

MESSENGER Propulsion System: Strategies for Orbit-Phase Propellant Extraction at Low Fill Fractions

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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. After expending the vast majority of its propellant to reach the planet, the MESSENGER dual-mode propulsion system required a new set of operating procedures to extract the remaining fuel and oxidizer. Those updated guidelines were used to successfully execute five orbit-correction maneuvers during the one-year primary orbital mission. After the completion of the primary mission objectives, an additional one-year extended mission began that required the propulsion system to exhaust all of its remaining usable oxidizer and empty the usable fuel from one of its main tanks. To accomplish this goal, the recently updated propellant extraction techniques had to be further modified to safely deplete the remaining propellant from the near-empty tanks.

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 valves 1 and 2
AFTPSV	=	auxiliary fuel tank propellant service valve
B1, -2, -3, and -4	=	4.4-N attitude control thruster
C1, -2, -3, and -4	=	22-N thrust vector control thruster
CFD	=	computational fluid dynamics
CM	=	center of mass
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
FT1HSV and -PSV	=	fuel tank 1 service valve (helium and propellant)

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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
 MOI = Mercury orbit insertion
 MPS = MESSENGER propulsion system
 MR = mixture ratio ($\dot{m}_{\text{oxidizer}}/\dot{m}_{\text{fuel}}$)
 OCKV1 and -2 = oxidizer check valves 1 and 2
 OCM = orbit-correction maneuver
 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 = auxiliary fuel tank pressure (sensor A and sensor 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
 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
 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. All of the science

objectives were met during the yearlong primary orbital mission, providing invaluable revelations about Mercury's interior, surface, exosphere, and magnetosphere. In the wake of these achievements, a one-year extended mission was granted that allowed for more targeted observations, closer planetary passes, and an unprecedented opportunity to operate during some of the most active periods of solar activity.¹

After the MESSENGER spacecraft was inserted into orbit about Mercury, the effects of solar radiation pressure, solar gravity, and variations in Mercury's gravity began to perturb its trajectory. To counteract these forces and maintain the desired orbit, the MESSENGER propulsion system (MPS) performed five orbit-correction maneuvers (OCMs) during the one-year nominal mission. These maneuvers were executed approximately once every 44 days, with the first OCM occurring 89 days after the MOI maneuver. The odd-numbered OCMs were used to lower the periapsis altitude back to 200 km; in doing so, these maneuvers also decreased the orbit period. The interspersed even-numbered OCMs served to restore the desired 12-h orbit period. Given that the periapsis-lowering maneuvers all required relatively high velocity change ($\Delta V \sim 26$ m/s), they were all candidates for bipropellant operation. The ~ 4 m/s period-increasing maneuvers could be monopropellant maneuvers.²

With only $\sim 13\%$ of the original main fuel tank load and $\sim 3\%$ of the original oxidizer load remaining after orbit insertion, extracting propellant became a challenge. The two annular baffles in each of the main propellant tanks, designed to provide nutation damping during launch, proved problematic at low propellant fill fractions. Use of the standard thruster firing routines would cause a substantial amount of propellant to splash onto the baffles and adhere to the upper and lower sides because of surface tension. Figure 1 depicts the propellant geyser that would result from firing two 22-N thrusters with the pre-orbit propulsion system operation procedures (the snapshot captures the propellant state 10.2 s after ignition of the thrusters). In addition, the unconstrained slosh of the remaining propellant would lead to intermittent and unpredictable periods of gas flow to the thrusters. To avoid these scenarios, the propulsion team (The Johns Hopkins University Applied Physics Laboratory and PMD Technology) performed analyses to determine the optimal thruster operation and tank-switching strategies that would both minimize propellant lost to the baffles and prevent gas ingestion to the thrusters. These guidelines were successfully implemented to complete the first five OCMs. Each of the next three maneuvers posed a special challenge that required an adjustment to the orbit strategies, exercising the propulsion system in new ways. In this paper, we describe the analysis and operational strategies that were used for all eight OCMs and the propulsion system performance that resulted.

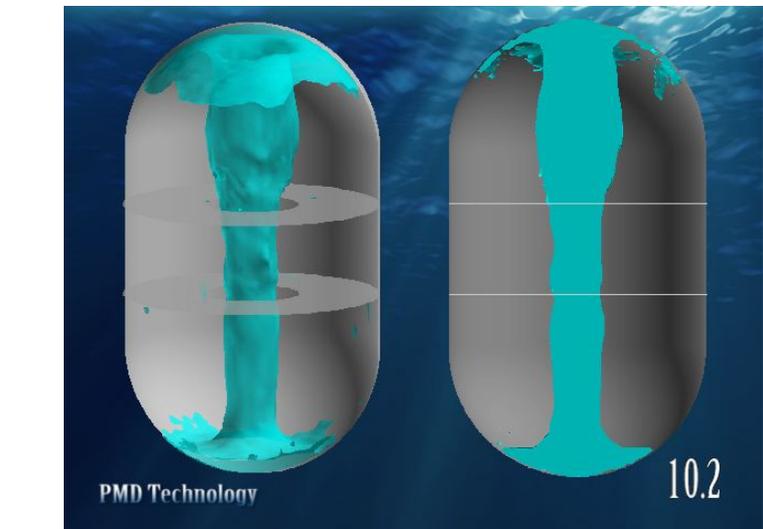
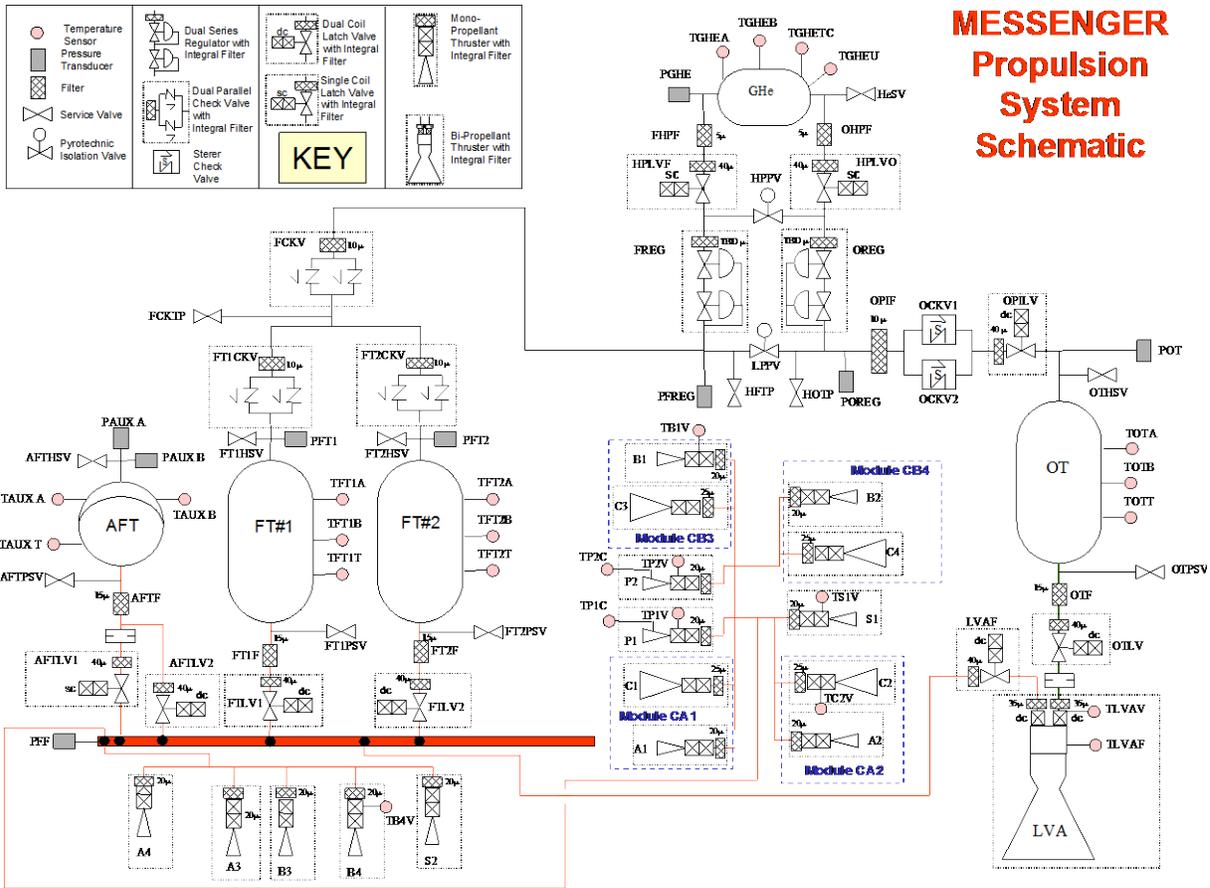


Figure 1. Effect of thruster-induced acceleration on propellant motion.

II. Propulsion System Design

The high ΔV requirement of the mission necessitated a mass efficient propulsion system design. The MPS is a lightweight, 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. This section summarizes how the propulsion system functions and highlights key characteristics that are relevant in subsequent sections. A more detailed description of the propulsion system was provided previously.³ Figure 2 shows the MPS components in schematic form. Figure 3 identifies the major MPS subassemblies.



MESSENGER Propulsion System Schematic

Figure 2. MPS schematic. See the nomenclature list for the full names of abbreviated component names.

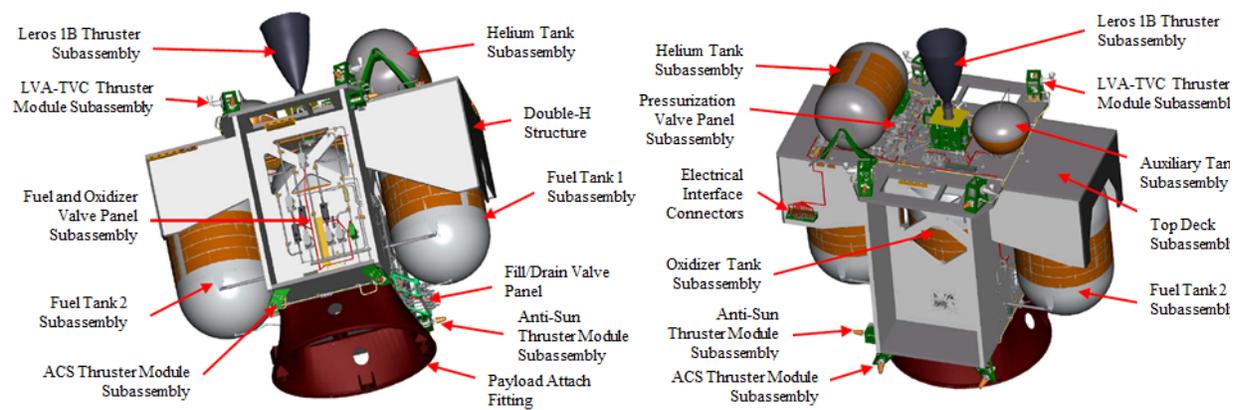


Figure 3. MPS subassemblies. ACS denotes attitude control system; TVC, thrust vector control.

A. MPS Propellant and Pressurant Tanks

Propellant is stored in three identical main tanks (two fuel and one oxidizer) and the refillable auxiliary fuel tank, and helium is stored in a single pressurant tank. The auxiliary tank uses an elastomeric diaphragm for positive propellant expulsion, and the propellant in the main tanks is expelled (after settling force is provided by thrusters fed from the auxiliary tank) by using the helium pressurization system.

Each main tank contains a vortex suppressor used to stabilize flow at the outlet and two annular baffles designed to inhibit propellant slosh during launch.⁴ The impact of the tank baffles on orbital operations is explored in a subsequent section. Table 1 shows the main tank propellant loads at various points during the mission. Note that after OCM-8 the propellant levels in both fuel tank 1 and the oxidizer tank were too low for the propellant to be reliably accessed, i.e., accessed without an unacceptably high risk of pressurant gas ingestion, rendering the two tanks effectively empty.

Table 1. Total propellant load in each main tank during the mission.

Tank	Pre-Launch Load (kg)	Pre-MOI Load (kg)	Post-MOI Load (kg)	Post-OCM-8 Load (kg)
Fuel Tank 1	178.0	74.7	23.6	0.6
Fuel Tank 2	178.0	74.1	23.4	5.2
Oxidizer Tank	231.6	91.4	7.7	1.9

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 Figure 4. The large-velocity-adjust (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.

The LVA, which has been 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 1.69 and 1.99 MPa (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.

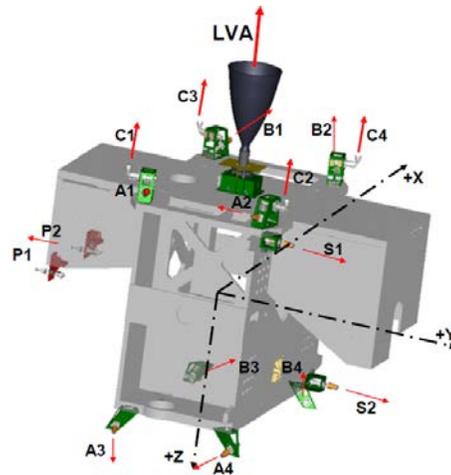


Figure 4. MPS thruster locations and directions.

C. MPS Operational Modes

The MPS has operated in three distinct modes for thruster operation and is maintained in a passive thermal management mode at 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. As detailed in a subsequent section, a one-time adjustment to this abort response was implemented at OCM-7.

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.

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 two primary segments: settle burn and main burn. Given that the main propellant tanks do not have propellant-management devices (PMDs) (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 (see Fig. 4 for the spacecraft coordinate system), the A1, A2, B1, and B2 top deck 4.4-N thrusters are fired for a predetermined period of time. 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 by using one of the pressurized main fuel tanks as the primary propellant source.

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 primary segments: settle burn, refill burn, main burn, and trim burn. The settle segment is the same as it is in 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 [OPLV]) are opened, and the LVA is operated by 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]).

D. Impact of Tank Design on Operations in Orbit

The propulsion system was optimized for mass and volume, and its design had to accommodate many challenges, including the facts that it was launched “upside-down” (i.e., the tank outlets were “up”) and that internal baffles were required in the main propellant tanks to keep the system’s nutation time constant sufficiently high to maintain stability during the portion of the flight that was on the spinning upper stage of the launch vehicle. The price paid for this optimization, however, was that removing the last remnants of propellant from the main tanks became complicated.

The maneuver execution difficulty posed by the baffles during the spacecraft’s journey to Mercury has been documented previously.⁵ Although the cruise problems were effectively circumvented, the low post-MOI propellant levels in the main tanks introduced three new problems. The first two problems listed below were caused by the absence of an internal PMD; the third problem was directly caused by the baffles:

1. The settling strategies used during the cruise phase were no longer effective in bringing enough propellant to the outlet to ensure gas-free propellant flow.
2. Even if the initial settling operations were successful in moving the propellant to the outlet, subsequent ignition of the C thrusters or the LVA engine during the main burn segment could disturb the propellant pool and uncover the outlet, thereby flowing pressurant gas to the thrusters rather than propellant. If these standard cruise-phase techniques were applied, a propellant geyser would be generated, as pictured in Figure 1.
3. An unintended consequence of the baffles was their impact on the amount of propellant available to be expelled. Because of the slight out-of-flatness inherent in the baffle manufacture, the baffles physically trap propellant on their surfaces during propulsion system operation. In addition to the propellant trapped on the baffles as a result of their geometry, there is an additional quantity that (because of surface tension forces) attaches to the surfaces of the baffle, the adjacent tank wall, and even the surface of the propellant pool trapped on the baffle. These areas of trapped propellant are depicted in Figure 5.

III. Strategies for Propellant Extraction During the Primary Mission Period

Before orbit insertion, settling the propellant over the main tank outlets required that the four $-z$ -direction-facing A and B thrusters fire for 15 s. After MOI, this settling procedure would have settled only a small portion of the remaining propellant in the main tanks. To bring more propellant toward the outlet and ensure gas-free propellant expulsion before ignition of the larger thrusters, this settling time had to be extended to 60 s. At this

duration, the nominally 4.0-N of $-z$ -direction force from the A/B thrusters would settle the maximum amount of propellant possible at that thrust level. This 60-s settling period was standard for all of the orbital maneuvers. The requisite operational segments that followed the initial 60-s settle varied with the maneuver type and propellant tank fill level. The propulsion system guidelines outlined in this section were used during the nominal orbital mission, spanning OCM-1 to OCM-5.

A. Mode-3 Maneuvers

The mode-3 burn sequence was designed to accomplish three goals. First, propellant adhering to the lower baffle had to be brought down to the outlet so that it could be accessed. At low fill levels, the A/B thrusters could not accomplish this. Second, the propellant outlet had to be continuously submerged with an adequate depth of propellant to ensure gas-free propellant delivery. If gas came too near the outlet, the surface dip effects would allow the gas to be ingested into the propulsion system and the thrusters. Although some gas ingestion was acceptable, the desire to eliminate risk required us to avoid gas ingestion if possible. Third, at burn termination it was important to ensure that any residual propellant motion would not cause the propellant to geyser up the centerline of the tank and be deposited above the lower baffle where further access would prove difficult if not impossible.

The burn was broken into several segments, each addressing one or more of the three concerns listed above. The burn duration of each segment was explored with the computational fluid dynamics (CFD) code FLOW-3D from Flow Science, Inc. Minimum durations for each segment were established to minimize dynamics and ensure propellant access.

The A/B thrusters were fired to move as much propellant as possible to the aft end of the tank. Unfortunately, hydrazine's surface tension forces around the baffles meant that a substantial amount of hydrazine would remain attached to the lower baffle at the end of the A/B burn. In addition, the pool formed in the bottom of the hydrazine tank would be highly curved, as shown in Figure 6. As a result of the surface tension forces and the low fill levels, firing the LVA immediately after an A/B settling burn, which worked for the prior burns, was not viable. Upon A/B termination, there was insufficient propellant settled in the bottom of the tank for an LVA ignition without gas ingestion.

Analysis also showed that although an LVA burn could move the vast majority of the propellant from above the baffles to the outlet, the A/B thrusters could not. This meant that if liquid were deposited above the baffles during a burn sequence, this propellant would be inaccessible for thruster ignitions. At low fill levels, this situation would lead to gas ingestion during the main burn segment. As a result, depositing propellant above the baffles was to be avoided.

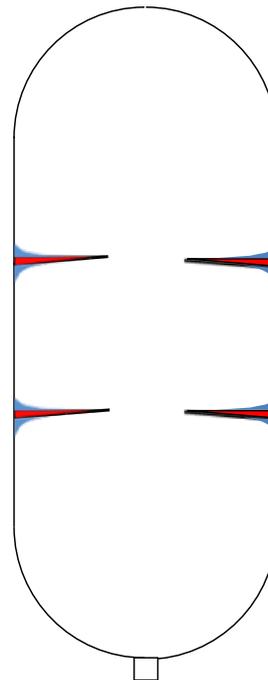


Figure 5. Unusable propellant on the main tank baffles. Red shading indicates propellant trapped as a result of baffle geometry, and blue shading indicates propellant trapped because of surface tension.

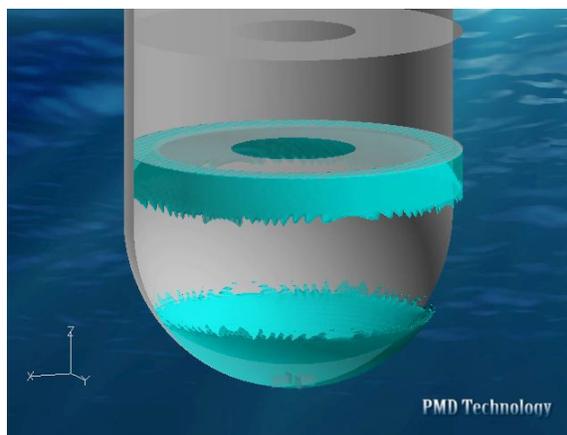


Figure 6. Fuel position at end of A/B-thruster settling.

To bring more of the propellant that had adhered to the lower baffle to the aft end of the tank, the larger C thrusters would have to be fired before LVA ignition. Firing the C thrusters would also reduce the curvature of the pool, placing propellant closer to the outlet. The questions became (a) how long must the thrusters be fired, (b) how many thrusters should be fired, and (c) how much propellant must be in the tank to avoid putting liquid above the baffles? The longer the C-thruster firing, the less efficient the burn and the more hydrazine that is required. To achieve propellant equilibrium and a quiescent propellant pool, an exceptionally long C-thruster burn was required. In addition, we compared firing two C thrusters to firing four C thrusters. The acceleration produced by two C thrusters proved to be sufficient to overcome the surface tension forces adhering propellant to the baffles, produced significantly less propellant dynamics (i.e., slosh) during the burn, and would require less fuel during the burn. When the two C thrusters were fired, propellant moved from the baffles to the outlet along the tank walls. When the liquid reached the outlet, it moved upward along the tank centerline, forming a geyser, as shown in Figure 7. If there were <7.35 kg of fuel in a fuel tank, liquid would geyser above the lower baffle,

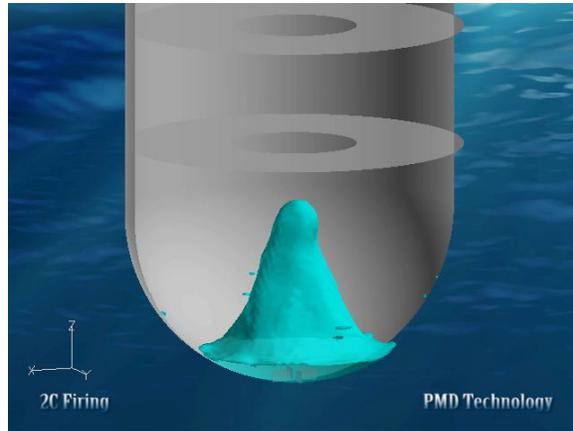


Figure 7. Fuel geyser during two-C-thruster ignition.

potentially increasing fuel residuals (throughout the rest of this document, the 7.35-kg fuel limit will be referred to as the “minimum per tank fuel load limit”). As the C burn continued, the geyser would fall and propellant would slosh in a periodic motion: outboard-inboard-outboard-inboard. If the C burn were terminated and the LVA were ignited too soon, the inboard-to-outboard slosh would be excited by the higher LVA acceleration. With CFD, the minimum two-C-thruster burn was determined to be 23 s. This duration would ensure that the slosh dynamics had sufficiently dampened to avoid unacceptable LVA excitation, even if LVA ignition occurred at maximum liquid potential energy. It should be noted that we did not try to time the ignition to the slosh frequency, an approach that we deemed to be too difficult and risky. The C-thruster burn was sufficiently long that the LVA could be ignited with the liquid at its highest, worst-case position. Unacceptable LVA excitation would create a geyser that deposited liquid above the lower baffle. This calculation established the minimum C-thruster firing duration.

Because a 23-s, two-C-thruster firing is insufficient to produce a quiescent propellant pool, the subsequent LVA firing would excite some inboard-to-outboard slosh. If the LVA were terminated too soon, the residual propellant motion could again deposit liquid above the lower baffle via a centerline geyser. Avoiding this situation yields a minimum LVA burn duration. After a 23 s, two-C-thruster firing, the LVA must be fired for at least 12 s to ensure that no liquid would geyser above the lower baffle after the LVA termination.

Finally, and in addition to the minimum LVA burn duration, a trim burn was required to keep the liquid at the aft end of the tank. Because the trim burn was a part of normal operations, it was used to minimize the required LVA duration. The minimum required trim duration was established to be 61 s by the oxidizer geyser formed after a 12-s LVA burn. During the last LVA burn, the trim could be shortened to 36 s minimum because the oxidizer tank was not going to be used further and the time required to eliminate a termination geyser in the fuel tank was less.

Using this sequence of burns, the propellant could be kept at the aft end of the tank and the thrusters could be fired without gas ingestion. The details of each segment are captured in Tables 2 and 3. The following summarizes the rationale for each segment:

- Segment 1 (settle), 60-s A/B minimum: to move as much propellant off of the baffles as possible with A/B-only thrust.
- Segment 2 (settle/refill), 23-s, two-C-thruster minimum: to make the propellant sufficiently quiescent that LVA ignition would not cause a geyser that reached beyond the bottom baffle.
- Segment 3 (main), 12-s LVA minimum: to dampen the propellant excitation (caused by the initial LVA ignition) sufficiently so that upon LVA shutdown, the sudden loss of force would not cause a geyser that reached beyond the bottom baffle.
- Segment 4 (trim), 61-s (36 s for last LVA burn) two-C-thruster minimum: “soft landing” segment to further stabilize the propellant after LVA shutdown.

- If Segment 3 (main) were shorter than 12 s, there is no amount of Segment 4 (trim) time that would contain the geyser in the lower compartment.
- Segment 4 minimum duration was allowed to be shortened to 36 s for the last LVA burn because the oxidizer geyser was the driver (i.e., 36 s is the minimum Segment 4 duration to prevent a large fuel geyser).

Table 2. Nominal post-MOI LVA burn sequence.

Burn Order	Burn Type	Thruster(s)	Minimum Duration (s)	Propellant Source
1	Settle	A1, A2, B1, B2	60	Aux Tank
2	Settle/Refill	C1 & C4 or C2 & C3	23	Main Tanks
3	Main	LVA	12	Main Tanks
4	Trim	C1 & C4 or C2 & C3	61	Main Tanks

Table 3. Post-MOI final LVA maneuver burn sequence.

Burn Order	Burn Type	Thruster(s)	Minimum Duration (s)	Propellant Source
1	Settle	A1, A2, B1, B2	60	Aux Tank
2	Settle/Refill	C1 & C4 or C2 & C3	23	Main Tanks
3	Main	LVA	12	Main Tanks
4	Trim	C1 & C4 or C2 & C3	36	Main Tanks

B. Mode-2 Maneuvers

Similar to the mode-3 maneuvers, the mode-2 maneuvers required specific minimum burn durations to (a) move propellant adhered to the lower baffle to the outlet so that it could be accessed, (b) maintain the outlet submerged in propellant, and (c) prevent liquid from forming a geyser that reached above the lower baffle. The 60-s minimum A/B settling burn did not change, but the 23-s, two-C-thruster burn required for LVA ignition had to be lengthened with no LVA firing. The minimum two-C-thruster burn duration was 35 s to ensure that the residual propellant motion did not allow the liquid to rise above the lower baffle. It should be noted that the residual motion could create a geyser, but if the burn were sufficiently long, the residual velocities in the geyser (moving the propellant upward) would be overcome by the surface tension forces pulling the propellant aft. A 50-s A/B-thruster minimum trim segment was required after the 35-s minimum two-C-thruster firing.

Also, at the lower fill levels for future burns (below the minimum per tank fuel load limit), the C-thruster firings could not acquire gas-free propellant from the main tanks during the initial portion of the burn. For the first 40 s of the C-thruster firing, gas exposure of the outlet was possible. Therefore, at low fill levels, the auxiliary diaphragm tank had to be used for the first 40 s of C-thruster firing; thereafter the main fuel tanks could be used for propellant.

The details of each segment are captured in Tables 4 through 7. The following summarizes the rationale for each segment:

- Segment 1 (settle), 60-s A/B minimum: to move as much propellant off of the baffles as possible with A/B-only thrust.
- Segment 2 (main), 35-s, two-C-thruster minimum: if two C thrusters fired for any shorter period, then a propellant geyser would form after C-thruster shutdown that would rise above the lower baffle and potentially deposit propellant on top (this would happen regardless of how long the A/B thrusters were fired after the two C thrusters stopped firing).
- Segment 3 (trim), 50-s A/B minimum: “slow landing” for the geyser so that the change in acceleration caused by the two C thrusters shutting off would not cause the formation of a geyser that passed the bottom baffle.
 - This duration is actually dictated by the oxidizer. The oxidizer pool requires a longer “trim” duration to ensure that propellant is not deposited onto the baffles.
 - As captured in Tables 6 and 7, if the two-C-thruster main burn segment were at least 67 s, an A/B-trim segment would not be necessary (i.e., the additional two-C-thruster firing time would sufficiently dampen the propellant motion).

Table 4. Post-MOI nominal mode-2 maneuver burn sequence with main fuel tank fill fraction greater than the minimum per tank fuel load limit.

Burn Order	Burn Type	Thruster(s)	Minimum Duration (s)	Propellant Source
1	Settle	A1, A2, B1, B2	60	Aux Tank
2	Main	C1 & C4 or C2 & C3	35	Main Tanks
3	Trim	A1, A2, B1, B2	50	Main Tanks

Table 5. Post-MOI nominal mode-2 maneuver burn sequence with main fuel tank fill fraction less than the minimum per tank fuel load limit.

Burn Order	Burn Type	Thruster(s)	Minimum Duration (s)	Propellant Source
1	Settle	A1, A2, B1, B2	60	Aux Tank
2	Main	C1 & C4 or C2 & C3	35	First 40 s: Aux Tank After 40 s: Main Tanks
3	Trim	A1, A2, B1, B2	50	If Main Burn < 40 s: Aux Tank If Main Burn > 40 s: Main Tanks

Table 6. Post-MOI no-trim mode-2 maneuver burn sequence with main fuel tank fill fraction greater than the minimum per tank fuel load limit.

Burn Order	Burn Type	Thruster(s)	Minimum Duration (s)	Propellant Source
1	Settle	A1, A2, B1, B2	60	Aux Tank
2	Main	C1 & C4 or C2 & C3	67	Main Tanks

Table 7. Post-MOI no-trim mode-2 maneuver burn sequence with main fuel tank fill fraction less than the minimum per tank fuel load limit.

Burn Order	Burn Type	Thruster(s)	Minimum Duration (s)	Propellant Source
1	Settle	A1, A2, B1, B2	60	Aux Tank
2	Main	C1 & C4 or C2 & C3	67	First 40 s: Aux Tank After 40 s: Main Tanks

IV. Strategies for Propellant Extraction During the Extended Mission Period

Each of the next three maneuvers introduced a different variable that had not been accounted for previously: OCM-6 was designed to use four C thrusters for the main burn rather than the orbit-standard two C thrusters, OCM-7 was designed as an oxidizer depletion burn and started with one fuel tank below the minimum per tank fuel load limit, and OCM-8 was designed as a main-tank fuel-depletion maneuver and started with both main fuel tanks below the minimum per tank fuel load limit. In addition, the tank-switching and thruster-selection schemes of OCM-7 and OCM-8 were entirely dependent on the performance of the preceding maneuver. The details of these maneuvers are explored in section V.

A. OCM-6 Operational Guidelines

OCM 6 was designed as a periapsis-lowering maneuver with a ΔV of ~ 19 m/s. Although this value was greater than the typical 18 m/s threshold required for mode-3 maneuver application, a conservative mode-2 approach was used given that this would be the first maneuver within the time frame of MESSENGER's extended mission. The previous OCM was of a similarly high magnitude (~ 22 m/s), but the mission design engineers requested that OCM-6 be executed with all four C thrusters, rather than repeating the lengthy two-C-thruster main burn used at OCM-5 (232 s). This four-C-thruster approach was used as a test case in preparation for OCM-7 and OCM-8. Both were large maneuvers that needed shorter burn times to increase maneuver execution efficiency. Although OCM-7 was designed as an LVA maneuver, if there were far less oxidizer available than estimated, the C thrusters would be responsible for a greater portion of the ΔV .

The original orbit maneuver guidelines were for two C thrusters for the mode-2 main burn sequences because they created more manageable propellant dynamics than would all four thrusters. To minimize the propellant accelerations during a four-C-thruster main burn to an acceptable level (to prevent the propellant geyser from reaching beyond the lower baffle), OCM-6 required the same pre-settling sequence used for orbit-phase LVA operation. And to complete the maneuver without an A/B-thruster trim segment, the four-C-thruster main burn had to last for at least 41 s. The updated guidelines are captured in Table 8.

Table 8. Updated maneuver guidelines for OCM-6.

Burn Order	Burn Type	Thruster(s)	Minimum Duration (s)	Propellant Source
1	Settle	A1, A2, B1, B2	60	Aux Tank
2	Settle/Refill	C1 & C4 or C2 & C3	23	Main Tanks
3	Main	C1-C4	41	Main Tanks

B. OCM-7 Operational Guidelines

The next two OCMs were used to reduce the orbit period from 12 h to 8 h. Selected to achieve the maximum scientific return from the extended mission, the lower orbit period yielded more orbits per day and more time close to the planet. To lower the period, the spacecraft had to deplete its remaining usable oxidizer in one final bipropellant maneuver. Four days later, a monopropellant maneuver would follow to complete the orbit transition, exhausting the remaining usable fuel in one of the main tanks in the process. OCM-7 proved to be the most complex maneuver of the mission because the uncertainty with regard to the level of remaining oxidizer introduced the potential for premature oxidizer depletion and consequent uncertainty in how the main engine would react.

Further complicating the maneuver was the possibility of a temporary gas-ingestion event, as had occurred on the oxidizer side during the OCM-3 LVA burn. Analysis showed that there would likely be a recurrence of this gas ingestion in the early portion of the OCM-7 LVA segment. In response to this eventuality and the potential early depletion of oxidizer (less oxidizer actually available than estimated), new autonomy and thruster operation procedures were introduced specifically for OCM-7.⁶

Changes made to the OCM-7 thruster operation procedures were meant to mitigate the effects of early oxidizer depletion. To prevent the fuel geyser from reaching the baffles in the event of early LVA cutoff, four C thrusters were planned to fire at ~100% duty cycle (off-pulsed) during the main burn. In addition, the pre-LVA settling duration was extended to further stabilize the propellant. However, in the event of maximum LVA operation during the main burn, the four-C-thruster trim had to be a minimum of 41 s in order to prevent a post-LVA-burn geyser that might transfer fuel to the baffles. Because fuel tank 1 (FT1) was below the minimum per tank fuel load limit, fuel tank 2 (FT2) had to be used for the first two segments after the A/B settle. The updated guidelines are captured in Table 9.

Table 9. Updated maneuver guidelines for OCM-7, given that sufficient usable oxidizer remained.

Burn Order	Burn Type	Thruster(s)	Minimum Duration (s)	Propellant Source
1	Settle	A1, A2, B1, B2	60	Aux Tank
2	Settle/Refill	C1 & C4 or C2 & C3	70	FT2
3	Main	LVA, C1-C4	29	FT2
4	Trim	C1-C4	41	Main Tanks

C. OCM-8 Operational Guidelines

The thruster selection and firing duration for OCM-8 were dependent on the amount of fuel that had been consumed or lost to the baffles during OCM-7. Given that the bipropellant portion of OCM-7 lasted for the maximum duration, OCM-8 had the maximum possible available fuel. And because FT2 had been used for the entire OCM-7 maneuver, for the first time in the mission both main fuel tanks were below the minimum per tank fuel load limit. For this reason, the propellant in those tanks could not be accessed until later in the two-C-thruster main burn segment (after the usual 60-s A/B-thruster settle period), during which time the propellant had to be drawn from the auxiliary tank. Further analysis indicated that the 40-s period that had been previously recommended for this auxiliary-tank-fed, two-C-thruster settle segment could safely be reduced to 35 s. This shorter duration was

implemented at OCM-8. And because OCM-8 was designed to deplete the main fuel tanks, there were no time restrictions on the four-C-thruster main burn segment. The updated guidelines are captured in Table 10.

Table 10. Updated maneuver guidelines for OCM-8.

Burn Order	Burn Type	Thruster(s)	Minimum Duration (s)	Propellant Source
1	Settle	A1, A2, B1, B2	60	Aux Tank
2	Settle	C1 & C4 or C2 & C3	35	Aux Tank
3	Main	C1-C4	N/A	Main Tanks

V. MPS Performance in Orbit

Three months after the MOI event and nearly seven years after MESSENGER's launch, the propulsion system performed its first OCM using guidelines that had been developed just one year earlier. Except for what appeared to be a brief gas-ingestion event at OCM-3, discussed further below, propulsion system performance during the first five OCMs was nominal. The maneuver data for each of these OCMs are captured in Table 11.

Table 11. OCM performance details.

Event	Date	Burn Length (s)	LVA On Time (s)	Performance			Propellant Consumed		Ending Total Propellant Mass (Unusable + Usable)			
				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)
OCM-1	15 Jun 2011	207	15	27.840	78.258	260.632	4.707	1.522	10.534	23.562	23.362	7.700
OCM-2	26 Jul 2011	218	N/A	4.036	10.628	121.803	1.918	N/A	10.608	20.065	19.622	7.700
OCM-3	7 Sep 2011	194	13	24.936	74.057	254.096	4.325	1.318	10.422	17.840	17.666	4.891
OCM-4	24 Oct 2011	189	N/A	4.141	12.459	131.628	1.797	N/A	10.557	17.238	16.230	4.891
OCM-5	5 Dec 2011	319	N/A	22.183	39.227	207.718	6.057	N/A	10.410	11.268	16.230	4.891
OCM-6	3 Mar 2012	198	N/A	19.212	53.858	208.942	5.162	N/A	10.526	8.671	13.468	4.891
OCM-7	16 Apr 2012	217	29	53.257	136.149	264.184	8.176	2.972	10.572	8.671	5.200	1.919
OCM-8	20 Apr 2012	273	N/A	31.420	62.520	214.945	7.942	N/A	10.725	0.576	5.200	1.919

A. OCM-3 Gas-Ingestion Event

The OCM-3 maneuver began as expected, but 7 s into the LVA segment, the total spacecraft thrust dropped suddenly by ~75 N. After quickly reaching this nadir, the thrust ramped back up to steady state over a period of ~1.5 s. This discrete decrease in thrust was approximately coincident (~1 s after) with a switch of the main tanks. The OCM-1 data showed no such thrust transients. Likewise, the thrust profile at the end of MOI did not suggest gas ingestion. The preliminary conclusion was that because the level of usable oxidizer remaining in the tank was very low, the spacecraft accelerations caused the oxidizer pool to briefly move away from the outlet. Although the gas ingestion occurred after a fuel tank switch, subsequent analysis ruled out the possibility that either fuel tank was the source.

After recreating the maneuver in a simulation, however, the low-oxidizer-fill-level theory was deemed unlikely. Further analysis indicated that the most likely cause of the gas-ingestion event was a drop of propellant pouring off of an oxidizer tank baffle. Under this scenario, the temporary gas ingestion would have been caused by the wake of the droplet as it entered the shallow propellant pool.

The CFD analysis conducted to establish minimum burn durations for OCM-3 examined the fluid dynamics of the liquid adhered to the bottom of the baffle. It was assumed that OCM-2 moved all of the propellant aft and that thermal or other effects did not condense liquid forward of the lower baffle. After gas ingestion was seen in

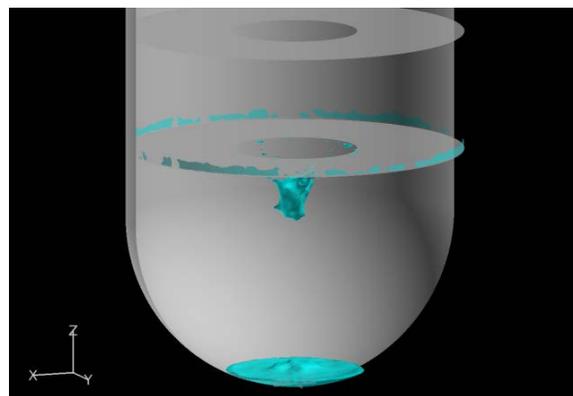


Figure 8. Droplet formation from fuel above the lower baffle.

OCM-3, further CFD analysis showed that this assumption was not likely to hold. As shown in Figure 8, if some liquid were above the lower baffle, the LVA ignition would cause it to move aft. When this large drop of oxidizer impacted the propellant pool, the liquid around the outlet would be forced outboard and the outlet would be exposed to gas, as shown in Fig. 9. The timing of the gas ingestion was consistent with the time required for oxidizer above the lower baffle to move inboard and drop into the pool over the outlet and then for a gas bubble to transit the propellant lines. Furthermore, the duration of the gas ingestion was also consistent with CFD predictions of the outlet's exposure to gas due to a drop of a specific size impacting the shallow pool.

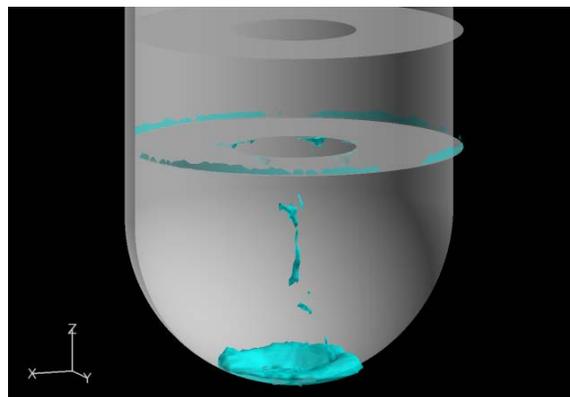


Figure 9. Gas ingestion as drop impacts pool.

Before OCM-7, CFD analysis was conducted to predict the timing of gas ingestion should another drop of liquid fall from above the lower baffle. The predicted timing matched a gas-ingestion event witnessed during OCM-7. The gas-ingestion duration was shorter during OCM-7 than during OCM-3, indicating a smaller drop size in OCM-7 (less liquid above the lower baffle).

B. MPS Performance During OCM-6 to OCM-8

At OCM-6, a miscommunication between the propulsion and G&C engineers led to the auxiliary tank being used for longer than originally intended. Instead of pulling from one of the main fuel tanks for the 23-s, two-C-thruster settling segment, the auxiliary tank was used (this difference was caught early enough that a change could have been made, but since the impact was minimal the team elected not to update the sequence). Although this procedure resulted in a larger disparity between fuel tank expenditures than intended, the difference was sufficiently small that it had no major impact on the minimum projected post-OCM-7 main fuel tank load. In addition, this benign oversight proved serendipitous because the two-C-thruster auxiliary tank segment results were used to design a similar segment in OCM-8. The 3 March 2012 OCM-6 was used to impart 19.212 m/s ΔV , successfully lowering the periapsis altitude back to 200 km and setting the stage for the transition into the extended mission orbit. The as-executed maneuver sequence is captured in Table 12.

Table 12. As-executed OCM-6 maneuver sequence.

Burn Order	Burn Segment	Primary Thruster(s)	Duration (s)	Propellant Source
1	A/B-Thruster Settle	A1, A2, B1, B2	60	Aux Tank
2	Two-C-Thruster Settle	C1 & C4	23	Aux Tank
3	Four-C-Thruster Main	C1-C4	33	FT2
4	Four-C-Thruster Main	C1-C4	56	FT1

The first in a pair of 8-h orbit-transition maneuvers, OCM-7 was designed to deplete the remaining usable oxidizer. Because OCM-7 was the first mode-3 maneuver after the OCM-3 temporary gas-ingestion event, the team worried about the potential implications on the pivotal maneuver. If the anomaly occurred because of low oxidizer levels, the duration of the LVA segment would be far shorter than expected. But if it had been produced by a propellant droplet, as was believed, then there was only the potential for another very brief drop in thrust.

Fortunately, the LVA operated for the maximum 29 s. Corroborating the propellant drop theory, there was a short period (~0.3 s) of gas ingestion at the front end of the LVA segment. The rest of the maneuver proceeded with uninterrupted oxidizer flow. And although the four C thrusters fired for 29 s after the LVA segment instead of the required 41 s, there was enough margin in the propellant dynamics analysis that it is likely that the geyser did not reach beyond the lower baffle. The shorter four-C-thruster firing time was due to a higher-than-expected LVA thrust, which was, in turn, caused by an increase in the oxidizer tank's pressure when its pressurization latch valves were opened prior to LVA ignition (the oxidizer regulator was not fully closed). The as-executed maneuver sequence is captured in Table 13.

Table 13. As-executed OCM-7 maneuver sequence.

Burn Order	Burn Segment	Primary Thruster(s)	Duration (s)	Propellant Source
1	A/B-Thruster Settle	A1, A2, B1, B2	60	Aux Tank
2	Two-C-Thruster Settle	C1 & C4	70	FT2
3	LVA + Four-C-Thruster Main	LVA, C1–C4	29	FT2
4	Four-C-Thruster Trim	C1–C4	29	FT2

Four days after the execution of the previous maneuver, OCM-8 completed the 8-h orbit transition on 20 April 2012. The maneuver was planned to deplete the main fuel tanks down to their conservative unusable propellant levels. However, because of a previously unidentified singularity in the G&C tank-switching code, the planned FT1 to FT2 switch never occurred.⁶ Fortunately, sufficient margin existed in the FT1 unusable propellant estimate to allow the maneuver to proceed without any interruption in propellant flow. Given that FT1’s remaining propellant load is now too low to be reliably settled (i.e., there would be an unacceptably high risk of gas ingestion), the tank will not be accessed again. For future OCMs that use FT2, the same 35-s, two-C-thruster settling period will be followed. The as-executed maneuver sequence is captured in Table 14.

Table 14. As-executed OCM-8 maneuver sequence.

Burn Order	Burn Segment	Primary Thruster(s)	Duration (s)	Propellant Source
1	A/B-Thruster Settle	A1, A2, B1, B2	60	Aux Tank
2	Two-C-Thruster Settle	C1 & C4	35	Aux Tank
3	Four-C-Thruster Main	C1–C4	146	FT1

After the MESSENGER spacecraft was safely nestled into its new, shorter-period orbit, no further OCMs were needed before the end of the extended mission. However, the unexpected bounty of usable propellant that was made available by the OCM-8 maneuver has given the mission an opportunity to address questions about Mercury’s nature and history that could not have been raised before the MESSENGER’s discoveries from orbit, and a second extended mission has been proposed.

VI. Conclusion

After the MOI maneuver, the MPS required updated propellant settling techniques to ensure that the remainder of the propellant was used as efficiently as possible. The propulsion team was able to identify updated operational guidelines that mitigated significant propellant deposition on the main tank baffles and prevented potentially problematic gas ingestion to the thrusters. The original guidelines were successfully used in the first five OCMs, but modifications had to be made to fit the special needs of OCM-6 to OCM-8. Except for two brief, benign instances of gas ingestion during OCM-3 and OCM-7, the propulsion system operated nominally, depleting all of the usable propellant from the oxidizer tank and one of the main fuel tanks.

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