BepiColombo – The Mercury Transfer Module

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Abstract: BepiColombo is an ESA cornerstone mission executed in collaboration with its partner JAXA, designed to place 2 spacecraft into orbit around Mercury. This makes use of the Mercury Transfer Module (MTM), which provides the propulsion and supporting hardware to enable the transfer from Earth to Mercury. The MTM is comprised of a structure; thermal control; an electric propulsion system, to provide the primary propulsion for the transfer from Earth to Mercury; a bipropellant chemical propulsion system, to provide attitude and orbit control support during the transfer and high thrust manoeuvres in preparation for the planetary fly-bys; a power system; and data handling (control and telemetry) interfaces to the chemical propulsion and thermal control systems. The MTM does not contain any communications to ground, or any on-board computer (OBC); these are provided by the Mercury Planetary Orbiter (MPO), and all control and telemetry gathering for the MTM is performed by the MPO via a 1553 bus link to the MTM. This paper provides a description of the MTM, with a particular focus on the electric propulsion system.

I. Introduction

BepiColombo is an ESA cornerstone mission to Mercury executed in collaboration with its partner the Japan Aerospace Exploration Agency (JAXA), designed to place 2 spacecraft into orbit around Mercury. Airbus

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Defence and Space is the overall System prime and is additionally responsible for the development and provision of the Mercury Planetary Orbiter (MPO) and the Mercury Transfer Module (MTM). JAXA is responsible for the development and provision of the Mercury Magnetospheric Orbiter (MMO).

The BepiColombo spacecraft has a dedicated transfer module, which provides all the propulsion and power needed to deliver the 2 orbiters to Mercury. This makes extensive use of electric propulsion through a number of thrust arcs. The use of electric propulsion for orbital transfer between bodies within the solar system is now well established, with its use on the Deep Space 1[1], Smart-1[2], Hayabusa Explorer[3], Dawn[4,5] and Hayabusa2[6] programmes. This follows the increasing use of electric propulsion for large telecommunications satellites.

The BepiColombo mission exploits this heritage. A substantial energy reduction is needed to reach Mercury. The high specific impulses which can be provided by electric propulsion systems offer the ability to achieve this large velocity increment with significantly reduced propellant mass when compared with chemical propulsion systems. As a mission to Mercury will also inherently require flight trajectories with reducing sun-earth distances, the power available from the solar arrays will increase as Mercury is approached, ensuring adequate power for electric propulsion operations.

The design, development and qualification of the BepiColombo electric propulsion system is based on previous developments and flight heritage of similar electric propulsion technologies, from a variety of applications.

II. The BepiColombo Mission

A. Mission Objectives

Mercury is an extreme of our planetary system. Since its formation, it has been subjected to the highest temperature and has experienced the largest diurnal temperature variation of any object in the solar system. It is the closest planet to the Sun and has the highest uncompressed density of all planets. Solar tides have influenced its rotational state. Its surface has been altered during the initial cooling phase and its chemical composition may have been modified by bombardment in its early history. Mercury therefore plays an important role in constraining and testing dynamical and compositional theories of planetary system formation.

To date, only the American probes Mariner 10 and Messenger have returned significant data from Mercury. Although these data have been fully exploited, a lot of gross features remain unexplained. Many conclusions are still speculative and have evoked a great number of new questions.

The main scientific objectives of the BepiColombo mission are:

- Investigation of the origin and evolution of a planet close to its parent star
- Investigation of Mercury’s figure, interior structure, and composition
- Investigation of the interior dynamics and origin of its magnetic field
- Investigation of the exogenic and endogenic surface modifications, cratering, tectonics, and volcanism
- Investigation of the composition, origin and dynamics of Mercury’s exosphere and polar deposits
- Investigation of the structure and dynamics of Mercury’s magnetosphere
- Test of Einstein’s theory of general relativity

The mission will achieve these objectives by delivering 2 separate spacecraft into orbit around Mercury, namely the Mercury Magnetospheric Orbiter (MMO) and the Mercury Planetary Orbiter (MPO). These 2 spacecraft will be placed into different orbits around Mercury. The MPO has an initial polar elliptic orbit, with an altitude of between 400 and 1508 km; the MMO also has an initial polar elliptic orbit, with an altitude of between 400 and 11824 km.

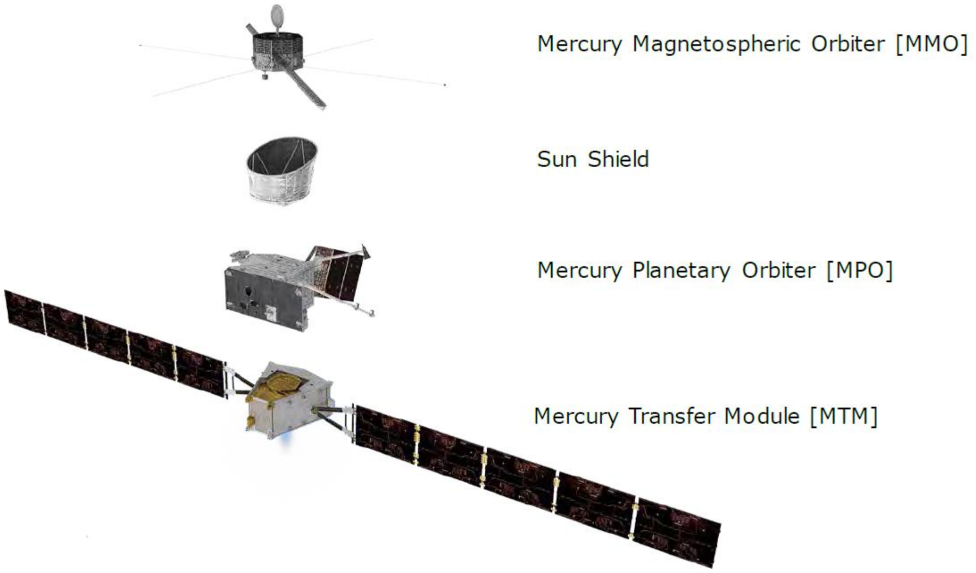
The overall mission is described in more detail in Ref. 7.

B. Mission Analysis and Propulsion System Usage

The spacecraft was launched by Ariane 5 from Kourou at 03:45 CEST on 20th October 2018; Mercury arrival and orbit insertion will be in December 2025, giving an overall transfer duration of 7.2 years.

Both chemical and electric propulsion systems are required to achieve the mission requirements. The selected mission profile uses the launcher for direct injection into an interplanetary trajectory. The electric propulsion system is then used over a number of thrust arcs, with intermediate coast phases and a number of planetary fly-bys. A gravitational capture, via the Mercury-Sun Lagrange point, is finally used to place the spacecraft into a weakly bound Mercury orbit. A bipropellant chemical propulsion system on the transfer module is used for attitude and orbit control during the transfer, where higher thrust levels are required. A dual mode chemical propulsion on the MPO is used in bipropellant mode for lowering into the final operational orbits; this is then used in monopropellant mode for orbit and attitude control of the MPO during the operational phase of the mission.

III. Spacecraft Configuration



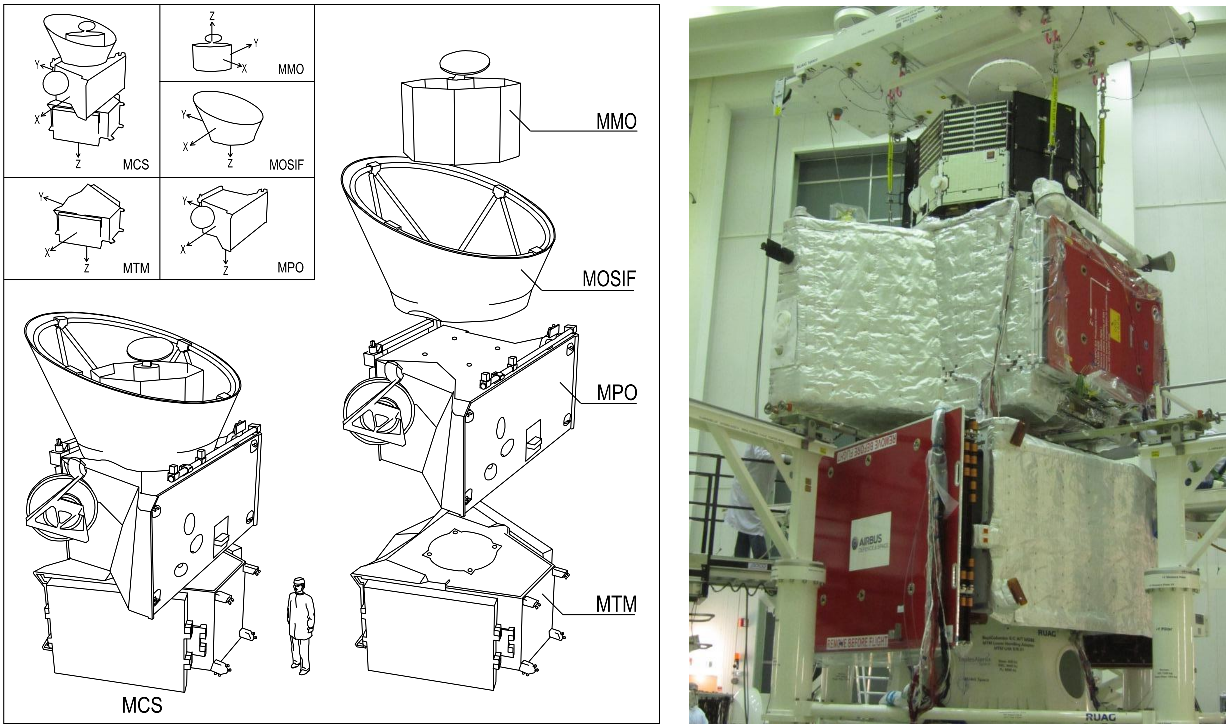


Figure 1. BepiColombo configuration and module staging.

The composite spacecraft configuration for the BepiColombo mission is illustrated in Figure 1. The spacecraft comprises the following elements:

- The Mercury Transfer Module (MTM) contains a conventional bipropellant chemical propulsion system, and the electric propulsion system used for the transfer to Mercury. It also contains the corresponding power generation hardware
- The MPO, as well as providing scientific instrumentation, provides all communications, data handing, and control functions for the complete spacecraft, as well as the housekeeping function for the Mercury

orbital phase of the MPO operations. This module includes a dual mode propulsion system for Mercury orbit insertion, and orbit and attitude control of the MPO during the operational phase of the mission

- The MMO provides scientific instruments, as well as its own housekeeping and communications functions for operations after separation from the remainder of the composite spacecraft
- The MMO Sunshield and Interface Structure (MOSIF) is a sunshield to protect the MMO during the mission cruise phase

All parts of the spacecraft are 3-axes stabilized, with the exception of the MMO which is spin-stabilized after separation from the composite spacecraft; the MMO separation system includes the corresponding spin-up capability.

A standard Ariane 5 launch adapter is used to connect the spacecraft to the launcher.

IV. Mercury Transfer Module (MTM) Design

The MTM is comprised of the following elements:

- MTM structure
- Thermal control of the MTM, including heat pipes, heaters, thermal sensors, radiators and sun shields
- The MTM electric propulsion system (MEPS), to provide the primary propulsion for the transfer from Earth to Mercury
- A bipropellant chemical propulsion system (CPS), to provide attitude and orbit control system (AOCS) support during the transfer and high thrust manoeuvres in preparation for the planetary fly-bys
- A power system including solar arrays, a power control and distribution unit (PCDU) and battery
- Data handling (control and telemetry) interfaces to the CPS and thermal control system

The MTM does not contain any on-board computer (OBC), or any communications to ground; these are provided by the MPO, and all control and telemetry gathering for the MTM is performed by the MPO via a 1553 bus link to the MTM.

A. MTM Structure

The MTM structure design is driven by the following main requirements:

- Spacecraft stiffness to avoid coupling with low frequency excitations from the launch vehicle
- Propellant and Xenon tanks (see sections IV.C and V.C.0) and two solar arrays (SA) (see section IV.D) constrain the structure height
- Centre of mass constraints
- Compatibility with thermal environment temperature range of -30°C to +90°C
- Compatibility with the launch vehicle adaptor interface
- Loads resulting from launch environment and lifting / handling / transportation cases
- Mass minimisation

The MTM structure consists of a central cone connected to four shear panels and to two main tank floor panels. Three radiator panels connected to the tank floor, shear panels and struts to the base of the cone, as well as the +Y sunshield support structure, form the complete MTM structure. The central cone contains a thruster floor panel, with 4 solar electric propulsion system (SEPS) thrusters and pointing mechanisms.

Figure 2 shows an exploded view of the structure with the main components identified.

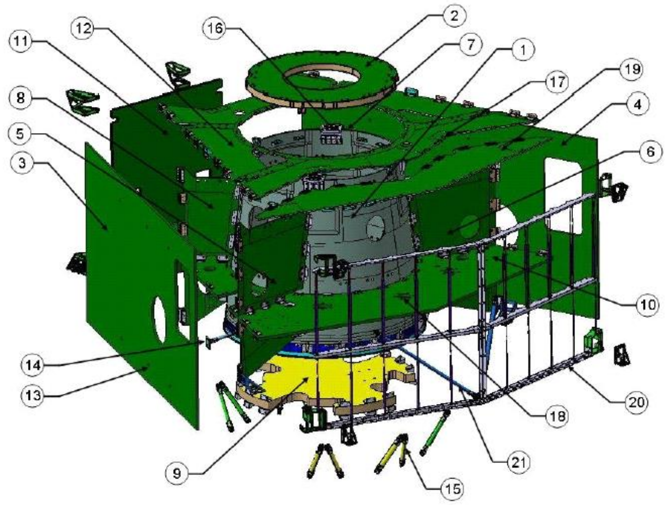
1. Central Cone Assembly

The direct load carrying capability of the Spacecraft and MTM is provided by the central cone structure. The cone is designed to accommodate the MPO separation brackets and the interface to the launch vehicle adapter. The primary central cone structure upper interface to the MPO is via four hard points, and the lower interface to the Launch Vehicle Adaptor (LVA) is via a clampband. The cone carries the main structure interface loads to the MPO and provides the main axial and lateral stiffness for the MTM structure and spacecraft.

The central cone is a carbon fibre sandwich construction. A top cover closes the cone on the upper part and gives stiffness to the central structure.

The LVA ring provides the interface between the cone and the launcher adapter. The ring is made from a round forging of aluminium.

Contained within the central cone structure are 4 off SEPS thrusters and pointing mechanisms mounted to the thruster floor. This panel needs large cut-outs to avoid clashing with the thruster pointing mechanisms when they are



Item No	Description	Quantity
1	Central Cone Structure	1
2	Top Floor Panel	1
3	-X Radiator Panel	1
4	+X Radiator Panel	1
5	+Y -X Shear Panel	1
6	+y +X Shear Panel	1
7	-Y +X Shear Panel	1
8	-Y -X Shear Panel	1
9	Thruster Floor Panel	1
10	Lower Tank Floor Panel	1
11	-Y Radiator Panel	1
12	Upper Tank Floor Panel	1
13	Solar Array Hold Downs	12
14	Solar Array Support Strut	2
15	Lower Tank Support Struts	10
16	MTM – MPO Separation Brackets	4
17	Upper Tank Support Bosses	5
18	Lower Tank Support Bosses	5
19	Upper Closure Panel	1
20	Sunshield Support Structure	1
21	Sunshield Support Structure Struts	2

Figure 2. **Exploded view of MTM structure.**

deployed. The thruster platform is a sandwich panel with CFRP layers and aluminium honeycomb. This panel is a dismountable platform joined by means of cold inserts and titanium screws.

2. Upper and Lower Tank Floors

The upper and lower tank floors interface to the tanks, shear walls, radiator panels and SA hold down points, carrying the loads to the central cone and giving radial stiffness to the cone. Additionally, they provide support to various equipments and high temperature MLI structures mounted on them. Both are non-dismountable panels and access to upper and lower sides is achieved by removing the radiator panels.

The tank floors are sandwich platforms with CFRP layers and aluminium honeycomb. The tanks are supported by bosses on the upper and lower tank floors.

3. Shear Walls

The shear walls interface to support floors, lateral radiator panels and solar array hold down points, and carry the loads to the central cone. There are no equipments mounted on the shear walls. These panels give the main contribution to the required solar array hold down interface points stiffness.

There are 4 shear walls in the MTM structure, 2 of them connected with an angle of 90º with the cone (-Y shear walls) and 2 with an angle of 61º/123º (+Y shear walls). Each shear wall is split into two panels: one is between the upper and lower floors and another one protruding under the lower floor. The shear walls are made by a sandwich with CFRP layers and aluminium honeycomb.

4. Tank bosses and struts

The tank support structure minimises bending moments at the upper boss via a bearing and the lower boss using struts which are aligned with the centre of the tank axis. They provide the axial stiffness to the interface.

Although the envelope of the propellant and Xenon tanks is geometrically identical, the struts are different because the Xenon tanks are heavier than the propellant tanks.

The lower tank bosses restrain the lower end of the tank in the 3 translation directions and three rotations, joining it to the lower tank floor and to the tank struts. The main load carrying capability of the floor is the in plane loads, with the out of plane load being carried by the struts to the LVA ring through the tank I/F bracket. Loads are transferred to the struts by means of 2 lugs.

The lower tank boss is mechanically fastened to the lower tank floor with cold bonded inserts in the panel. This joint fixes the top side and underside tank brackets to the panel. The tank is fixed mechanically through titanium bolts joining the tank strut bracket and passing through the underside tank bracket, the locking ring and the top side tank bracket to screw in the tank flange.

The struts are made of a CFRP tube and 2 aluminium end fittings.

5. *Solar Array Hold Downs*

There are 6 solar array hold downs on each lateral radiator panel. The purpose of these is to provide hard points for the solar arrays to be attached to when stowed. The attachment of each hold down to the structure is done via bolts passing through the radiator panels directly to the core structure without transmitting any load to the radiator panels themselves. On the MTM core structure there are 5 brackets and one strut on each side.

Each of the solar array struts is made of a CFRP tube and two aluminium end fittings.

6. *Radiator Panels*

The outer shape of the MTM is driven by thermal considerations, as discussed in section IV.B. The anti-sun face (-Y) and the two adjacent side panels (+X, -X) provide radiator area on which high heat dissipating units, including the power conditioning and distribution unit (PCDU) and SEPS power processing units (PPUs) are mounted. The radiator panels are equipped with embedded and surface heatpipes to allow for efficient heat dissipation from the units.

The radiator panels are constructed of aluminium face skins and aluminium honeycomb core. The sandwich panel of the lateral radiator panels incorporates embedded heat-pipes running vertically. Transverse surface heat-pipes on the inside radiator surfaces form an orthogonal network. In the case of the –X and –Y radiator panels, the heatpipes also link the two radiator panels together.

All 3 radiator panels are removable by design. However, the –X and –Y panels are kept as a subassembly once the surface heatpipes are installed.

7. *Sunshield Support Structure and Sunshield Skirt*

The sun-facing (+Y face) of the MTM contains a sunshield structure that provides thermal protection to the Xenon and propellant tanks. The structure consists of a framework of beams to support 32 cables between the upper and lower tank floor and the sunshield skirt in the lower side of the MTM. The cables are bonded to the sunshield support structure. The high temperature MLI, the inner MLI and the titanium sunshield skirt are supported by this structure. The titanium skirt is mechanically joined to the titanium profile.

B. MTM Thermal Control

The primary design drivers for the thermal control system are detailed in Table 1. The overall concept of the spacecraft thermal design is shown in Figure 3.

Table 1. Primary thermal design drivers.

Design Driver	Comments
1.16 AU 'weak' solar flux	This is the largest sun distance which occurs during the mission, and represents the lowest level of solar flux which the spacecraft will ever receive (other than during eclipse): ~0.74 solar constants. This is therefore the heater sizing case.
0.298 AU 'strong' solar flux	This is the smallest sun distance which occurs during the mission, and represents the highest level of solar flux which the spacecraft will ever receive: ~11.3 solar constants. This is therefore the radiator sizing case.
SEPS dissipation	Activating the SEPS increases the internal dissipation of the spacecraft by a factor of 4. This change in internal dissipation is much more significant in terms of spacecraft temperatures than the change in sun distance. This means that even at 1.16AU with SEPS ON are relatively hot cases, and equally at 0.298 AU with the SEPS OFF the spacecraft is relatively cool.
Venus eclipse	The Venus eclipse is the longest eclipse experienced by the spacecraft (50 minutes) and is the battery sizing case.

The spacecraft flies with the +Y side facing the sun at all times. A sunshield is present on this side to block and re-radiate the vast majority of the incoming solar flux the MTM receives in the 0.298 astronomical unit (AU) condition. The small amount of heat which does pass through the sunshield is then radiated from the back of the sunshield onto the radiators, or into the primary structure. The sunshield consists of multiple layers of Nextel, titanium foil, aluminium foil and Upilex foil.

The heat dissipated from the two main internal heat sources (the SEPS PPUs and the PCDU), plus any heat which passes through the +Y sunshield, is spread across 3 large radiating areas. A network of embedded and surface heatpipes ensures that the heat is evenly spread around the radiating area. The radiators have been sized to ensure that the units and structure remain within required limits in the hottest case of the mission.

In order to dissipate the very large internal dissipations of the SEPS (and the

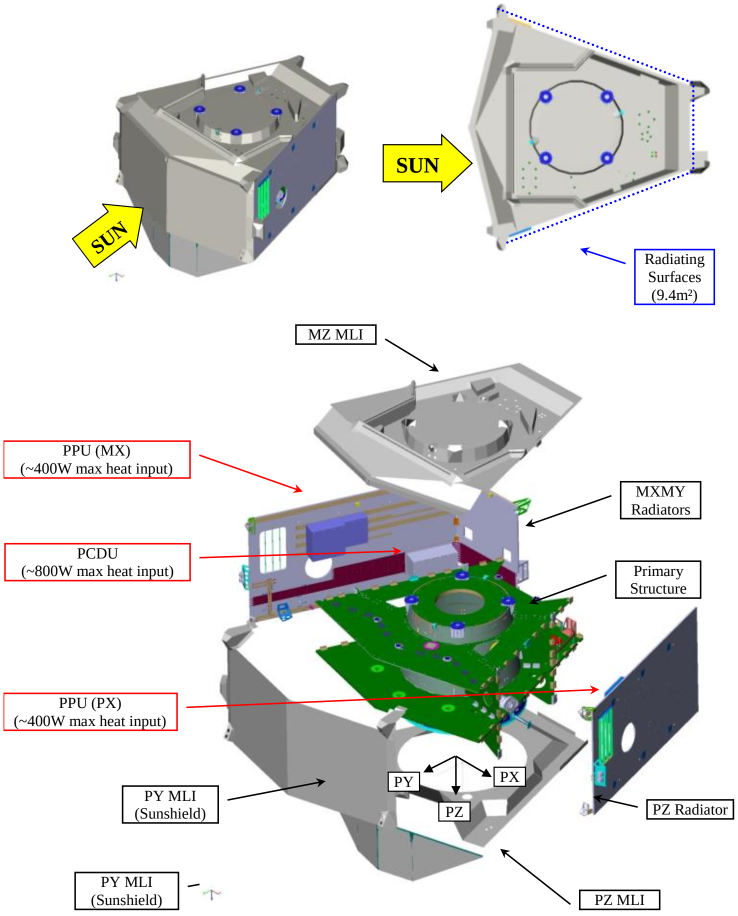


Figure 3. MTM overall thermal design concept.

heat which does get through the heatshield), the radiator size must clearly be maximised. This is achieved by constructing the rest of the spacecraft as a wedge shape, as shown in Figure 3. The +X and -X radiators are swept back by 20° to ensure that they are not illuminated during the rotation about Z axis manoeuvres. Together they provide approximately 9.4 m² of radiating area.

The high dissipating units are fitted directly onto the radiators to ensure the best possible rejection of their heat to space. The units are fitted with thermal fillers to ensure maximum thermal conductivity.

All 3 radiators include a network of embedded and surface ammonia filled heatpipes. These are primarily designed to spread the heat from PPUs and PCDU over the whole radiating surface. This spreading also explains why the overall spacecraft temperature is so strongly driven by whether the SEPS is ON or OFF. When the SEPS is active, the entire heatpipe network and radiators warm up, and so all temperatures inside the spacecraft increase as well.

A skirt is fitted in the +Y+Z region of the spacecraft underneath the main heatshield to ensure that the electric propulsion thruster bay is mostly in shadow throughout the mission.

The remaining 2 sides of the spacecraft (the +Z and -Z faces) are covered with MLI to prevent additional heat loss.

A number of heater circuits are provided within the MTM. In general the heaters within each circuit are wired in series, so that the failure of any heater will cause the whole line to fail, thus triggering the failure detection, isolation and recovery (FDIR) system to activate the redundant line (even if the failed heater is some distance away from the controlling point, as is the case for pipework heater lines). However, in the case of the PPU, PCDU, battery and high pressure regulator (HPR) heater circuits, some or all of the heaters are wired in parallel with each other. In these cases the heaters are fitted close together and to unit base-plates, heatpipes or structure which will be largely isothermal. Consequently the failure of a single heater within a line may simply cause the line to cycle more quickly without needing to switch to the redundant circuit. If the heater line becomes saturated and is unable to maintain the required temperature limit, then the FDIR system will trigger the redundant line to activate.

C. MTM Chemical Propulsion System

1. CPS Requirements

The MTM chemical propulsion system (MTM CPS) provides attitude and orbit control alongside the electric propulsion system operations. The electric propulsion system provides the ΔV for the cruise phase and is used for the majority of this phase, whereas the MTM CPS provides larger thrust impulses when such manoeuvres are required. This can be summarised into the following specific types of control:

- Rate and attitude control during initial phase of mission (until switchover to Normal Mode on reaction wheels)
- Perform attitude and orbital control manoeuvres during the planetary fly-bys during the cruise to Mercury
- Perform reaction wheel off loading manoeuvres

- Perform recovery manoeuvres, as required, in emergency mode

In addition to attitude control longer sequences of burns are performed in order to adjust the ΔV, if required, prior to each planetary fly-by.

The key design drivers for MTM CPS are as follows:

- Provide steady state thrust between 10 N and 7 N
- Provide pulse mode performance down to 15 mNs

2. CPS Design

Following trade–offs of various monopropellant and bipropellant options, and regulated or blowdown pressurisation options, a blowdown bipropellant configuration was selected.[8] This is a helium pressurised system using monomethyl hydrazine (MMH) as the fuel and mixed oxides of nitrogen with 3% nitric oxide (MON-3) as the oxidant. A common propellant storage and feed system supplies the Orbit Control Thrusters (OCTs) and the Reaction Control Thrusters (RCTs). The initial pressure of the propellant tanks is ~24 bar which blows down to > 10 bar at the end of the mission.

As the MTM CPS and the electric propulsion system are accommodated on the same module, a key driver is the ability to combine the physical attributes of both systems in the same structure, making tank selection a key consideration. The tank sizes afforded by the MON/MMH selection allowed the inclusion of similar sized tanks (based on Eurostar 2000+ heritage) to the Xenon storage tanks.

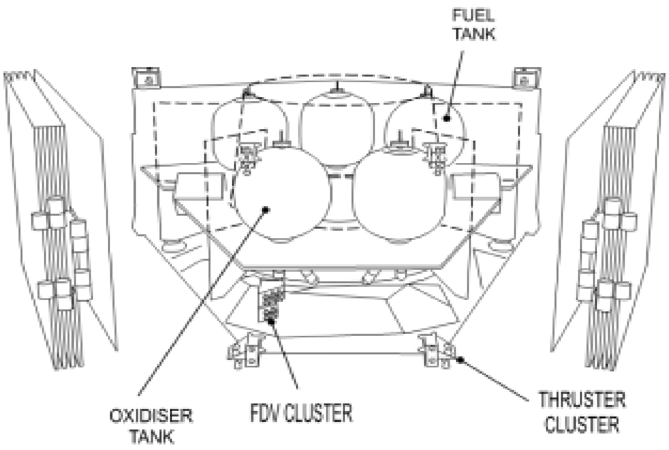


Figure 4. CPS tank positions (see also Figure 12).

The MTM CPS baselines heritage components, design philosophies, and techniques developed for other scientific missions and Eurostar satellite fleet experience. It has been designed to re-use, wherever possible, the same sub-system equipments that have been flight proven for earth, observation and scientific, and telecommunications applications.

The propellant tanks are part filled to 55% and then pressurised up to 24 bar prior to launch. The subsystem is designed such that the propellant tanks are isolated from the combustion chambers of the thrusters by a minimum of three series independent mechanical inhibits, by means of pyro valves (PVs), latch valves (LVs) and flow control valves (FCVs). LVs contain the pressure and propellant within the tanks for the launch sequence, until commissioning. PVs provide mechanical barriers against unplanned propellant flow to the thruster injectors, and, in combination with the LVs and thruster FCVs, the three barrier requirement is met.

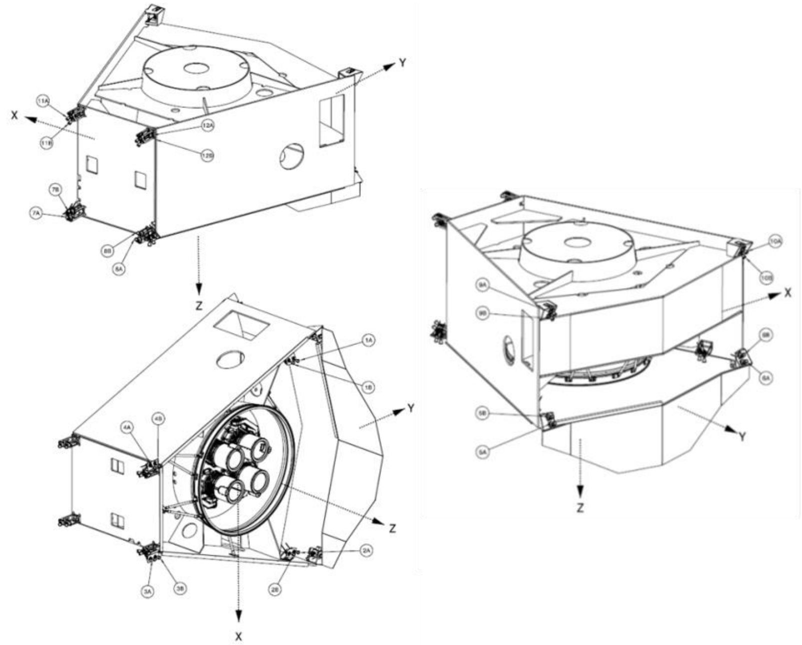


Figure 5. Thruster locations.

Both the fuel and oxidiser branches contain three fill and drain valves (FDVs) to allow filling, pressurisation and draining. Each of these valves also features three mechanical barriers. Firing open the normally closed PVs allows the propellant to flow into the previously gas-evacuated lines in order to prime the system. Once primed, the system is maintained in the same configuration, and only used as required throughout the cruise phase. Each fuel/oxidiser branch features two pressure transducers for redundancy. Thrusters are divided into the attitude control specific, and orbit control specific branches. Prime and redundant branches are selected by a single latch valve. Single seat thrusters are used. In this configuration single point failures are eliminated.

The CPS thruster locations are shown in Figure 5 and Figure 6. Note that Figure 6 also shows the fuel tank location, and the location of some of the MEPS hardware; the OCTs shown in this photograph have covers installed.

The thrusters' operational box needed to be extended to meet 24 bar. This gives a better operational performance, and was covered by a delta qualification programme.

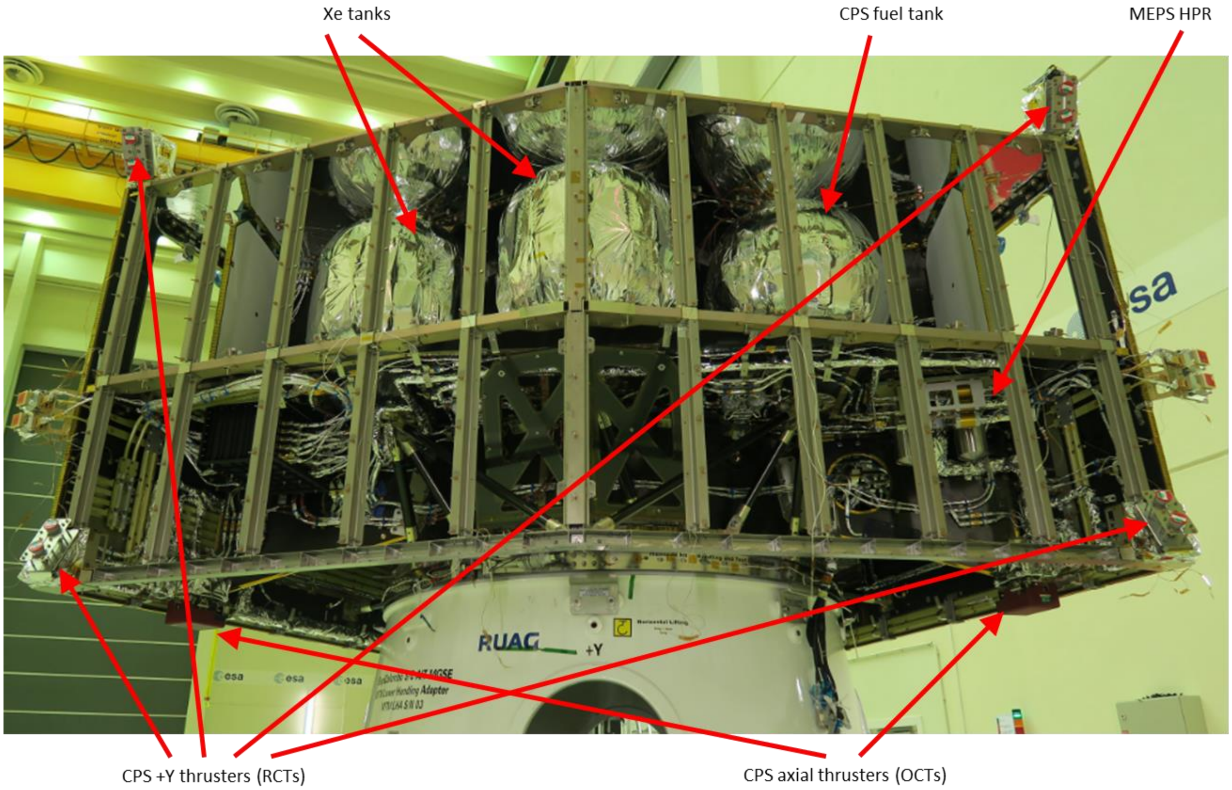


Figure 6. CPS equipment locations (note some MEPS equipment locations are also identified).

3. *CPS Operations*

For launch, the propellant tanks are initially pressurised to a maximum level equivalent to 24 bar at the maximum launch temperature. The propellant feed lines between PVs and the thrusters are pressurised with helium at nominally 3.5 barg. By having a positive pressure differential between the CPS and the environment, any potential ingress of contamination prior to and during the launch is eliminated. Low flow latch valves remain closed during launch with equal helium pressure on both sides.

The CPS initialisation sequence starts within 60 seconds after separation from the launch vehicle adaptor since it is needed to perform AOCS functions at any time during the cruise phase.

After separation from the launcher the propellant feed lines are evacuated by opening the low flow latch valves and the thruster flow control valves of one thruster from each branch. The system is then primed with propellants by opening the pyrovalves.

During the cruise, the propellants are delivered to the thrusters in blow-down pressure mode as the ullage volume gradually expands in the propellant tanks.

The propellant supply lines to each thruster branch can be isolated by the bi-stable bipropellant low flow latch valves. In normal circumstances the 'A' branch orbit control and reaction control thrusters will be used, with the 'B' branch kept as a redundant set and isolated from the 'A' branch. The 'B' branch will normally only be brought into service if a failure on the 'A' branch necessitates shut down of that branch. The total usable propellant is therefore available for use by all thruster branches.

4. *CPS Status Monitoring*

The health of the MTM propulsion system is monitored via the telemetry provided by the pressure transducers (PTs), temperature sensors (tanks, thrusters, PVs, PTs and pipework) and LV status indicators.

5. *Propellant Tank Design*

A key development for the MTM CPS was the design of the two propellant tanks. In order to launch at operational pressure the tanks need to have a proof pressure level of 1.5xMEOP, and a burst level of at least 2xMEOP.

The propellant tank is an all titanium pressure vessel utilising surface tension forces to control propellants and ensure gas-free delivery for all mission phases. The design of the tank is derived from the Eurostar 2000+ propellant tank. It is near spherical with hemispherical ends and is mounted at the poles.

The tank design utilises a propellant management device (PMD) to ensure that gas free propellants are delivered to the thrusters during all mission phases and modes of operation during the cruise. The PMD incorporates a reservoir to ensure that a liquid supply is available even when the inertial forces on the spacecraft are such that propellant would normally be driven away from the outlet. In order to supply the thruster sets with propellant throughout the cruise phase, the internal vanes are extended to the top of the tank.

The approach uses existing Eurostar heritage PMD, forgings and processes. The additional qualification required for the tank is offset by the simplicity and heritage of the rest of the system.

D. MTM Power System

The MTM power subsystem functional block diagram is depicted in Figure 7, and identifies all units contributing to the subsystem.

The MTM power subsystem consists of:

- Two Solar Array (SA) wings, each with five panels
- Two Solar Array Drive Mechanisms (SADM) with relevant Solar Array Drive Electronics (SADE) to operate the SA wings during the cruise
- One Power Conditioning and Distribution Unit (PCDU)
- One battery

The MTM SA consists of two wings, single sided populated with solar cells, providing an active PVA photovoltaic assembly (PVA) area of about 34.7 m². The panels and the yoke of each wing are fixed in stowed condition during launch. One of the SA wings is shown in Figure 8, shortly after its deployment after launch.

Each wing can be rotated via dedicated SADMs and one SADE. Technological limitations on the solar arrays require off-pointing the MTM SA at closer sun distances to avoid overheating, constraining the maximum amount of power available; above 0.62 AU distance, there are no constraints, while below that distance significant off-pointing of the array may be required. The SADM and SADE provide SA control/steering capability in order to suitably control the SA temperature and to ensure that this will not exceed a

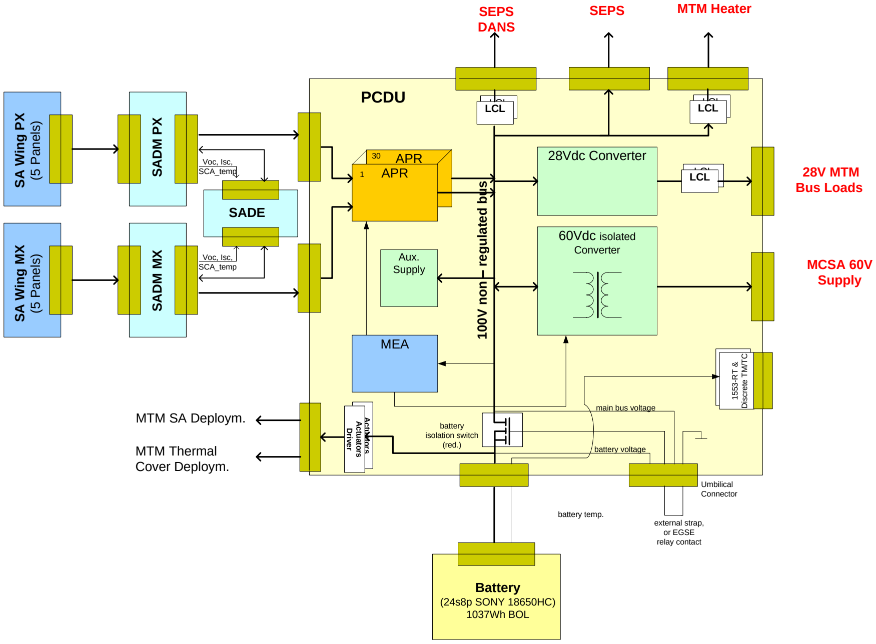


Figure 7. BepiColombo MTM power subsystem functional block diagram.

maximum operational temperature of 190°C, while optimizing the solar array sun aspect angle for maximum power at larger sun distances. Both mechanisms are driven and supplied by cold redundant electronics.

The power generated by and supplied from the MTM SA is routed through the two SADMs to the MTM PCDU. The SA power is conditioned by the MTM PCDU and distributed to both the MTM PCDU users and the MPO module during interplanetary cruise. The MTM PCDU is able to condition up to 13.3 kW.

Each of the two SA wings are divided in 15 sections (30 sections in total), with each SA section being connected to its dedicated Array Power Regulator (APR) within the MTM PCDU. The 30 APRs are sequentially operated in accordance with the MCS power demand; the activation/deactivation of the APRs is autonomously done by using a ladder network approach controlled by a reliable Main Error Amplifier (MEA) inside the MTM PCDU.

The MTM PCDU APRs convert the SA power in a 100V sunlit semi-regulated power bus (i.e. regulated in sun exposed condition and not regulated in eclipse). Because of the different sun flux due to the significant change of distance to sun especially at beginning and at end of cruise, the APRs need to work as a step-down converter, and also as a step-up converter (boost topology).

The main user of the 100 V power bus is the SEPS, to which power is provided via both unprotected and protected lines. Each of the two unprotected outlets is designed with a rated output current capability of 60 A. Protection is implemented at user level which guarantees the required safety and reliability at system level. Four protected lines are also provided to the electrical propulsion system; their protection is provided inside the PCDU by using 10 A LCLs. 100 V regulated power is also distributed to the thermal control system, while an additionally 28 V regulated power bus is implemented to supply other MTM equipment such as the SADE and Remote Interface Unit (RIU).

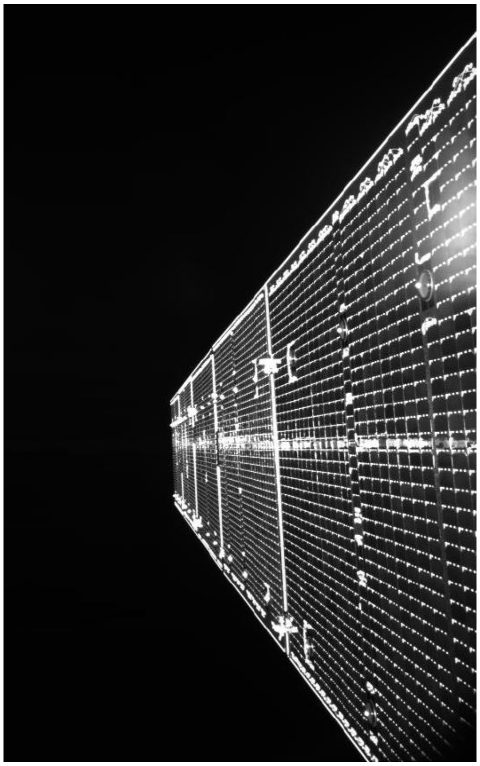


Figure 8. BepiColombo MTM SA wing deployed in flight.

In addition, the PCDU provides a 60 V MTM-to-MPO power link starting from the 100V sunlit power bus, for powering the MPO and MMO satellites during cruise to Mercury, to minimize the satellite solar array degradation before reaching Mercury.

The MTM battery is a 12 Ah Li-ion battery with a voltage range of 60 V to 100.8 V. The MTM battery provides the power requested from MTM equipment (excluding SEPS) and heaters during launch and eclipses.

The MTM PCDU includes the necessary electronics for battery charge and sensor for monitoring of battery discharge. Telemetry and feedback to the MEA is provided for charge regulation. The battery charging is fully autonomous and does not require any ground control or support from the on-board computer.

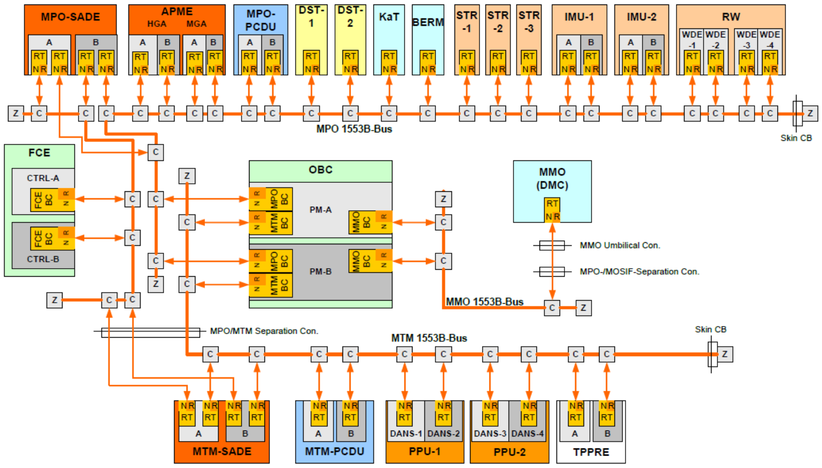


Figure 9. BepiColombo MIL-STD-1553B bus system topology.

E. MTM Data Handling

MTM data handling, as far as related to the MEPS, is performed via a dedicated fully redundant MIL bus controlled by the On-Board Computer OBC located in the MPO satellite. Remote terminals are implemented in the PPUs and the thruster pointing and pressure regulation electronics (TPPRE) of the MEPS, as well as the MTM PCDU and MTM SADE. See Figure 9.

The MEPS operations are

performed via a dedicated software, the MEPS Control Function (MCF), which is a separate software module running in the MPO OBC. This MCF software establishes the operational interface between the AOCS software and the MEPS units, essentially translating thrust demand and thruster orientation into MEPS unit commands, generating necessary parameter settings (electrical, Xenon flow etc.), and acquiring housekeeping data for observation on-ground.[9,10] See section V.C for further details.

V. Electric Propulsion System

A. Requirements

The electric propulsion system requirements are based on a compromise between the need to provide adequate thrust to achieve the transfer within the given time frame (including planning for contingencies), maximizing the specific impulse (to minimize the propellant mass requirements), and minimizing the power requirements (to minimize the power generation system mass). The need to achieve a suitable compromise between thrust, specific impulse and input power is inherent in using electric propulsion systems, as increasing the thrust or specific impulse will increase the power requirement.

The overall mission analysis and transport optimisation has been performed by Airbus Defence and Space and ESA, and is reported elsewhere.[11,12] The key driving requirements and parameters for the electric propulsion system have been selected as shown in Table 2, based on the mission requirements and technology capabilities.

Table 2. Key EP system requirements.

Thrust range	75 to 250 mN
Total impulse	17.2 MNs
Average specific impulse	3800 s
Propellant budget	581.5 kg
Input power at maximum thrust	10.5 kW

The corresponding thrust profile is illustrated in Figure 10; it should be noted that the minimum and maximum thrust levels are within the range shown in Table 2, with a small amount of margin. For further details, see Ref. 13.

The QinetiQ T6 gridded ion thruster is used to meet these mission requirements. This has been qualified for operation up to 145 mN; however, the life test has been conducted at 125 mN in line with the mission requirements, which also avoids high beam-out rates induced by test facility impacts (in particular, high rates of sputter material being deposited on the thruster during the life test).

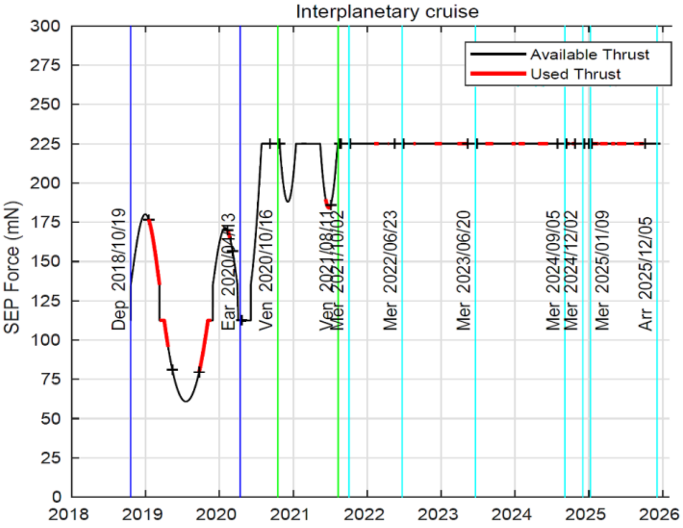


Figure 10. Electric propulsion thrust profile as planned prior to launch.

The BepiColombo mission also introduces a number of additional design constraints for the electric propulsion system, in particular the ability to withstand the high solar heat load (corresponding to 10 solar constants at Mercury); operation of 2 thrusters simultaneously; and a high level of autonomy (to avoid excessive ground operations during the long thrust periods).

The thermal impacts of the high solar heat load are mitigated by the inclusion of a sun shield; thruster operation in direct sunlight is required only from 0.87 AU upwards.

In order to support autonomous electric propulsion thruster operations, on-board monitoring of the electric propulsion system is provided; in case any anomaly or failure is encountered, the corresponding hardware is disabled, and the propulsion system autonomously reconfigured and restarted. This reconfiguration will be limited to an autonomous switch-over from a primary to a redundant (pre-defined from the ground) operational chain. It should be noted that any reconfiguration of the operating thrusters also requires reconfiguration of the overall spacecraft, as the thruster and spacecraft pointing angles, and overall attitude and orbit control system (AOCS), are impacted. This is described further in Refs. 9 and 13.

Operation of 2 thrusters simultaneously has been demonstrated up to the highest thrust levels required by BepiColombo, with no adverse interactions being seen. The impacts of twin thruster operations are described further in Ref. 14.

B. System Configuration

In order to achieve the required thrust range and life capability, a system of 4 thrusters is used, with 1 thruster being used at thrust levels up to 125 mN, and 2 thrusters being used simultaneously to achieve the required thrust levels of between 125 and 250 mN, as the available power increases. 3 thrusters are required to achieve the overall mission life, and the 4th thruster is provided for redundancy.

Each thruster is mounted on its own pointing mechanism. These mechanisms are used mainly to correct the thrust vector due to centre of mass (CoM) evolution over the mission life. The selected configuration also allows attitude control of the overall spacecraft to be provided around 2 axes during single thruster firing periods, and around all 3 axes during 2 thruster firing periods, by differential pointing of the mechanisms.

The thrusters and mechanisms are configured in a square arrangement on the bottom face of the MTM, as shown in Figure 11.

Figure 11. Electric propulsion thruster and pointing mechanism configuration.

The mechanisms are operated so that the thrust vectors are nominally pointed as follows:

- During single thruster operations, the thrust vector passes through the spacecraft CoM
- During operation of adjacent thrusters, the operating thrusters are parallel to one another with the overall net thrust vector passing through the spacecraft CoM
- During operation of opposite thrusters, both operating thrusters are parallel to the spacecraft longitudinal axis

It should be note that for nominal operations, the thrusters are operated singly or in adjacent pairs; operation of opposite thrusters is only required in the event of a failure which results in a thruster becoming unavailable.

Further details are given in Refs. 8, 9 and 12.

C. Electric Propulsion System Architecture Overview

The overall scope of BepiColombo MTM Electric Propulsion System (MEPS) is as follows:

- A Xenon storage and feed system, comprising storage tanks, valves, filters, and pipework
- Electric propulsion thrusters, with their associated power supplies and flow control units. This assembly, including the interconnecting harness and pipework, is referred to as the Solar Electric Propulsion System (SEPS). The SEPS is supplied by QinetiQ (UK), with major equipments supplied by CRISA (Spain) for the power supplies and Bradford Engineering (Netherlands) for the flow control units
- A pressure regulation system, comprising

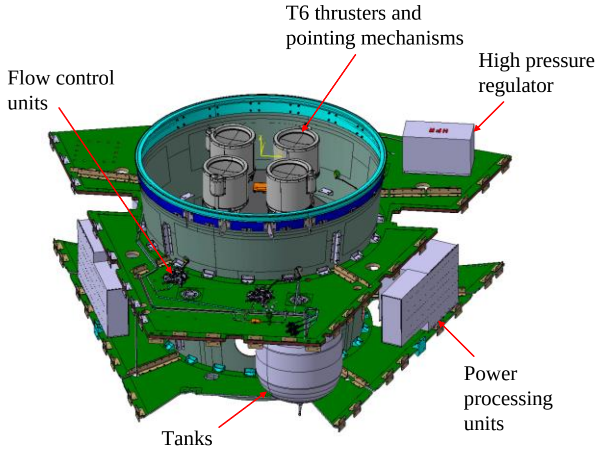


Figure 12. MEPS layout.

the high pressure regulator and its driving electronics. This assembly, with its interconnecting harnesses, is referred to as the High Pressure Regulation System (HPRS). The HPRS is provided by Airbus Defence and Space UK, with the electronics provided RSA (Austria)

- Pointing mechanisms, each supporting a single thruster, and their associated drive electronics. This assembly, with its interconnecting harnesses, is referred to as the Thruster Pointing Assembly (TPA). The TPA is provided by RSA (Austria)

The MEPS layout is shown in Figure 12, and the corresponding product tree is given in Table 3. Note that the pressure regulation electronics (PRE) and thruster pointing electronics (TPE) are shown as functionally distinct units in this product tree; however, these are combined into a single electronics unit designated Thruster Pointing and Pressure Regulation Electronics (TPPRE).

Table 3. MEPS product tree.

Acronym	Name
MEPS	MTM Electric Propulsion System
├ XST	Xenon Storage Tank
├ FDV	Fill and drain valve
├ TIV	Tank isolation valve (NC pyro)
├ XEF	Xenon filter
├ HPRS	High pressure regulation system
│ HPR	High pressure regulator
│ ├ HPT	High pressure transducer
│ └ LPT	Low pressure transducer
│ ├ PRE	Pressure regulator electronics
│ └ PRH	Pressure regulator harness
├ SEPS	Solar electric propulsion system
│ ├ SEPT	Solar electric propulsion thruster
│ ├ FCU	Flow control unit
│ ├ PPU	Power processing unit
│ ├ SEPH	SEPS harness
│ └ SEPP	SEPS pipework
├ TPA	Thruster pointing assembly
│ ├ TPM	Thruster pointing mechanism
│ ├ TPE	Thruster pointing electronics
│ └ TPH	Thruster pointing assembly harness
└ MEPP	MEPS pipework

The electric propulsion system is controlled by an on-board software package referred to as the MEPS Control Function (MCF), under the direction of the spacecraft AOCS; this is embedded in the on-board computer (OBC) software in the MPO, with the corresponding commands and telemetry being routed to the MTM via a 1553 bus and direct high level commands. The MCF modes and corresponding operations of the MEPS are shown in Figure 13 and Table 4.

Table 4. MEPS modes.

Mode	Description
OFF	All parts of the MEPS are OFF
BASIC	• The selected PRE is ON • HPRS sensors are enabled and providing TM; the HPR is not regulating, and all valves are closed
START_UP_PREP	In addition to BASIC: • The selected TPE is ON, and controls the TPMs according to commands from the AOCS • All items associated with the SEPS are OFF
START_UP	In addition to START_UP_PREP: • The inverters and auxiliary power supplies are ON • All supplies to the thruster and FCU are disabled; all FCU valves are closed
STANDBY	START_UP is augmented as follows: • The selected SEP thrusters are operating with discharges only • The HPR is regulating
THRUST	STANDBY is augmented as follows: • The thruster is generating thrust at the commanded level
SHUTOFF	• The SEP thrusters are shut down • The TPA is switched off • The HPRS is providing TM only

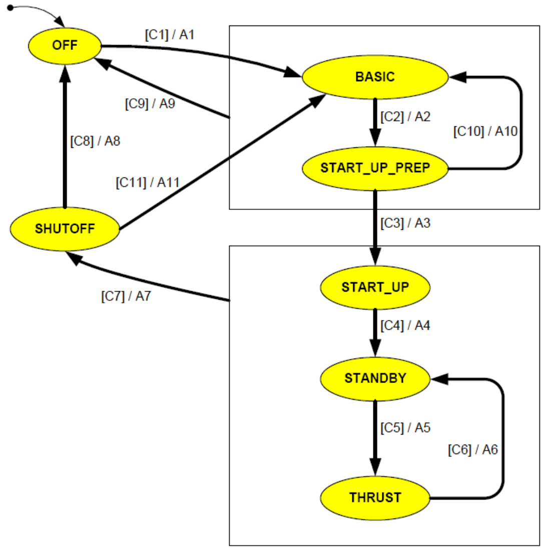


Figure 13. MEPS mode transitions.

It should be noted that for a number of the initial MEPS commissioning activities (see ref. 15), the MCF is “unlocked” from the AOCS control. This allows manual commanding of the MEPS; these commands are limited to specific commands to the PPUs and TPPRE to enable e.g. valve opening, etc. In case of any anomaly in this case, the AOCS will return the MCF to BASIC mode.

The SEPS, TPA and HPRS have all been specifically developed for the BepiColombo programme, based on heritage from previous product development (and for the HPRS, flight) programmes, using modified "building blocks" from these programmes to achieve the BepiColombo equipment designs.

1. Feed System

The Xenon feed system sizing is driven by the high total impulse and thrust levels required to achieve the BepiColombo mission. These result in the need to store and deliver at least 494.1 kg of Xenon (including all losses and residuals), with the full tank capacity of 581.5 kg actually loaded, at flow rates of up to 7.5 mg/s (worst case with 2 thrusters firing simultaneously). The only other known deep space mission which requires such a high level of Xenon processing is Dawn, which has a Xenon budget of approximately 450 kg.[4,5]

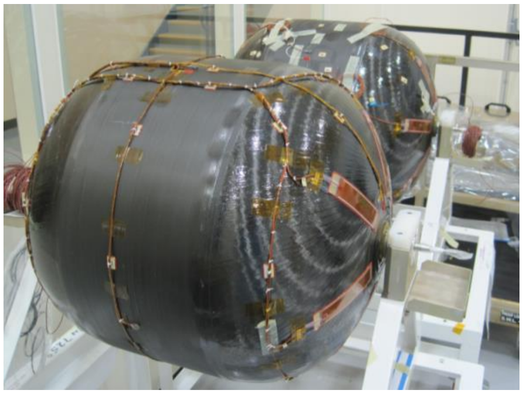


Figure 14. Xenon tanks.

Airbus Defence and Space have based the BepiColombo Xenon feed system design on the extensive heritage gained on their Eurostar 3000 platform, which requires up to 300 kg of Xenon[16,17] (noting that more recent telecommunications platforms such as Eurostar NEO have Xenon loads up to ~1000 kg). The feed system maximum pressures are 150 bar in the high pressure section, and 5 bar in the low pressure section.

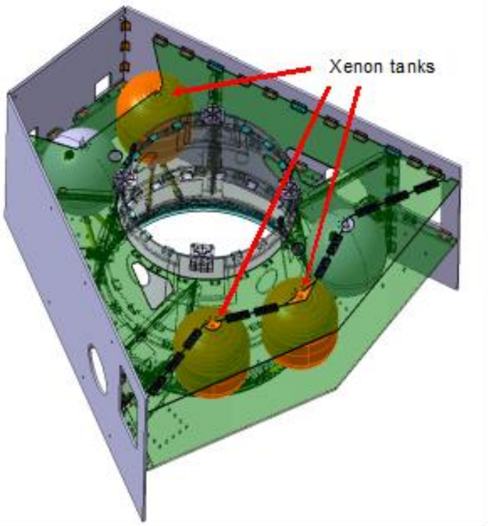


Figure 15. Xenon tank accommodation.

The main changes required for BepiColombo compared to Eurostar 3000 are a larger tank volume, and increased capacity (throughput, flow rate, and inlet pressure) of the Xenon regulation system. A configuration using 3 tanks has been selected to provide the required volume (366 litres total tank volume is provided). Each tank assembly is a composite overwrapped pressure vessel (COPV) with a metallic liner, provided by Arde (see Figure 14). The COPV is polar mounted, and it incorporates 2 ports to aid tank preparation and filling activities at the launch site.

The tanks are mounted along with the 2 tanks for the MTM CPS between 2 structure "floors". The Xenon tanks have the same height as the CPS propellant tanks, and hence fit within the MTM configuration constraints. This is illustrated in Figure 12 (although only 1 Xenon tank is visible in this view; the other 2 Xenon tank and one CPS tank can be seen in Figure 6), and Figure 15. The Xenon tanks are joined to a common pipework manifold, which connects them to the HPRS inlet. A second pipework manifold connects the HPRS outlet to the SEPS Flow Control Unit (FCU) inlets. Fill and drain valves (FDVs) provide access for Xenon filling and system testing at the tanks, HPRS inlet and HPRS outlet.

Figure 16. HPR.

2. HPRS Summary

An electronic regulation scheme designated HPRS (which comprises the regulator and its drive electronics) is used, with the following key requirements:

- Regulation from tank pressure down to nominally 2.5 to 3.2 bar outlet pressure
- Fully redundant, and avoidance of any single point failures
- Provision of 3 independent barriers

between the high and low pressure sections

The HPR is a development of the Xenon Regulation and Feed System (XRFS) currently in operation of Eurostar 3000, and is shown in Figure 16. It has been developed and manufactured by Airbus Defence and Space UK. This is a “bang-bang” type regulator; plenums are filled with Xenon on opening a regulation valve; when the pressure reaches a pre-defined threshold, the regulation valve is closed and the plenum pressure drops as Xenon is consumed by the thrusters. This is illustrated in Figure 17.

The regulation is controlled by the TPPRE; a field-programmable gate array (FPGA) in this unit stores the upper and lower regulation thresholds and provides all the control logic, whilst the PRE includes all the valves drivers and pressure sensor acquisition circuits.

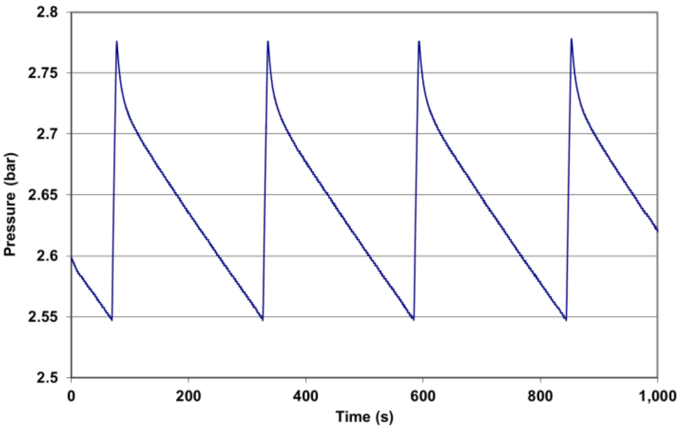


Figure 17. HPRS pressure profile.

The main modifications for the HPR with respect to the Eurostar XRFS required to achieve the BepiColombo requirements are as follows:[8,18]

- Doubling of the plenum volume (from 1 to 2 litres) to accommodate the increased Xenon throughput; this is achieved using 2 plenums of 1 litre each
- Change in restrictor sizing to enable higher flow rates
- Adoption of a European pressure transducer (provided by Bradford Engineering)
- Reconfiguration of the mechanical design

The HPR was qualified using an EQM, supplemented by a life test for the regulation valve.

All HPRS electrical interfaces to the spacecraft are through the TPPRE.

3. *SEPS*

In order to provide adequate redundancy and sharing of life between thrusters, the SEPS has been designed with 4 separate functional branches, each comprising a solar electric propulsion thruster (SEPT) and associated flow control unit (FCU). The BepiColombo mission requires the combined thrust from two T6 ion engines throughout most of the cruise phase. There are 2 power processing units (PPUs) which interface directly with the thrusters and FCUs.

The T6 is a Kaufman type gridded ion thruster, and is illustrated in Figure 18 and Figure 19. The principle of operation for the T6 is as follows:

- A cathode located at the back of the discharge chamber provides an electron source for the discharge ionization
- Xenon is flowed into the discharge chamber, and is ionized by bombardment by the electrons from the cathode as they are accelerated towards the discharge chamber anode. A set of solenoids generate an internal magnetic field, which force the electrons to follow a spiral path, increasing the ionization efficiency, and allow fine thrust control
- The positive Xenon ions are extracted and accelerated to high velocity by the potential difference between the screen and accelerator grids; this acceleration process produces the thrust
- A neutralizer provides a source of electrons which are drawn into the external ion beam, to prevent spacecraft charging

Figure 18. T6 electron-bombardment ion thruster.

The thruster has demonstrated the ability to achieve thrust levels from 75 up to 145 mN, and has an estimated operating life capability in excess of 14500 hours, providing good margin against the mission requirements.

Each PPU is comprised of the following elements:

- Discharge Anode Neutraliser Supply (DANS) (2 off). This contains the control electronics, an AC inverter, high and low voltage referenced thruster supplies, thruster switches, FCU drive electronics, and auxiliary power. The high voltage referenced supplies provide power to the loads within a thruster which are referenced to the discharge chamber (this is at beam potential less the anode voltage)
- Beam Supply Unit (BSU). This is comprised of 4 parallel Beam Supply Modules (BSM) configured in a fail-safe architecture. Each BSM supplies the full beam potential but only a fraction of the total beam current

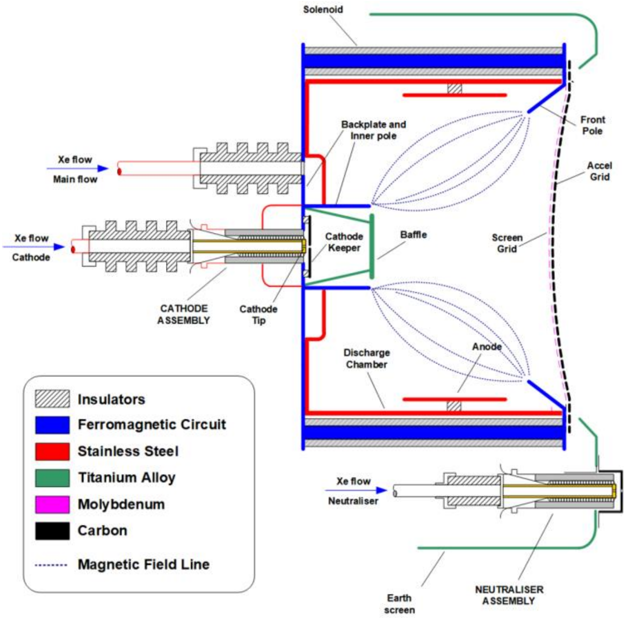


Figure 19. T6 electron-bombardment ion thruster schematic.

The overall PPU configuration is such that it provides internal redundancy, with 2 parallel DANS; the 2 DANS share a common BSU, with the BSU being able support either DANS. The BSM have a “3 out of 4” redundancy scheme; only 3 BSM are required to meet the BepiColombo maximum thrust requirement of 125 mN (per thruster), with the fourth module being provided for redundancy. Each BSM is protected by a latch current limiter (LCL).

To enable maximum flexibility in the event of a unit failure, each DANS is connected to two thrusters via relay switches (see Figure 20). This architecture enables any pair of thrusters to be operated simultaneously and ensures mission requirements can be met after failure of any single unit.

A DANS is considered to be in “local” configuration if it is connected to a thruster with the same index number (e.g. DANS1 connected to SEPT1); the other switch configuration is referred to as “remote”. For nominal SEPS operations, all DANS are used in “local” configuration, with the pairs DANS1+DANS3 and DANS2+DANS4 being used alternately. This enables the mission life to be shared between all 4 thrusters without any need for switching of the relays. Only one DANS in each PPU can be used at any one time.

All SEPS electrical and communications interfaces to the spacecraft and internal control within the SEPS is provided within the PPU, using an FPGA controller. The PPU interfaces directly with the thrusters and FCUs. Power is provided from a 100V regulated main bus (see section IV.D). Command, and control and return TM is via a 1553 bus, or direct high level TM/TC.

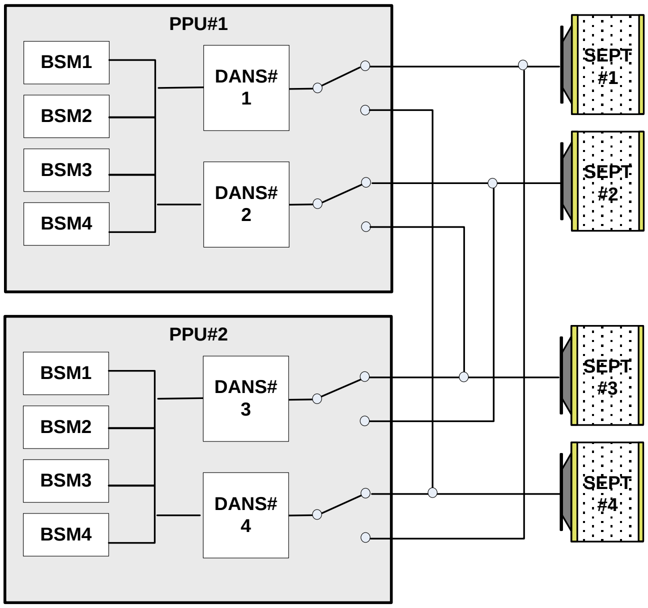


Figure 20. SEPS architecture.

The PPU is illustrated in Figure 21.

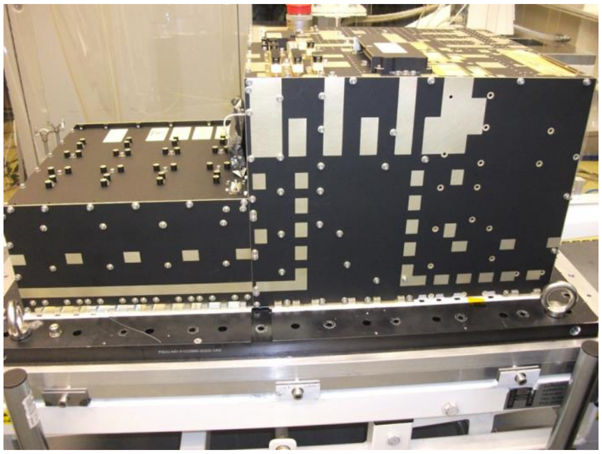


Figure 21. PPU.

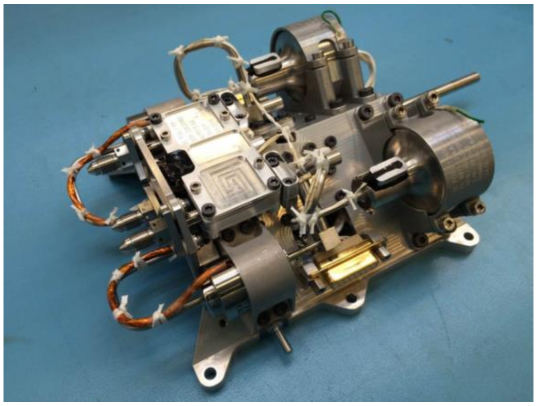


Figure 22. FCU.

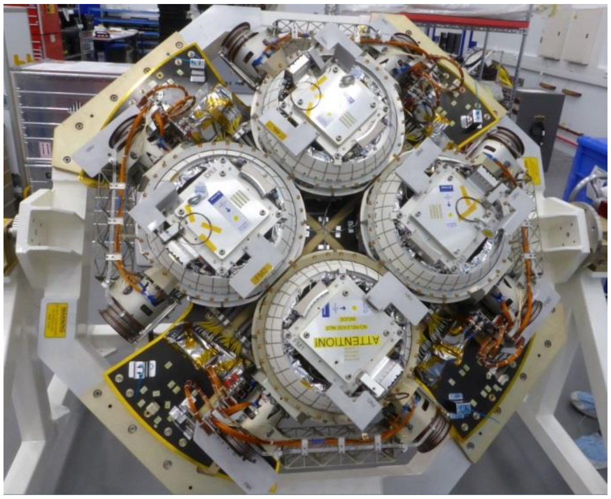


Figure 23. Thruster pointing mechanisms.

The FCU is illustrated in Figure 22. Flow rates to the discharge chamber and cathode (which are varied according to the thrust level) are controlled by means of variable flow control valves feeding into fixed restrictors (using pressure control); the neutralizer flow (which is fixed throughout the mission) is controlled thermally. The flow control algorithms are implemented within the PPU.

4. TPA

The TPA is supplied by RUAG Space GmbH (RSA), Vienna, and consists of the drive electronics and 4 thruster pointing mechanisms. Each pointing mechanism supports an individual T6 thruster in the stowed configuration during launch, by means of a dedicated Hold-Down and Release Mechanism (HDRM). The HDRM is equipped with a single, central release actuator. The HDRM is also equipped with an elastomer damping system that reduces the launch loads on the thruster to an acceptable level.

Upon release of the HDRM, the pointing mechanism platform can be tilted around two perpendicular axes. This motion is facilitated by two geared high detent torque rotary actuators. For the design of the mechanism, existing building blocks are reused in order to minimize effort and development risk.

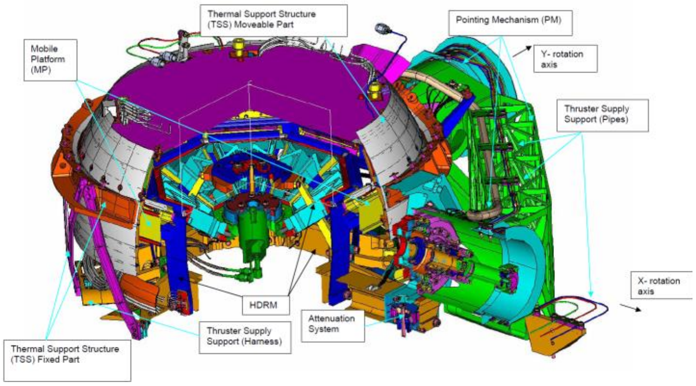


Figure 24. Thruster pointing mechanism (reproduced by permission of RSA).

The TPM has a large pointing range; a total range of >24° around each axis is required to achieve all the various thruster firing combinations and associated pointing requirements.

The TPPRE has one nominal and one redundant TPE, each able to operate any 2 out of 4 TPMs simultaneously.

All TPA electrical interfaces to the spacecraft are through the TPPRE.

VI. Conclusion

The BepiColombo MTM provides all the propulsion and associated hardware to deliver 2 orbiters to Mercury. A major part of this is the electric propulsion system, based on the QinetiQ T6 thruster, which provides a large total impulse capability as part of the transfer. The electric propulsion configuration uses 4 ion thrusters, with either one or two thrusters being used simultaneously to achieve the required thrust level. Each thruster is mounted on its own pointing mechanism; this configuration enables operation of any single or pair of thrusters. The Xenon storage and feed system requirements are driven by the high total Xenon processing requirements.

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