MESSENGER Propulsion System Flight Performance

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Abstract

Study of the planet Mercury is fundamental to acquiring insight into the evolution of the inner solar system. NASA's seventh Discovery mission, the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission, will orbit a spacecraft around Mercury for 1 Earth year to gather scientific data. To make this mission possible, a lightweight dual-mode propulsion system capable of delivering 2,300 m/s was designed, developed, and qualified over a period of 30 months. Following integration with the spacecraft and an extensive checkout and test period, the spacecraft was launched by a Delta-II launch vehicle on 3 August 2004. The MESSENGER propulsion system includes three pressurized propellant tanks, an auxiliary fuel tank, propellant and pressurant control components, 16 monopropellant thrusters, and a single 667-N bipropellant large-velocity adjustment (LVA) thruster. The MESSENGER propulsion system has four operational modes: a passive thermal management or cruise phase mode and three active thruster operational modes. A mode-1 maneuver fires monopropellant thrusters with fuel fed in a blow-down mode from the auxiliary tank. A mode-2 maneuver fires monopropellant thrusters with fuel from pressurized main fuel tanks. A mode-3 maneuver fires the bipropellant LVA using propellants from pressurized fuel and oxidizer tanks. In both the mode-2 and -3 maneuvers, the propulsion system's small auxiliary tank is refilled with fuel from one of the two main fuel tanks. In the passive thermal management mode, spacecraft and thermostatically controlled heaters maintain the propellant and propulsion components within their operational pressure and temperature ranges. This paper presents the performance of the MESSENGER propulsion system since launch. To date, all elements of the propulsion system have been exercised with the successful execution of nine propulsion maneuvers including five mode-1 maneuvers, three mode-2 maneuvers, and one mode-3 maneuver. Of the five mode-1 maneuvers, two were attitude control maneuvers only: one was used to detumble the spacecraft following launch while the second was a commanded momentum dump performed in early 2006. The single mode-3 maneuver, completed in December 2005, imparted the largest spacecraft velocity change to date. The 474-s burn of the propulsion system's bipropellant thruster adjusted the spacecraft velocity by 315.72 m/s.

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Nomenclature

ACS = attitude control system
BTI = burn time integration
CMD = commanded momentum dump
ΔV = delta-velocity
DSM = deep space maneuver
GN&C = guidance, navigation, and control
JHU/APL = The Johns Hopkins University Applied Physics Laboratory
LVA = large velocity adjustment
MESSENGER = MErcury Surface, Space ENvironment, GEochemistry, and Ranging
MPS = MESSENGER propulsion system
MR = mixture ratio
N_2H_4 = hydrazine
N_2O_4 = nitrogen tetroxide
PAUX-A = pressure, auxiliary tank side a
PAUX-B = pressure, auxiliary tank side b
PFF = pressure, fuel feed
PVT = pressure, volume, temperature
TVC = thrust vector control

I. Introduction

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft was successfully launched from Cape Canaveral Air Force Station, Florida on 3 August 2004 aboard a Delta-IIH launch vehicle. To reach Mercury, the MESSENGER spacecraft requires both an innovative trajectory and a highly capable, mass-effective, and operationally flexible propulsion system. The MESSENGER trajectory is an optimized series of planet flybys and deep-space maneuvers (DSMs) designed to minimize onboard propellant requirements. A total of six planet flybys (one Earth, two Venus, and three Mercury) and five large velocity changes (DSMs) will be used to position the spacecraft for final insertion burn into Mercury orbit.

The MESSENGER propulsion system (MPS) is designed to be both lightweight and highly operational. Fig. 1 shows the spacecraft in its flight configuration. The MESSENGER spacecraft features a large ceramic cloth sunshade that protects the spacecraft from the Sun as it approaches and while in orbit around Mercury. The MPS is designed around a lightweight composite structure and three mass-efficient main propellant tanks. The MPS includes 17 thrusters that are used to perform propulsive maneuvers necessary to control spacecraft attitude and provide the required velocity changes. Propulsive maneuvers, conducted using three different modes of operation, include commanded momentum dumps (CMDs) and trajectory correction maneuvers (TCMs) of varying magnitudes with the largest being the DSMs and Mercury orbit insertion. In total, the propulsion system has a ΔV capability of 2,300 m/s.

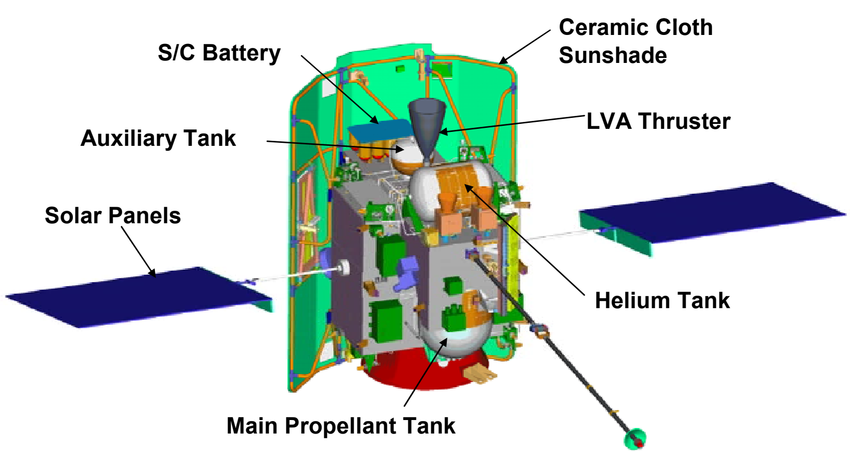

Figure 1. MESSENGER Flight Configuration

To date, a total of nine propulsion maneuvers have been successfully completed as shown in Table 1. With the exception of TCM-10, all propulsive maneuvers were consistent with pre-maneuver predictions. TCM-10 differed slightly from pre-maneuver predictions due to thruster plume impingement effects on the spacecraft solar arrays. TCMs 4, 7, and 8 were not required and thus were not performed. DSM-1 was also called TCM-9.

Table 1. MPS propulsion maneuvers completed to date.

Event Name	Event Date	Mode	ΔV Thrusters Used	ACS Thruster Used	ΔV Magnitude, m/s		Duration, s	Cumulative ΔV, m/s
					Goal	Achieved		
Desat	8/3/2004	1	N/A	A&B	0.000	0.460	0.00	0.460
TCM-1	8/24/2004	2	C	A&B	18.000	17.901	203.00	18.361
TCM-2	9/24/2004	2	C	A&B	4.590	4.589	62.93	22.949
TCM-3	11/18/2004	2	C	A&B	3.236	3.247	48.93	26.197
TCM-5	6/23/2005	1	S	A&B	1.145	1.103	171.23	27.300
TCM-6	7/21/2005	1	P	A&B	0.147	0.150	22.73	27.450
DSM-1	12/12/2005	3	LVA	A&B	315.720	315.633	553.00	343.084
CMD-1	1/10/2006	1	N/A	A&B	0.000	0.011	66.00	343.095
TCM-10	2/22/2006	1	B	A	1.407	1.281	135.00	344.375

II. MESSENGER Trajectory

The MESENGER trajectory reduces the amount of spacecraft-imparted ΔV by using multiple planet flybys prior to its final orbit insertion burn. As shown in Fig. 2, the MESSENGER spacecraft flew by the Earth once and will fly by Venus twice and Mercury three times. The cruise phase also provides for early science opportunities at the second Venus and all three Mercury flybys. In between planet flybys there are five DSMs coupled with numerous smaller TCMs and CMDs as needed. Mercury orbit insertion is planned for 18 March 2011. MESSENGER will remain in orbit around Mercury for one Earth year.

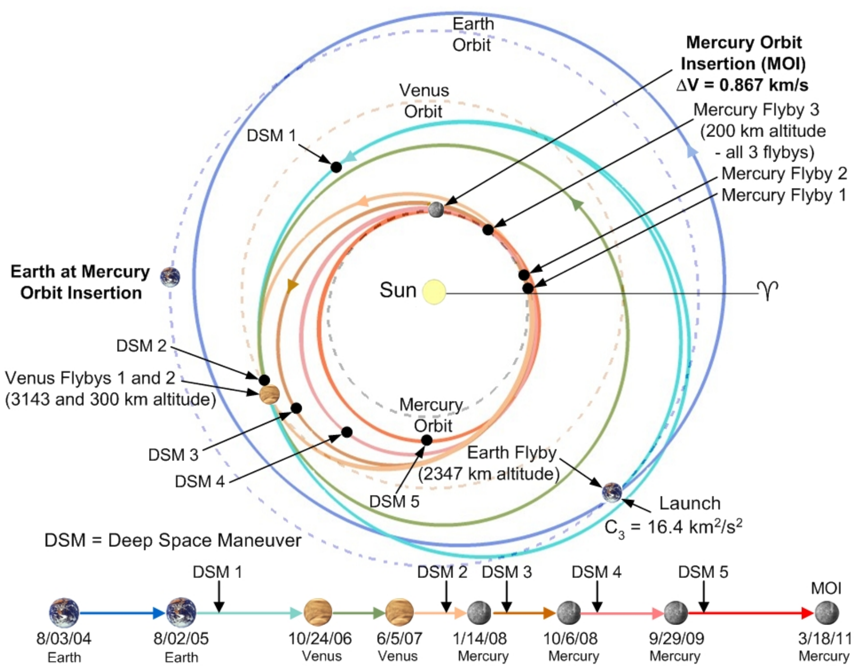

Figure 2. MESSENGER spacecraft trajectory.

III. MESSENGER Propulsion System

The MPS, shown in layout form and schematically in Figs. 3 and 4, respectively, is a pressurized bipropellant dual-mode system using hydrazine (N_2H_4) and nitrogen tetroxide (N_2O_4) in the bipropellant mode and N_2H_4 in the monopropellant mode. Three main propellant tanks (two fuel and one oxidizer), a refillable auxiliary fuel tank, and a helium pressurant tank provide propellant and pressurant storage. At launch, the auxiliary tank and each main fuel tank contained 9.34 kg and 178.0 kg of N_2H_4, respectively, while the oxidizer tank contained 231.61 kg of N_2O_4. The auxiliary tank, main fuel tanks, and oxidizer tank were pre-pressurized to 250 psia, 220 psia, and 150 psia, respectively, prior to launch. The helium tank contained 2.295 kg of helium at a launch pressure of 3,375 psia. The total MPS propellant and pressurant load was 599.24 kg—54 percent of the total spacecraft launch mass.

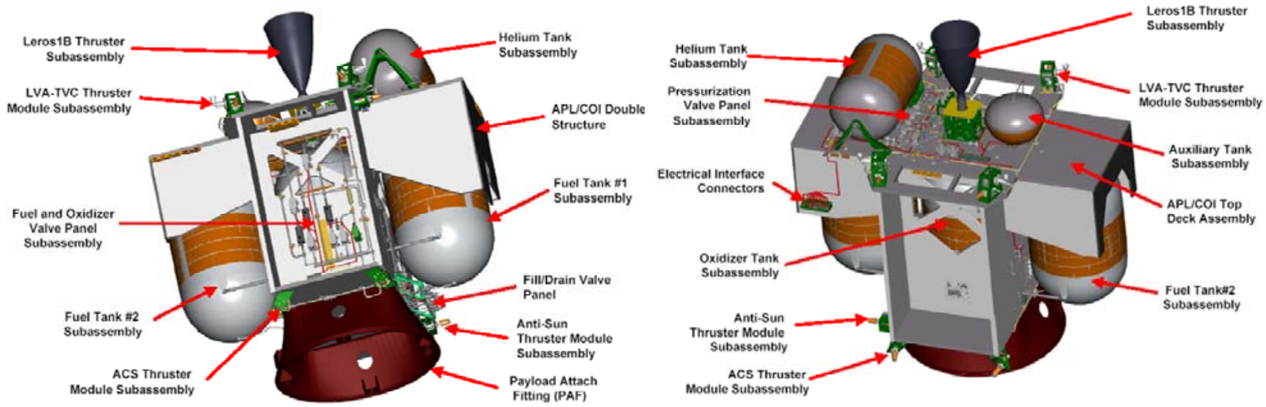

Figure 3. MPS layout.

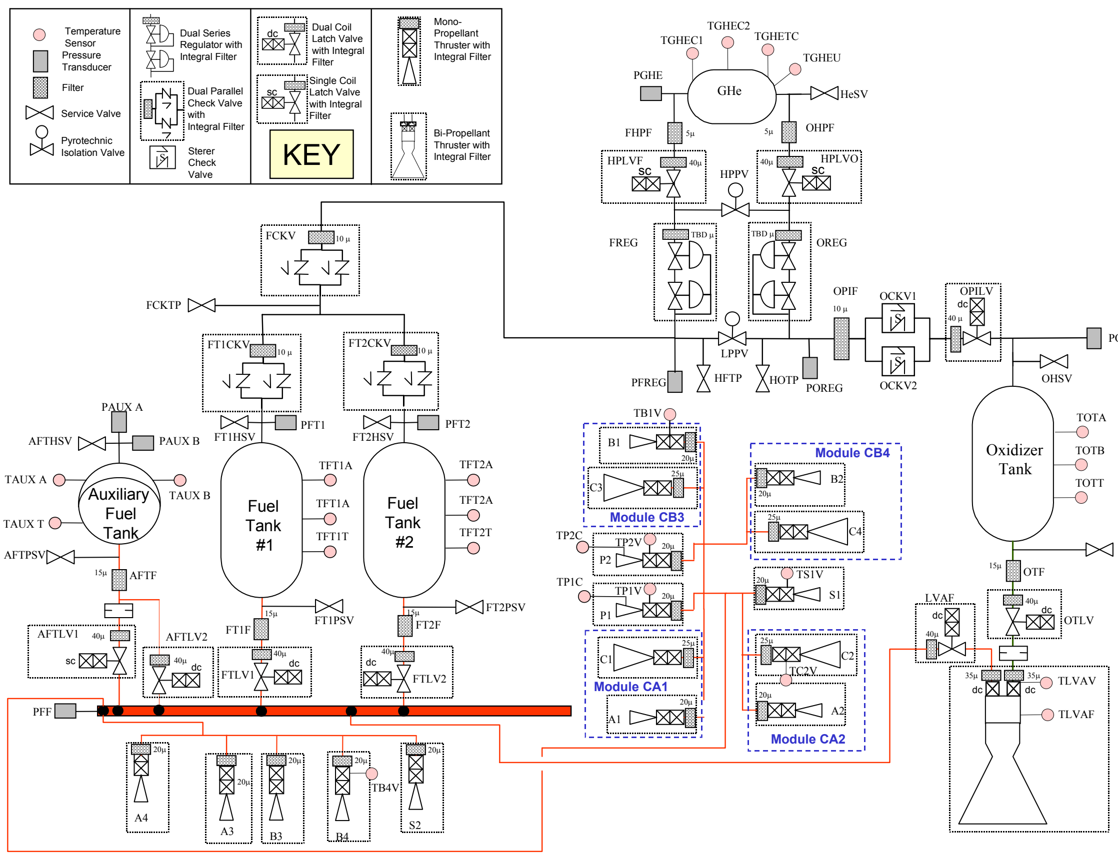

Figure 4. MPS schematic.

The MPS hydraulic system consists of four main subsystems: pressurization, fuel feed, oxidizer feed, and thruster modules. Additional MPS elements include the secondary structures, electrical subsystem, and thermal management subsystem. Total propulsion subsystem dry mass is 81.74 kg.

The MPS includes a total of 17 thrusters. Three thruster types, arranged in five different thruster module configurations, provide the required spacecraft forces as shown in Fig. 5.

The LVA thruster is a flight-proven Leros-1b provided by Ampac-ISP. The LVA operates at a nominal mixture ratio (MR) of 0.85, provides a minimum of 667.0-N of thrust, and operates at a specific impulse of 316 s. Four 22.0-N monopropellant LVA thrust vector control (TVC) thrusters (also identified as C-thrusters) provide thrust vector steering forces during LVA thruster burns and primary propulsion for most of the smaller ΔV maneuvers. The LVA TVC thrusters are flight-proven Aerojet P/N MR-106Es that have a specific impulse of 234 s. They are fed with

N_2H_4 in both the pressurized and blow-down modes. Twelve monopropellant thrusters provide 4.4-N of thrust at a specific impulse of 227 s for fine attitude control burns, small ΔV burns, and momentum management. The 4.4-N thrusters are flight-proven Aerojet P/N MR-111Cs.

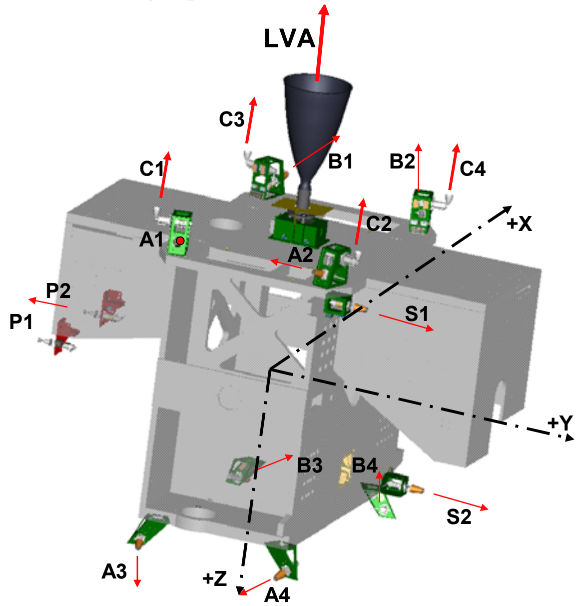

Figure 5. MPS thruster arrangement.

These thrusters are also fed with N_2H_4 in both the pressurized and blow-down modes. Eight 4.4-N thrusters (A and B) are arranged in double canted sets of four for redundant three-axis attitude control. Two 4.4-N thrusters (S) provide velocity changes in the sunward direction. The final two 4.4-N thrusters (P) provide velocity changes in the anti-Sun direction. The P thrusters are located on the spacecraft –Y side and protrude through the spacecraft sunshade. The P and S thrusters point along the spacecraft + and –Y axis to provide ΔV thrust in a different direction from the C-thrusters and LVA.

The MPS thermal system employs heaters to maintain acceptable system temperatures. Heaters are used during the cruise phase to maintain propellant temperatures and in the operational phases to pre-heat thrusters in preparation for operation. These heaters can total 143 W (primary string only). Cruise-phase heaters are installed on the propellant and pressurant tanks, thruster valves, valve panel, fill and drain valve bracket, and various propellant manifolds. Cruise-phase heaters are controlled by spacecraft software (helium and main propellant tanks) and with mechanical thermostats (all remaining cruise-phase heaters). Operational phase heaters include monopropellant thruster catalyst bed heaters and the LVA flange heater. When enabled, all catalyst bed heaters are time controlled while the LVA flange heater is controlled with mechanical thermostats. The operational heaters can total 69W.

IV. MPS Operation

The MPS has four operational modes: a passive thermal management or cruise phase mode and three active thruster operational modes.

MPS Cruise Phase Mode: During the MPS cruise phase mode, propulsion system temperatures are maintained within their operational band using heaters**.** Spacecraft autonomy controllers verify appropriate propulsion sytem temperatures and notify ground controllers if a temperature limit has been reached.

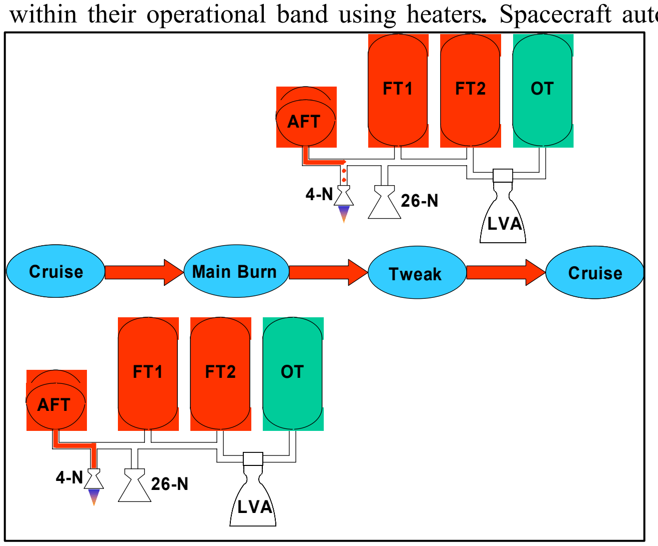

Figure 6. MPS Mode-1.

MPS Mode-1: MPS Mode-1, shown in Figure 6, is used for small ΔV maneuvers, and commanded or autonomous momentum dumps. A Mode-1 maneuver can use either 4.4-N or 22-N thrusters. During this maneuver, fuel is supplied to the required monopropellant thrusters from the auxiliary tank operating in blow-down mode. A Mode-1 burn is divided into two segments: main burn and tweak. Prior to the main burn element, thruster catalyst bed heaters are powered-on approximately 60 minutes prior to the burn to pre-heat the thrusters. Just prior to the main burn, the auxiliary tank latch valve is opened, enabling fuel flow.

Propulsion system autonomy rules verify correct system pressure prior to start of any thruster firing. During the main burn element, thrusters are fired as required to change spacecraft velocity or maintain attitude while altering momentum for a dump. After completion of the main burn element, the maneuver transitions into the tweak mode. At the end of the tweak segment, the propellant feed system is "safed" and attitude control is returned to the spacecraft reaction control wheels.

MPS Mode-2: MPS Mode-2, shown in Fig. 7, is used for medium ΔV maneuvers and uses the 4.4-N (ACS) and 22-N (LVA TVC) monopropellant thrusters pressure-fed from the main tanks. The mode is divided into three segments: setting, main burn, and tweak. Just as in the Mode-1 burn, thruster catalyst bed heaters are powered to pre-heat thrusters, the auxiliary tank outlet latch valves are configured for fuel flow, and spacecraft guidance software verifies that the propulsion system is ready to fire thrusters. The settling segment settles propellant in the main tanks by firing the top deck attitude control thrusters (A1, A2, B1, and B2) using fuel from the auxiliary tank in a blow-down mode. Total settling time is dependent on the level of propellant in the auxiliary tank. The main fuel tanks are also pressurized during the settling segment by opening the fuel side high-pressure helium latch valve. Just prior to the main burn segment, one of the main fuel tank latch valves is opened. During the main burn segment, LVA-TVC thrusters are fired using pressurized and regulated fuel from the main fuel tanks to achieve the required spacecraft ΔV. During the main burn, the main fuel tank outlet latch valves are cycled open and closed so that fuel is used from only one tank at a time. This fuel management scheme maintains the spacecraft center of mass well within control authority limits of the LVA TVC thrusters. The settling segment typically will achieve only a portion of the desired ΔV, while the remainder of the target ΔV is achieved during the main burn segment. Primary attitude control is provided by off-pulsing of the LVA TVC thrusters. The 4.4-N A&B thrusters provide supplemental attitude control throughout the maneuver. In this mode, an "opportunistic" auxiliary tank refill is performed simultaneously with the main burn. The refill is considered opportunistic since the main burn is terminated when the ΔV target is achieved and not necessarily when the auxiliary tank is refilled. At the end of the main burn segment, the maneuver transitions into the tweak mode and then is safed in the same manner as a Mode-1 maneuver.

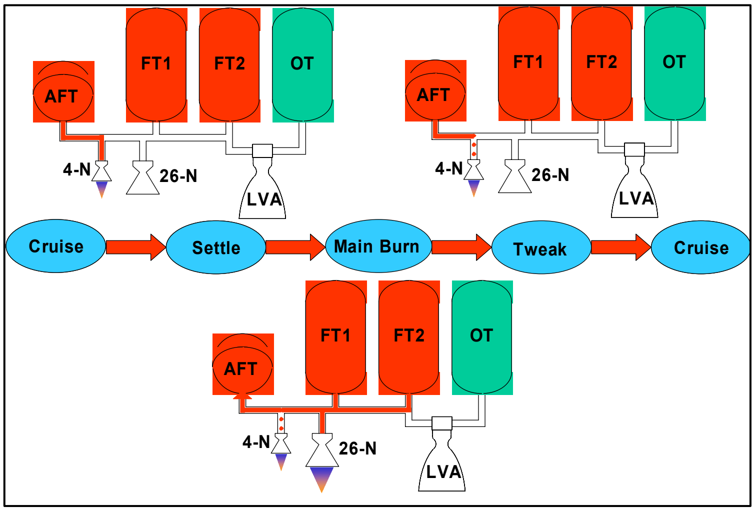

Figure 7. MPS Mode-2.

MPS Mode-3. MPS Mode-3 is used for large ΔV maneuvers and uses the bipropellant LVA thruster, which is pressure-fed from the main fuel and oxidizer tanks. As shown in Fig. 8, the mode is divided into five segments: propellant settling, stand-alone auxiliary tank refill, main burn, final trim burn, and tweak.

The settling phase readies the system for accessing the main tanks in the same manner as described in Mode-2 except that both the fuel and oxidizer tanks are pressurized by opening the fuel and oxidizer high-pressure helium latch valves. With the propellant settled, one of the main fuel tank outlet latch valves is opened and the auxiliary tank refilled. The top-deck 4.4-N thrusters continue to fire during the refill maneuver to keep the main tank settled. Refill is determined by a pre-computed time duration. Also during refill, the LVA isolation latch valves are opened in preparation for firing. At completion of refill, the system enters the main burn phase when the LVA thruster is fired. On-pulsing the 22-N (LVA TVC) thrusters provides for TVC. The 4.4-N attitude control system (ACS) thrusters provide supplemental attitude control as required. As the target ΔV is approached, the LVA thruster is shut down and the 22-N thrusters take over responsibility of completing the remaining ΔV. During both the main burn and final trim phase, spacecraft center-of-mass control is maintained by main fuel tank outlet latch valve switching at regular intervals. At completion of the final trim burn, the main fuel tank outlet latch valves are closed and the tweak segment is completed using propellant from the auxiliary tank. At completion of the tweak segment, attitude control is returned to the reaction wheels and the propulsion system is safed.

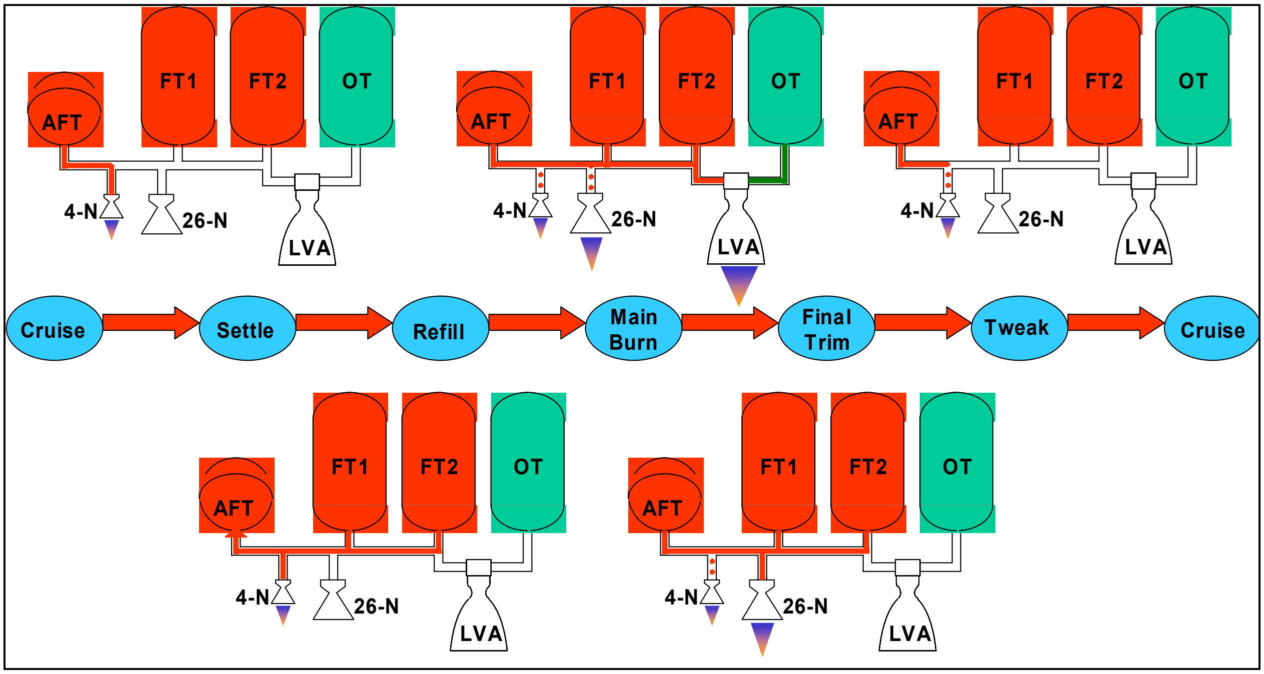

Figure 8. MPS Mode-3.

V. MPS Propulsion System Flight Performance

To date, the MPS has successfully executed nine propulsion maneuvers. To ensure successful propulsion system operation, extensive planning occurs prior to each maneuver to verify that both the propulsion system and spacecraft are ready. Both the GN&C and propulsion groups predict performance of the system. Included with the planning effort are numerous Monte Carlo simulations that examine all potential system variations. Maneuvers are only attempted after completion of all planning activities and independent review by the spacecraft systems engineering team. After completion of a propulsive maneuver, all aspects of the maneuver are reconstructed to verify that it matched predictions. The navigation; guidance, navigation, and control (GN&C); and propulsion system teams each complete reconstruction efforts. Propellant usage is determined by thruster burn-time-integration (BTI) and for Mode-1 maneuvers by auxiliary tank pressure-volume-temperature (PVT) relationships.

Launch Detumble. First use of the MPS was the detumble maneuver, successfully completed after separation from the launch vehicle's third stage. In preparation for first use of the propulsion system, the propellant manifolds were evacuated to vacuum by pulsing open several thrusters. Once evacuated, the auxiliary tank outlet Latch 1 (bleed valve) was opened and the fuel manifold filled. A&B ACS thrusters were then fired to detumble and stabilize the spacecraft. A total of 160 s of thruster firing using all eight ACS thrusters was used. After completion of thruster firings and system safing, cruise phase propulsion system heaters were enabled.

TCM-1. Approximately 3 weeks after launch on 24 August 2004, the MPS was used to remove launch vehicle injection errors. Maneuver planning called for removing launch errors using two TCMs (-1 and -2). TCM-1 called for a Mode-2 maneuver imparting 18 m/s of ΔV. After burn preparations were completed, the main tanks were settled using a 15-s burn of the top deck ACS thrusters. The main burn started using fuel Tank 2 and after 135 s switched to fuel Tank 1. The total maneuver lasted 234 s and used 8.88 kg of fuel. MPS pressure performance matched pre-burn predictions. During the main burn, main fuel tank pressures were held between 277.0 psia and 283.3 psia. Figure 9 shows propulsion system pressures during the first portion of the burn including the "opportunistic" auxiliary tank refill. Figure 9 is representative of all Mode-2 maneuvers conducted to date. The auxiliary tank was refilled in approximately 28 s. Table 2 provides additional burn details. TCM-1 provided first use of the C-thrusters (22-N LVA TVC) and fuel pressurization system. TCM-1 also demonstrated refill of the auxiliary tank and effectively used main fuel tank switching to maintain spacecraft center-of-mass.

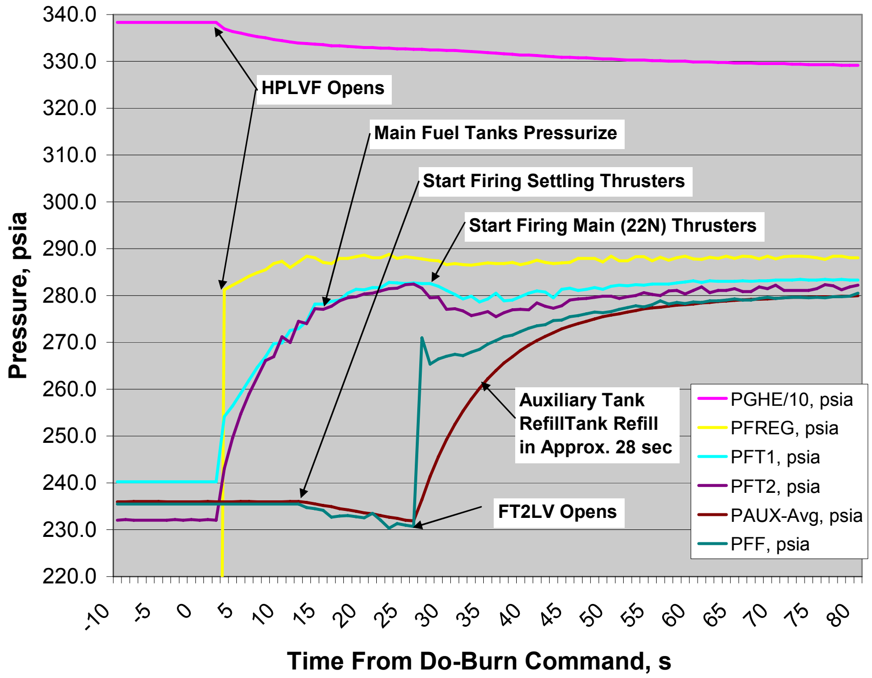

Figure 9. TCM-1 (Mode-2) early burn pressure performance.

TCM-2. TCM-2 was conducted 24 September 2004 to correct the remaining launch injection error. TCM-2 called for a Mode-2 maneuver imparting 4.59 m/s of ΔV. The entire maneuver was conducted using fuel Tank 1, lasted 89 s, and used 2.354 kg of fuel. Pressure performance for TCM-2 was very similar to TCM-2. Table 2 provides additional TCM-2 burn details.

TCM-3. TCM-3 conducted 18 November 2004 was a small deterministic correction required for the August launch trajectory. TCM-3 was a Mode-2 maneuver imparting 3.24 m/s of ΔV. The maneuver was conducted using Fuel Tank 1, lasted 64 s, and used 1.705 kg of fuel. Additional TCM-3 burn details are provided in Table 2.

Table 2. TCM-1, -2, and –3 Mode-2 burn details.

Event Name	Event Date	ΔV Thrusters Used	Total ΔV Thruster On-Time, s	ACS Thrusters Used	Total ACS Thruster On-Time, s	ΔV Achieved m/s	Fuel Used, kg	Effective Main Burn Thruster Isp, s
TCM-1	8/24/2004	C	749.8	A&B	200.6	17.90	8.880	230.5
TCM-2	9/24/2004	C	191.4	A&B	88.4	4.59	2.354	230.4
TCM-3	11/18/2004	C	135.4	A&B	90.6	3.24	1.705	228.7

Spacecraft Flip and MPS Cruise Phase Thermal Management. While the spacecraft is designed to fly with the sunshade pointed toward the Sun, the spacecraft flies with its backside pointed toward the Sun during the outer cruise phase of the mission. This is done to reduce power required by spacecraft heaters. During the early cruise phase, the spacecraft is "flipped" (sunshade to the Sun) and "flopped" (back side to the Sun) depending on distance from the Sun. On 8 March 2005, the spacecraft was flipped so that the sunshade now pointed toward the Sun while the backside pointed to deep space. Soon after the flip maneuver, the main propellant tank and helium tank temperatures dropped to their yellow limits of 10 ºC. Upon reaching the 10 ºC limit, spacecraft autonomy turned on the secondary tank heaters. Tank temperatures soon stabilized in their nominal range. Subsequent investigation revealed that the spacecraft exhibited higher heat leaks around the helium tank and through the spacecraft adapter than were measured during thermal balance testing. Secondary tank heaters remained on until the spacecraft was flopped. The flop maneuver positioned the spacecraft so that the backside of the spacecraft was once again facing the Sun. The flop maneuver was completed 14 June 2005—a few weeks prior to TCM-5.

TCM-5. The originally planned TCM-4 was not required so the next propulsive maneuver, TCM-5, was conducted 23 June 2005. TCM-5 was the first Mode-1 ΔV maneuver and used to target the spacecraft trajectory for the Earth flyby. TCM-5 also represented the first firing of the 4.4-N S-thrusters. The maneuver imparted 1.103 m/s of ΔV, lasted approximately 185 s, and used 0.715 kg of fuel. Figure 10 shows the blow-down pressures in the auxiliary tank and fuel feed manifold, and is representative of all Mode-1 maneuvers conducted to date. Additional TCM-5 details are provided in Table 3.

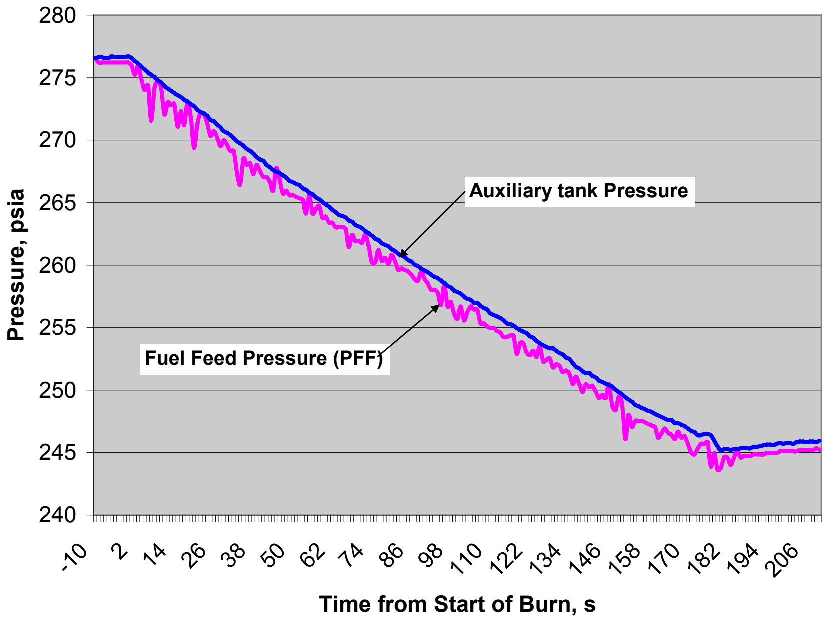

Figure 10. TCM-5 (Mode-1) MPS Feed System pressures.

TCM-6. TCM-6, conducted 21 July 2005, was used to further refine the targeting for the Earth flyby. TCM-6 was a Mode-1 maneuver and the first firing of the 4.4-N P-thrusters. TCM-6 imparted 0.150 m/s of ΔV, lasted approximately 36 s, and used 0.100 kg of fuel. TCM-6 performance was similar to that of TCM-5; however, the TCM-6 effective maneuver ΔV was approximately 10 percent lower than TCM-5. Subsequent investigation showed that the A and B ACS thrusters during TCM-5 provided a greater portion of the maneuver ΔV than TCM-6. Total propellant usage for both the Mode-1 TCM-5 and -6 was determined using both the BTI and PVT methods. Propellant usage using these two methods agreed with each other within 0.5 percent.

Table 3. TCM-5 and –6, Mode-1 maneuver details.

Event Name	Event Date	ΔV Thrusters Used	Total ΔV Thruster On-Time, sec	ACS Thrusters Used	Total ACS Thruster On-Time, s	ΔV Achieved m/s	Auxiliary Tank Pressure Range, psia	Fuel Used, kg	Effective Main Burn Thruster Isp, s
TCM-5	6/23/2005	S	305.4	A&B	110.6	1.103	276-245	0.715	188.8
TCM-6	7/21/2005	P	43.6	A&B	16.6	0.150	250-246	0.100	168.9

DSM-1. The first DSM was successfully executed 12 December 2005 and represented the most complex propulsion maneuver completed to date. DSM-1 imparted 315.7 m/s of ΔV and positioned the spacecraft for its first Venus flyby planned for 24 October 2006. DSM-1 was the first use of the main bipropellant LVA thruster and oxidizer system. The total maneuver duration was 550 s and included 15 s for propellant settling, 11 s for auxiliary tank refill, 474 s of LVA thruster firing, 24 s of final trim firing using the LVA-TVC thrusters, and 27 s to stabilize attitude before returning to wheel control (tweak). In total, the maneuver used 106.42 kg of propellant (59.41 kg of fuel and 47.01 kg of oxidizer) or 18 percent of the total propellant load.

Figure 11 illustrates the pressure performance of the propulsion system for the entire maneuver. Actual flight performance closely matched pre-maneuver predictions including the dedicated auxiliary tank refill. Figure 12 shows calculated spacecraft acceleration versus spacecraft measured acceleration in the LVA thrust direction. The close match between these two acceleration values demonstrates an excellent understanding of the propulsion system and propellant expended to date. LVA thruster and specific impulse performance matched pre-flight prediction as well as acceptance test data. Determined thrust was 683-N compared to a pre-maneuver prediction of 667-N. Determined specific impulse was 316.71 s, compared to a pre-maneuver prediction of 316.5 s.

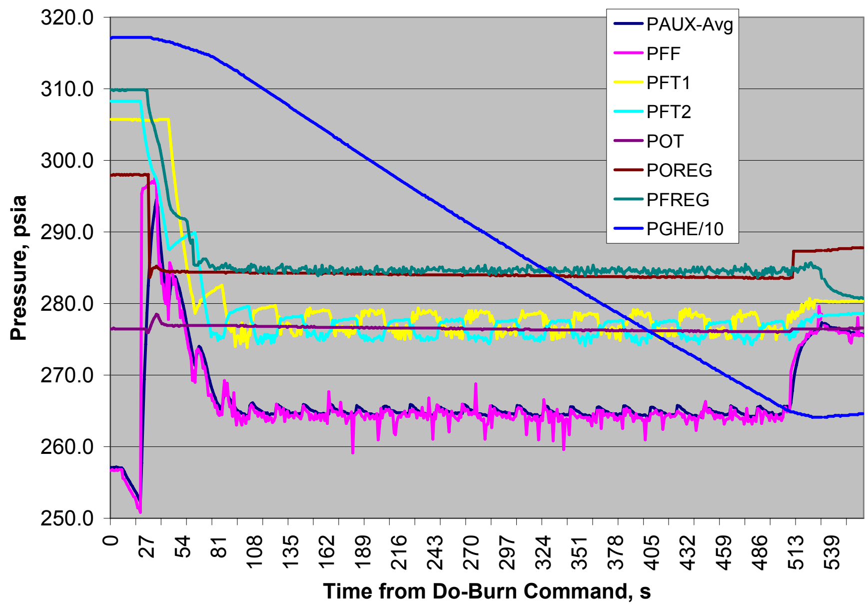

Figure 11. DSM-1 Pressure Performance.

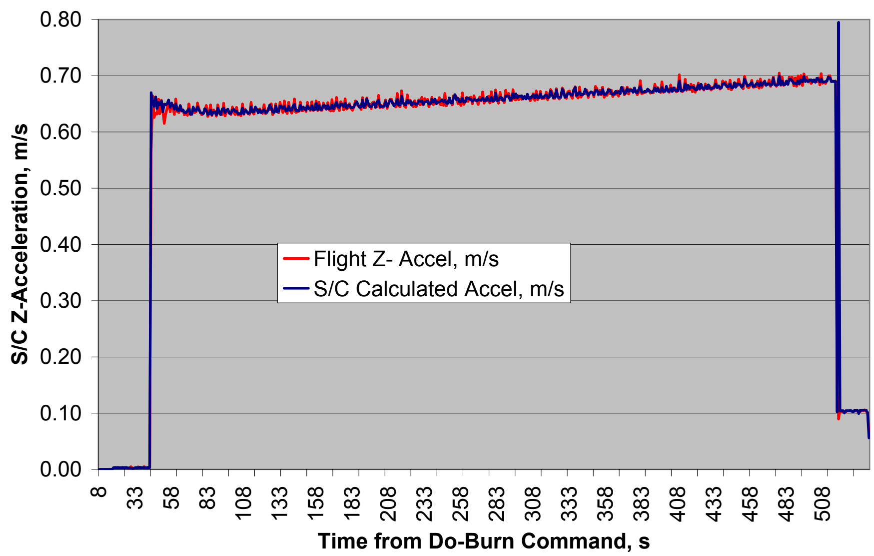

Figure 12. Calculated vs. measured DSM-1 spacecraft acceleration.

Prior to DSM-1, extensive analyses and simulations were conducted. Of particular concern was the expected MR range at start of the maneuver. As previously discussed, with the spacecraft flipped sunshade to the Sun, secondary heaters were required to maintain acceptable propellant temperatures. Because the heat leak from the oxidizer tank was greater than expected, the fuel tank temperatures prior to DSM-1 were much higher than the oxidizer tank temperature. The fuel tanks were at 20.5 ºC and 23.5 ºC for Tanks 1 and 2, respectively, while the oxidizer tank was 18.5 ºC. While these temperatures were within the qualified limits of the LVA thruster, the temperature effect combined with the smaller fuel tank ullage resulted in higher pressure in the fuel tank pressure than the oxidizer tank.

The propulsion system limit checks used during the maneuver—especially at the start—were also of concern. The spacecraft uses the difference between the fuel and oxidizer tanks to ensure that the LVA stays within its qualified MR range. Fuel tank switch timing as well as pressure limit checks were reexamined. This ensured that the subsequent shift in MR after the starting tank pressure blew down and the first fuel tank switch occurred would be within qualified MR limits and not prematurely shut down the burn. Results from updated analyses showed the original 20-s tank switch to be adequate and that a slight adjustment in pressure limit checking would be required. While the original plan was to close the auxiliary tank latch valve just prior to LVA firing, the updated analysis showed that leaving the auxiliary tank outlet latch valve open during the burn would soften early burn MR excursions. As the system switched to the higher-pressure fuel tank, total system fuel flow would increase; however, fuel would enter the auxiliary tank, reducing fuel flow to the LVA. This effect is shown in Fig. 13. As the fuel tank switches occur, fuel flows into the auxiliary tank, increasing pressure. Without the mitigating effect of the auxiliary tank, the qualified MR range of the LVA would have been violated in the early portion of the burn. Figure 14 shows the reconstructed LVA MR range as determined post burn from spacecraft GN&C and propulsion system data.

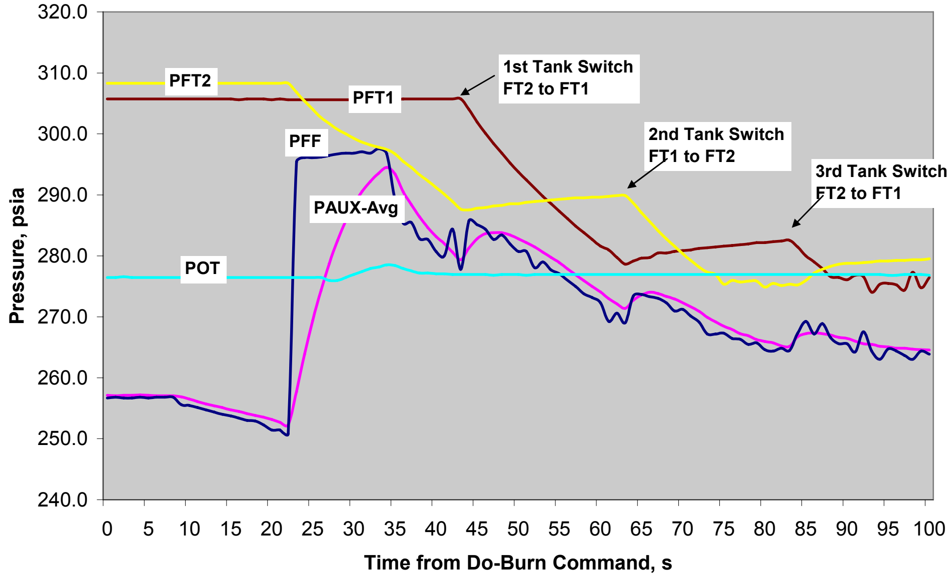

Figure 13. Tank pressures through the first three fuel tank switches.

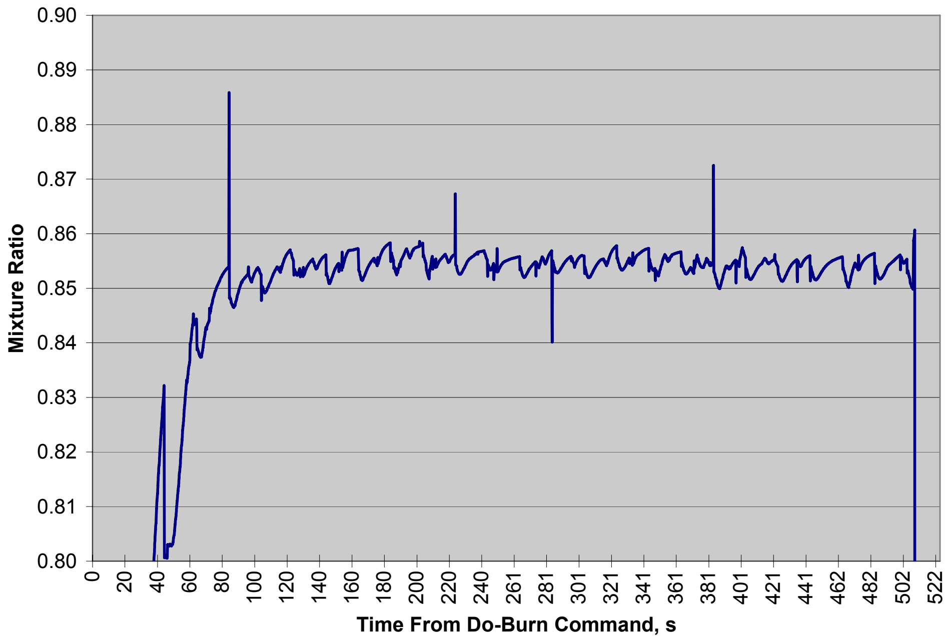

Figure 14. DSM-1 LVA mixture ratio range.

Pre-maneuver active propellant tank thermal management activities, adjustments to the propulsion system limit checks, and use of the auxiliary tank resulted in keeping the LVA within its qualified limits throughout the entire burn.

CMD-1. Prior to DSM 1, spacecraft momentum management was accomplished passively by changing the spacecraft aspect angle relative to the Sun and biasing the individual solar-panel angles. Propellant usage during DSM-1 and the subsequent position of the propellant within the spacecraft caused a momentum buildup that required a commanded momentum dump. CMD-1 was a Mode-1 propulsive maneuver that used the A and B ACS thrusters. The maneuver used 0.024 kg of fuel provided by the auxiliary tank operating in the blow-down mode. Propulsion system performance was similar to other completed Mode-1 burns. Table 4 provides additional Mode-1 maneuver details.

Table 4. Post DSM-1 Mode-1 propulsive maneuver detail.

Event Name	Event Date	ΔV Thrusters Used	Total ΔV Thruster On-Time, s	ACS Thrusters Used	Total ACS On-Time, s	ΔV Achieved m/s	Auxiliary Tank Pressure Range, psia	Fuel Used, kg	Effective Main Burn Thruster Isp, s
CMD-1	1/10/2006	N/A	N/A	A&B	14.0	0.011	258-257	0.024	N/A
TCM-10	2/22/2006	B	484.7	A	57.66	1.281	267-234	0.901	142.8

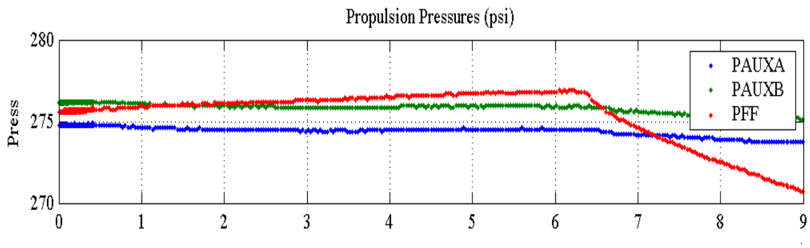

Figure 15. Post DSM-1 auxiliary tank pressure tracking.

Auxiliary Tank Pressure Transducer Anomaly. Following DSM-1, passive phase monitoring of the propulsion system noted a change in auxiliary tank pressure transducer performance. During passive operation, three pressure transducers sense auxiliary tank pressure: two that measure ullage pressure (PAUX-A and PAUX-B) and one that measures outlet manifold pressure (PFF). Normally, all three pressure transducers rise and fall as the auxiliary tank temperature varies between its heater thermostat set points; however, Fig. 15 shows that the two ullage pressure transducers appeared to stick as the manifold pressure transducer continued to track with temperature. The spacecraft was flying in its cold configuration (sunshade toward the Sun) when the pressure transducer sticking was first noticed. Subsequent investigation appears to indicate that freezing over time of hydrazine—that diffused past the auxiliary tank diaphragm—in the tank's pressurant tube was the most likely cause. Hydrazine diffusing through the tank's diaphragm has occurred in other similar applications and was expected. As shown in Fig. 16, a thermal blanket stretched tightly around the auxiliary tank pressurant tube might be shorted, causing a localized cold spot. The behavior of the ullage pressure transducers continued until the spacecraft was "flopped" back into its warmer configuration in March 2006. Since the flop, pressure performance on the auxiliary tanks has returned to normal. Due to this pressure transducer behavior, the normal auxiliary pressure transducer checks will not be performed prior to future thruster firings. The manifold pressure transducer (PFF) will be used as the auxiliary tank monitor for all remaining propulsion maneuvers.

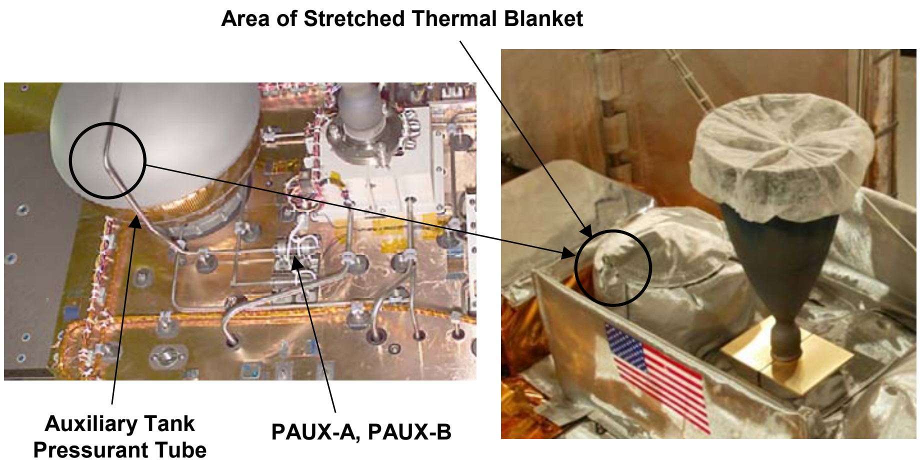

Figure 16. Auxiliary Tank Pressurant Tube Thermal Blanket

TCM-10: The first planned DSM-1 cleanup burn was TCM-10 conducted 22 February 2006. TCM-10 was a Mode-1 maneuver and the first use of the B-side ACS thrusters as the ΔV thrusters. Table 4 provides additional Mode-1 maneuver details. The 1.281 m/s maneuver lasted 135 s and used 0.901 kg of fuel. TCM-10 was the first propulsive maneuver that was terminated by a GN&C event timer—not by achieving the targeted ΔV of 1.41 m/s. Burn termination by the event timer resulted in a 9 to 10 percent under-burn. Initial post-burn analysis examined the thruster operations and required attitude control forces. Since the DSM-1 burn settled propellant within the main tanks, the center-of-mass of the spacecraft was offset from the center-of-thrust produced by the B-side ACS thrusters. To maintain the spacecraft center of mass, the two top Deck B-side ACS thrusters remained on 100 percent of the time while the two lower Deck-B side thruster off-

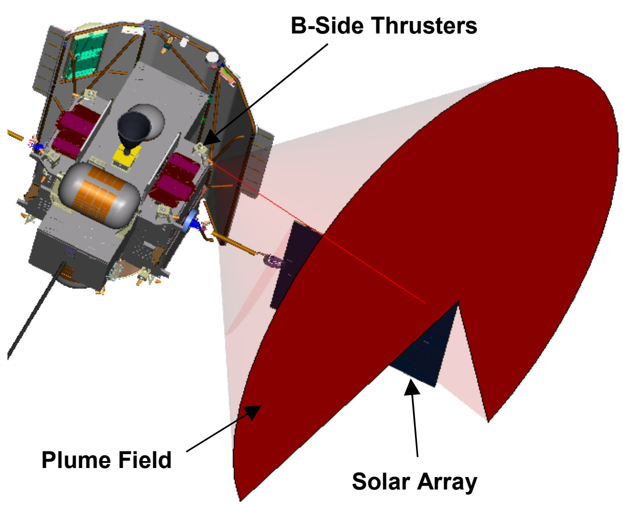

Figure 17. Simplified Spacecraft B-Thruster Plume Impingement Model

pulsed and fired approximately 73 percent and 87 percent of the time. A-Side ACS thrusters also fired to maintain spacecraft center of mass. While the ΔV thruster off-pulsing and ACS thruster pulsing did contribute to the under-burn, it represented only a small fraction of the total under-burn. Further maneuver review efforts focused on thruster performance. Thruster fuel usage using both the BTI and PVT methods agreed and matched previous Mode-1 performance suggesting nominal thruster operation. Plume impingement was the next area for examination given TCM-10 used the B-side ACS thrusters that point toward the +X solar array. The first indication of solar array plume impingement came from solar panel temperatures that showed an approximate 15 °C rise on inboard temperature sensors and a slightly lower rise (approximately 5 °C) on the outboard temperature sensors. A simplified spacecraft plume geometry model, shown in Figure 17, was constructed to examine solar array plume impingement. The simplified geometry combined with existing thruster plume models showed a potential reduction in thruster performance due to plume impingement. The combination of ΔV thruster off-pulsing, opposite direction ACS thruster usage, and solar array plume impingement sufficiently explain the observed under-burn. Future maneuvers using the A and B ACS thrusters as the ΔV thrusters will consider plume impingement as part of the pre-maneuver planning process.

Propellant and Thruster Usage. Propellant usage to date for all maneuvers completed is summarized in Table 5. Thruster usage to date is summarized in Table 6.

Table 5. Propellant Usage

Event	Auxiliary Tank Mass, kg	Fuel Tank 1 Mass, kg	Fuel Tank 2 Mass, kg	Oxidizer Tank Mass, kg	Helium Tank Mass, kg
Initial Conditions	9.34	178.00	178.00	231.61	2.295
Launch and Detumble	-0.58	0.00	0.00	0.00	0.000
TCM-1, Mode-2 Burn	1.06	-2.45	-7.42	0.00	-0.060
TCM-2, Mode-2 Burn	-0.09	-2.26	0.00	0.00	-0.007
TCM-3, Mode-2 Burn	0.36	-2.06	0.00	0.00	-0.007
TCM-5, Mode-1 Burn	-0.71	0.00	0.00	0.00	0.000
TCM-6, Mode-1 Burn	-0.10	0.00	0.00	0.00	0.000
DSM-1, Mode-3 Burn	0.31	-29.36	-30.36	-47.01	-0.265
Momentum Dump 1	-0.02	0.00	0.00	0.00	0.000
TCM-10 Main Burn	-0.90	0.00	0.00	0.00	0.000
Propellant Remaining	**8.66**	**141.87**	**140.22**	**184.60**	**1.96**

Table 6. Thruster Usage

Maneuver/Thruster	A1	A2	A3	A4	B1	B2	B3	B4
Launch and Detumble	21.62	17.82	22.90	22.90	17.52	23.04	17.64	20.78
TCM-1, Mode-2 Burn	41.06	61.68	4.10	4.26	31.10	50.80	5.20	2.44
TCM-2, Mode-2 Burn	21.28	23.12	0.64	2.42	15.78	20.94	3.92	0.34
TCM-3, Mode-2 Burn	22.80	21.42	2.08	2.74	18.90	18.90	2.80	1.00
TCM-5, Mode-1 Burn	32.36	3.60	12.60	2.88	42.38	3.18	10.84	2.74
TCM-6, Mode-1 Burn	0.12	7.22	0.20	0.32	0.50	7.58	0.24	0.44
DSM-1, Mode-3 Burn	29.60	58.28	5.74	2.72	37.58	74.00	5.58	0.80
Momentum Dump 1	0.28	2.70	2.66	0.00	0.00	3.64	4.34	0.38
TCM-10, Mode-1 Burn	0.26	0.22	43.86	13.32	134.40	134.78	98.52	117.00
Total On-Time, s	**169.38**	**196.06**	**94.78**	**51.56**	**298.16**	**336.86**	**149.08**	**145.92**

Maneuver/Thruster	S1	S2	P1	P2	C1	C2	C3	C4	LVA
Launch and Detumble	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0
TCM-1, Mode-2 Burn	0.00	0.00	0.00	0.00	186.92	187.66	187.38	187.80	0.0
TCM-2, Mode-2 Burn	0.00	0.00	0.00	0.00	47.86	47.86	47.86	47.86	0.0
TCM-3, Mode-2 Burn	0.00	0.00	0.00	0.00	33.80	33.86	33.86	33.86	0.0
TCM-5, Mode-1 Burn	166.82	138.32	0.00	0.00	0.00	0.00	0.00	0.00	0.0
TCM-6, Mode-1 Burn	0.00	0.00	22.24	21.36	0.00	0.00	0.00	0.00	0.0
DSM-1, Mode-3 Burn	0.00	0.00	0.00	0.00	26.06	70.22	23.10	36.82	474.0
Momentum Dump 1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0
TCM-10, Mode-1 Burn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0
Total On-Time, s	**166.82**	**138.32**	**22.24**	**21.36**	**294.64**	**339.60**	**292.20**	**306.34**	**474.00**

VI. Conclusion

With the successful completion of all propulsion system maneuvers to date, the MESSENGER spacecraft is well on its way to Mercury. On 23 March 2006, the MESSENGER spacecraft passed the billion-mile mark on its continuing journey. All propulsion system elements have been exercised and demonstrated through the successful completion of five Mode-1 maneuvers, three Mode-2 maneuvers, and one Mode-3 maneuver. The next planned propulsive event is CMD-2, currently planned for 11 May 2006. This will be followed by TCM-11, currently planned for 12 September 2006, which will target the spacecraft trajectory for the first Venus flyby on 24 October 2006.

Acknowledgments

The authors thank the entire MESSENGER spacecraft and operations teams for their dedication and hard work. The combined efforts of the propulsion, spacecraft, and operations teams have resulted in successful completion of nine propulsive maneuvers.

References

Wiley S., K. Dommer,, and L. Mosher, Design and Development of the MESSENGER Propulsion System, American Institute of Aeronautics and Astronautics/Society of Automotive Engineers/American Society of Mechanical Engineers (AIAA/SAE/ASME) Joint Propulsion Conference, Paper AIAA-2003-5078, 20 pp., Huntsville, AL, 21-24 July 2003.