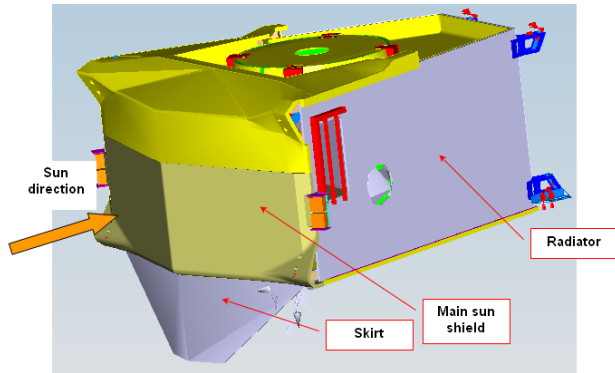


Figure 2 - the Mercury Transfer Module

In mid-2008 it was decided to switch from the Soyuz launch vehicle to Ariane 5, mostly because of the mass growth that had occurred during the first part of Phase B. This resulted in a new mission profile, as well as significant changes to the hardware, such as deletion of the main engine and addition of an LVA ring.

Following a direct launch into an escape trajectory, the MTM must provide solar electric propulsion for an approximately 6 year cruise to Mercury, all of the electric power for the 3 modules and it must perform most of the attitude and orbit control capability for the stack. The cruise phase includes one Earth, two Venus and four Mercury gravity assists. Finally, the MTM brings the two Mercury orbiting modules into a position from which they can reach their final orbits. These functions bring a range of thermal control challenges, not least because the mission cannot simply be flown with the spacecraft stack in a single, sun-pointing orientation.

The MTM has to survive all conditions up to the Mercury orbit insertion point, at which time it is ejected from the stack. In addition, it must survive a specified period following its ejection in order that it not place debris into the orbits of the other two modules. To accomplish this, it has a novel sun shield design, special high temperature MLI and in excess of 9m^2 radiator area. When exposed to the 14.5kW/m^2 solar flux at 0.3AU , it must allow any two 5kW electric thrusters to run simultaneously, while maintaining temperatures suitable for 24 bi-propellant reaction control thrusters, internal electronic equipment with standard temperature ranges, thruster pointing mechanisms and the Xenon system, while still allowing significant flexibility in its orientation to the sun and the ability to survive short-term losses of attitude.

KEY ASPECTS OF THE MISSION

LAUNCH & EARLY OPERATIONS PHASE (LEOP)

During this nominally 4 day phase, the critical items for thermal control are the Xenon storage system for the solar electric propulsion and the battery. It is currently foreseen that deployment of the solar arrays can occur approximately 68 minutes after launch. By pre-heating of some units on the launch pad before switch over to battery power, it has been avoided that the launch case becomes the sizing case for the battery. In addition, the Xenon needs to be kept above about 27°C in order to avoid the possibility of sloshing. The large thermal inertia in most of the chemical propellant subsystem means that only the thrusters will require heating during this phase. The hold-down and release mechanism of the electric thruster pointing mechanisms has a narrower temperature range than the mechanisms themselves (a maximum temperature of 60°C compared with 100°C for the mechanism), but the analysis has shown that no extra measures are required for these.

NEAR EARTH COMMISSIONING PHASE (NECP)

This is a 3 month period during which the electric propulsion system is checked out and commissioned. In addition, the complete payload complements of the MPO and MMO will be commissioned using power provided by the MTM. The attitude of the stack is nominally with the MTM sun shield pointing to the sun. The stack may be inclined up to 50° towards the sun vector (i.e. bringing sun onto the bottom of the MTM) or up to 18° away from it (i.e. bringing sun onto the top of top of the MTM, but not quite onto the MMO) - in order to perform attitude control of efficient thrusting.

MERCURY CRUISE

This phase sees the attainment of both the maximum and minimum distances to the sun, namely 1.13AU and 0.296AU . These are, respectively, the heater power and radiator sizing cases for the MTM.

It is a long phase - approximately 5.5 years in duration - with many specific aspects for the MTM thermal control. The hottest part of the MTM mission occurs at the end of the cruise and during each of the 4 Mercury fly-bys, where 0.3AU is reached and two 5kW SEP engines are running simultaneously. The high dissipation within the MTM that accompanies this (over 2kW) is what drives the radiator design. As the sun distance decreases, the available electric power increases and a switch over from one to two electric engines occurs at around 0.83AU . The temperature of the solar arrays also increases during the cruise phase and a strategy of tilting these gradually off the normal from the sun direction both ensures acceptable temperatures and reduced solar pressure on these devices. The MTM solar arrays are fully covered with cells, with no OSRs being employed for thermal control. An adequate offset from the

radiators, however, is very important as they are a significant source of heat for the radiators. This has been accomplished with the design of the yokes, which keep the first solar array panel nearly 2m from the radiator. Compared with a yoke of a more "typical" length, this reduces the infra-heating of the radiators by the solar array by as much as 500W.

Two gravity-assist manoeuvres are also made around Venus. Although these are not a driving thermal cases, the first one (with a 50 minutes eclipse), is the sizing case for the battery. Fortunately, the MPO relies on its own battery during all of the fly-by eclipses. This is the only time it uses its own power sources before the Mercury orbit insertion. It is important that navigation and trajectory correction manoeuvres can be carried out as efficiently as possible at all of these key milestones during cruise and therefore the pointing constraints imposed by the MTM and its propulsion equipment must be carefully considered. This has been a key determining factor in the design of the sun shield "skirt".

THERMAL DESIGN OF KEY SUBSYSTEMS

MULTILAYER INSULATION (MLI)

A special high temperature MLI has been developed for the BepiColombo mission. It consists of an external, high temperature portion, made up of in excess of 20 layers followed by a more standard, internal MLI consisting of aluminised Kapton layers. The two are employed in conjunction in some areas, such as the MTM sun shield, while in others areas, only the outer blanket is used (in order to save mass). The outer blanket has a Nextel external layer, followed by a light-blocking layer, several layers of VDA titanium and aluminium and then the remaining layers use Upilex, a higher temperature polyimide. A special high temperature spacer material is used between all layers. The type depends on the position in the blanket, but is either a glass fibre or a polyimide foam.

The specification on the high temperature MLI is for the effective emittance to be <0.009 . Measurements on samples tested thus far have been significantly lower than this and therefore, it is expected that required performance will be achieved with the real blankets.

SUN SHIELD

A number of different candidate designs have been examined for the main sun-shield, although two main concepts have been studied in greatest detail. Their predicted performances have changed as various development tests progressed, specifically those in which the materials were subjected to prolonged simulated solar illumination at >10 solar constants.

The first design consists of a high temperature MLI blanket (as described above), followed by a cavity and then a second blanket, which varies between standard

MLI and a reduced thickness high temperature MLI. The reason for this is that some parts of this "internal" blanket could be exposed to sun briefly in the advent of a loss of attitude. The blankets are supported by a lightweight, high temperature-compatible frame and a grid of support cables.

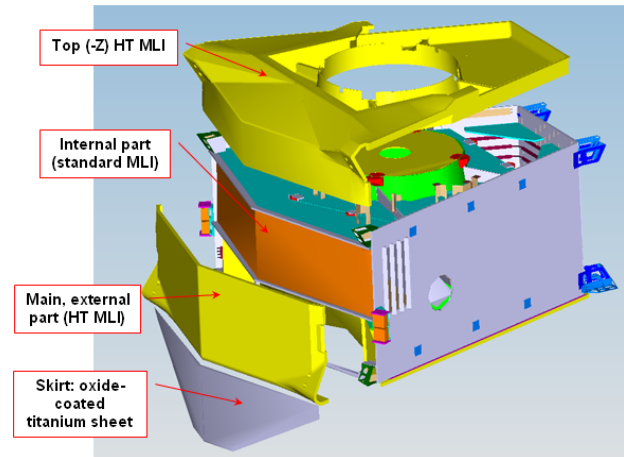


Figure 3 - the main sun shield of the MTM

The second concept employs an aluminium oxide-coated, pseudo-conical thin skinned aluminium shell, followed by a cavity and then the same inner MLI as for the first concept. As the observed degradation of the solar absorptivity of the outer layer materials for the two concepts have changed in relation to each other (and initial expectations), the competitiveness of the two concepts has changed, both in terms of their thermal performance and total mass. Also, it was found that the support structure required for the aluminium shell design was considerably heavier than the final, all-blanket design which has been selected and is shown in Figure 3.

At the lower side of the sun shield there is a skirt, made from oxide-coated titanium sheet. This prevents direct solar illumination of the electric thrusters and other propulsive equipment at the 0.3AU extreme, where a maximum of only 12° tilting of the stack can be tolerated. This allows sufficient flexibility in the pointing of the stack so as to enable some reduction in the propellant required for attitude control and other manoeuvres.

SOLAR ELECTRIC PROPULSION SUBSYSTEM

The electric thrusters are of the gridded ion type, delivering up to 145mN thrust each. Each thruster requires a little over 5kW electric power. The MTM carries 4 such thrusters, for reasons of redundancy, life and the ability to perform thrusting as well as orbit and attitude control of the stack (thereby reducing the amount of chemical propellant required for the cruise phase). The thrusters themselves are not thermally sensitive (they generate very high temperatures $>500^\circ\text{C}$), except for the high voltage electrical harness