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Flight Performance of the MESSENGER Propulsion System from Launch to Orbit Insertion

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The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission was designed to unlock the secrets of our solar system's innermost planet, revealing clues to the planet's enigmatic geological history, unusually high density, and radar-reflective materials at the poles, among many other decades-old unanswered questions. MESSENGER began its journey on 3 August 2004, when it was launched from the Cape Canaveral Air Force Station in Florida, and the spacecraft was successfully inserted into its destination orbit about Mercury on 18 March 2011. On its way to Mercury, the MESSENGER spacecraft completed 12 trajectory-correction maneuvers, five deep-space maneuvers, and one critical Mercury orbit-insertion maneuver. The MESSENGER dual-mode propulsion system is composed of 12 monopropellant Aerojet 4.4-N MR-111C thrusters, four monopropellant Aerojet 22-N MR-106E thrusters, and one large bipropellant AMPAC In-Space Propulsion (ISP) Leros 1b 660-N engine. This paper describes the operation and performance of the propulsion system during the MESSENGER spacecraft's interplanetary cruise phase and through its insertion into orbit about Mercury.

Nomenclature

ΔV = change in velocity
A1, -2, -3, and -4 = 4.4-N attitude control thruster
ACS = attitude control system
AFTF = auxiliary fuel tank filter
AFTHSV = auxiliary fuel tank helium service valve
AFTLV1 and -2 = auxiliary fuel tank latch valve 1 and 2
AFTPSV = auxiliary fuel tank propellant service valve
AMD = autonomous momentum dump
AUX1 and -2 = adapter heaters 1 and 2
B1, -2, -3, and -4 = 4.4-N attitude control thruster
C1, -2, -3, and -4 = 22-N thrust vector control thruster
CM = center of mass
CMD = commanded momentum dump
CP = center of pressure
DSM = deep-space maneuver
FCKTP = fuel-side check valve test port
FCKV = fuel-side check valve
FHPF = fuel-side high pressure filter
FREG = fuel-side regulator
FT1 and -2 = main fuel tanks 1 and 2
FT1CKV = fuel tank 1 check valve
FT1F = fuel tank 1 outlet filter

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FT1HSV and -PSV = fuel tank 1 service valve (helium and propellant)
FT2CKV = fuel tank 2 check valve
FT2F = fuel tank 2 outlet filter
FT2HSV and -PSV = fuel tank 2 service valve (helium and propellant)
FTLV1 and -2 = main fuel tank outlet latch valve (tank 1 and tank 2)
G&C = guidance and control
HeSV = helium tank service valve
HFTP = fuel-side pressurant test port
HOTP = oxidizer-side pressurant test port
HPLVF and -O = high-pressure latch valve (fuel and oxidizer)
HPPV = high-pressure pyro valve
LPPV = low-pressure pyro valve
LVA = large-velocity-adjust (engine)
LVAF = LVA fuel latch valve
MLA = Mercury Laser Altimeter (instrument)
MOI = Mercury orbit insertion
MPS = MESSENGER propulsion system
MR = mixture ratio ($mdot_{oxidizer}/mdot_{fuel}$)
OCKV1 and -2 = oxidizer check valve 1 and 2
OHPF = oxidizer-side high-pressure filter
OHSV = oxidizer tank helium-side service valve
OPIF = oxidizer pressurant inlet filter
OPILV = oxidizer tank pressurant inlet latch valve
OPSV = oxidizer tank propellant-side service valve
OREG = oxidizer-side regulator
OTF = oxidizer tank filter
OTLV = oxidizer tank latch valve
P1 and -2 = 4.4-N anti-sunward thruster
PAUXA, -B, and -AVE = auxiliary fuel tank pressure (sensor A, sensor B, and average of sensors A and B)
PFF = fuel manifold pressure
PFREG = fuel regulator pressure
PFT1 and -2 = main fuel tank pressure (tank 1 and tank 2)
PGHE = pressurant tank pressure
POREG = oxidizer regulator pressure
POT = oxidizer tank pressure
S1 and -2 = 4.4-N sunward thruster
SKI = “Sun keep-in” (spacecraft attitude requirement)
SRP = solar radiation pressure
TAUXA, -B, and -T = auxiliary fuel tank temperature (sensor A, sensor B, and test sensor)
TB1V = thruster B1 valve temperature
TB4V = thruster B4 valve temperature
TC2V = thruster C2 valve temperature
TCM = trajectory-correction maneuver
TFT1A, -B, and -T = fuel tank 1 temperature (sensor A, sensor B, and test sensor)
TFT2A, -B, and -T = fuel tank 2 temperature (sensor A, sensor B, and test sensor)
TGHEA, -B, -TC, and -U = helium tank temperature (sensor A, sensor B, test sensor, and umbilical sensor)
TOTA, -B, and -T = oxidizer tank temperature (sensor A, sensor B, and test sensor)
TP1C and -V = thruster P1 temperature (chamber and valve)
TP2C and -V = thruster P2 temperature (chamber and valve)
TLVAF and -V = LVA temperature (flange and valve)
TS1V = thruster S1 valve temperature
TVC = thrust vector control

I. Introduction

AFTER 6.6 years in flight, the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft achieved Mercury orbit insertion (MOI) on 18 March 2011, becoming the first spacecraft in history to orbit the solar system's innermost planet. Designed and operated by The Johns Hopkins University Applied Physics Laboratory under the auspices of NASA's Discovery Program, the MESSENGER spacecraft was conceived to explore the mysterious planet to an unprecedented level of detail. By revealing some of Mercury's most closely held secrets, MESSENGER will make substantial contributions to mankind's understanding of the formation and evolution of our solar system's planetary bodies.[1]

To succeed in this ambitious endeavor, the MESSENGER mission had to overcome three key challenges: the intense thermal conditions of the near-Sun environment, the high ΔV required to reach and orbit Mercury, and the stringent mass limits imposed by this high ΔV requirement. The specialized ceramic-cloth sunshade solved the thermal challenges, the innovative trajectory design enabled a feasible ΔV target, and the unique integral propulsion system/composite structure design allowed for a mass-efficient spacecraft.[2] Ensuring that the spacecraft is protected as it nears the Sun, strict "Sun keep-in" (SKI) attitude requirements are followed to maintain the appropriate sunshade orientation. The sunshade, solar panels, and other key spacecraft components are shown in Fig. 1.

To help propel the spacecraft to its ultimate destination, the MESSENGER propulsion system (MPS) was exercised a total of 27 times. Continuing from previously released work,[2] this paper details all of the propulsion system challenges and triumphs experienced in the final five years leading up to MOI. Beginning with a summary of the mission trajectory and propulsion system operation, this paper transitions to a discussion of the maneuvers that positioned the spacecraft for the final Mercury encounter and then delves into the preparation and execution of the insertion maneuver. Before the final summary, this paper includes a brief accounting of the limited set of component anomalies that arose during the mission.

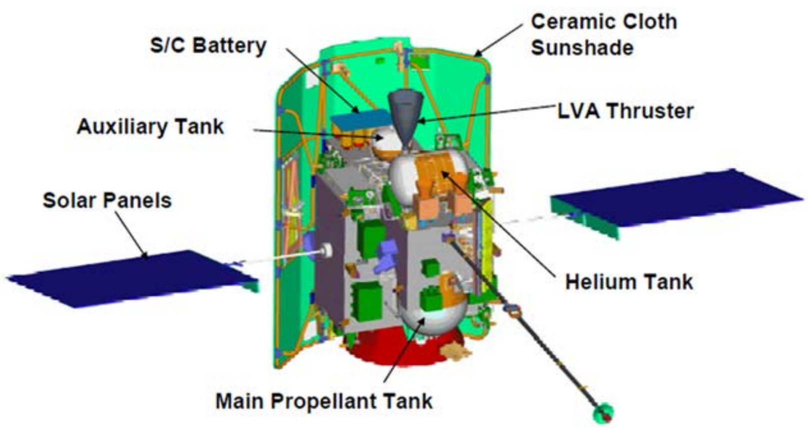

Figure 1. MESSENGER flight configuration. LVA denotes large-velocity-adjust; S/C, spacecraft.

II. MESSENGER Trajectory

The MESSENGER spacecraft used a combination of six planetary flybys and five deep-space maneuvers (DSMs) as the primary sources of ΔV. The trajectory is depicted in Fig. 2. The cruise phase and MOI maneuver design were covered in detail previously.[3]

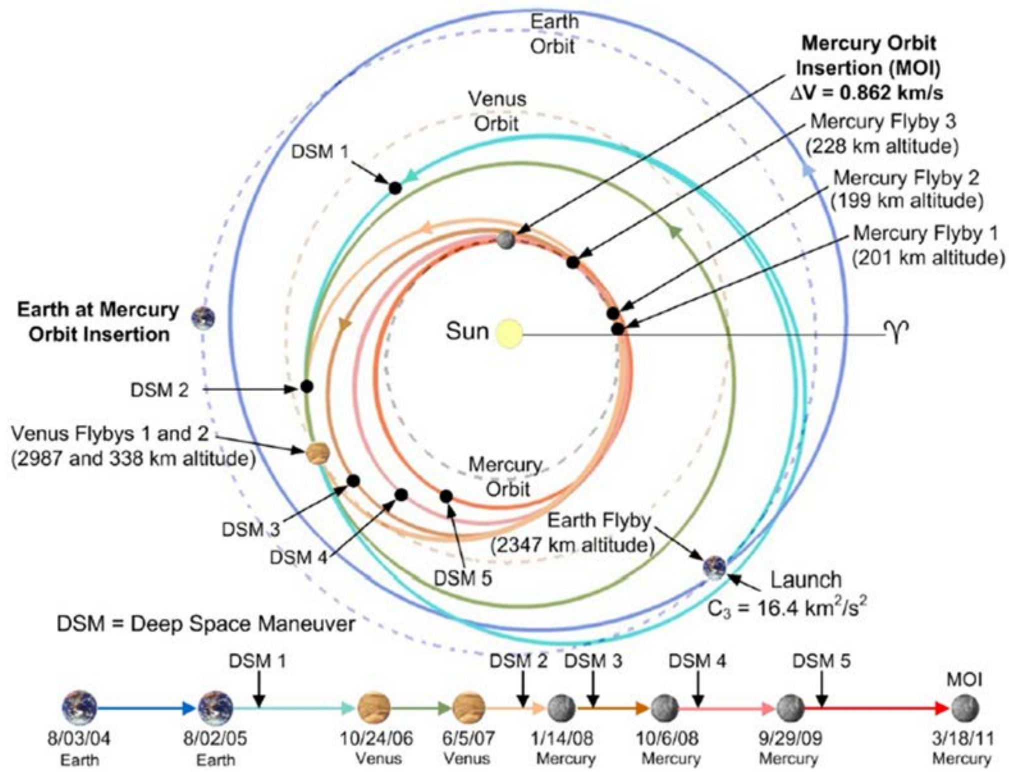

Figure 2. MESSENGER trajectory.

The primary purpose of the DSMs was to position the spacecraft for the planetary flybys and, ultimately, for the MOI burn. Trajectory-correction maneuvers (TCMs) were used to clean up residual DSM execution errors as well as navigation errors that propagate between flybys (chiefly due to uncertainty in solar radiation pressure). Leading into the first Mercury flyby, the MESSENGER team determined that the solar radiation pressure (SRP) exerted on the spacecraft (specifically the sunshade and solar arrays), once regarded as a disturbance to be compensated, could instead be used to counteract the DSM errors. Although SRP had been successfully used during the mission to passively manage system angular momentum, this was the first time it was applied to trajectory modification. This discovery led to a reduction in propellant consumption (increased ΔV margin) and the elimination of the planning and execution of several TCMs (reduced staff hours and risk). These "solar sailing" techniques were covered in detail previously.[4]

III. MESSENGER Propulsion System

The MPS is a unique, pressurized, dual-mode bipropellant system designed and built by Aerojet. It uses hydrazine (N_2H_4) and nitrogen tetroxide (N_2O_4) in the bipropellant mode and hydrazine alone in the monopropellant mode. Figure 3 shows the MPS components in schematic form. Figure 4 identifies the major MPS subassemblies.

A. MPS Propellant and Pressurant Tanks

Propellant is stored in the three main tanks (two fuel and one oxidizer) and the refillable auxiliary fuel tank, and the helium pressurant is stored in the sole pressurant tank. Before launch, the auxiliary tank and each of the main fuel tanks were loaded with 9.34 and 178.0 kg of N_2H_4, respectively. The oxidizer tank was loaded with 231.61 kg

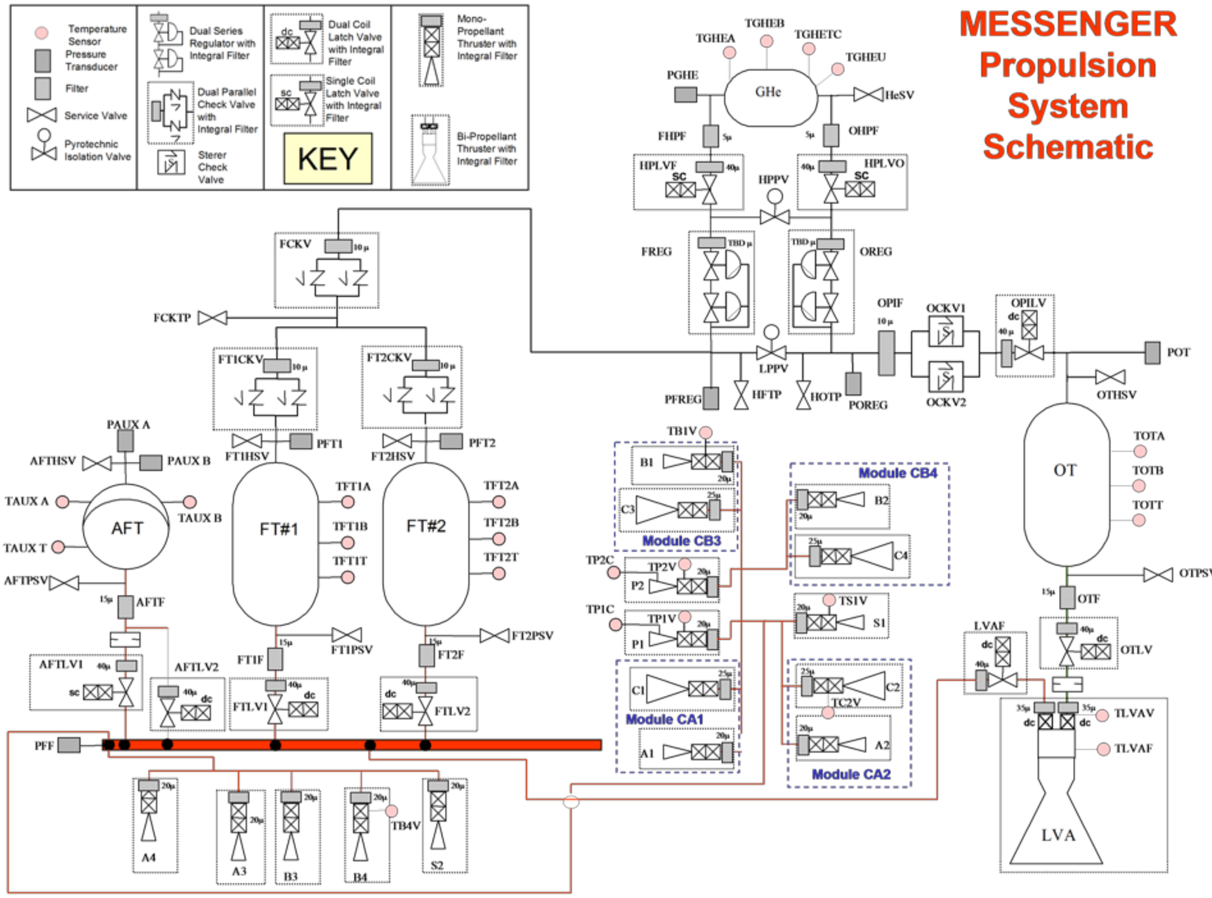

Figure 3. MPS schematic. See the nomenclature list for the full names of abbreviated component names.

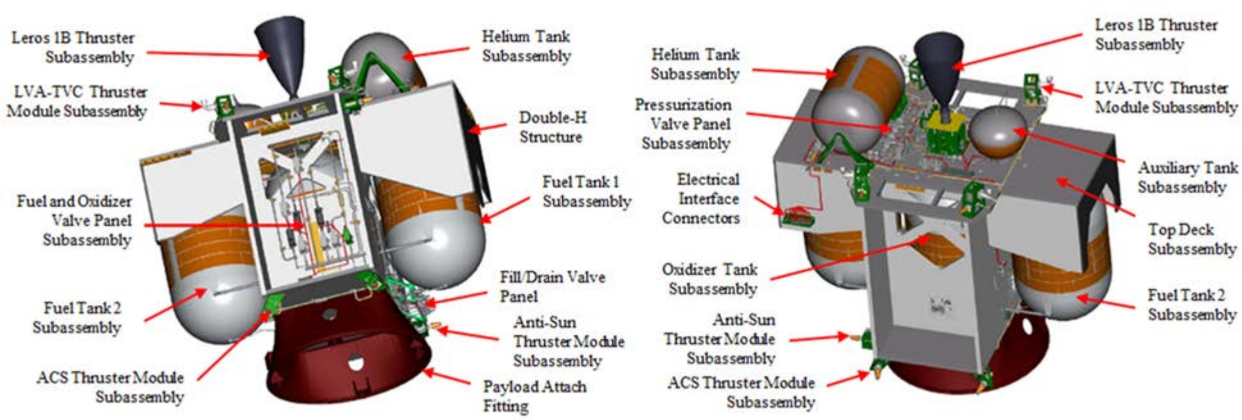

Figure 4. MPS subassemblies. ACS denotes attitude control system; TVC, thrust vector control.

of N_2O_4, and the pressurant tank was filled with 2.295 kg of helium. Both main fuel tanks were prepressurized to 250 psia, whereas the auxiliary and oxidizer tanks were prepressurized to 220 and 150 psia, respectively. The amount of helium loaded into the pressurant tank brought its pressure to 3375 psia.[5]

B. MPS Thrusters

The MPS is equipped with 17 total thrusters of three distinct types. These thrusters are arranged in five different thruster module configurations to provide the spacecraft forces depicted in Fig. 5. The LVA module contains the flight-proven AMPAC In-Space Propulsion (ISP) bipropellant Leros-1b, denoted as the LVA, along with four flight-proven Aerojet monopropellant MR-106Es, denoted as C-thrusters. The remaining thrusters are all flight-proven Aerojet monopropellant MR-111Cs, divided into A, B, S, and P thruster modules. Each monopropellant thruster uses N_2H_4 in both the pressurized and blow-down modes.

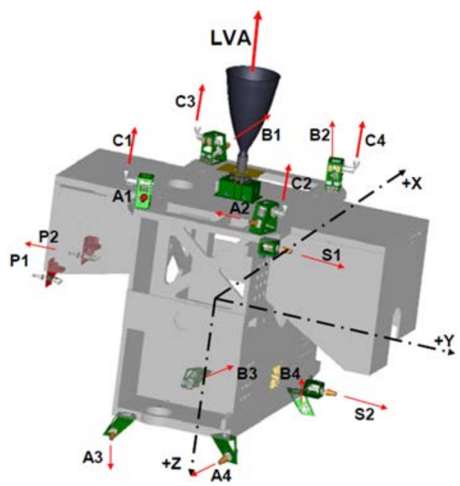

Figure 5. MPS thruster locations and directions.

The LVA, which is used for the largest ΔV maneuvers, nominally operates at a mixture ratio (MR = oxidizer flow rate/fuel flow rate) of 0.85, a thrust of 667.0 N, and a specific impulse of 316 s. The LVA was qualified to operate in an MR box ranging from 0.8 (fuel-rich operation) to 0.9 (oxidizer-rich operation) at propellant inlet pressures between 245 and 288 psia. In addition to providing thrust vector control during LVA operation, the nominally 22.0-N C-thrusters are used for ΔV maneuvers of intermediate magnitude. The C-thrusters nominally deliver a specific impulse (I_{sp}) of 230 s.

To allow for redundant three-axis attitude control, the A- and B-thrusters are arranged in double-canted sets of four. The S- and P-thrusters are mounted on opposite sides of the spacecraft. The two S-thrusters provide spacecraft velocity changes in the sunward direction, and the two P-thrusters propel the spacecraft in the anti-sunward direction. MR-111C thrusters have a nominal thrust of 4.4 N and an I_{sp} of 220 s.

During operational modes, the catalyst bed heaters on the monopropellant thrusters and the LVA flange heater are activated. When enabled for thruster firing, catalyst bed heater operation is time controlled, whereas the LVA flange heater operation is based on mechanical thermostats.

C. MPS Operational Modes

The MPS operates in three distinct modes for thruster operation and a passive thermal management mode during all other times. For the thruster operation modes, the guidance and control (G&C) system monitors propulsion system pressures before the maneuver and during execution to ensure that the pressures stay within the acceptable ranges that were identified for the event. If the limits are violated, the G&C system aborts the burn. When the propulsion system is not in use, the MPS temperatures are maintained within their operational bands with heaters. Spacecraft autonomy controllers verify the propulsion system temperatures against identified yellow and red limits and notify ground system controllers once those limits are reached.

1. MPS Mode-1

MPS mode-1 is distinguished by the use of the auxiliary fuel tank for the entire maneuver. In this mode, either the 22-N or the 4.4-N monopropellant thrusters are operated in blow-down to provide propulsion for small-ΔV maneuvers or momentum dumps. Mode-1 maneuvers execute in two segments: main burn and tweak. The main burn segment is used to achieve the ΔV target, and the tweak segment follows to maintain spacecraft attitude. Momentum dumps are executed only as a tweak segment because they are not meant to impart any net ΔV.

2. MPS Mode-2

MPS mode-2 is distinguished by the use of the main fuel tanks as the primary propellant source for operation of the monopropellant thrusters. Mode-2 maneuvers execute in three segments: settle burn, main burn, and tweak. Given that the main propellant tanks do not have propellant-management devices (internal tank vanes or other apparatuses that wick propellant to the outlet), a monopropellant thruster settling burn must be executed from the auxiliary tank to move the propellant to the main tank outlet before it can be accessed. To provide the necessary *–z*-

direction settling force, the A1, A2, B1, and B2 top deck 4.4-N thrusters are nominally fired for 15 s. For the main burn, the high-pressure fuel latch valve (HPLVF) is opened, and the 22-N thrusters (or 4.4-N thrusters oriented in the –*z* direction) are operated using one of the pressurized main fuel tanks as the primary propellant source. As with a mode-1 maneuver, the main burn segment ends when the ΔV target is achieved, and the tweak segment follows to maintain spacecraft attitude. Because both auxiliary fuel tank latch valves (AFTLV1 and AFTLV2) remain open for the entirety of the maneuver, the auxiliary tank is refilled while the main burn proceeds. Throughout the maneuver, attitude control is accomplished by off-pulsing the primary thrusters and on-pulsing 4.4-N thrusters, as necessary.

3. MPS Mode-3

MPS mode-3 is distinguished by the use of the main fuel and oxidizer tanks to operate the bipropellant LVA. Mode-3 maneuvers execute in four segments: settle burn, refill burn, main burn, and tweak. The settle and tweak segments are the same as those of a Mode-2 maneuver. For Mode-3 operation, the settle burn is followed by a separate refill segment. During this segment, the top deck 4.4-N thrusters are fed by a main fuel tank and fire for a predetermined duration to refill the auxiliary tank. For the main burn, all three latch valves upstream of the main propellant tanks (HPLVF, the high-pressure oxidizer latch valve [HPLVO], and the low-pressure oxidizer latch valve [OPILV]) are opened, and the LVA is operated using the pressurized main fuel and oxidizer tanks as the primary propellant sources. The four 22-N thrusters are on-pulsed for LVA thrust vector control, and the 4.4-N thrusters are on-pulsed for fine attitude control. After the LVA has achieved a certain percentage of the required ΔV, the MPS transitions to the trim segment. During trim, the 22-N thrusters are used to ensure a more precise completion of the required ΔV. To maintain a manageable spacecraft center of mass (CM), the main fuel tanks from which propellant is being drawn are switched every 20 s during the main and trim burn segments by opening and closing their outlet latch valves (fuel tank latch valve 1 [FTLV1] and fuel tank latch valve 2 [FTLV2]).

IV. MPS Cruise Phase Flight Performance

This section explores the cruise phase maneuvers that have been executed since the report of initial MPS flight performance.[5] That report captured the first DSM and commanded momentum dump (CMD) along with the first six TCMs. Note that in MESSENGER nomenclature, DSMs are considered special types of TCMs (e.g., DSM-1 is also called TCM-9), and any skipped TCM opportunities are still counted in the TCM numbering system. In the time between TCM-10 and MOI, the propulsion system performed an additional six TCMs, five DSMs, and five momentum dumps. These propulsive events are summarized in Table 1. The MOI maneuver will be covered in section V. As is noted in this section, to minimize the risk associated with the orbit insertion burn, the MESSENGER team planned early propulsion maneuvers to mitigate as many first-use risks during MOI as possible.

Table 1. Summary of propulsion system events and planetary flybys.

Event	Date	Mode Type	ΔV Thrusters	Notes
Launch	3 Aug 2004	N/A	N/A	
Manifold bleed	3 Aug 2004	N/A	N/A	
Propulsive detumble	3 Aug 2004	1	A&B	Detumble spacecraft.
TCM-1	24 Aug 2004	2	C	Pressurized fuel tank, first Mode-2 burn.
TCM-2	24 Sep 2004	2	C	Mode-2 burn, only fuel tank 1 (FT1) used.
TCM-3	18 Nov 2004	2	C	Mode-2 burn, only FT1 used.
TCM-5	23 Jun 2005	1	S	First use of the S-thrusters.
TCM-6	21 Jul 2005	1	P	First use of the P-thrusters.
Earth flyby	2 Aug 2005	N/A	N/A	
DSM-1	12 Dec 2005	3	LVA	First use of the LVA. CM shift led to high post-burn momentum accumulation.
CMD-1	10 Jan 2006	1	A&B	First commanded momentum dump due to DSM-1 CM shift.
TCM-10	22 Feb 2006	1	B	First use of B-thrusters for primary ΔV. Burn timed out because of B-thruster impingement on solar arrays.
CMD-2	15 May 2006	1	A&B	Momentum dump necessitated by the post-TCM-10 momentum state.
TCM-11	12 Sep 2006	2	C/S	First multicomponent maneuver. Orthogonal components required to remain within SKI safe attitude limits.
TCM-12	5 Oct 2006	1	B	
Venus flyby 1	24 Oct 2006	N/A	N/A	
Autonomous momentum dump 1 (AMD-1)	7 Nov 2006	1	A&B	Main processor reset led to first autonomous momentum dump.
TCM-13	2 Dec 2006	3	P/LVA/P	First three-component maneuver. Mode-3 burn second in order to refill auxiliary tank for final component.
TCM-15	25 Apr 2007	1	B	Burn timed out because of G&C algorithm error.
TCM-16	25 May 2007	1	B	Standard Mode-1 B-thruster maneuver.
Venus flyby 2	5 Jun 2007	N/A	N/A	
DSM-2	17 Oct 2007	3	LVA/B	First multicomponent DSM. Lateral component burn for CM management.
TCM-19	19 Dec 2007	1	B	Final TCM of the mission. Future trajectory corrections were made using solar sailing techniques.
Mercury flyby 1	14 Jan 2008	N/A	N/A	
DSM-3	19 Mar 2008	3	LVA	First active trajectory guidance burn ("turn while burn") Mode-3 maneuver used to practice for MOI.
Mercury flyby 2	6 Oct 2008	N/A	N/A	
DSM-4 Part 1	4 Dec 2008	3	LVA	First time HPLVO telltale stopped functioning.
DSM-4 Part 2	8 Dec 2008	3	LVA	First open-loop maneuver. Used as practice for failed-accelerometer MOI contingency.
Mercury flyby 3	29 Sep 2009	N/A	N/A	
DSM-5	24 Nov 2009	3	LVA	First use of thermal conditioning activities to mitigate against effects of helium transfer into main fuel tanks.
CMD-3	18 Aug 2010	1	A&B	Not necessary for momentum management. Only used to practice for orbit operations.
CMD-4	25 Aug 2010	1	A&B	Not necessary for momentum management. Only used to practice for orbit operations.
CMD-5	27 Aug 2010	1	A&B	Not necessary for momentum management. Only used to practice for orbit operations.
MOI	18 Mar 2011	3	LVA	New autonomy rules introduced. Updated thermal conditioning used to ensure Safe LVA operation.

A. CM Management

Before MESSENGER was launched, it was believed that the propellant in the main tanks would return to the center of the tanks after DSMs were completed, providing a predictable CM and allowing for passive momentum management with spacecraft sunshade tilting. However, the spacecraft angular momentum magnitude began to increase at an unexpectedly high rate after the execution of the first DSM, far faster than the passive technique could countermand. As a result, a CMD with the thrusters was required.

Subsequent analysis[6] indicated that, because of surface tension forces causing propellant to adhere to the baffles in the main propellant tanks, the propellant actually remained at the outlet end of the tanks after DSM-1. After the execution of the next TCM, it became apparent that when lateral (*x* and *y* direction) maneuvers followed these +*z*-directed DSMs, the propellant moved to a more favorable position for momentum management. For this reason, the team planned to follow all future DSMs with lateral-component burns. Although this strategy worked to mitigate against the potential post-DSM momentum buildup, it did not completely address all of the problems presented by the tank baffle-induced CM uncertainty. These complexities were finally resolved when the team devised a new spacecraft attitude alternation (and solar array articulation) strategy heading into the first Mercury flyby. From that point through orbit insertion, momentum dumps were no longer required and DSMs could be executed purely with *z*-direction thrust. As a result, the aforementioned lateral component approach was used only for DSM-2.

B. Momentum Dumps

CMDs are used to desaturate the momentum wheels when the system angular momentum reaches a certain threshold (~5.5 Nms). These mode-1 events are intended to impart zero net ΔV to the spacecraft using the A- and B-thrusters (although some trajectory perturbation is introduced). During the cruise phase, ground-commanded CMDs were required only after DSM-1 and TCM-10. A performance summary of all of the cruise phase momentum dumps is included in Table 2.

Table 2. Momentum dump performance details.

Event	Date	Burn Length (s)	Fuel Consumed (kg)	Auxiliary Tank Ending Mass (kg)
CMD-1	10 Jan 2006	68	0.024	9.682
CMD-2	15 May 2006	95	0.025	8.756
AMD-1	7 Nov 2006	58	0.055	8.150
CMD-3	18 Aug 2010	34	0.006	10.198
CMD-4	25 Aug 2010	12	0.001	10.197
CMD-5	27 Aug 2010	44	0.004	10.193

The next momentum dump, Autonomous Momentum Dump 1 (AMD-1), was performed autonomously by the spacecraft on 7 November 2006. Heading into the solar conjunction period (a period in the mission when the Sun–Earth–probe angle is <3° and ground–probe communication is not available) from 17 October to 18 November, the team loaded the momentum management solar sailing commands to the spacecraft. That command load was lost, however, when the main processor experienced an anomalous reset on 23 October 2006. Without the active solar sailing sequence, the momentum wheels saturated and the spacecraft performed a momentum dump autonomously. Once the conjunction passed and the ground team restored normal spacecraft operations, the standard solar sailing activities continued and no further CMDs were required.

The next three cruise-phase CMDs were performed as part of an orbital phase flight test. During this time, the flight system was exercised in nearly identical conditions as those that would be experienced in orbit.

C. Trajectory Correction Maneuvers

TCM-11 and -12 were used after DSM-1 to clean up the remaining trajectory errors leading into Venus flyby 1. In the time between the first and second Venus flybys, TCM-13, -15, and -16 were executed. TCM-19, the final TCM of the mission, followed DSM-2 and targeted the first Mercury flyby. This section highlights unique aspects of each TCM. A full summary of their performance is included in Table 3.

The first multicomponent burn of the mission, TCM-11 was carried out on 12 September 2006. This maneuver had to be split into two orthogonal components because firing in the desired ΔV direction would have violated spacecraft attitude SKI limits.[6] In accordance with the CM management guidance, the –*y*-direction component was executed after the +*z*-direction component was executed. Component 1 was executed as a 55-s mode-2 burn with the C-thrusters as the primary set, and component 2 was a 202-s mode-1 burn using the S-thrusters. The TCM burned all the way to the timeout (the maximum burn duration set for each maneuver to guard against anomalous burns) with only a slight overburn in ΔV magnitude (0.1%) but a large error in burn direction (11.2°). Postmaneuver analysis indicated that the explanation for the large direction error was threefold:

Table 3. TCM performance details.

Event	Date	Burn Length (s)	Performance			Propellant Consumed		Ending Mass			
			ΔV (m/s)	Effective Thrust (N)	Effective I_{sp} for Entire Burn (s)	Fuel (kg)	Oxidizer (kg)	Auxiliary Tank (kg)	FT1 (kg)	FT2 (kg)	Oxidizer Tank (kg)
TCM-1	24 Aug 2004	234	17.901	104.560	227.750	8.834	0.000	9.820	175.526	170.585	231.607
TCM-2	24 Sep 2004	89	4.589	105.910	218.068	2.353	0.000	9.730	173.263	170.585	231.607
TCM-3	18 Nov 2004	64	3.247	105.700	212.833	1.703	0.000	10.091	171.199	170.585	231.607
TCM-5	23 Jun 2005	185	1.103	7.320	171.997	0.715	0.000	9.376	171.199	170.585	231.607
TCM-6	21 Jul 2005	36	0.151	7.000	167.736	0.100	0.000	9.276	171.199	170.585	231.607
TCM-10	22 Feb 2006	135	1.281	9.19	142.949	0.901	0.000	8.781	142.045	140.872	183.556
TCM-11	12 Sep 2006	257	2.296	104.48/7.17	148.146	1.556	0.000	8.553	140.692	140.872	183.556
TCM-12	5 Oct 2006	59	0.498	8.29	143.132	0.348	0.000	8.205	140.692	140.872	183.556
TCM-13	2 Dec 2006	3426	35.709	4.5/174.245/4.949	209.907	14.374	2.541	4.695	135.573	135.071	181.015
TCM-15	25 Apr 2007	140	0.568	3.913	94.783	0.590	0.000	4.105	135.573	135.071	181.015
TCM-16	25 May 2007	36	0.213	5.708	141.433	0.148	0.000	3.957	135.573	135.071	181.015
TCM-19	19 Dec 2007	111	1.104	8.916	144.827	0.698	0.000	8.222	113.100	113.4135	150.384

1. Given the maneuver design, component 2 had to operate with tighter steering constraints (to maintain SKI compliance). As a result, the attitude control thrusters had insufficient authority to correct the accumulating direction error.
2. The S-thrusters were commanded to fire at 100% duty cycle rather than allowed to off-pulse (which is usually done for enhanced attitude control). Because TCM-11 was also being used to dump momentum, this restriction had been put in place to ensure that the dump would complete in a predictable amount of time.
3. The +*z*-direction component 1 burn caused the propellant to move toward the outlet, yielding an offset between the CM and the center of pressure (CP) that was too difficult to manage with the thrusters available for component 2.

The mode-1 TCM-12 was conducted on 5 October 2006 to clean up the residual TCM-11 error. All four B-thrusters were used for the duration of the 59-s maneuver. Because of the solar array positioning (the solar arrays rotate away from the thrusters as the spacecraft gets closer to the Sun to maintain proper array surface temperatures), impingement of the thruster plumes on the arrays caused a 15% reduction in their effective thrust, decreasing the efficiency of the maneuver. The same solar array impingement occurred during all of the other maneuvers that used the B-thrusters for ΔV (TCM-10, -15, -16, and -19).

Split into three components, the 2 December 2006 TCM-13 was the most complex maneuver executed up to that point in the mission. As with TCM-1, this maneuver had to be split into multiple components to attain the desired ΔV direction without violating SKI limits. However, because the lateral component required a burn length that was longer than the auxiliary tank fuel load could support, the lateral component was split into two, with the axial component 2 providing the +*z*-direction velocity change as well as refilling the auxiliary tank (lateral maneuvers have to use the auxiliary tank because main tank operation requires axial thrust to move propellant to the outlets). The mode-1 first component used the P-thrusters for 1713 s, consuming 4.798 kg of fuel from the auxiliary tank and decreasing the tank's pressure from 218 to 133 psi, its lowest operating pressure of the mission. The mode-3 component 2 burn transferred 6.491 kg of fuel to the auxiliary tank during the 35-s refill and fired the LVA for 25 s. Component 3 fired the P-thrusters for an additional 1599 s. The pressures during the entire maneuver are captured in Fig. 6.

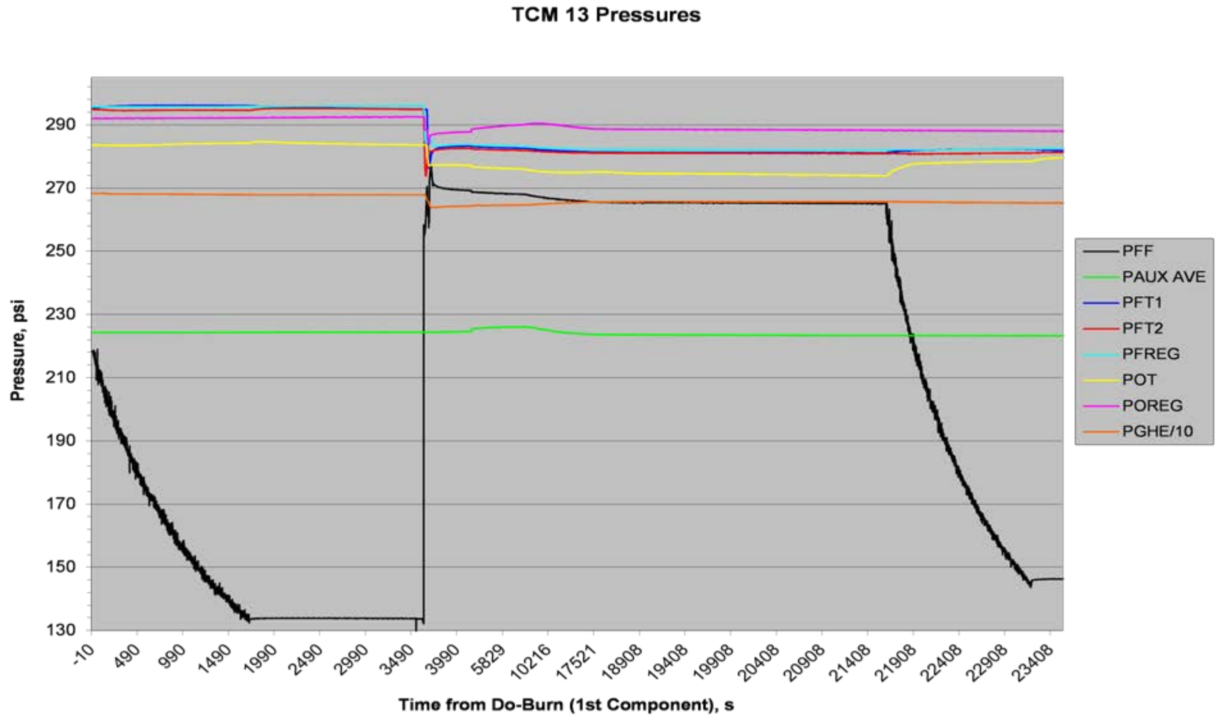

Figure 6. TCM-13 pressure profile. PAUX AVE denotes auxiliary fuel tank pressure (average of sensor A and B); PFREG, fuel regulator pressure; PFT1/2, main fuel tank (1 or 2) pressure; PGHE, pressurant tank pressure. POREG, oxidizer regulator; POT, oxidizer tank pressure.

Designed as a standard mode-1 maneuver with the B-thrusters as the primary set, TCM-15 completed on 25 April 2007 with a 26% underburn. In-flight data indicated that the A-thrusters, meant only to provide attitude control during the maneuver, fired at a 23% duty cycle. Because the A-thrusters fired in the opposite direction of the B-thrusters, the maneuver continued all the way to the timeout without achieving the ΔV target. During TCM-10 and -12, the previous B-thruster maneuvers, the A-thruster duty cycle was only ~10%. Subsequent analysis determined that the performance shortfall was the result of an error in the G&C flight algorithm. The high-fidelity G&C software was updated to resolve the problem and was successfully used to execute TCM-16 on 25 May 2007. As with the previous maneuver, TCM-16 used the B-thrusters for ΔV, but this time the A-thruster duty cycle reduced to the expected value of ~10%. The final TCM of the mission, TCM-19, proceeded nominally on 19 December 2007 with the same thruster set. After this maneuver, the solar sailing techniques were used to correct DSM execution errors.

D. Deep-Space Maneuvers

Split into two components, DSM-2 successfully executed on 17 October 2007. A total of 226.0 m/s of ΔV was imparted during the 418-s burn time. Component 1 was a mode-3 burn used to target the first Mercury flyby. Given that the auxiliary tank had been used for the entirety of the 1599-s final component of TCM-13, the auxiliary tank refill period for DSM-2a (component 1) had to be extended from the nominal 15 to 45 s. Responsible for the bulk of the ΔV, the LVA fired for 304 s. Component 2 executed as a mode-1 burn with the B-thrusters as the primary thruster set. Imparting only 1.4 m/s of ΔV, this component was executed to move the propellant mass to a more favorable location. This "propellant-centering" burn reduced the spacecraft CM-CP offset, thereby lowering the likelihood that a momentum dump would occur during the upcoming solar conjunction. All subsequent DSMs were executed while the updated solar sailing techniques were in use, eliminating the need for a lateral component burn.

During the standard mode-3 pre-burn activities for DSM-2, the LVA fuel latch valve (LVAF) was opened 70 s before burn start. When the valve opened, the PFF transducer indicated a large, unexpected drop in pressure, as indicated in Fig. 7. Subsequent analysis showed that the drop in pressure was caused by a slow leak through the

LVA fuel valve that evacuated the lines from the thruster valve to LVAF. A further accounting of this leak and others that followed is included in section VI.

Targeting the second Mercury flyby, DSM-3 fired on 19 March 2008, delivering 72.3 m/s of ΔV. This burn was the first opportunity to practice the active trajectory guidance ("turn while burning") approach necessary for MOI. The maneuver proceeded nominally except for a +3-psi shift in the regulated fuel pressure. Whereas the regulated

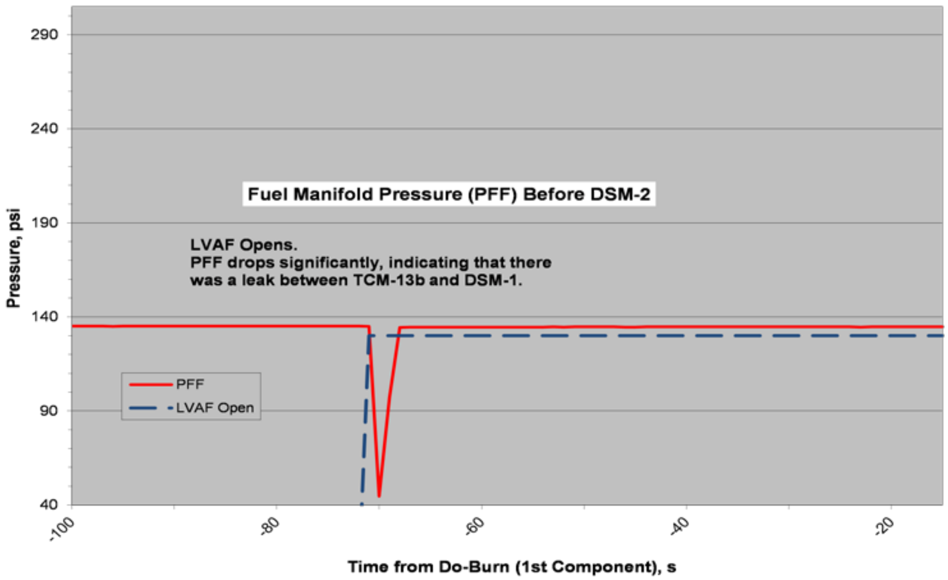

Figure 7. Manifold pressure drop at LVAF opening before DSM-2.

fuel pressure during the previous four mode-3 maneuvers was ~284.7 psi, the pressure at DSM-3 was closer to 288 psi. As a result, the average LVA MR was 0.835 as compared with the nominal 0.85. The same regulator pressure shift recurred during DSM-4 parts 1 and 2. This component anomaly is further described in section VI.

Before DSM-4, all of the ΔV maneuvers had been controlled in a closed-loop fashion with the main burn thrusters shutting off once a certain amount of ΔV had been achieved. Given the criticality of the timing of MOI, the team wanted to be prepared to execute the maneuver even if the accelerometers failed before the burn. Therefore, rather than executing DSM-4 as a standard mode-3 maneuver, the team elected to take the opportunity to test the ability to perform an open-loop (timed) maneuver. To do so, the DSM was broken into two parts. DSM-4 part 1 used the typical closed-loop control, and four days later, DSM-4 part 2 executed as a purely timed maneuver with a turn rate matched to the MOI design. Executed on 4 and 8 December 2008, both DSMs performed nominally. Parts 1 and 2 lasted 347 and 103 s, respectively, delivering 222.1 and 24.7 m/s. In addition to the aforementioned fuel-regulated pressure shift, DSM-4 part 2 also exhibited a shift in oxidizer-side regulated pressure of +3 psi. This was the only occurrence of the oxidizer-side shift during the nominal mission.

Table 4. DSM performance details.

Event	Date	Burn Length (s)	LVA On Time (s)	Performance			Propellant Consumed		Ending Mass			
				ΔV (m/s)	Effective Thrust (N)	Effective I_{sp} for Entire Burn (s)	Fuel (kg)	Oxidizer (kg)	Auxiliary Tank (kg)	FT1 (kg)	FT2 (kg)	Oxidizer Tank (kg)
DSM-1	12 Dec 2005	563	474	315.633	683.5	313.971	58.437	48.051	9.706	142.045	140.872	183.556
DSM-2	17 Oct 2007	551	304	227.500	497.728/ 9.577	309.289	39.166	30.631	8.920	113.100	113.414	150.384
DSM-3	19 Mar 2008	183	90	72.176	308.367	306.749	12.143	9.086	9.930	106.211	106.452	141.298
DSM-4 Part 1	4 Dec 2008	347	270	222.148	551.997	312.935	33.888	27.160	10.000	89.326	89.379	114.138
DSM-4 Part 2	8 Dec 2008	103	26	24.732	199.99	294.288	4.306	2.635	10.097	87.135	87.168	111.504
DSM-5	24 Nov 2009	278	199	177.606	502.580	310.560	25.474	20.077	10.204	74.652	74.071	91.427

The final DSM before MOI, DSM-5, executed nominally on 24 November 2009. Leading up to this maneuver, the propulsion team observed that, between pressurized maneuvers, the helium mass in the pressurant tank had been decreasing and the helium mass in the fuel tanks had been increasing. The rate of this helium transfer was an order of magnitude higher than the maximum expected leak rate across HPLVF. As a result, the main fuel tank pressures throughout the mission had been steadily increasing. To prevent the DSM-5 LVA burn segment from proceeding in a fuel-rich state, a proactive plan was pursued, using a combination of tank heaters and thermally connected powered components to decrease the main fuel tank pressures and increase oxidizer tank pressure (POT). Consequently, the entire DSM-5 LVA maneuver occurred within the qualified MR box, allowing the maneuver to safely impart 177.8 m/s of ΔV. Because they were also used in preparation for the MOI, a more detailed discussion of these thermal conditioning activities is included in the following MOI section. A full summary of DSM performance is included in Table 4.

V. MPS MOI Performance

The culmination of years of work from a myriad of contributors, the 18 March 2011 MOI maneuver was the most critical of the mission. MOI was designed to insert the spacecraft into a 12-h orbit about Mercury where it would gather science data for one year. From the standpoint of future insertion opportunities, there were very few favorable partial burn outcomes for the maneuver. In some partial burn scenarios, the next available insertion opportunity was more than six years from the initial burn date. For this reason, it was essential that the maneuver was robust to potential failures. However, it was equally important to strike a balance between protecting the spacecraft and preventing false aborts. This section begins with a discussion of the measures taken to ensure successful propulsion system operation and transitions to an accounting of the burn performance.

A. System Faults and Mitigation Strategy

There are a number of possible system faults in the MPS, but most of them are mitigated by redundancy in the system. Although there is no redundancy in the LVA, a single failure of any monopropellant thruster could be accommodated. Other components that do not have redundancy include the filters, pressure transducers, and service valves. For filters, the failure mode is blockage. Given that the filters are conservatively sized and had not blocked up to that point in the mission, the most likely failure would have been an increased pressure drop rather than complete blockage. Pressure transducers are single-point failures, but fault management was built in so that one false reading would not activate an autonomy rule that would pre-emptively shut down the burn. Service valves fail by leaking, but because there had been no evidence of leak before MOI, there was no reason for them to fail heading into the maneuver. As with the DSMs, failure of the filters, check valves, and regulators was modeled before MOI, and the propulsion system was shown to be robust to these events in the simulations. The latch valves are also sources of potential single-point failures. Table 5 lists the failure scenarios for each latch valve and, where applicable, the possible mitigation response.

Table 5. Latch valve failure mitigation. OTLV, denotes oxidizer tank latch valve; OREG, oxidizer regulator.

Latch Valve	Failed-Open Mitigation	Failed-Closed Mitigation
HPLVF	Fuel regulator (FREG) will control downstream pressure.	Open LPPV and use HPLVO to flow helium from pressurant tank.
HPLVO	OREG will control downstream pressure.	Open LPPV and use HPLVF to flow helium from pressurant tank.
OPILV	Decreased vapor migration protection.	No mitigation. Biprop operation no longer possible.
OTLV	Downstream LVA oxidizer valve will be closed.	No mitigation. Biprop operation no longer possible.
LVAF	Downstream LVA fuel valve will be closed (with some leaking at low pressure).	No mitigation. Biprop operation no longer possible.
LVA Fuel Valve	Upstream LVAF will be closed.	No mitigation. Biprop operation no longer possible.
LVA Oxidizer Valve	Upstream OTLV will be closed.	No mitigation. Biprop operation no longer possible.
FTLV1	Depending on when failure occurs, may be able to complete mission.	Depending on when failure occurs, may be able to complete mission.
FTLV2	Depending on when failure occurs, may be able to complete mission.	Depending on when failure occurs, may be able to complete mission.
AFTLV1	N/A (always open).	N/A (Will close only if AFTLV2 open. Both failing closed is not considered.)
AFTLV2	No mitigation. No major effect.	No mitigation. Can no longer settle or perform mode-1 maneuvers.

In the days leading up to MOI, various risk-reducing measures were used. A pressurization test, during which the latch valves upstream of the main propellant tanks (HPLVF, HPLVO, and OPILV) are opened for a set amount of time to detect leaking regulators, was performed one week before MOI. If either regulator was found to be leaking, its flow path would be isolated by opening the low-pressure pyro valve (LPPV), leaving the other regulator to manage both the fuel and oxidizer sides. This test is usually performed one day before mode-3 maneuvers, but given the criticality of MOI, the team wanted to leave ample time to respond in the event of a failure and monitor the results of any action that was taken. To mitigate against a failure of one of the two command decoders to open the latch valves, HPLVF, HPLVO, and OPILV were all opened 48 h before the burn and left open through MOI. The main tank latch valves (FTLV1, FTLV2, and OTLV) were not opened because the propellant was not settled; opening these valves would have introduced gas into the downstream propellant lines, putting the LVA at risk. LVAF was not actuated either because the risk mitigated by opening this valve was less than the risk associated with potential fuel leakage (see section VI for further discussion of this leakage). Instead of being left open, AFTLV2 was cycled; this AFTLV had to be closed when LVAF was opened to ensure that all flow would be through the surge-suppression orifice upstream of AFTLV1 in case of surge flow associated with a leaky LVA fuel valve. In addition, the LVA flange heater was activated 48 h before the burn to allow plenty of time for any residual propellant in the injector from possible LVA fuel valve leakage to boil off.

Given that the high-pressure latch valves would be open for a substantial amount of time before the maneuver, new rules were created to close the valves autonomously if the regulators began leaking at a high rate. The selected fuel-side pressures were the highest starting pressures possible that would still allow for an acceptable duration of operation outside of the qualified MR box. The oxidizer pressures were chosen to be just high enough that the entire LVA burn would execute within the LVA's qualified operating box (given nominal expected fuel tank pressures) because there was no need for POT to be any higher. Reaching the fuel and oxidizer maximum limits would have resulted in the closing of the corresponding high-pressure latch valve. The values used in the autonomy are included in Table 6.

Table 6. MOI preburn autonomy pressure limits.

Pressure (psi)				
PFT1	**PFT2**	**PFREG**	**POT**	**POREG**
301	296	297	286	301

To prevent tank pressures from exceeding limits and causing undesirable MR excursions during the maneuver, additional autonomy rules were introduced. These autonomy rules replaced G&C checks that were in place for all previous mode-3 maneuvers. Whereas the G&C checks respond by aborting the burn, the new autonomous actions would allow the maneuver to proceed by isolating the anomalous regulator and using the remaining one to manage both the fuel and oxidizer sides. Using data from LVA qualification tests and in-flight performance, pressure limits were identified for the fuel and oxidizer sides that met the dual requirement of preventing dangerous MRs and mitigating against an abort when LVA operation is still acceptable. The pressure thresholds used in the autonomy are listed in Table 7.

Table 7. MOI in-burn pyro valve autonomy pressure limits.

	Pressure (psi)					
	PFF	**PFT1**	**PFT2**	**PFREG**	**POT**	**POREG**
Min Limit	248	258	258	265	264	271
Max Limit	300	310	310	317	298	305

In the case of either low or high fuel pressures, the autonomy would close HPLVF and open LPPV. In the oxidizer case, HPLVO, rather than HPLVF, would be closed. To make the autonomy robust to pressure transducer failures, multiple pressure readings were tied to the action. For the fuel-side autonomy to execute, two of the four fuel pressure readings (PFF, PFT1/2, and PFREG) would have to exceed the limits. For the oxidizer side, both the POT and the oxidizer regulator pressure (POREG) would have to be out of range.

B. Main Propellant Tank Thermal Conditioning

As was noted in the discussion of DSM-5, the out-of-specification helium transfer across HPLVF was causing the main fuel tank pressures to rise sufficiently above the POT that MOI would have started with a long fuel-rich period. Given the potential for mission-ending engine damage in this scenario, a variety of thermal-conditioning activities were undertaken in the months before MOI to ensure that the tank pressures would start in benign ranges. Before implementing these strategies, the MESSENGER team tested their effectiveness and repeatability during two periods when the spacecraft had the same thermal environment that it would have leading into MOI (all three periods occur when the spacecraft enters perihelion, the hottest environment). To close the gap between the low oxidizer and higher fuel tank pressures, the activities were designed to do the following:

1. In the months leading to perihelion, increase the fuel tank pressures such that the fuel regulator locks up and helium flow ceases.
2. In the weeks leading to perihelion, begin to decrease the fuel tank pressures.
3. In the weeks leading to perihelion, begin to increase the POT.

For the August 2010 perihelion, the software-controlled primary-heater set points were used to control the main fuel tank pressures. Unfortunately, increasing the oxidizer tank primary-heater set point caused a greater increase in PFT2 than it did in POT, rendering that method for POT increase relatively useless. Instead, nearby components were activated that were thermally tied to the oxidizer tank. Both adapter heaters (AUX1 and AUX2) were turned on. In addition, the propulsion team was allowed to activate the Mercury Laser Altimeter (MLA, the instrument with the most thermal input to the oxidizer tank). A timeline of the actions is listed in Table 8, and the effect on the tank pressures is indicated in Fig. 8. One event that was not anticipated was the activation of the thermostatically controlled secondary tank-heater circuit. When the software-controlled fuel tank temperatures fell too far, the thermostatically controlled heaters activated, driving the main tank pressures higher (especially PFT2). After final review, the actions during this test were found to be effective in lowering PFT2 and increasing POT but had negligible effect on PFT1.

Table 8. August thermal conditioning test timeline. OT denotes oxidizer tank.

Activity	Execution Time	Purpose
Increased FT1 and FT2 primary heater set points.	12 May 2010, UTC 132 19:40	Wanted to lock up regulators and prevent further helium flow from helium tank to main fuel tanks. Increasing heater set points would cause heaters to come on more frequently and increase the temperature and pressure of the tanks.
- old set points were:		
FT1: 18–19°C, FT2: 18–19°C, oxidizer tank (OT): 24–25°C		
- new set points were:		
FT1: 25–26°C, FT2: 25–26°C, OT: 24–25°C		
Increased FT2 primary heater set points.	14 May 2010, UTC 134 18:20	Whereas the FT1 primary heater did come on more frequently, the FT2 primary heater did not.
- old set points were:		
FT1: 25–26°C, FT2: 25–26°C, OT: 24–25°C		
- new set points were:		
FT1: 25–26°C, FT2: 27–28°C, OT: 24–25°C		
Decreased FT1 and FT2 primary heater set points to nominal values.	22 Jul 2010, UTC 203 19:10	Beginning of plan to thermally condition tanks in order to get the fuel tank pressures low enough and oxidizer tank pressure high enough to allow MOI burn within the MR box (also would help us better predict MOI pressures). This would decrease fuel tank pressures.
- old set points were:		
FT1: 25–26°C, FT2: 27–28°C, OT: 24–25°C		
- new set points were:		
FT1: 18–19°C, FT2: 18–19°C, OT: 24–25°C		
Activated AUX1.	4 Aug 2010, UTC 216 15:15	Attempt to increase OT pressure.
Activated AUX2.	10 Aug 2010, UTC 222 07:17	Attempt to increase OT pressure.
Activated MLA.	12 Aug 2010, UTC 224 13:33	Attempt to increase OT pressure.
Heater set points increased back to high values.	18 Aug 2010, UTC 230 17:30	Saw that helium transfer rate was increasing again, therefore increased set points to previous highs.
- old set points were:		
FT1: 18–19°C, FT2: 18–-19°C, OT: 24–25°C		
- new set points were:		
FT1: 25–26°C, FT2: 27–28°C, OT: 24–25°C		

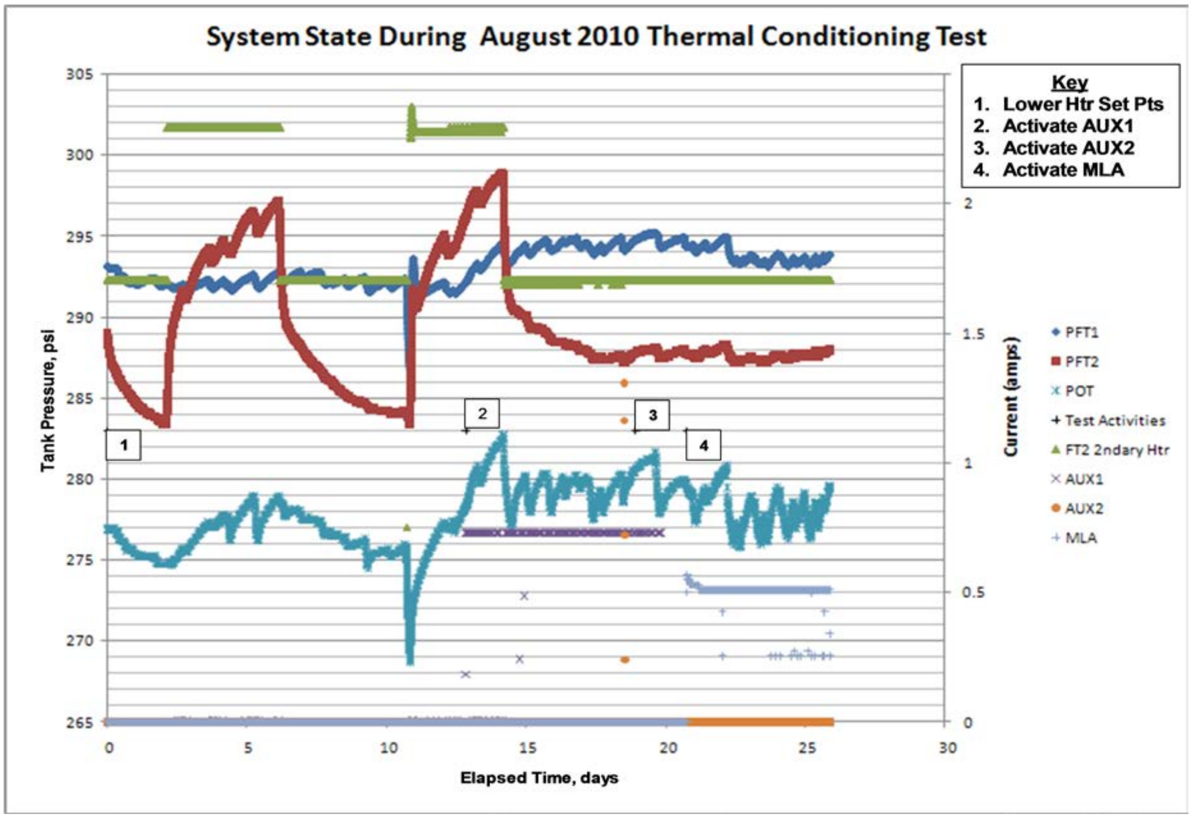

Figure 8. System state during August 2010 thermal conditioning test.

The next perihelion opportunity came during November 2010. This period was used to validate the repeatability of the previous activities and introduce one more. In addition to what had been done before, the back antenna heaters, which are thermally connected to FT1, were deactivated. This action had the intended effect of lowering PFT1, an outcome that was not realized in the August test. Because the Operations Team intended to have the instruments and adapter heaters off during MOI, the November test was also used to determine the optimum time to deactivate them. The results indicated that the best time to do so was at the very beginning of the available 48-h pre-MOI window.

A comparison of the timeline for the August and November thermal conditioning activities is included in Table 9. Because solar distance was the primary driver in the MOI thermal environment comparison, the timeline for each test period in the table is anchored against the perihelion passage point. The effect on the pressures at the November opportunity are indicated in Fig. 9 (note that the November test ended after 30 days, with the spikes in PFT1 and POT depicted in the figure occurring after the test was completed and the component states were restored).

Table 9. Comparison between August and November thermal conditioning test timelines.

Date during Nov 2010 Test	Time from Dec 2010 Perihelion (days)	Solar Distance (AU)	Activity	Time from Aug 2010 Perihelion (days)	August Distance (AU)
4 Nov 2010	–27	0.479208			
5 Nov 2010	–26	0.472439	Lower set points.	–26	0.47
8 Nov 2010	–23	0.450943			
9 Nov 2010	–22	0.443424			
10 Nov 2010	–21	0.435755			
12 Nov 2010	–19	0.420048			
16 Nov 2010	–15	0.387891			
18 Nov 2010	–13	0.372006	Activate AUX1.	–13	0.37
19 Nov 2010	–12	0.364272			
21 Nov 2010	–10	0.349507			
22 Nov 2010	–9	0.342607			
23 Nov 2010	–8	0.336123			
24 Nov 2010	–7	0.330131	Activate AUX2.	–7	0.33
26 Nov 2010	–5	0.319922	Activate MLA.	–5	0.32
30 Nov 2010	–1	0.308551	Turn off back antenna heaters.	N/A	
1 Dec 2010	0	0.307895			
3 Dec 2010	2	0.309346	Turn off AUX1, AUX2, and instruments (to simulate 24- to 48-h MOI deactivation).		
6 Dec 2010	5	0.318111	End of test. Return heater set points, AUX1, AUX2, and instruments to their previous states (hot pole test dictates).		
6 Dec 2010	5	0.318111			

Using the pressures at the end of the November test as starting pressures for the propulsion model, a simulation of the MOI maneuver indicated that the burn would be fuel rich for <10 s at the outset. On the basis of LVA qualification data and consultation with Richard Driscoll, former Director of Engineering at AMPAC In-Space Propulsion and the engineer who oversaw the engine's acceptance testing, it was determined that any MR excursion lasting <30 s (the time for the combustion chamber to reach thermal equilibrium) would be benign. The November test was deemed a success, and the thermal conditioning was repeated before the insertion burn.

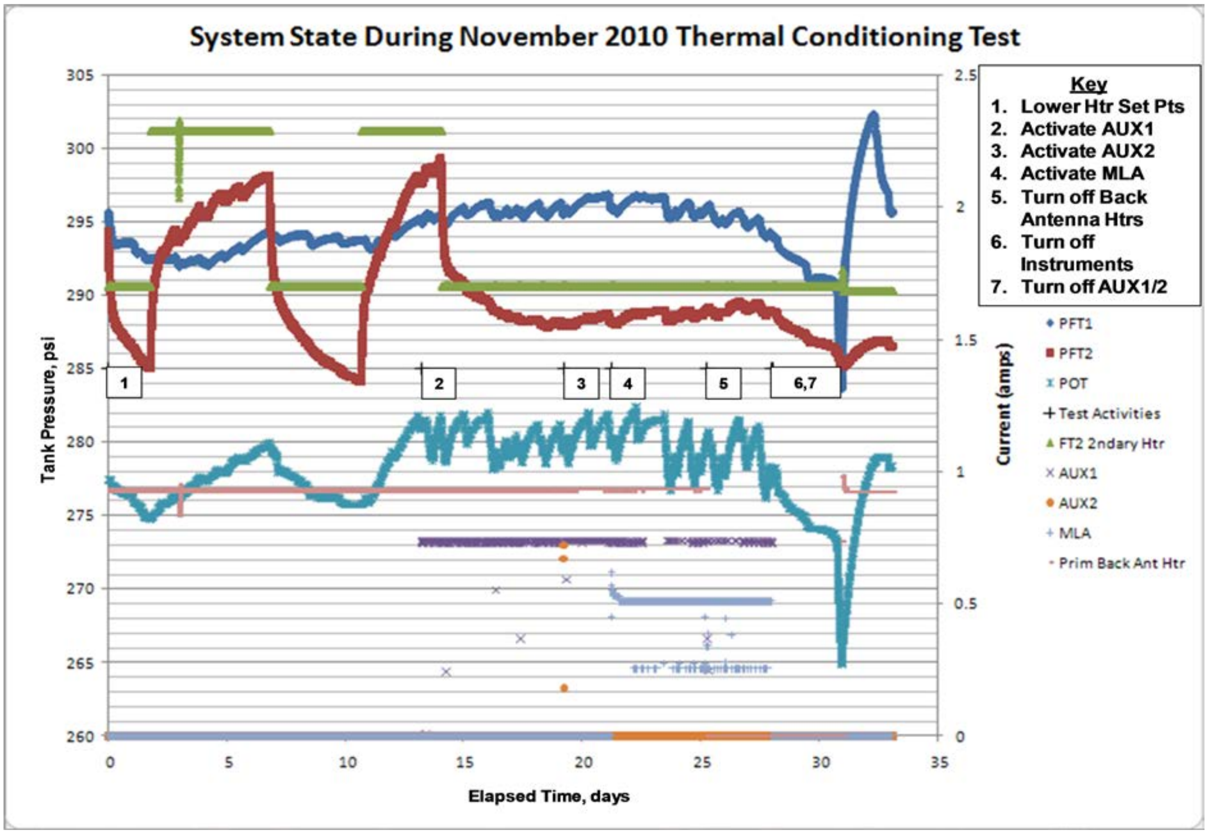

Figure 9. System state during November 2010 thermal conditioning test.

C. MOI Execution

As was planned, HPLVF, HPLVO, and OPILV were actuated and left open for 48 h before MOI. No anomalous regulator leaks were observed, and the pre-burn period proceeded nominally. After implementation of the aforementioned thermal conditioning activities, the MOI starting pressures were as indicated in Table 10.

Table 10. MOI starting pressures.

Pressure (psi)					
PFF	**PFT1**	**PFT2**	**PFREG**	**POT**	**POREG**
280.1	296.8	288.7	291.8	280.1	285.5

Imparting 861.7 m/s of ΔV, the MOI maneuver proceeded nominally with a burn duration of >15 min. In total, 101.891 kg of hydrazine and 83.727 kg of oxidizer were consumed during the maneuver, 28% and 36% of the original hydrazine and oxidizer loads, respectively. After the standard settle and refill periods, the LVA fired for 834 s. Although the LVA segment lasted 4 s longer than the G&C team expected, the magnitude error was <0.1% and the direction error was <0.01°. To ensure an even balance in the main fuel tanks during and after the maneuver, FT1 was used for the first 2 s of the main burn before the 20-s main tank switching began. For the duration of the LVA burn, the average MR was 0.843 and the engine's average thrust was 680.8 N. And because of the increased spacecraft temperature induced by the prolonged LVA firing, the frozen auxiliary tank pressure transducer lines (detailed in the earlier report of MPS performance[5] and highlighted in section VI) temporarily unfroze toward the end of the maneuver (only to refreeze two weeks later). The in-burn pressure profile is depicted in Fig. 10.

To mitigate against an off-nominal MR after the first tank switch, the MOI main burn started with the higher-pressure main fuel tank (FT1). As a result of this tank-switching strategy and, more importantly, the thermal conditioning, MOI experienced only 3 s of fuel-rich operation at the beginning of the LVA burn segment.

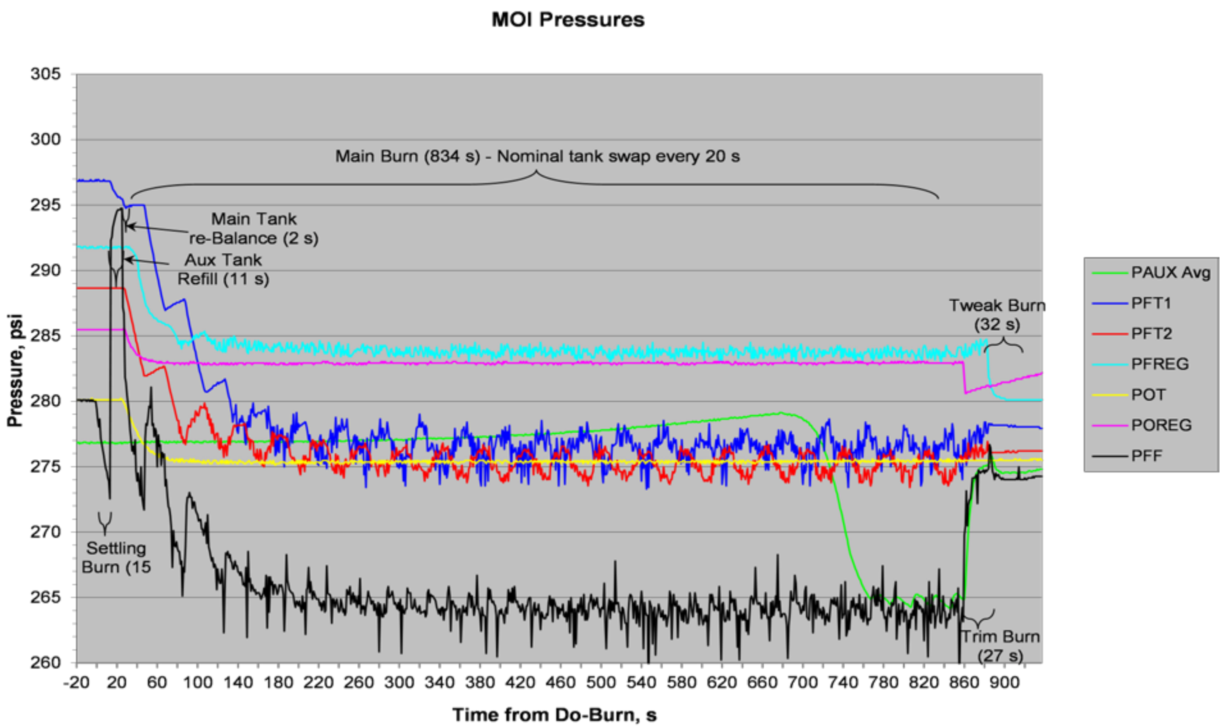

Figure 10. MOI pressure profile.

VI. Summary of MPS Component Anomalies

In the nearly seven years from launch to MOI, the MPS operated with very few anomalies. The MESSENGER team was able to mitigate successfully against the propulsion system ailments that did arise. The component anomalies are highlighted in Fig. 11.

1. Auxiliary Tank Pressure Measurement Anomaly

The first problem occurred when the main fuel tanks were accessed at DSM-1. Because five mode-1 TCMs had been executed before DSM-1, the auxiliary tank pressure was much lower than the main fuel tank pressures. When the DSM-1 refill segment began, the active main fuel tank pressure was ~308 psi, whereas the auxiliary tank pressure was ~253 psi. The pressure surge that followed probably compressed the hydrazine frost in the pressure transducer line (hydrazine that permeated the diaphragm and became cold because of a cold spot on the pressurant line) into solid ice. This event was described in further detail in the earlier MPS report.[5] All autonomy rules that were tied to the auxiliary fuel tank pressure sensor readings (PAUXA and PAUXB) have since been disabled, and PFF has been used to determine the auxiliary tank pressure. The pressure transducer line intermittently thaws as the thermal environment around the auxiliary tank warms (as it did during MOI).

2. LVA Fuel Thruster Valve Leak

The next anomaly occurred before the execution of DSM-2. In compliance with standard mode-3 maneuver procedures, LVAF was opened 70 s before the burn started. Although the maneuver completed successfully, post-burn data analysis showed that when the valve opened, PFF instantaneously decreased from 135.05 to 44.35 psi, recovering to 134.32 psi a few seconds later. Subsequent analysis determined that the mass of the leak approximately equated to the amount of hydrazine in the line between LVAF and the LVA fuel thruster valve. Given this information, and other evidence, the propulsion team concluded that a slow leak had developed across the LVA fuel thruster valve after the execution of TCM-13b. As indicated in Table 11, measurable leaks were detected at the times of three of the next six mode-3 maneuvers. The amount of fuel leaked tended to increase with duration between maneuvers.

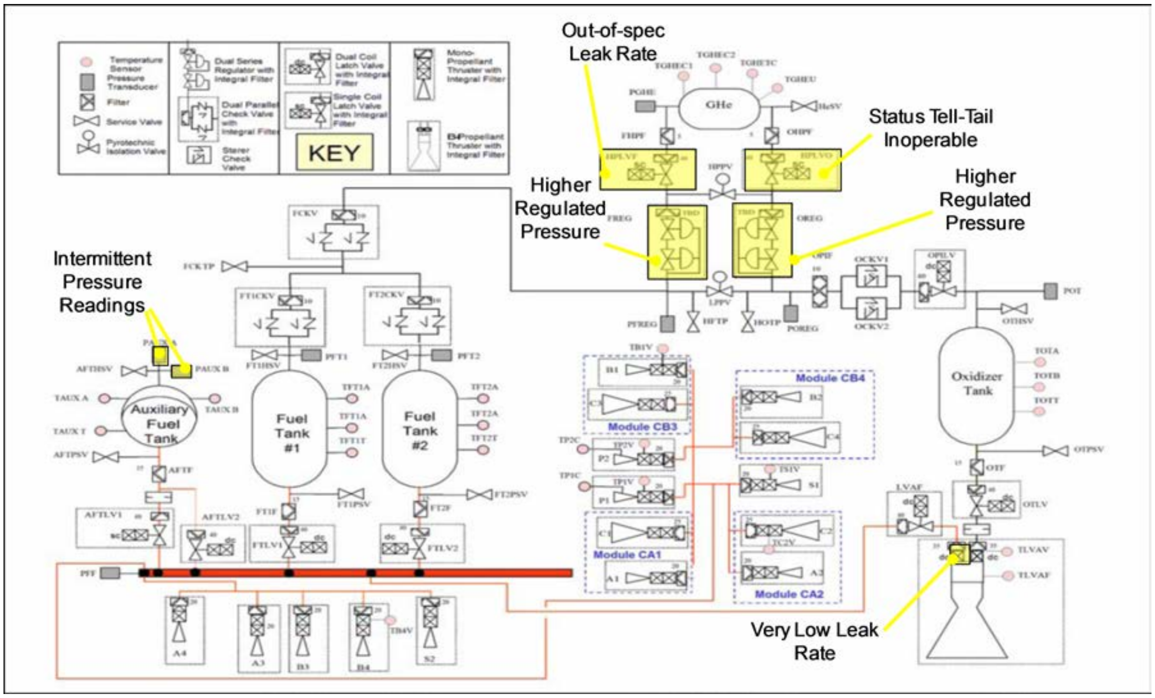

Figure 11. MPS component anomalies.

Table 11. Effect of duration between mode-3 maneuvers on mass loss.

Mode-3 Burn	Date of Execution	Duration Since Previous Mode-3 Burn Executed (days)	Mass Loss (kg)
DSM-1	12 Dec 2005	N/A	N/A
TCM-13b	2 Dec 2006	355	N/A
DSM-2	17 Oct 2007	318	0.032
DSM-3	19 Mar 2008	154	0.000
DSM-4 Part 1	4 Dec- 2008	259	0.008
DSM-4 Part 2	8 Dec 2008	4	0.000
DSM-5	24 Nov 2009	351	0.010
MOI	18 Mar 2011	479	0.012

3. HPLVO Telltale Failure

As is done for all standard mode-3 maneuvers, HPLVO was commanded open shortly before the start of the DSM-4 part 1 LVA burn segment. However, telltale status telemetry from the maneuver indicated that the latch valve never opened. Given that pressure and performance data showed that the oxidizer side did in fact regulate during the maneuver, it became clear that the HPLVO telltale was not functioning properly. Since that time, the telltale has continued to report incorrectly the latch valve as being closed even though all subsequent mode-3 maneuvers regulated on the oxidizer side. The likely cause of this anomaly was a failure of the HPLVO reed switch to properly operate. This failure does not indicate anything about the actual performance of the valve, and the telltale has never been tied to any autonomy rule.

4. *Regulator Pressure Shift*

During the first three LVA maneuvers (DSM-1, TCM-13b, and DSM-2a), the regulated fuel pressure hovered around ~284.7 psi, which is well within the 282 ± 5 psi range of the design specification. For all of the next three mode-3 maneuvers (DSM-3, DSM-4 Part 1, and DSM-4 part 2), however, the regulated fuel pressure shifted ~3 psi above the value recorded at the previous burns. Although only slightly above the expected range and benign from an engine health perspective, this pressure shift did indicate a marked departure from what had been expected. The regulated fuel pressure returned to its previous nominal value at DSM-5, only to decrease by ~1 psi at MOI. And although the oxidizer regulated pressure generally fell within a tight range for all mode-3 maneuvers, there was a temporary ~3 psi increase during DSM-4 part 2 for the oxidizer side as well. Although these changes in regulator pressures are interesting to note, they do not indicate anything inherently faulty in the regulators, nor have they ever posed a danger to the engine or the mission. The regulated fuel and oxidizer pressure for all of the mode-3 maneuvers through MOI are pictured in Figs. 12 and 13.

5. *HPLVF Out-of-Spec Leak Rate*

As was mentioned in previous sections, the decrease of helium mass in the pressurant tank and the corresponding mass increase in the fuel tanks between maneuvers indicated that HPLVF was leaking at a high rate. It was found that the leak rate was actually an order of magnitude higher than the design specification indicated it should be. As a consequence, the aforementioned thermal conditioning measures were pursued to ensure that the MOI maneuver could safely execute.

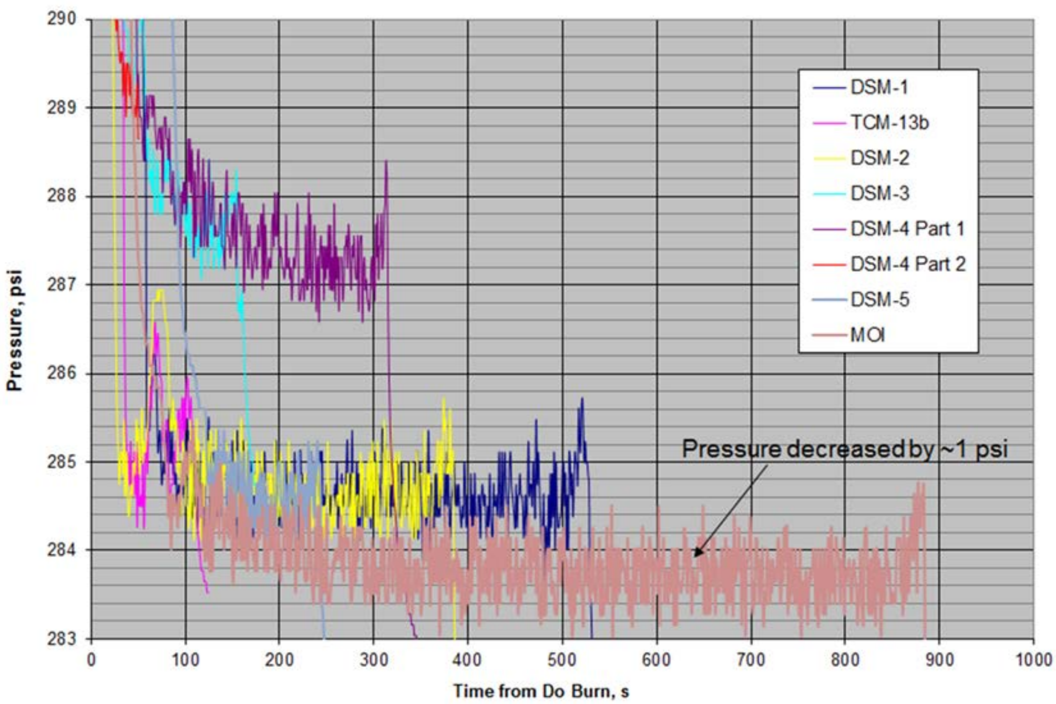

Figure 12. Regulated fuel pressures for all mode-3 maneuvers.

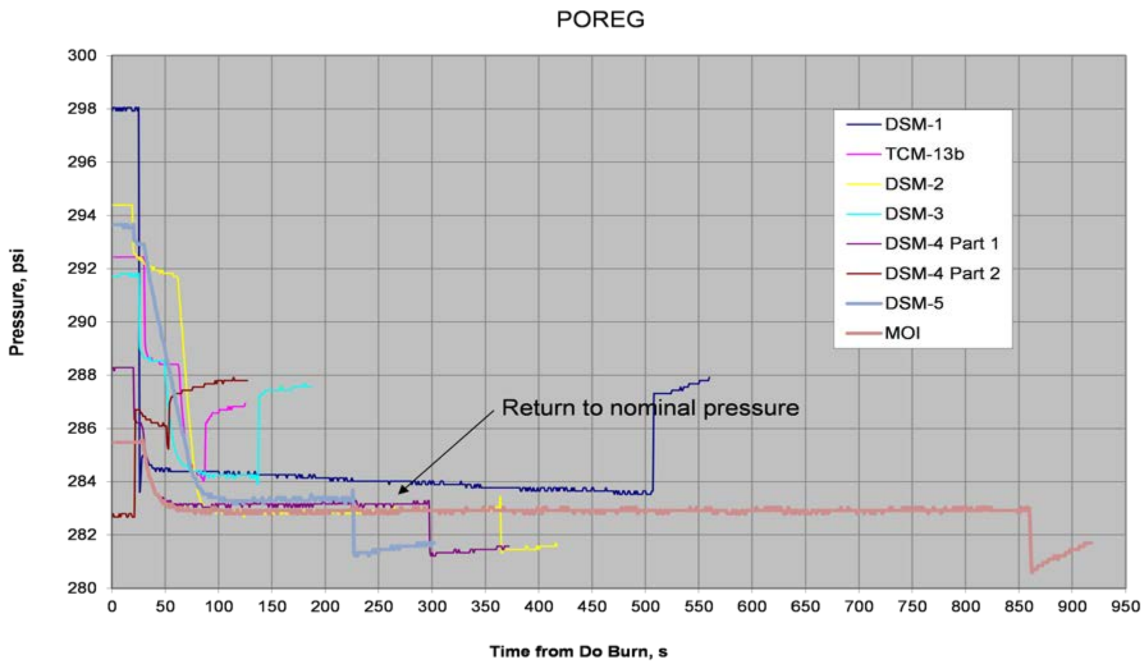

Figure 13. Regulated oxidizer pressures for all mode-3 maneuvers.

VII. Conclusion

The innovative design of the MPS enabled the success of this groundbreaking mission to Mercury. During the 6.6 years in flight prior to orbit insertion at Mercury, the MPS was used a total of 27 times, operating in each of the three propulsive modes on multiple occasions. The flexibility of the propulsion system was in full display as it was operated to overcome a number of unforeseen challenges. The few flight anomalies that befell the MPS were successfully mitigated, and in the most important maneuver of the mission, the propulsion system exhibited near-flawless execution as it propelled the MESSENGER spacecraft to its final destination in orbit about Mercury.

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