The MESSENGER Spacecraft Power System: Thermal Performance Through the First Mercury Flyby

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The MErcury, Surface, Space, ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft is a NASA Discovery Program spacecraft developed and operated by The Johns Hopkins University Applied Physics Laboratory. It was launched on August 3, 2004. The spacecraft is currently on schedule for Mercury orbit insertion in March 2011. To date, the mission trajectory has taken the spacecraft to minimum solar distances of 0.332 and 0.313 Astronomical Units, and on January 14, 2008, the first flyby of Mercury in 33 years took place. From launch through the latest perihelion passage, the thermal performance of the power system electronic boxes, battery, and solar arrays has been as expected. The paper will review the thermal design of the different power system components and describe the thermal performance of these components to date.

Nomenclature

AASC	=	Applied Aerospace Structures Corporation
APL	=	The Johns Hopkins University Applied Physics Laboratory
AU	=	Astronomical Units
CIW	=	Carnegie Institution of Washington
CPV	=	Common Pressure Vessel
DC	=	Duty Cycle
DSS	=	Digital Sun Sensor
GRC	=	Glenn Research Center
MESSENGER	=	MErcury Surface, Space ENvironment, GEochemistry, and Ranging
OSR	=	Optical Solar Reflector
PDU	=	Power Distribution Unit
PSE	=	Power System Electronics
SAJB	=	Solar-Array Junction Box
S/C	=	Spacecraft

I. Mission Description

MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER), shown in Fig. 1, is a NASA Discovery Program spacecraft designed and built by The Johns Hopkins University Applied Physics Laboratory (APL). It will orbit the planet Mercury for one Earth year. During the orbital phase of the mission, MESSENGER will take scientific measurements using a suite of specialized instruments.[1] MESSENGER was launched on a Delta 7925H-9.5 launch vehicle on August 3, 2004. The spacecraft trajectory requires two gravity-assist flybys from Venus and three from Mercury (Fig. 2). The spacecraft-to-Sun distance varies between 1.075 and 0.3 Astronomical Units (AU). The solar illumination, which varies inversely with the square of the Sun distance, has a severe impact on the thermal design of the solar-array panels and spacecraft.

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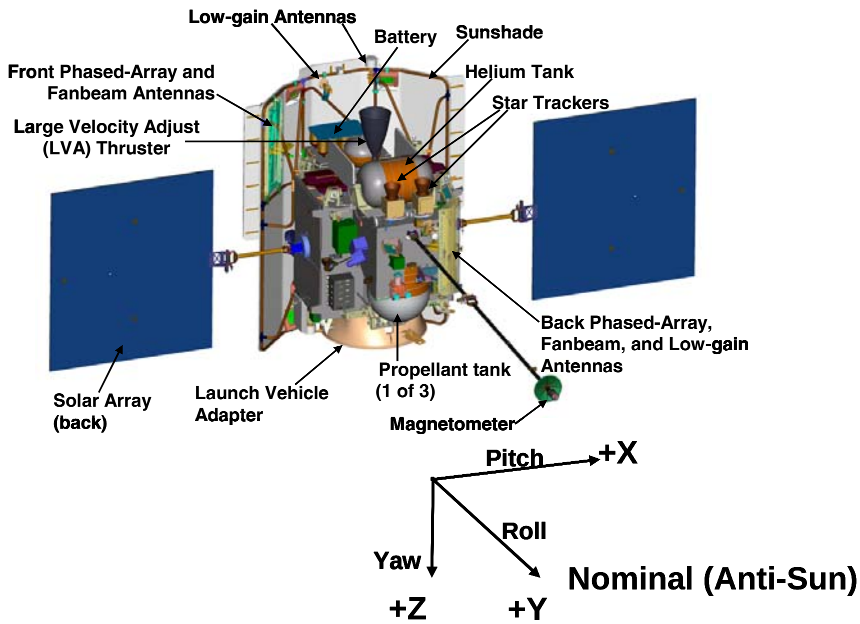

Figure 1. The MESSENGER spacecraft and flight coordinate system.

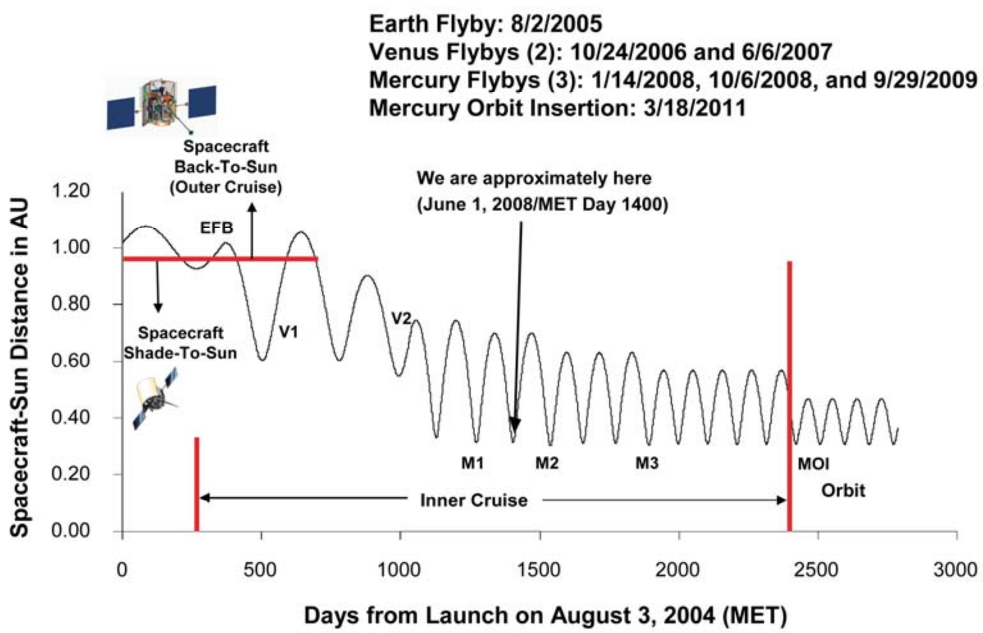

Figure 2. Variation in spacecraft-to-Sun distance as a function of elapsed mission day. Key mission events are highlighted. Currently, the MESSENGER mission is approximately at the midpoint of its duration. EFB, Earth flyby; M1, Mercury flyby 1; M2, Mercury flyby 2; M3, Mercury flyby 3; MET, mission elapsed time; MOI, Mercury orbit insertion; V1, Venus flyby 1; V2, Venus flyby 2.

II. Thermal Design Overview

The thermal design and operation of the MESSENGER spacecraft addresses three mission phases: outer cruise, inner cruise, and Mercury orbit.[2] 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 Fig. 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, electrical components, and thermal blanketing materials. The solar arrays, shown in Fig. 4, required nonstandard thermal design and specialized construction. The solar arrays 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 and the solar arrays will experience as much as 11 times the solar radiation near Earth. During this time, the sunshade temperature will rise to >300°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. The battery is 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. The high-powered Power System Electronics (PSE), Power Distribution Unit (PDU), and Solar-Array Junction Box (SAJB) required dedicated radiators and could not be packaged in a manner similar to the battery to reduce environmental heating from Mercury. The PSE instead required a specialized thermal design to allow for full, unrestricted operation during all parts of the orbital mission phase. Diode heat pipes, which are shown in Fig. 5, 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 Fig. 6. 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 Fig. 7. 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.[3]

Figure 3. The MESSENGER spacecraft two weeks before launch. Highlighted here are the ceramic-cloth sunshade, the four digital Sun sensors (DSSs) with attenuating filters, the phased arrays and low-gain antennas under high-temperature radomes, and the 4.4-N pro-Sun thrusters.

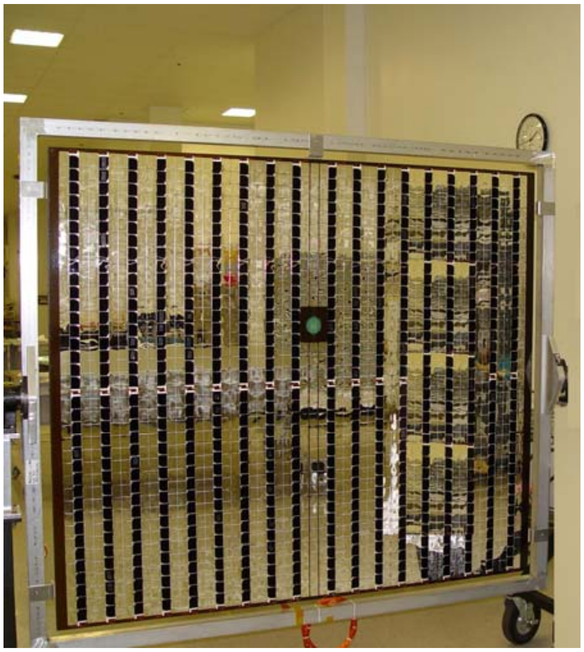

Figure 4. The MESSENGER +X solar array before spacecraft integration. Each solar array has a 2:1 ratio of OSRs to triple-junction gallium-arsenide solar cells.

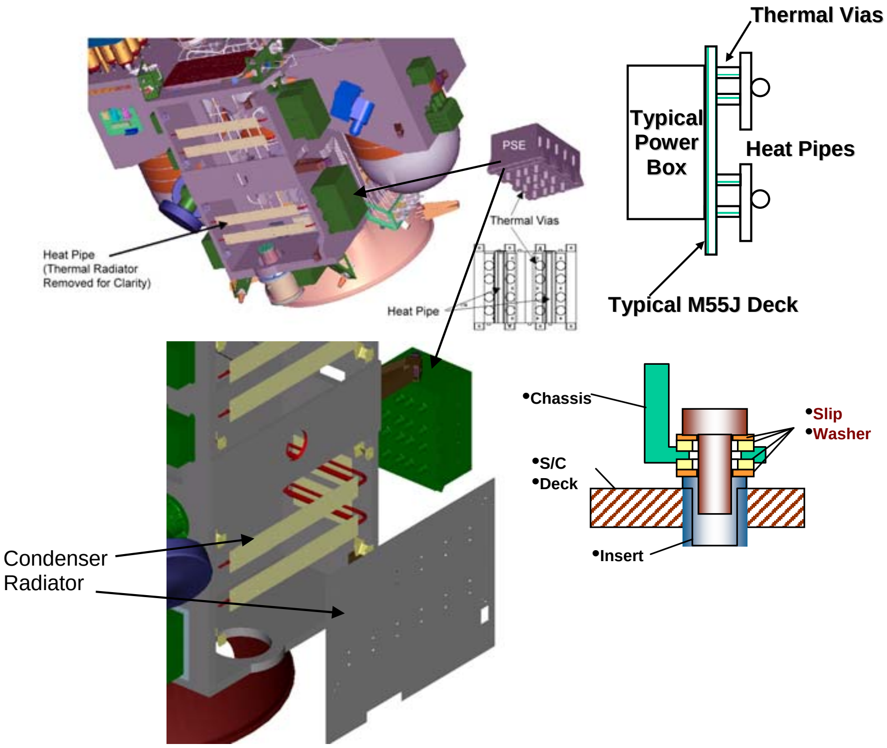

Figure 5. Driven by the Mercury orbit phase, liquid-trap diode heat pipes constructed from aluminum and filled with ammonia were necessary to protect spacecraft electronics from the intense heat emitted by Mercury. The PSE, shown here, is one of eight electronics boxes requiring a dedicated radiator. 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.

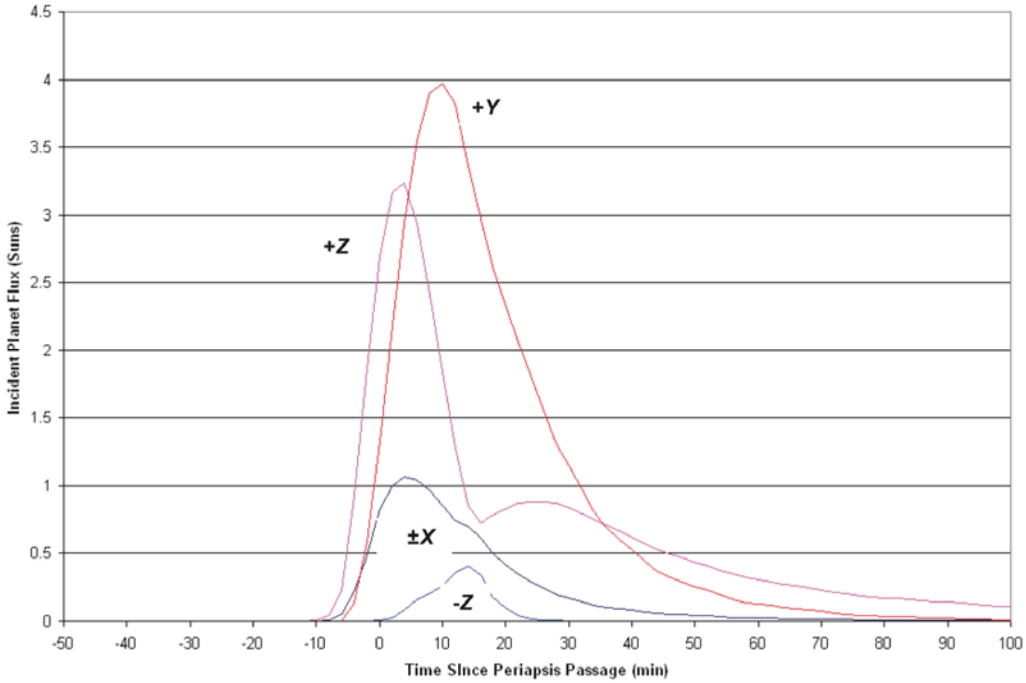

Figure 6. Incident thermal flux emitted by Mercury as calculated for different locations on the spacecraft. Spacecraft thermal-control radiators are located in the –*Z* and ±*X* directions. Liquid-trap diode heat pipes were implemented to protect the PSE, PDU, and SAJB connected to the ±*X* radiators from thermal energy back-flow when MESSENGER receives peak infrared heating. Approximately 1.2 m^2 of ±*X* radiator area was required to dissipate all electronics waste heat. As shown, the +*Y* and +*Z* directions are not desirable locations for radiators.

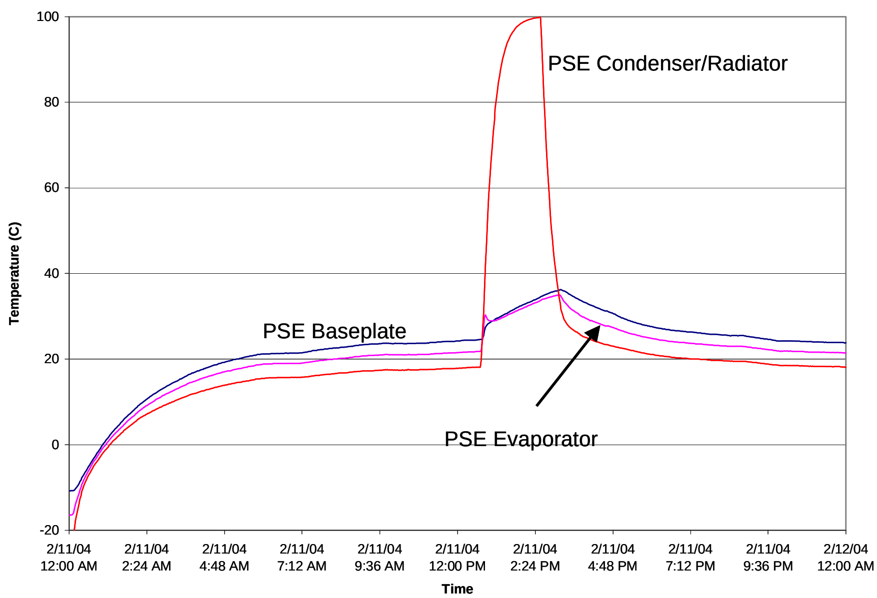

Figure 7. PSE temperature response for a simulated Mercury orbit during spacecraft thermal vacuum testing at Goddard Space Flight Center in February 2004. This figure represents the expected behavior for boxes connected to diode heat pipes while in orbit at Mercury. Barring any spacecraft attitude anomaly, the diode heat pipes will remain dormant during the remainder of inner cruise.

Much emphasis has been placed on the extreme heat and high temperatures associated with a spacecraft orbiting Mercury. With the sunshade pointing toward the Sun and the spacecraft in nearly complete shadow, the spacecraft will use heater power to maintain critical temperatures. During outer cruise, when the spacecraft was outside 0.95 AU, MESSENGER was flipped (configured to fly with the sunshade pointed away from the Sun), such that the anti-Sun side was illuminated so as to reduce heater-power consumption and increase solar-array power margin. MESSENGER flew in this reversed orientation during intervals between launch and June 2006, and on the basis of measurements made during flight, the difference in heater power between these two configurations averaged ~220 W, as shown in Fig. 8.

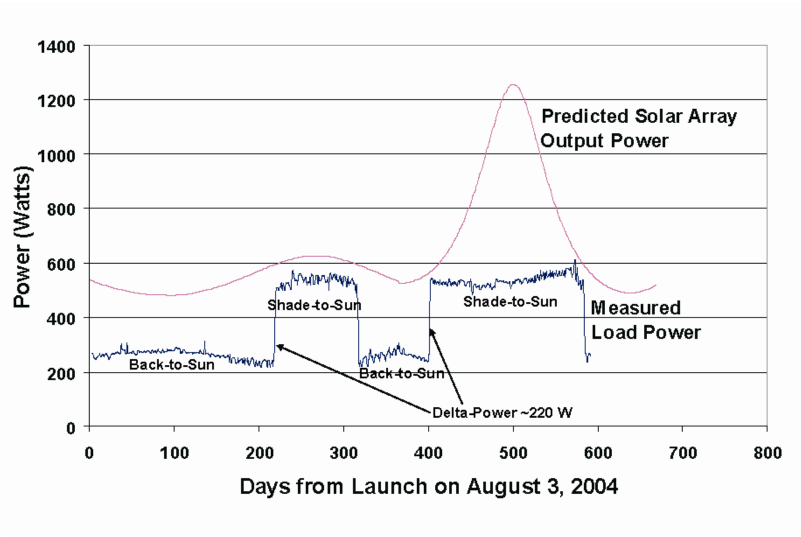

Figure 8. Power lean near Earth's solar distance, the MESSENGER spacecraft was designed to be maneuvered so as to illuminate the spacecraft body, represented by the Back-to-Sun label, as a means to reduce heater-power demand. When the power margin was adequate (<0.95 AU), the spacecraft was maneuvered into the shade-to-Sun (nominal flight attitude) orientation. As shown, the power difference between the two Sun orientations was ~220 W.

III. Solar-Array Thermal Design and Flight Performance

Covered with a blend of Optical Solar Reflectors (OSRs) and solar cells, the MESSENGER solar array consists of two deployed single-panel wings (Fig. 4). Each wing contains 18 strings of 3 cm × 4 cm triple-junction cells, manufactured by the EMCORE Corporation, with minimum efficiency of 28%. To protect the solar-array materials from the expected worst-case thermal environment, each string of cells uses two equal-area strings of OSRs equating to a 33% packing factor. The mirrors were manufactured by Pilkington and use 0.15-mm CMX glass as the substrate. The cells and mirrors were applied in alternating parallel rows allowing for heat spreading across the face and through the back of each panel. Aggregately, each panel will reflect ~60% of the incident solar energy. The cell and mirror lay-down process and all solar-panel electrical fabrication were carried out by Northrop Grumman Space Technology. Each 1.54-m-wide × 1.75-m-long panel utilizes high-thermal-conductivity RS-3/K13C2U composite face sheets with an aluminum honeycomb core. Applied Aerospace Structures Corporation (AASC) was selected over four other composite-structure suppliers to provide all of the substrates used during solar-array qualification testing and flight-panel substrate fabrication. For heat-conduction reasons, the face sheets have a minimum thickness of 0.6 mm, with local stiffeners in high-stress regions. To demonstrate the survivability and validate the thermal analysis, qualification panels successfully completed a series of high-temperature tests, including infrared heater and high-intensity illuminated high-temperature tests in vacuum, at the Tank 6 facility at NASA Glenn Research Center (GRC). Four major U.S. cell lay-down manufacturers using EMCORE solar cells and Pilkington mirrors fabricated qualification-test solar panels using AASC-supplied substrates. All of the qualification panels went head-to-head during the qualification program and were tested in vacuum over a temperature range from –130°C to 270°C at APL.[4] Once they had successfully passed APL's tests, the panels were then tested at GRC using the Tank 6 facility, where they were subjected to 11-Sun intensity illumination. The panels were also life-cycled successfully over the range –130°C to 150°C in a nitrogen environment at the Aerospace Corporation in Los Angeles. The rate of change in temperature was 80-100°C/minute to simulate the thermal shocks expected at exit from Mercury eclipse. Upon completion of the qualification test program, the flight panels were cycled in vacuum over the –140°C to 240°C maximum operational temperature range. The flight panels were not exposed to temperatures over the substrate material's glass-transition temperatures, >240°C, because of concerns about possible weakening of the substrate mechanical strength required for launch.

Operationally, the solar-array temperature is accurately managed during flight by single axis rotations relative to the Sun. As the MESSENGER spacecraft gets closer to the Sun, the solar arrays are rotated to operational angles per predictions made by the power thermal model. The model balances the power output of the solar arrays with operating temperature. Currently, five operational and safe-mode solar-array tilt angles for solar distance ranging from 1.0 AU to 0.30 AU have been placed into the flight operations database. These angles optimally balance temperature and power output. Three years after launch, on August 1, 2007, the MESSENGER solar arrays were operationally tilted for the first time.

The thermal design of each panel, and hence the design driver for packing factor, allows for steady-state survivability at any Sun angle at any mission solar distance. During nominal operation, if the spacecraft is at or near solar distances >0.55 AU, the solar arrays are maintained normal to the Sun. When the spacecraft solar distance is <0.55 AU, solar-array temperature management is accomplished by tilting each array to a predetermined off-normal Sun angle that was predicted by the power thermal model. This procedure ensures that an adequate power margin exists and that each array can be thermally controlled to temperatures that are similar to those experienced by Earth-orbiting spacecraft. Figure 9 shows the measured solar-array temperature performance and the predicted power output as a function of solar distance and Sun offset angle. To date, the solar arrays have been maintained at <130°C with no adverse power effects to the spacecraft.

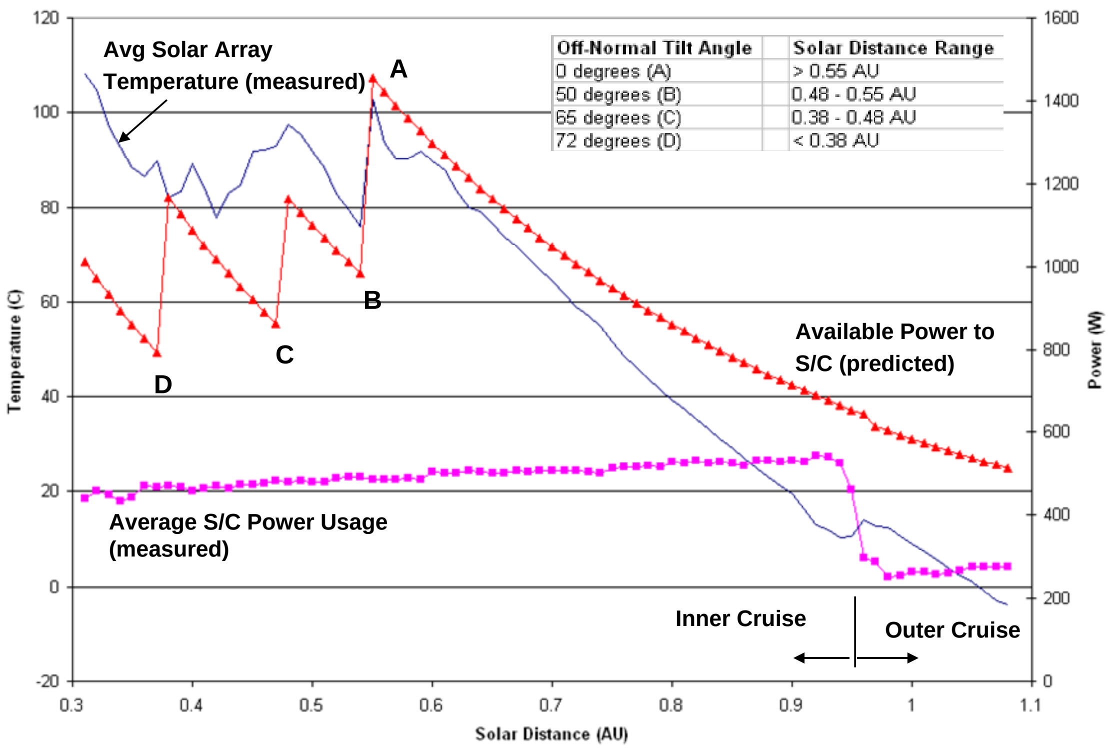

Figure 9. Measured solar-array power and temperature performance summarized as functions of solar distance. From the predicted available power, it is apparent that there is abundant power margin to accommodate transient peaks when loads, such as heaters, switch on and off. S/C, spacecraft.

IV. Battery Thermal Design and Flight Performance

The MESSENGER spacecraft battery was designed and built at APL. The nickel hydrogen common-pressure-vessel (CPV) cells were manufactured by Eagle Picher Space Energy Products Division. The 11-cell CPV cells are housed in a compact three-piece machined aluminum frame that is a clam-shell-type design. The battery frame is thermally isolated from the spacecraft deck and conductively coupled to a space-facing silver-Teflon-covered radiator that has an area of ~0.13 m^2. Spacecraft structural requirements dictated the frame wall thicknesses, and corresponding thermal analysis verified, as did battery thermal vacuum testing, that this design would meet the maximum cell-to-cell temperature-difference requirement of <3.0°C.[5]

Battery temperature control relies on two redundant heater circuits that are independently controlled by single mechanical thermostats. Heater control is augmented with 5 W of internal heat dissipation resulting from the constant trickle charge rate that maintains the battery at 100% state of charge. Each circuit has a peak power at 32.8-V direct current of 32 W. The thermostats are separated by ~1°C, so as to avoid dual activation. Located directly behind the sunshade to minimize planetary heating when in orbit but still allow for battery temperature maintenance to be dominated by the thermostatically controlled primary heater circuit, the battery shown in Fig. 10 experienced temperature and heater-power duty cycles, as illustrated in Figs. 11 and 12. During reverse-sunshade orientation when the spacecraft was near 1.0 AU, the battery was maintained at <0°C with trickle charge and a small amount of heater power. When the spacecraft was flipped and the sunshade was oriented toward the Sun, the battery temperature was maintained at a nearly constant temperature of approximately −5°C with 32 W of heater power and 5 W of trickle charge. As the solar distance decreased from near 1.0 AU to 0.63 AU, battery temperature increased from −5°C to approximately −1°C with the primary heater at 100% duty cycle. Once inside of 0.63 AU, the battery temperature cycled between −5°C and −1°C with the duty cycle varying as a function of solar distance (Table 1). To date, MESSENGER has been inside of 0.33 AU three times, and the battery duty cycle was measured to be between 39% and 41%. This is an indication that the thermal performance of the sunshade has not shifted dramatically, if at all, and the battery temperature remains <0°C and always under heater control.

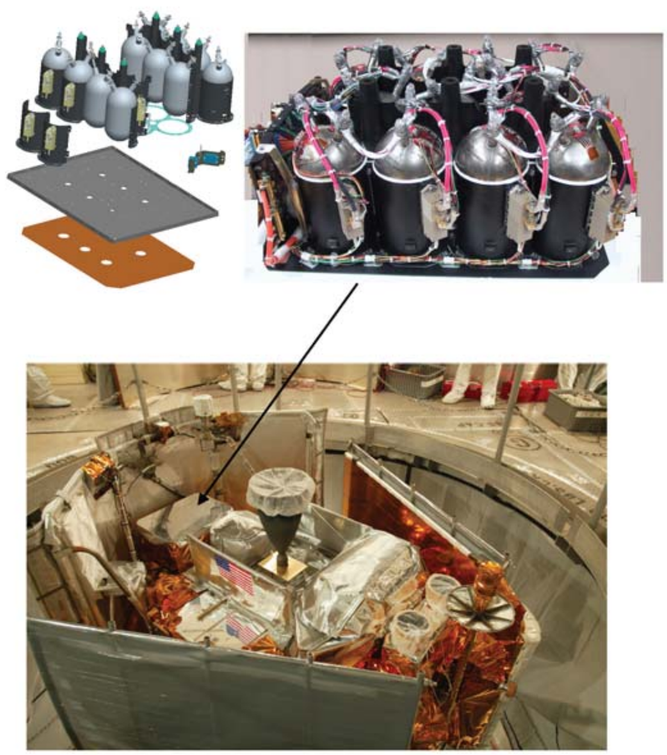

Figure 10. Packaged directly behind the sunshade on the –*Z* deck, the MESSENGER battery consists of 11 two-cell NiH_2 CPVs housed in a three-piece clam-shell-type mechanical design that meets all thermal-gradient requirements. Although the battery placement provides ideal protection from Mercury's day side when in orbit, the space-facing radiator used for heat rejection actually receives detectable heat input from the back of the sunshade as the spacecraft solar distance decreases. When the spacecraft reaches the mission minimum of 0.30 AU, the frontal sunshade temperature will approach 350°C. To date, the minimum spacecraft solar distance has been 0.31 AU. Also located on the –*Z* deck are redundant Advanced Star Trackers and redundant Solid-State Power Amplifiers.

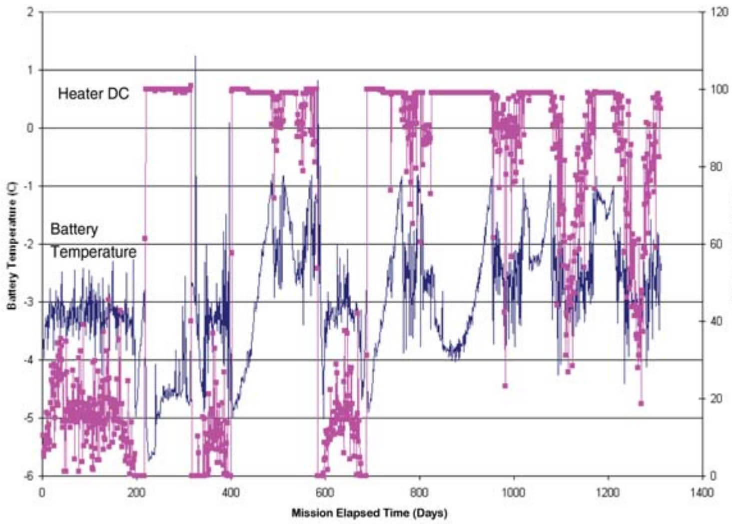

Figure 11. MESSENGER battery thermal performance as a function of elapsed mission day. Other than a few operational excursions, the bulk battery temperature (blue) has been maintained at <0°C through the mission to date by using heater power (pink). DC, duty cycle.

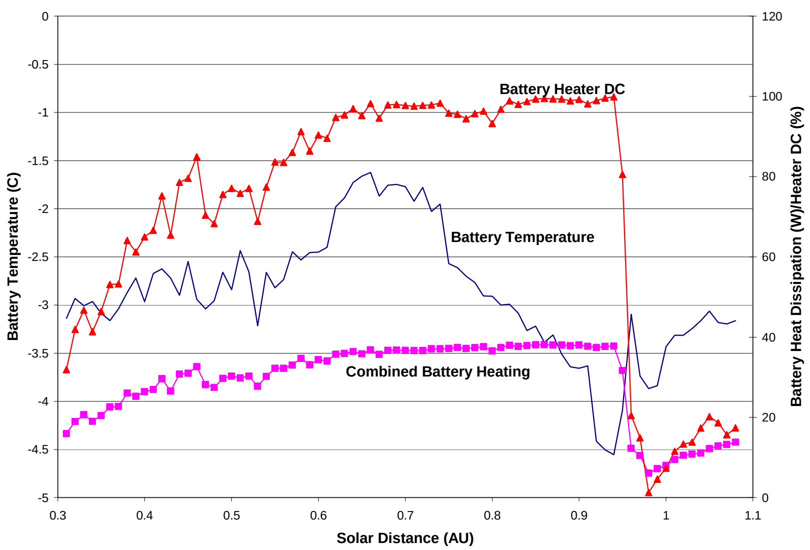

Figure 12. MESSENGER battery performance as a function of solar distance and electrical heat dissipation (trickle charging plus heater). The battery heater begins to cycle at ~0.65 AU. DC, duty cycle.

Table 1. During inner cruise, the battery-heater duty cycle is affected by sunshade frontal temperature, which is a function of solar distance. When the spacecraft was flown in the reverse-sunshade orientation during outer cruise, the battery-heater duty cycle averaged between 0% and 20%.

Solar Distance (AU)	Heater Duty Cycle (%)
>0.65	100
0.63	93
0.56	89
0.50	81
0.42	70
0.39	51
0.31	34

V. Power Electronics Thermal Design and Flight Performance

The PSE box thermal control is a passive thermal-conduction design where each electronic slice has an independent thermal path to the heat sink. Each box is designed to operate with a base-plate temperature that varies from –34°C to +65°C. Nominal heat dissipations range from 15 W to 40 W in the worst-case conditions. The waste heat is conducted into individual diode heat pipes and transported to designated radiators on the ±*X* sides of the spacecraft for rejection to space.

To date, the electronics box thermal designs have performed as expected. Figure 13 shows the measured PSE, PDU, and SAJB temperatures as functions of solar distance since launch. The PSE Peak Power Tracker, SAJB, and PDU temperatures are well within their predicted allowable flight limits.

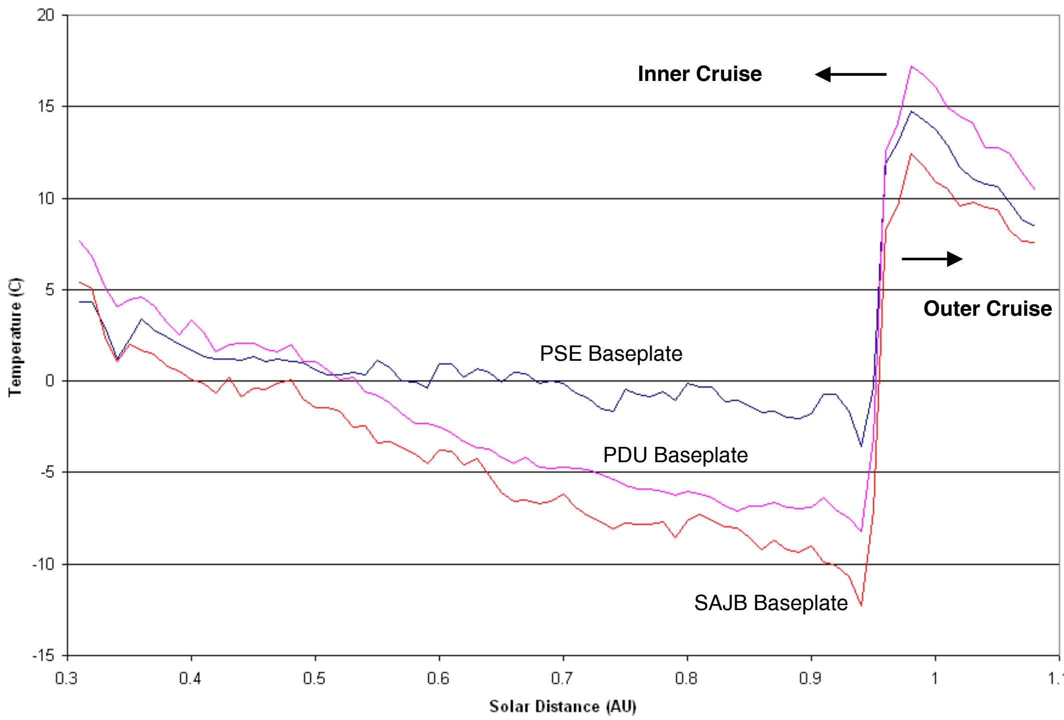

Figure 13. Temperatures of PSE boxes controlled by external radiators that are located on the ±*X* and –*Z* sides of the spacecraft.

VI. Mercury Flyby 1

On January 14, 2008, at 19:04:39 UTC (2:04:39 PM EST), the MESSENGER spacecraft flew ~200 km (124 miles) above Mercury's surface. This marked the first spacecraft encounter with Mercury in 33 years and the first encounter at a solar distance inside of 0.46 AU. Because thermal emissions from Mercury are a function of solar distance and position relative to the subsolar point, spacecraft temperature response is sensitive to both the trajectory phase angle and distance from the planet surface. During Mercury flyby 1, the solar distance was 0.35 AU and the trajectory was such that the phase angle and altitude were never at minimum levels together. To achieve orbit, two more gravity-assist flybys of Mercury are necessary and are scheduled for October 6, 2008, and September 29, 2009. The thermal impacts on the spacecraft from Mercury during any of the flybys are relatively benign when compared with the environments expected during the orbital phase, as shown in Fig. 14. Overall, the first Mercury encounter went as expected from a spacecraft subsystem standpoint and was an outstanding success. All temperatures were benign, there were no power problems, the spacecraft was precisely pointed, and the science instruments collected information that was never seen before (Fig. 15).

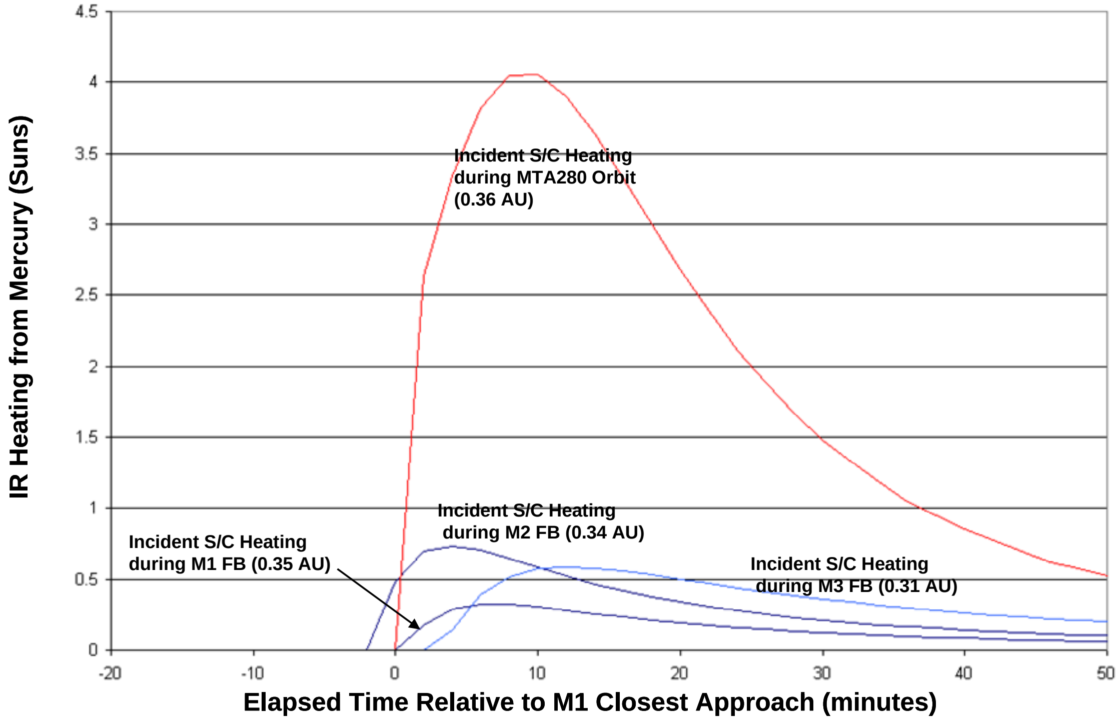

Figure 14. Comparison of the incident heating of the spacecraft from the three flybys with the incident spacecraft heating when in orbit about Mercury. Environments encountered during the orbital phase posed the most serious thermal design challenges. IR, infrared; M1 FB, Mercury flyby 1; M2 FB, Mercury flyby 2; M3 FB, Mercury flyby 3; MTA, Mercury True Anomaly; S/C, spacecraft.

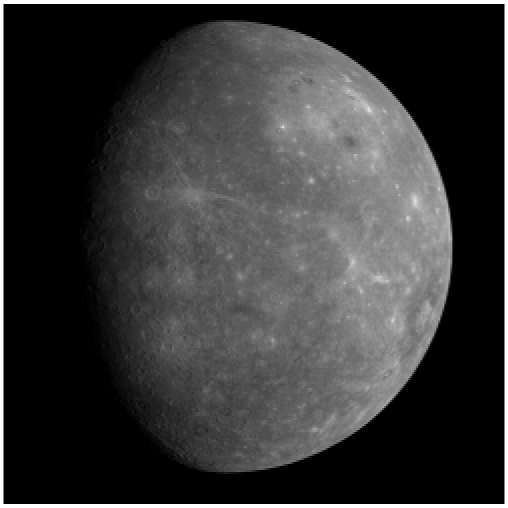

Figure 15. When Mariner 10 flew past Mercury three times in 1974 and 1975, the same hemisphere was in sunlight during each encounter. As a consequence, Mariner 10 was able to image less than half the planet. Approximately three-fourths of the daylit surface in this image obtained by the MESSENGER spacecraft on January 14, 2008, had not been viewed by Mariner 10.

VII. Summary

The power and thermal systems for a spacecraft mission to orbit Mercury are challenging. The designs presented meet the MESSENGER mission requirements. The spacecraft and the power system have been operating as designed since launch on August 3, 2004. Extensive solar-array development and testing were conducted to characterize and qualify the design. The solar-array design approach should be directly applicable to spacecraft missions that require high-temperature operation. Packaging and thermal design of the electronics were effective for system boxes with high power dissipation. The spacecraft composite structure required to minimize the spacecraft mass generated complexity for the high dissipater boxes and for the electromagnetic interference control. These issues were resolved successfully. The spacecraft continues its trajectory for a Mercury orbit insertion in 2011.

Acknowledgments

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