

Return to Mercury: An Overview of the MESSENGER Spacecraft Thermal Control System Design and Up-to-Date Flight Performance

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ABSTRACT

Launched on August 3, 2004, MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Ranging) will be the first spacecraft to orbit the planet Mercury. Designed and built by The Johns Hopkins University Applied Physics Laboratory in conjunction with the Carnegie Institution of Washington, MESSENGER will study Mercury during a 1-year orbital phase that will begin in March 2011. Currently the spacecraft is in the middle of a 7-year cruise phase that so far has included a flyby of the Earth (August 2005), two flybys of Venus (October 2006 and June 2007), and the first of three flybys of Mercury (January 2008). The January 2008 Mercury flyby marked the first spacecraft visit since Mariner 10 (1975) and made MESSENGER the first spacecraft to encounter Mercury when near the planet's perihelion. This paper will provide an overview of the thermal design challenges for both the cruise and orbital phases, the solutions implemented to resolve those challenges, and the flight temperature and power data that verify the performance of the thermal control subsystem over the mission to date.

INTRODUCTION

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission will characterize Mercury in detail by observing the planet from orbit for one Earth year. Although it had long been desired to follow the initial flybys with an orbital mission, early studies had deemed this infeasible, or at least prohibitively expensive, due to mass and thermal constraints. MESSENGER utilizes a trajectory (illustrated in Figure 1) that was discovered by analysts at the Jet Propulsion Laboratory (JPL) [1,2] and later refined by analysts at The Johns Hopkins University Applied Physics Laboratory (APL). This mission design has allowed a launch mass of 1107 kg (including propellant) on a Delta-II heavy while keeping the overall mission cost within the allowable cap. Flybys of Earth, Venus,

and Mercury itself are interspersed with five large deterministic deep-space maneuvers (DSMs) that target the spacecraft for its Mercury orbit insertion (MOI) maneuver in 2011.

The highly varying thermal environments expected during the cruise and Mercury orbital phases were a key engineering challenge in the spacecraft design. Driven by solar distances as small as 0.30 AU, the spacecraft thermal protection is accomplished with a large sunshade that shields most spacecraft components from direct solar exposure and allows them to operate at conditions typical of other interplanetary spacecraft without much temperature variation. After launch and during the early part of the mission (known as the outer cruise phase) when the trajectory took MESSENGER multiple times to solar distances >0.95 AU (shown in Figure 2), the spacecraft was flown in a reverse attitude, exposing the core vehicle to solar heating. During this phase of the mission when solar-array output power was the least, the reversed flight configuration substantially reduced heater-power usage while passively maintaining all spacecraft temperatures well within allowable flight limits. Once in orbit at Mercury, the orbital geometry as a function of Mercury True Anomaly (MTA) was chosen via comprehensive thermal environment analysis to minimize the thermal hazards on the day side of Mercury [3] by factoring analytical thermal constraints into the mission design. During this time, MESSENGER will experience steady-state heating from the Sun and transient heating from Mercury, both of which are functions of Mercury's solar distance, which varies between 0.3 AU (perihelion) and 0.46 AU (aphelion). Because most of the spacecraft hardware is protected by the sunshade, no specialized thermal designs were required. Certain hardware [the solar panels, sunshade, phased-array and low-gain antennas, and Digital Sun Sensor (DSS) heads] is necessarily exposed to the Sun throughout the mission and was specially designed to handle the temperatures and solar flux input expected at 0.3 AU [4-7].

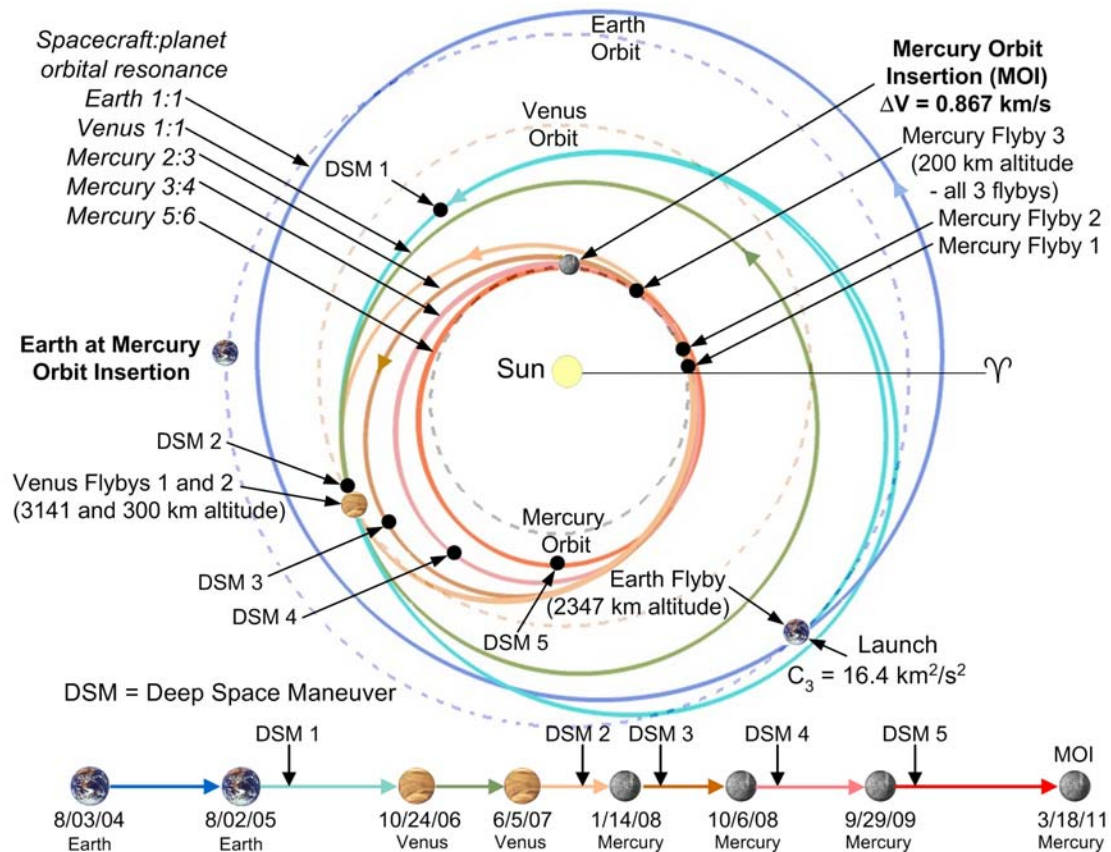


Figure 1. MESSENGER's heliocentric trajectory (viewed from north of Earth's orbital plane).

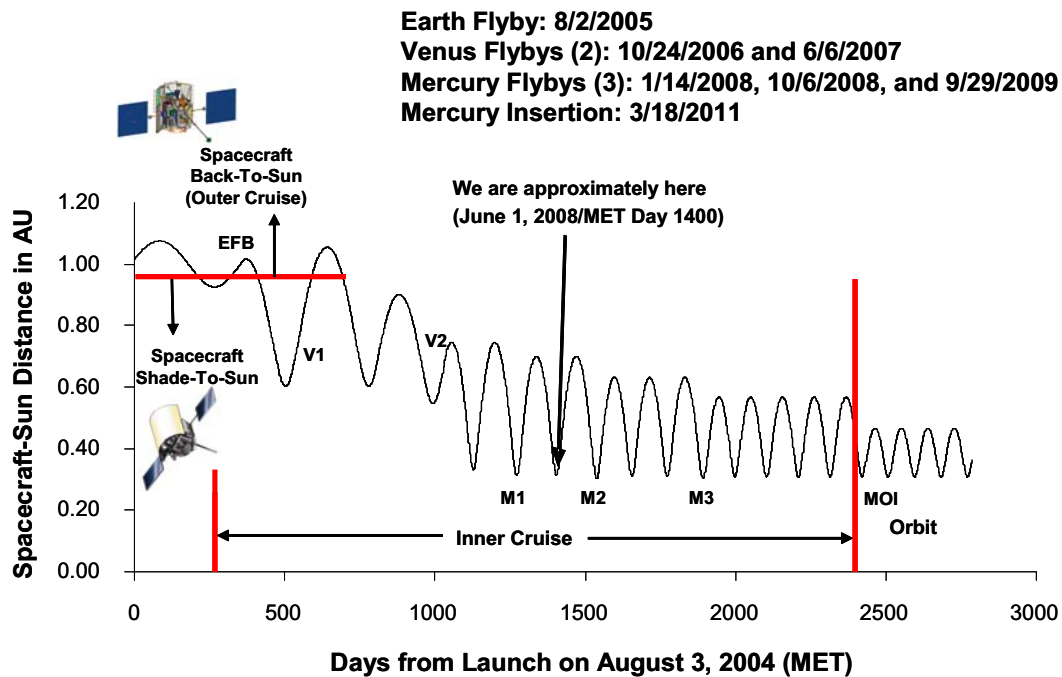


Figure 2. The spacecraft-to-Sun distance variation as a function of elapsed mission day. Key mission events are highlighted. Currently, the MESSENGER mission is approximately at the midpoint of its duration. EFB, Earth flyby; MET, mission elapsed time.

The MESSENGER mission is a collaboration between the Carnegie Institution of Washington (CIW) and APL and was selected as the seventh mission in NASA's Discovery Program, with a formal project start in January 2000. The spacecraft engineering and science instrument design evolved over the 3-year period from January 2000 to spring 2003. Assembly and integration of the spacecraft began in February 2003, and testing continued up to launch in August 2004. Flight operations are now supported from the Mission Operations Center at APL with communications through NASA's Deep Space Network (DSN) antennas.

OVERVIEW OF SPACECRAFT THERMAL DESIGN

The thermal design and operation of the MESSENGER spacecraft addressed three mission phases: outer cruise, inner cruise, and Mercury orbit. During the inner cruise and orbital phases, the thermal design relies on a ceramic-cloth sunshade to protect the vehicle from the intense solar environment encountered when inside of 0.95 AU. As shown in Figure 3, the sunshade creates a benign thermal environment when oriented with the $-Y$ axis pointed toward the Sun, allowing for the use of standard electronics and electrical components and thermal blanketing materials. The solar arrays, sunshade, DSSs, and phased-array antennas, which are shown in Figures 4 and 5, are Sun-exposed components that required non-standard thermal design and specialized construction. These components have been designed to operate throughout the Mercury year and also during orbits that cross over one of Mercury's "hot poles" that face the Sun at Mercury perihelion. When at spacecraft perihelion, the sunshade, the solar arrays, the sunshade-mounted DSSs, and the sunshade-mounted antenna suite will experience as much as 11

times the solar radiation near Earth. During this time, the sunshade temperature will rise to $>300^{\circ}\text{C}$. In certain orbits around Mercury, the spacecraft will pass between the Sun and the illuminated planet for ~ 30 minutes. During this period, the sunshade will protect the spacecraft from direct solar illumination, but the back of the spacecraft will be exposed to the hot Mercury surface. Components such as the battery and star trackers are positioned such that the spacecraft body blocks a substantial portion of the planet view, minimizing direct radiation from the planet surface when the spacecraft is in nominal operation. High-power spacecraft electronics that require dedicated radiators could not be packaged in a manner similar to that of the battery to reduce environmental heating from Mercury. These electronics boxes instead required specialized thermal design to allow for full, unrestricted operation during all parts of the orbital mission phase. Diode heat pipes, which are shown in Figure 6, were used in both the spacecraft and imager thermal designs to protect the attached components when radiator surfaces are exposed to day-side heating from Mercury. Thermal model results illustrating the variation of Mercury-induced heating received by MESSENGER are shown in Figure 7. During this peak heating period, the diode heat pipes will effectively stop conducting when the radiator surface becomes hot, as simulated during spacecraft-level thermal vacuum testing and shown in Figure 8. Once the planetary heating decays and the radiator cools, the heat pipe will resume conduction, restoring normal thermal control. Analysis of the near-planet environment as a function of orbit geometry and planet position was integrated into the mission design and has helped to phase the orbit plane relative to solar distance, minimizing infrared heating of the spacecraft by the planet and thus minimizing the mass required to accommodate such heating.

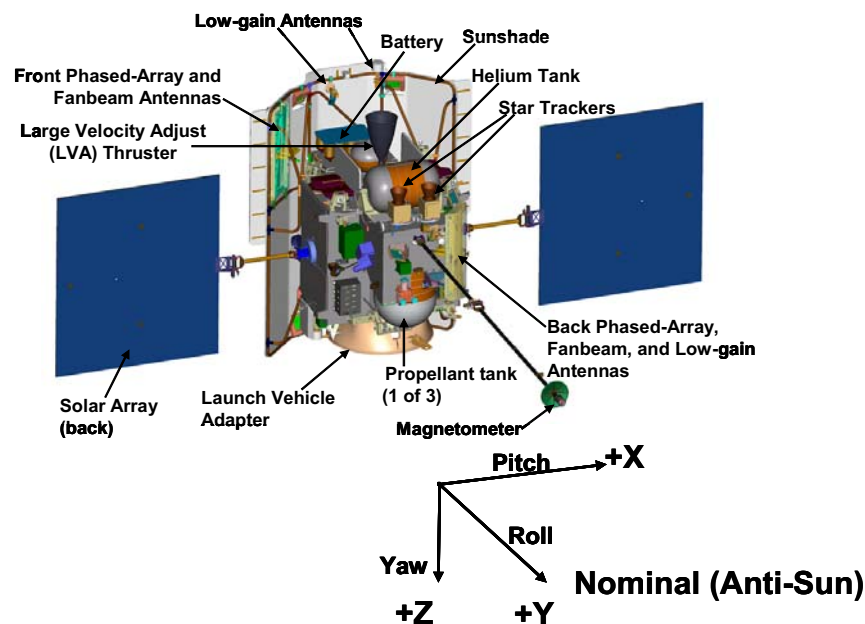


Figure 3. The MESSENGER spacecraft and flight coordinate system



Figure 4. The MESSENGER spacecraft 2 weeks before launch. Highlighted here are the ceramic-cloth sunshade, the four DSSs with attenuating filters, the phased arrays and low-gain antennas under high-temperature radomes, and the 4.4-N pro-Sun thrusters.

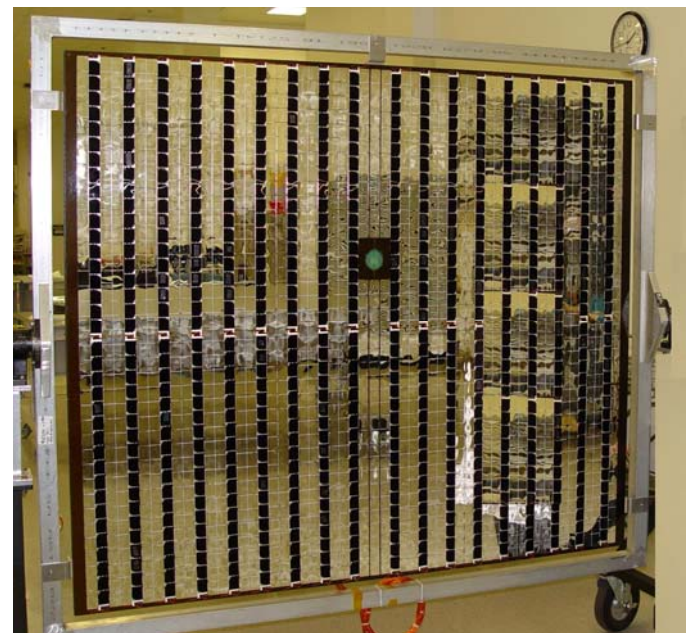


Figure 5. The MESSENGER +X solar array before spacecraft integration. Each solar array has a 2:1 ratio of OSRs to triple-junction gallium-arsenide solar cells.

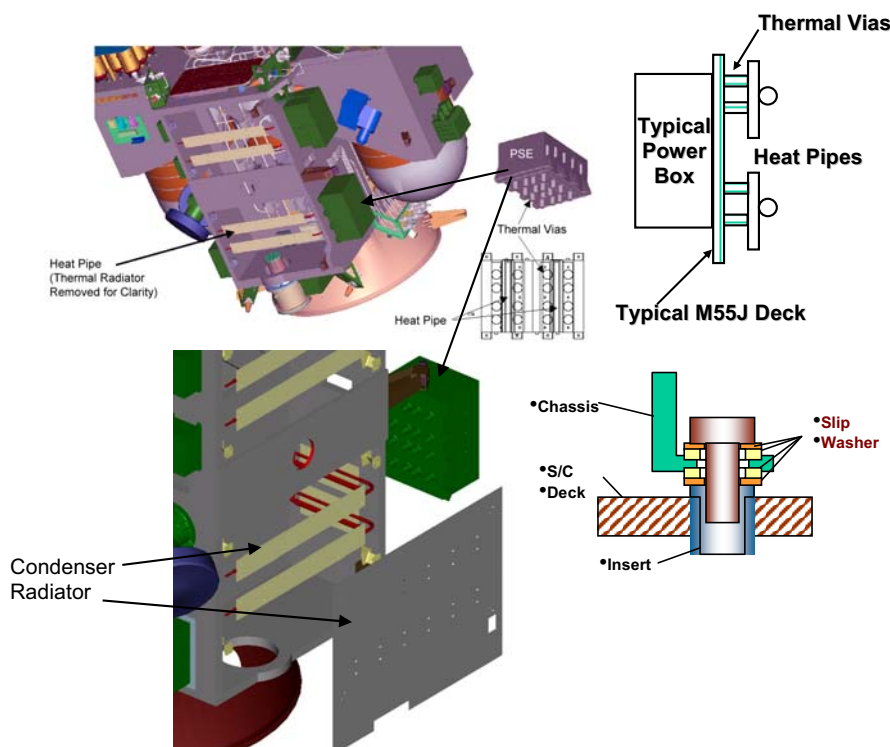


Figure 6. Driven by the Mercury orbit phase, diode heat pipes were used to protect high-power electronics. The PSE shown here required dedicated radiators. Because the MESSENGER structure was fabricated from a composite with a small coefficient of thermal expansion, a slip-mount design was used to fasten electronics boxes to the structure, and integral thermal vias connect specified electronics boxes directly to the heat pipes. S/C, Spacecraft.

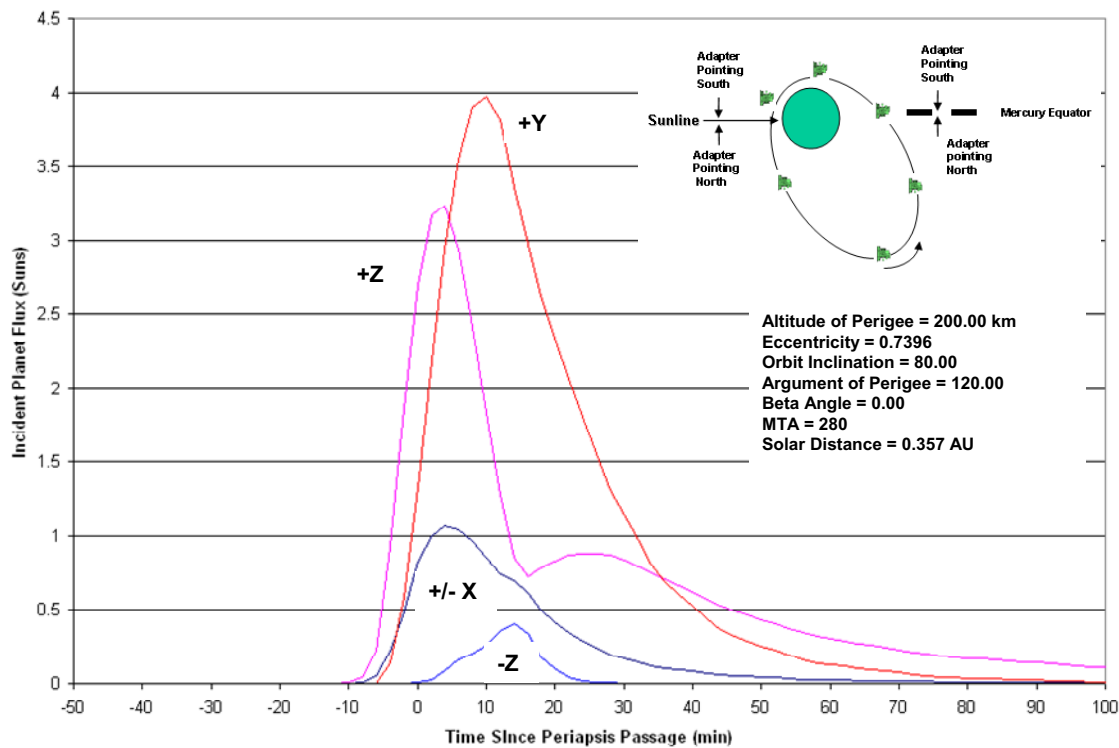


Figure 7. Incident thermal flux emitted by Mercury as seen at different locations on the spacecraft. Spacecraft thermal-control radiators are located in the $-Z$ and $\pm X$ directions. Liquid-trap diode heat pipes constructed from aluminum and filled with ammonia were necessary to protect electronics connected to the $\pm X$ radiators from thermal energy back-flow when MESSENGER receives peak infrared heating. Approximately 1.2 m^2 of $\pm X$ radiator area was required to dissipate electronics waste heat. As shown, the $+Y$ and $+Z$ directions are not desirable locations for radiators.

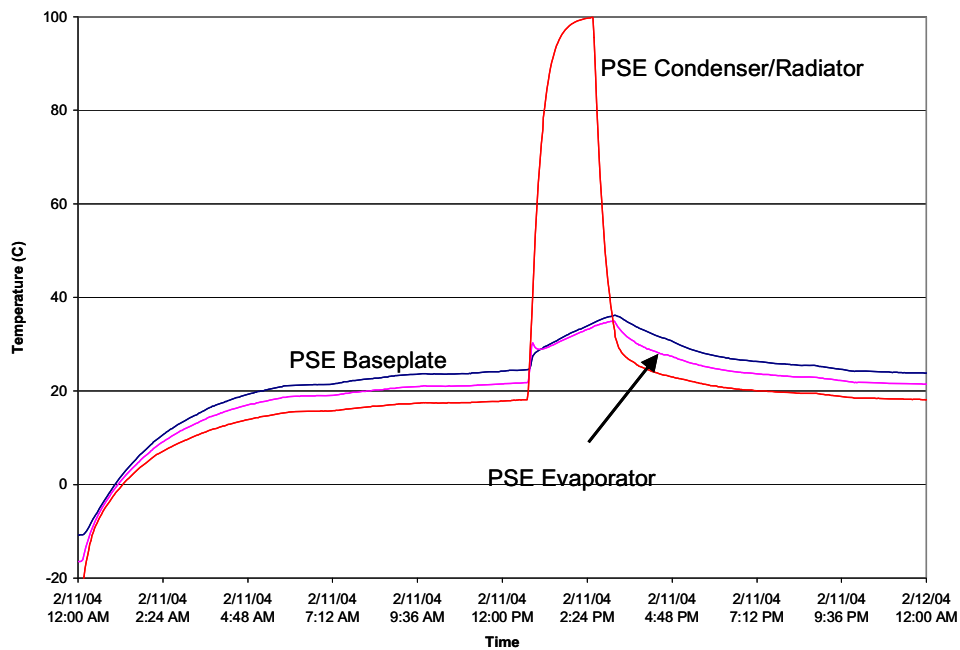


Figure 8. PSE temperature response for a simulated Mercury orbit during spacecraft thermal vacuum testing at GSFC in February 2004. This figure represents the expected behavior for boxes connected to diode heat pipes while in orbit at Mercury. Barring any spacecraft attitude anomaly, the diode heat pipes will remain dormant during the remainder of inner cruise.