Contingency Plans for MESSENGER's Mercury Orbit Insertion Maneuver

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MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Ranging) will be the first spacecraft to orbit the planet Mercury when it begins its one-year Mercury orbital mission phase next year. On 18 March 2011 MESSENGER will perform the critical 862 m/s Mercury orbit insertion (MOI) maneuver. This paper summarizes strategies for recovering MESSENGER's science mission in the event of an aborted or anomalous MOI maneuver. If 70% or more of the MOI burn is completed, MESSENGER will be captured into a high Mercury orbit. One or two maneuvers would then be required to achieve the planned 82.5°-inclination, 12.0-hour orbit, and all science objectives can be met for most of these cases. If less than 70% of the MOI burn is completed, MESSENGER would remain in a heliocentric orbit, and a recovery maneuver must occur either 10 to 14 days after the 18 March 2011 MOI attempt, or approximately one Mercury year (87.97 days) later in June 2011. For these heliocentric trajectories, solutions were found by which the spacecraft returns to Mercury after either one Mercury year or multiple (Earth) years (subsequent to completing one more or one less revolution of the Sun than Mercury). None of the successful return solutions exceeds the 7-year maximum preferred return time to Mercury.

Nomenclature

ΔV	=	delta-V or velocity change
⊕	=	Earth
☿	=	Mercury
⊙	=	Sun
CATO	=	Computer Algorithm for Trajectory Optimization
DSM	=	Deep-space maneuver
LVA	=	Large velocity adjust
MAnE	=	Mission Analysis Environment software
MESSENGER	=	MErcury Surface, Space ENvironment, GEochemistry, and Ranging
MGA	=	Mercury gravity-assist

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MOI	=	Mercury orbit insertion
NEAR	=	Near Earth Asteroid Rendezvous (mission or spacecraft)
OCM	=	Orbit-correction maneuver
S/C	=	Spacecraft
SKI	=	Sun keep-in
STK	=	Satellite Tool Kit
TA	=	True anomaly

I. Introduction

Designed and operated by the Johns Hopkins University Applied Physics Laboratory in Laurel, Maryland, MESSENGER draws leadership from the Carnegie Institution of Washington and benefits from key flight operations contributions from KinetX, Inc., NASA's Jet Propulsion Laboratory and Goddard Space Flight Center, and numerous universities, research institutions, and subcontractors. Supported by NASA's Discovery Program, the spacecraft successfully launched from Cape Canaveral, Florida, aboard a Delta II 7925H-9.5 launch vehicle on 3 August 2004. Since then the spacecraft has successfully performed six planetary flybys (one of Earth, two of Venus, and three of Mercury) and five large deep-space maneuvers (DSMs), accurately following its planned 6.6-year, 4.9-billion mile ballistic trajectory to Mercury.[1] The spacecraft is now on track for arriving at Mercury on 18 March 2011, when it will use its 660-N bipropellant large velocity adjust (LVA) engine to perform a 14.4-minute Mercury orbit insertion (MOI) maneuver. The spacecraft will slowly turn during the maneuver, keeping the velocity change (ΔV) direction close to the Mercury-centered anti-velocity direction to maximize the maneuver's braking effect. This strategy has been successfully tested on two of the DSMs. Some details of the planned MOI maneuver were published before[1], but the earlier designs used a two-burn strategy. The final plan is to accomplish MOI with one burn, to simplify operations and allow a quicker transition to science operations. Adopting the single-maneuver MOI is possible because of more relaxed target requirements on the science orbit, and from results of a recent analysis of the likely variations in the orbit after MOI. Although contingency plans were prepared for each DSM, none of those plans was needed.

Nevertheless, the MOI maneuver is MESSENGER's most time-critical event. Consequently, most autonomy rules will be suspended for MOI, and other steps will maximize the likelihood of accurate and timely maneuver execution. Although the MESSENGER team hopes that the MOI maneuver will be performed as accurately as the DSMs, with < 0.08% ΔV magnitude error and < 0.25º direction error, something unexpected can happen. The sections below describe the aborted main rendezvous burn of the Near Earth Asteroid Rendezvous (NEAR) mission, and how that mission was saved; a "five Mercury flyby" option that could have saved 150-200 m/s of MOI ΔV; an overview of MESSENGER's MOI contingency plan; details of recovery from an MOI maneuver that achieves 70% or more of the planned ΔV and leaves the spacecraft captured in Mercury orbit; details of recoveries from MOI maneuvers that achieve less than 70% of the planned ΔV and leave the spacecraft in heliocentric orbit; and conclusions, including some suggestions for additional work on contingency plans that might be completed before the March 2011 MOI maneuver.

II. Recovery from NEAR's Aborted 1998 Rendezvous Burn

On 20 December 1998, the NEAR spacecraft was programmed to perform the first and largest (650 m/s) of four maneuvers to rendezvous with the asteroid (433) Eros. A contingency plan had been developed beforehand in case there were any problems with that time-critical maneuver[3]. The first NEAR rendezvous burn started on schedule, but within seconds after NEAR's main bipropellant engine began firing, the spacecraft started tumbling and communication was lost. The spacecraft used about 29 kg of propellant to stop the tumble and point its solar panels toward the Sun, while imparting less than 5 m/s of useful ΔV. Onboard autonomy rules kept NEAR pointed at the Sun for 24 hours and then began a slow rotation that allowed the spacecraft to re-contact Earth with its fanbeam antenna and recovery to full operations two days after the attempted maneuver[4]. The NEAR spacecraft passed Eros on 23 December 1998 at nearly 1 km/s. The contingency plan was modified to account for the lost propellant and consequent lower margins by placing a single large maneuver 11 days after the asteroid flyby. This initial recovery maneuver virtually stopped NEAR's motion relative to Eros but left the spacecraft a million kilometers from its target. NEAR drifted back to the asteroid, allowing a successful rendezvous with Eros 13 months later than originally planned[5]. NEAR was able to recover from this serious anomaly due to comprehensive pre-maneuver recovery plans, a prepared flight team, and generous propellant margins. The MESSENGER team, having learned from the NEAR experience, is using a similar strategy for their mission.

III. Five Mercury Gravity-Assist Strategy

In 1999, Langevin[6] suggested adding 1-Mercury-year and ½-Mercury-year loops (adding about 132 days) in order to arrive at Mercury aphelion, therefore, lowering both the velocity relative to Mercury and the orbit insertion ΔV. Yen[7] described this strategy and refined it in 2001. This strategy was considered for MESSENGER, although it would add two more Mercury flybys to the three Mercury flybys already planned. During the first half of heliocentric cruise phase, through DSMs 1 and 2, such a five-Mercury-gravity-assist (5-MGA) strategy provided the potential for achieving full mission success while accommodating the longest DSM delays. For both the mid-December 2005 DSM-1, which targeted the first of two Venus flybys, and the mid-October 2007 DSM-2, which targeted the first of three Mercury flybys, the 5-MGA contingency option extended the latest possible date to complete the DSM and still have enough propellant to complete the mission. The number of planetary gravity-assist flybys and DSMs between DSM-1 or DSM-2 and MOI provided sufficient resiliency to re-optimize the heliocentric trajectory with substantial ΔV savings compared to flight paths that delivered the spacecraft to a mid-March 2011 MOI. This ΔV savings is about 150 m/s for long delays in DSM-1 or DSM-2 execution. The 5-MGA contingency for MOI does not apply to the final three DSMs, which target Mercury flybys 2, 3, and MOI during multiple-orbit heliocentric transfers, because recovery is possible from one-orbit delays in DSMs 3-5 implementation. Since the 5-MGA contingency requires substantial increase in mission complexity and a mission extension of about five months, this option was considered only as a last resort for recovery from the longest possible DSM-1 and DSM-2 delays. Although two types of 4-MGA recovery options were studied, neither option provided ΔV savings versus the nominal 3-MGA flyby sequence. The 5-MGA recovery option is composed of two phases - heliocentric transfer and Mercury orbit insertion.

Heliocentric trajectory changes between the 5-MGA and 3-MGA options include small changes to planetary encounter times and distances through Mercury flyby 2, as well as a larger change to the third Mercury flyby and the addition of a fourth and fifth Mercury flyby. The first DSM-1 or DSM-2 date that qualifies for use of the 5-MGA recovery option is the date on which recovery to the nominal 18 March 2011 MOI and subsequent six orbit-correction maneuvers (OCMs) requires 90% of the estimated propellant margin. For the nominal 12 December 2005 DSM-1, the 5-MGA option extends the latest date that DSM-1 could occur from 13 January 2006 to 7 February 2006. Beginning with a spacecraft state at this delayed DSM date, a preliminary 5-MGA patched-conic trajectory solution was generated using Space Flight Solution's MAnE (Mission Analysis Environment) software. The resulting trajectory supplied integrated optimal trajectory initial conditions for each DSM and planetary encounter target parameter through MOI. The CATO (Computer Algorithm for Trajectory Optimization) software developed by the Jet Propulsion Laboratory then provided an optimal integrated trajectory from the delayed DSM through MOI. Creating the optimal integrated trajectory required determination of the Mercury arrival periapse altitude, MOI thrust start time, maneuver duration, and thrust direction that provide the lowest ΔV while also complying with numerous MOI maneuver constraints discussed in the next section. Changes from the nominal MESSENGER trajectory to the 5-MGA trajectory include an altitude increase at Mercury flyby 3 from 200 km to 729 km, a Mercury flyby 4 (where MOI would normally occur) time shift 2.2 days earlier to 16 March 2011, and addition of a 2,000-km altitude dayside Mercury flyby 5 on 12 June 2011 near the middle of a short-duration solar conjunction (Sun-Earth-spacecraft angle = 1°). Since the Mercury flyby 3 and 4 locations are about the same, the nominal mission's DSM-5 two months after Mercury flyby 3 is no longer necessary. The 2000-km altitude is high enough to alleviate excessive thermal input from sunlight reflected off of Mercury onto the unprotected spacecraft bus. The fourth Mercury flyby includes a one-hour solar eclipse that is only 8-10 minutes below the longest eclipse allowable by battery depth of discharge. Mercury flybys 4 and 5 occur near consecutive Mercury perihelia. The spacecraft would never be far from Mercury between the fifth MGA and MOI, since the orbit period of the spacecraft and Mercury are nearly identical and the Mercury arrival direction limits optimal orbit insertion to 89° relative to Mercury's equator. The 25 July 2011 MOI occurs near Mercury aphelion only 43 days after Mercury flyby 5. The total delay from the nominal mission sequence 18 March 2011 MOI to the 5-MGA MOI is 129 days. These changes offer a number of operational risks that were not experienced during MESSENGER's heliocentric cruise phase.

Differences between the nominal 3-MGA and contingency 5-MGA Mercury orbit insertion strategy extend beyond differences in the heliocentric cruise phase. Because the spacecraft trajectory approaches Mercury near the planet's slowest heliocentric velocity, near aphelion, the arrival hyperbolic excess velocity is less than 1.5 km/s, compared to 2.2 km/s for the nominal MOI near Mercury perihelion. Because the initial Mercury orbit inclination is just over 89°, the initial orbit must be sufficiently high so that solar gravity perturbations act to lower orbit inclination as close as possible to the 82.5° goal for initial orbit inclination. With insertion into a 500-km periapse altitude by 86-hour period orbit, the time where the periapsis-placed apoapsis and period-reduction maneuver can occur with the spacecraft's sunshade able to protect the spacecraft at maneuver attitude is 24 August 2011, one month after MOI. By this point solar gravity perturbations have reduced orbit inclination to 83.0°, sufficiently close to the goal to achieve mission success. The primary science mission can then begin on 7 September 2011, after a two-week spacecraft checkout and science planning update period. Because the 5-MGA Mercury orbit orientation differs from that for the nominal 3-MGA solution, solar gravity alters the orbit parameters in the opposite direction. This means that periapse altitude decreases rapidly (with impact prevented by raising periapse altitude with OCMs), sub-spacecraft periapse latitude decreases to bring longer-duration eclipses, and orbit inclination decreases. The initial choice of 65°N periapse latitude would lead to 55°N periapse latitude and 66-minute duration eclipses one year after MOI. Another difference is in the starting point of the initial MOI maneuver relative to periapsis. In order to maintain Earth's view of the entire MOI while keeping the sunshade pointed to protect the spacecraft, MOI starts at 298° true anomaly – much earlier than 334° true anomaly for the 18 March 2011 MOI. While the nominal 3-MGA trajectory at the time of DSM-1 and DSM-2 had a two-maneuver MOI sequence with a 14.4-hour period orbit between MOI-1 and MOI-2, the 5-MGA trajectory requires the two MOI maneuvers described above plus four additional periapsis-raise maneuvers every six days. Table 1 provides a summary of the 5-MGA option MOI maneuvers.

Table 1. Mercury orbit insertion maneuver details for the 5-MGA contingency.

Name	Date (dd/mm/yyyy)	Location	ΔV (m/s)	Purpose
MOI-1	25/07/2011	periapsis	437.5	enter Mercury orbit
MOI-2	02/08/2011	apoapsis	11.6	raise periapse alt
MOI-3	08/08/2011	apoapsis	9.2	raise periapse alt
MOI-4	14/08/2011	apoapsis	8.0	raise periapse alt
MOI-5	20/08/2011	apoapsis	5.6	raise periapse alt
MOI-6	24/08/2011	periapsis	211.1	enter science orbit
Total ΔV (m/s)			683.0	

Although the 5-MGA contingency strategy for recovery from delayed DSM-1 or DSM-2 would have markedly increased mission risk and complexity, this contingency trajectory produces a workable sequence of planetary flybys and a six-maneuver MOI sequence. Although the delay in primary science orbit entry, from 21 March 2011 after MOI-2 to 24 August 2011 is just over five months, the addition of two planetary flybys and four orbit insertion maneuvers would have challenged the MESSENGER flight team.

IV. MESSENGER MOI Contingency Overview

The Mercury orbit insertion maneuver should capture MESSENGER into Mercury orbit from its heliocentric cruise trajectory in a way that will satisfy the scientific goals of the mission within the capabilities of the spacecraft. The spacecraft capabilities and the science goals impose the following constraints on the MOI maneuver and the desired initial Mercury orbit:

- Period 12.0 hours ± 10 minutes, to maintain operational schedules
- Inclination 82.5° ± 1.0° to Mercury's equator
- Periapse altitude 200 km ± 25 km, to achieve the desired resolution with the spacecraft's scientific instruments (for cases where perturbations raise the periapse altitude; the target is 500 km ± 25 km for cases where the perturbations lower the periapse altitude)
- Periapse latitude from +54° to +61° for observing the north polar region, minimizing eclipse duration, and spacecraft and instrument thermal requirements (for cases where perturbations increase the periapse latitude; +65° is needed if the perturbations decrease periapse latitude)
- The ΔV vector-Sun angle during the entire burn must remain at 90° ± 12° so that all of MESSENGER's critical components remain behind the sunshade
- The entire MOI burn must remain visible from the Earth in order to allow real-time monitoring. This means that not only must Mercury not block the line of sight from the spacecraft to the Earth, but also that the solar elongation (the Sun-Earth-spacecraft angle) must be greater than 3° to ensure communication without too much solar interference.

These initial orbit conditions were selected to take into account the predicted evolution of such an orbit (see Figure 1) in response to all non-gravitational forces, including solar perturbations, aspherical variations in Mercury gravity, and solar radiation pressure[1]. For example, Earth-based radar observations show that ice deposits may exist on the floors of permanently shadowed craters near Mercury's north pole; learning more about these deposits is an important goal of the mission. However, for the nominal MOI, the perturbations will raise periapsis; two OCMs will be performed three times, about 88 days (one Mercury year) apart, to lower periapsis altitude to 200 km (once it evolves to 450-500 km) and to change the orbit period back to 12.0 hours[2].

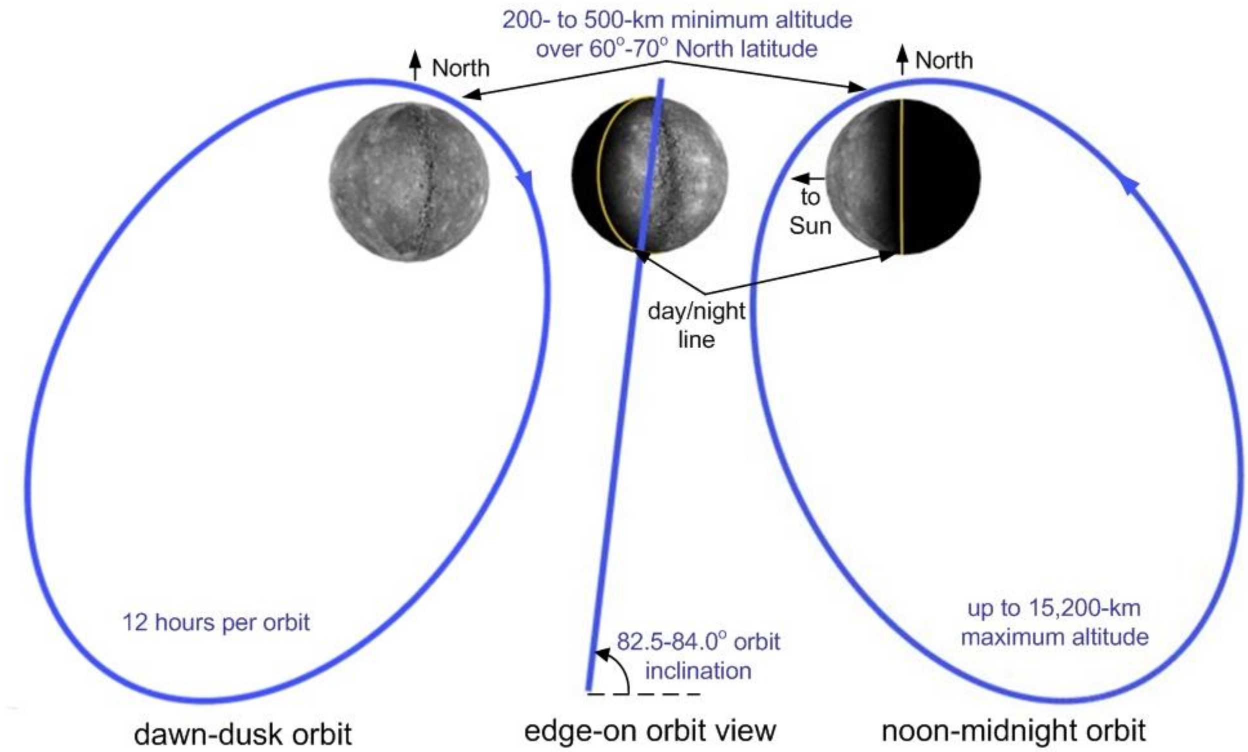

Figure 1. Variation of the MESSENGER science orbit at Mercury.

If the MOI burn is incomplete or missed, the same goals defined above should also be achieved by the maneuvers that constitute the recovery strategy. But any recovery strategy will result in a delay in achieving the science orbit and also will incur a ΔV penalty equal to the total of all ΔVs needed to achieve the orbit minus the percentage of the 862 m/s nominal MOI ΔV that has been completed. Thus, for the contingency cases, more constraints are added:

- The extra flight time from the attempted MOI (18 March 2011) to achieve the science orbit should be less than the maximum number of years (possibly 7) for which project support to continue operations of the 3-axis-stabilized spacecraft can be expected.
- The ΔV penalty should be less than 134 m/s to preserve potential for a fully successful science mission.
- A ΔV penalty between 134 and 224 m/s might result in a partially successful science mission.

Although it is best to minimize both the extra flight time and the ΔV penalty, these are often opposing goals for heliocentric cases (no Mercury orbit capture). For these cases only one goal can usually be achieved. Fortunately, there are several viable cases where the extra flight time is small, and the ΔV penalty is small enough, or vice versa.

For these contingency studies, a Satellite Tool Kit (STK) Astrogator sequence that accurately models the nominal MOI maneuvers was used. The MOI burn is a mode-3 burn, starting with a short propellant settling/refill segment that uses the smallest thrusters, continuing with the main LVA segment with over 99% of the total ΔV, and followed by a short trim segment that uses the four medium "C" thrusters, which are also used as attitude control for the LVA burn[2]. For MOI contingency cases presented in this paper, the duration of the LVA segment was shortened to model the effects of different "underburns" and the final trim segment was removed. These underburns are labeled as the percentage of the nominal MOI ΔV that was achieved. Thus, 0% MOI ΔV means that the MOI maneuver was not performed at all on the planned date of 18 March 2011; 50% MOI ΔV indicates that half of the ΔV, or about 431 m/s, was accomplished; and 100% MOI ΔV would mean that the full nominal MOI maneuver was accomplished. Only the magnitude of the MOI burn was varied for these studies, not its direction. Spacecraft pointing has remained within 0.25° of the planned orientation during all five DSMs.

Results of the contingency study are briefly summarized in Table 2. The table includes the ranges of % MOI ΔV achieved during the attempt on 18 March 2011 for cases involving viable recovery options. Figure 2 is a schematic showing when the recovery ΔVs are performed for the different cases, which are identified by "Code" letters in the first column of Table 2 and in the timeline of Figure 2. The upside-down triangles are for the first (or only, if there is only one) ΔV, identified as the first MOI contingency maneuver, or MOI-C1, and the lower upward-pointing triangles are for the second ΔV, called MOI-C2. In the timeline, "MOI" at the left end is 18 March 2011, the date of the nominal MOI maneuver.

Table 2. Summary of viable contingency recovery plans.

Code	Achieved MOI ΔV (%)	Mercury Capture?	Recovery Plan	Propulsive Mode	Flight Time
E	99.67 - 100.33	Yes	1 ΔV to fix anomalous MOI	2	< 10 days
D2	97.75 - 99.67	Yes	1 ΔV to fix MOI underburn	3	< 10 days
F	90.0 - 97.75	Yes	1 ΔV, delayed recovery	2 or 3	< 10 days
E	83.0 - 90.0	Yes	1 ΔV	2	< 10 days
D1	79.4 - 83.0	Yes	1 ΔV	3	< 10 days
C1	72.4 - 79.4	Yes	2 ΔVs, max. time to MOI C1 burn	2 and 3	< 10 days
C2	72.4 - 79.4	Yes	2 ΔVs, min. time to MOI C1 burn	2 and 3	< 10 days
B	70.7 - 72.4	Yes	2 ΔVs, avoid eclipses	2 and 3	< 10 days
B	70.0 - 70.7	Yes	2 ΔVs, with an eclipse	2 and 3	< 10 days
A1 or A2	20.0 - 40.0	No	2 ΔVs	2 and 3	< 2.3 years
A1 or A2	0.0 - 10.0+, & 50.0	No	2 ΔVs, min. flight time	1, 2, and 3	< 7 years

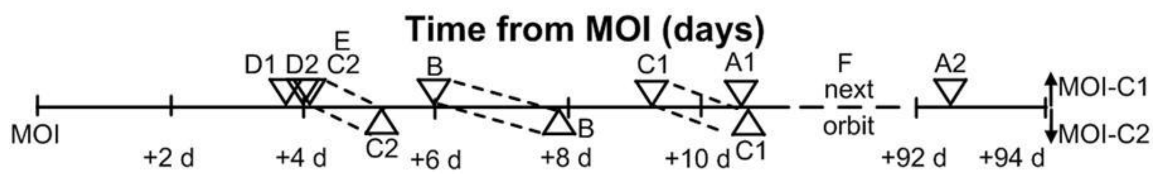

Figure 2. Timeline for contingency recovery maneuvers MOI-C1 and MOI-C2.

The contingency recoveries fall into two categories, depending on whether or not the spacecraft is captured into Mercury orbit, which occurs for MOI maneuver ΔVs of 70% or greater than the ΔV for the planned MOI maneuver.. These recoveries are described in detail in the next two sections.

V. Recovery from Mercury Orbit (≥ 70% MOI ΔV)

The underburn scenarios presented below for recovery from a high Mercury orbit fall into three classifications, large, medium, or small. A large underburn is one in which the spacecraft is captured around Mercury, but the orbit has such a large period that solar gravity perturbations are very influential. For a large underburn, the percent of the MOI maneuver ΔV that is completed falls between 70.0% and 79.4%, and a recovery requires two contingency maneuvers due to the inclination change necessary to achieve the initial science orbit. A medium underburn results in an orbit with period short enough to lessen the influence of solar perturbations and eliminate the need for inclination change to obtain the initial science orbit. Because no inclination change is needed, recovery from a medium underburn requires only a single large contingency maneuver. The orbit resulting from a small underburn at MOI possesses a period of 12 hours and 10 minutes or longer and requires only a single, smaller maneuver to correct to the initial science orbit. Large-underburn scenarios are discussed first.

For large underburns there are several limiting scenarios. For this study a limiting scenario is one in which a lower ΔV for the MOI maneuver would lead to a negative propellant margin at the end of the nominal 1-year orbit-phase mission and require a departure from either the initial science orbit requirements or the nominal orbit-phase mission plan that includes six OCMs. In order to achieve the initial primary science orbit after an MOI underburn that results in a very large orbit about Mercury, a two-maneuver recovery strategy is employed. The first maneuver occurs soon after apoapsis and corrects mainly for inclination and periapse altitude errors, and the second and larger maneuver occurs soon after periapsis and corrects mainly for apoapse altitude and period errors. There are three limiting scenarios that define recovery strategy transition points. The first scenario is the maximum MOI maneuver underburn possible while still achieving full recovery to the initial primary science orbit, the second is the maximum underburn possible while still being able to achieve full recovery without performing a contingency maneuver during an eclipse, and the third is the maximum underburn possible with the first contingency maneuver occurring soon after the second apoapsis crossing rather than the first. Since any underburn larger than this third case must have the first contingency maneuver performed soon after the first apoapsis crossing in order to achieve the initial science orbit, the shortest possible duration between the MOI maneuver and the first contingency maneuver for a large underburn is related to the percentage of MOI ΔV completed. The resulting contingency maneuver specifications, as well as the percentage of MOI ΔV completed for each of the scenarios resulting from a large underburn at MOI, are summarized in Table 3 below.

Table 3. Contingency maneuvers and initial science orbits for large-underburn scenarios.

	Maneuver	Mode	Start Time (UTC)	Duration (s)	ΔV (m/s)	TA (deg)	Sun Elevation Angle (deg)	Eclipse Timing
Scenario 1, 70.0% MOI ΔV completed	MOI-C1	2	25 Mar 2011 1:45:36.0	878.4	141.2	192.0	9.0	n/a
	MOI-C2	3	27 Mar 2011 21:2:58.5	289.9	262.1	14.0	-9.0	5.6 min into 23.6 min eclipse
Resulting initial science orbit	Periapse Altitude = 200.0 km, Period = 12.0 hr, Inclination = 82.5°, Periapse Latitude = 56.7°, RAAN = 341.8°							
Scenario 2, 70.7% MOI ΔV completed	MOI-C1	2	24 Mar 2011 0:35:2.9	636.2	99.5	192.0	9.0	n/a
	MOI-C2	3	25 Mar 2011 20:51:32.0	318.3	293.4	63.0	-9.0	1 min after eclipse end
Resulting initial science orbit	Periapse Altitude = 200.0 km, Period = 12.0 hr, Inclination = 82.5°, Periapse Latitude = 62.6°, RAAN = 344.0°							
Scenario 3, 72.4% MOI ΔV completed, MOI-C1 after second apoapse crossing	MOI-C1	2	27 Mar 2011 6:44:52.2	509.6	78.3	192.0	9.0	n/a
	MOI-C2	3	28 Mar 2011 15:20:57.7	326.1	301.9	73.9	-9.0	1 min after eclipse end
Resulting initial science orbit	Periapse Altitude = 200.0 km, Period = 12.0 hr, Inclination = 82.5°, Periapse Latitude = 64.8°, RAAN = 345.6°							
Scenario 4, 72.4 % MOI ΔV completed, MOI-C1 after first apoapse crossing	MOI-C1	2	22 Mar 2011 4:57:14.8	364.5	53.6	192.0	9.0	n/a
	MOI-C2	3	23 Mar 2011 7:30:17.1	279.5	241.0	37.2	-9.0	1 min after eclipse end
Resulting initial science orbit	Periapse Altitude = 200.0 km, Period = 12.0 hr, Inclination = 82.5°, Periapse Latitude = 59.7°, RAAN = 347.5°							

All contingency maneuvers in these scenarios are inertially fixed.

The pre-recovery and initial science orbits for the first three large-underburn scenarios listed in Table 3 are shown in Figure 3 below. The difference in percentage of MOI ΔV completed is only 2.4% between the largest pre-recovery orbit shown and the smallest. This size difference illustrates how sensitive the pre-recovery orbit is to the cutoff time of the MOI maneuver for these large-underburn scenarios. Also, it is apparent that the MOI maneuver must be very close to 70% percent of the total ΔV completed in order for the spacecraft to be captured into orbit around Mercury, given the sensitivity in this realm, and that this is the smallest percent of MOI maneuver completion possible while still being able to achieve a full recovery.

The 70.0% MOI ΔV completion scenario, first summarized in Table 3, is the largest underburn possible with capture into Mercury orbit with the potential for achieving all mission objectives. In this scenario, the recovery consists of the first contingency maneuver (MOI-C1) occurring 7.03 days after the MOI maneuver cutoff time and at a true anomaly of 192°. MOI-C1 is performed as an inertially fixed mode-2, or mono-propellant, maneuver with a ΔV of 141.2 m/s and duration of 878.4 s. The maneuver is designed such that the Sun elevation angle is 9.0° throughout the maneuver so as not to violate the spacecraft Sun-keep-in (SKI) constraint (this constraint maintains sunshade coverage for all heat-sensitive areas of the spacecraft) of ±12° Sun elevation angle. The second contingency maneuver (MOI-C2) is performed as an inertially fixed mode-3, or bi-propellant, maneuver 2.79 days after MOI-C1 at a true anomaly of 14° and a Sun elevation angle of -9.0°. The MOI-C2 ΔV is 262.1 m/s, and the duration is 282.9 s. In this particular scenario MOI-C2 occurs 5.6 minutes after entering the penumbra of an eclipse lasting a total of 23.5 minutes (total duration is measured from penumbra entry through total eclipse to penumbra exit). The initial science orbit resulting from these two maneuvers has a periapse altitude of 200.0 km, orbit period of 12.0 hours, 82.5° inclination, periapse latitude of 56.7°, and 341.8° longitude of the ascending node; all of which meet the constraints for a nominal initial science orbit. Furthermore, the remaining total ΔV margin at the end of the nominal 1-yr orbit-phase is only 1.7 m/s. While there is no mission precedent for performing any maneuver during an eclipse, it is possible that the maneuver would be attempted to rectify this extreme contingency situation.

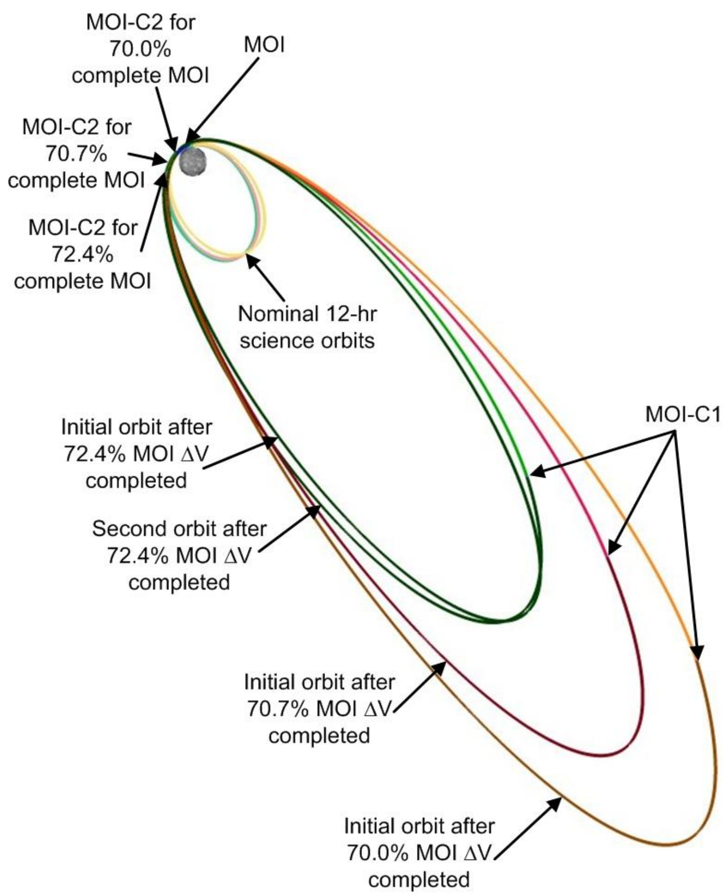

Figure 3. Orbits and correction maneuver locations for large-underburn contingency scenarios. *All scenarios are listed in Table 3. View is as seen from the Sun at the start of MOI. A small difference in the percent of MOI ΔV completed has a large impact on the size of the pre-recovery orbit.*

It is desirable to avoid performing any maneuvers during an eclipse if possible. A maneuver cutoff at 70.7% of MOI ΔV completion is the largest underburn at MOI that still allows for a recovery without performing any contingency maneuvers during an eclipse. The recovery strategy is similar to the previous scenario in that MOI-C1 is an inertially fixed, mode-2 maneuver that occurs at a true anomaly of 192° and has a Sun elevation angle of 9.0°. MOI-C1 begins 5.99 days after MOI, lasts for 636.2 s, and imparts a total ΔV of 99.5 m/s. The MOI-C2 maneuver is designed to begin 1 minute after coming out of partial eclipse, which corresponds to 1.84 days after MOI-C1 and a true anomaly of 63.0°. The inertially fixed mode-3 maneuver occurs at a Sun elevation angle of -9.0°, is 318.3 s long, and has a ΔV of 293.4 m/s. This contingency scenario produces an initial science orbit with a periapse altitude of 200.0 km, period of 12.0 hours, 82.5° inclination, and 344.0° longitude of the ascending node, which are within limits for a nominal initial science orbit. As the recovery maneuver is pushed beyond the end of the eclipse, it causes the resulting periapse latitude of the initial orbit to become higher. The periapse latitude in this scenario is 62.6°, which is 1.6° higher than the requirement; however, the periapse latitude was deemed acceptable given that this is an extreme contingency situation. For this scenario, there is only a 2.9-m/s total ΔV margin at the end of the nominal 1-yr orbit-phase.

A third scenario of interest is the maximum underburn possible with MOI-C1 occurring soon after the second apoapsis crossing rather than the first. A maneuver cutoff at 72.4% of MOI ΔV completion meets the above criteria. The MOI-C1 maneuver is then performed 9.24 days (approximately 1.5 orbits) after MOI at a true anomaly of 192° and a Sun elevation angle of 9.0°. MOI-C1 is an inertially fixed, mode-2 maneuver lasting 509.6 s and imparting 78.3 m/s of ΔV. The second recovery maneuver, MOI-C2 is an inertially fixed, mode-3 maneuver that occurs 1.35 days after MOI-C1. MOI-C2 occurs 1 minute after the end of a solar eclipse, which corresponds to a true anomaly of 73.9°. The second maneuver lasts 326.1 s, has a total ΔV of 301.9 m/s, and occurs at a Sun elevation angle of -9.0°. The resulting initial science orbit meets all requirements except for the periapse latitude. The orbit has a periapse altitude of 200.0 km, period of 12.0 hours, 82.5° inclination, 345.6° longitude of the ascending node, and periapse latitude of 64.8°. Since the recovery for this scenario was delayed by an extra orbit, the MOI-C2 maneuver occurs farther into the eclipse season and must be performed at a larger true anomaly in order to avoid the eclipse, causing the periapse latitude of the initial science obit to be higher than for the other scenarios. Once again the higher periapse latitude was deemed acceptable given the extreme nature of the contingency. At the end of the 1-yr, orbit-phase mission the total ΔV margin is only 0.8 m/s for this scenario. The 1-orbit delay scenario can easily be modified to find the shortest time possible between MOI and MOI-C1 for the realm of large underburns.

Since timing has several implications for contingency design as well as operations, knowing the minimum turnaround time for designing, planning, and uploading a contingency maneuver sequence is necessary. For the large-underburn classification, this time can be found simply by using the 72.4% MOI ΔV cutoff and performing an MOI-C1 maneuver after the first apoapsis crossing rather than the second as was done in the previous scenario. This timing results in MOI-C1 occurring 4.17 days after MOI at a true anomaly of 192°. As in previous scenarios, MOI-C1 is an inertially fixed, mode-2 maneuver and has a Sun elevation angle of 9.0°. The Maneuver lasts 364.5 s and imparts a total ΔV of 53.6 m/s. MOI-C2 occurs 1.10 days after MOI-C1, which corresponds to 1 minute after eclipse exit and a true anomaly of 37.2°. The maneuver is mode 3 and inertially fixed with a Sun elevation angle of -9.0°. The total ΔV is 241.0 m/s occurring over 279.5-s duration. The resulting initial science orbit meets all requirements with a periapse altitude of 200.0 km, period of 12.0 hours, 82.5° inclination, 347.5° longitude of the ascending node, and 59.7° periapse latitude. The minimum time of 4.17 days between the MOI maneuver cutoff and MOI-C1 is an acceptable duration for the design and testing of the contingency maneuver sequence. In fact, for medium and small classifications of underburns, the contingency maneuvers are designed to take place as close to 4.0 days after MOI maneuver cutoff as possible in order to provide the longest duration for contingency planning and testing while still performing MOI-C1 prior to the beginning of a solar eclipse season.

There are two scenarios of particular interest that fall into the classification of a medium underburn. (Recall that a medium underburn is one that results in an orbit that does not require a change in inclination and may be corrected with only a single large maneuver.) The first scenario of interest in this realm is the maximum mode-3 maneuver that would be needed in order to achieve the initial science orbit using only a single maneuver. Since any inclination change is much more efficiently performed using a two-maneuver cleanup strategy, the maximum single-maneuver cleanup occurs when the pre-recovery orbit has an inclination of 83.5°, which is the upper limit of the initial science orbit constraint. The other medium-underburn scenario of interest is the maximum underburn possible while still being able to recover and complete all OCMs in the nominal 1-year mission without firing the LVA bi-propellant thruster. The recovery maneuvers and the resulting initial science orbits for these two scenarios are summarized in Table 4 below.

Figure 4 depicts the pre-recovery and initial science orbits as well as the locations of the contingency maneuvers for the two medium-underburn scenarios as viewed from the direction of the Sun at the start of the MOI maneuver. It can be seen in the figure that the difference in the sizes of the pre-recovery orbits are much less than for the large-underburn scenarios in Figure 3 even though there is a 3.6% difference in the amount of ΔV completed, indicating that this classification of underburn is much less sensitive to the percentage of MOI ΔV completed than the large-underburn classification. Also, the scenario with 79.4% MOI ΔV completed defines the maximum underburn to fall into the medium-underburn classification, as this scenario is the limit of being able to efficiently recover to the initial science orbit with a single contingency maneuver.

Table 4. Contingency maneuvers and initial science orbits for medium-underburn scenarios.

	Maneuver	Mode	Start Time (UTC)	Duration (s)	ΔV (m/s)	TA (deg)	Sun Elevation Angle (deg)
Scenario 1, 79.4% MOI ΔV completed, max single mode 3 maneuver recovery	MOI-C1	3	21 Mar 2011 18:55:16.9	231.5	182.1	35.0	-4.0 to 2.2
Resulting initial science orbit	Periapse Altitude = 200.0 km, Period = 12.0 hr, Inclination = 83.5°, Periapse Latitude = 61.3°, RAAN = 348.8°						
Scenario 2, 83.0% MOI ΔV completed, max mode 2 maneuver recovery with no futher LVA use for mission	MOI-C1	2	22 Mar 2011 1:8:50.4	899.0	150.3	9.0	-9.0 to 1.6
Resulting initial science orbit	Periapse Altitude = 200.0 km, Period = 12.0 hr, Inclination = 83.2°, Periapse Latitude = 60.8°, RAAN = 349.2°						

All contingency maneuvers in these scenarios are performed while turning.

The first scenario summarized in Table 4 is the largest underburn possible while still achieving a full recovery with only a single mode-3 contingency maneuver. As noted above, this scenario defines the limit of being able to efficiently recover to the initial science orbit with a single contingency maneuver, since anything less than the 79.4% MOI ΔV completion would result in a pre-recovery orbit requiring an inclination correction. In this scenario, the recovery consists of the MOI-C1 occurring 3.75 days after the MOI maneuver cutoff time and at a true anomaly of 35°. MOI-C1 is performed as a turning mode-3 maneuver with a ΔV of 182.1 m/s and duration of 231.5 s. The maneuver is designed such that the Sun elevation angle is -4.0° at the beginning of the turn and increases to 2.2° at the end of the maneuver. This range is well within the ± 12° Sun elevation angle SKI constraint. The resulting initial science orbit possesses a periapse altitude of 200.0 km, orbit period of 12.0 hours, 83.5° inclination, periapse latitude of 61.3°, and 348.8° longitude of the ascending node. All of these parameters except periapse latitude meet the criteria for a nominal initial science orbit. As was the case with some of the large-underburn scenarios, the extra 0.3° in periapse latitude was deemed acceptable for a contingency situation.

The second scenario of interest that is summarized in Table 4 is to determine the maximum underburn possible while still being able to complete the recovery and all 6 OCMs in the nominal 1-year science mission using mono-propellant, or mode-2, thrusters only. This situation may occur if, after the MOI maneuver cuts off prematurely, the LVA thruster cannot be recertified for further use. In this scenario, 83% MOI ΔV completion is the maximum underburn from which recovery can be accomplished using a single mode 2 MOI-C1 maneuver. MOI-C1 occurs 4.01 days after the MOI cutoff time at a true anomaly of 9°. The maneuver is 899.0 s long, imparts a total ΔV of 150.3 m/s, and is performed while turning. During the turn, the Sun elevation angle increases from -9.0° at the beginning of the maneuver to 1.6° at the end. The resulting initial science orbit meets all requirements with a periapse altitude of 200.0 km, period of 12.0 hours, 83.2° inclination, 349.2° longitude of the ascending node, and 60.8°periapse latitude. The remaining scenarios of interest fall into the small-underburn classification.

A small underburn is one from which recovery is possible using only a single small contingency maneuver. After MOI, the minimum firing time for the LVA thruster is 12 s. For a settling thrust lasting 45 s, a refill thrust lasting 11 s pior to the LVA firing, and a trim thrust lasting 22 s after the LVA firing, the total minimum mode-3 burn duration is 90 s. The first scenario of interest in this realm is the underburn that corresponds to the minimum possible mode-3 contingency maneuver. The second scenario of interest defines the minimum possible recovery ΔV necessary. This minimum occurs when the period of the pre-recovery orbit is at the upper acceptable limit of 12 hours and 10 minutes. Both the 90-s mode-3 contingency maneuver and the minimum ΔV contingency maneuver are summarized in Table 5.

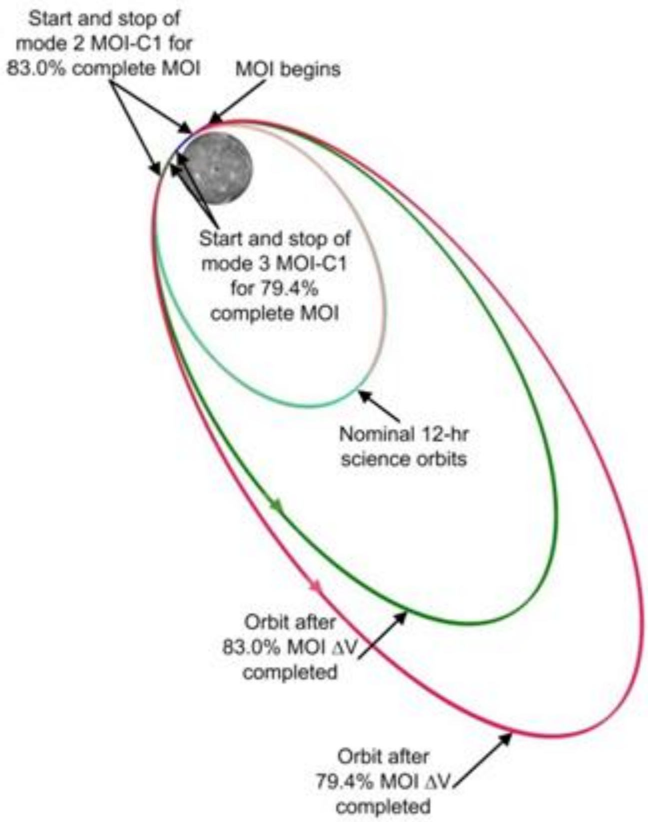

Figure 4. Orbits and correction maneuvers for medium-underburn scenarios. *Orbits and correction maneuver locations for the two contingency scenarios listed in Table 4 as viewed from the Sun at the start of MOI.*

Table 5. Contingency maneuvers and science orbits for small-underburn scenarios.

	Maneuver	Mode	Start Time (UTC)	Duration (s)	ΔV (m/s)	TA (deg)	Sun Elevation Angle (deg)
Scenario 1, 97.8% MOI ΔV completed, min single mode 3 maneuver recovery	MOI-C1	3	21 Mar 2011 21:14:44.9	90.0	18.5	3.0	-9.0
Resulting initial science orbit	Periapse Altitude = 211.1 km, Period = 12.0 hr, Inclination = 82.7°, Periapse Latitude = 59.6°, RAAN = 349.9°						
Scenario 2, 99.7% MOI ΔV completed, min recovery necessary	MOI-C1	2	22 Mar 2011 2:9:34.2	57.9	2.6	16.0	-9.0
Resulting initial science orbit	Periapse Altitude = 205.1 km, Period = 12.0 hr, Inclination = 82.7°, Periapse Latitude = 60.1°, RAAN = 349.9°						

All contingency maneuvers in these scenarios are inertially fixed.

Also, for the first scenario, the pre-recovery, initial science orbit, and the location of the recovery maneuvers are shown in Figure 5 below. Figure 6 contains the same information for the second scenario. Both figures depict the orbit as viewed from the Sun at the start of the MOI maneuver.

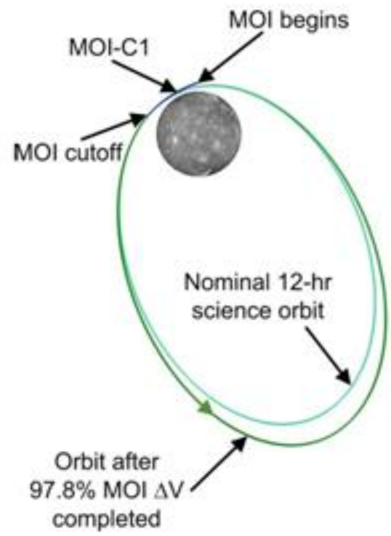

Figure 5. Orbit and correction maneuver for first small-underburn scenario. *The pre-recovery and initial science orbits with the correction maneuver location for the first scenario listed in Table 3 as seen from the Sun at the start of MOI.*

Recall that the first scenario of interest is the underburn corresponding to the minimum possible LVA thruster firing of 12 s, or a 90-s total maneuver duration when settle, refill, and trim thrust segments are all considered. This minimum possible mode-3 contingency maneuver occurs when 98.7% of MOI ΔV is completed. MOI-C1 takes place 3.84 days after the MOI maneuver cutoff time at a true anomaly of 3°. The 90-s maneuver occurs at a Sun elevation angle of -9.0°, is inertially fixed, and imparts a total ΔV of 18.5 m/s. The initial science orbit for this scenario has a periapse altitude of 211.1 km, period of 12.0 hours, 82.7° inclination, 349.9° longitude of the ascending node, and 59.6° periapse latitude, all within the requirements for a nominal initial science orbit.

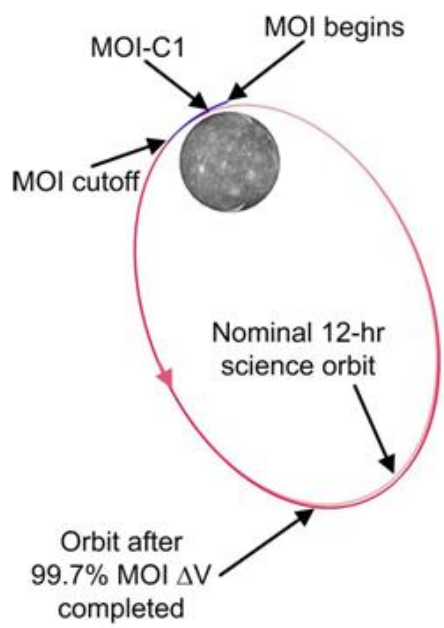

Figure 6. Orbit and correction maneuver for second small-underburn scenario. *The pre-recovery and initial science orbits with the correction maneuver location for the second scenario listed in Table 3 as seen from the Sun at the start of MOI.*

The final scenario of interest falling into the small-underburn category corresponds to the minimum possible ΔV that would be performed as a contingency maneuver. This occurs when the orbit period resulting from the MOI maneuver is 12 hours and 10 minutes, that is, the upper limit of the acceptable period range for a nominal initial science orbit. This period occurs when the MOI ΔV is 99.7% complete and results in an inertially fixed, mode-2, MOI-C1 maneuver occurring 4.05 days after the MOI cutoff time. This 57.9-s maneuver occurs at a true anomaly of 16.0°, a Sun elevation angle of -9.0°, and has a total ΔV of 2.6 m/s. The resulting initial science orbit falls within all requirements and has a periapse altitude of 205.1 km, period of 12.0 hours, 82.7° inclination, 349.9° longitude of the ascending node, and 60.1° periapse latitude.

The scenarios from all three underburn classifications indicate that a full recovery to the initial science orbit and an ability to perform the nominal 1-yr orbit phase mission are possible for anything above 70.0% of MOI ΔV completion. Furthermore, there is only a small range of underburns, between 70.0% and 70.7% of MOI ΔV completion, for which a contingency maneuver would be required during an eclipse. Also of note is that if the LVA thruster is unusable after the MOI cutoff, the full mission can be achieved using bi-propellant thrusters only as long as 83.0% of the MOI ΔV has been completed. Finally, the smallest underburn cleanup that would be performed corresponds to a pre-recovery orbit period of 12 hours and 10 minutes and only costs 2.6 m/s of ΔV.

VI. Recovery from Heliocentric Orbit (< 70% MOI ΔV)

If less than 70% of the MOI ΔV is achieved, MESSENGER will not be captured by Mercury but will escape the planet and end up in a heliocentric orbit with a period similar to Mercury's year. As described in the Contingency Overview section, Astrogator was used to numerically integrate the finite partial-MOI burns. For the trajectories that did not result in capture, Astrogator was used to propagate the trajectory with realistic full-force models to a point 900,000 km from Mercury, where the heliocentric state vector and other orbital parameters were computed. This distance from Mercury was selected as it is more than five times the 175,000-km distance to the Sun-Mercury L1 libration point when Mercury is near perihelion[8], which is the case during the nominal MOI on 18 March 2011. At that distance, the perturbations on the heliocentric trajectory by Mercury will be small enough that the osculating Keplerian heliocentric orbital elements, entered as a "user-defined" body, can be applied to calculate the trajectory to sufficient accuracy for many years using SpaceFlightSolution's patched-conic MAnE software. MAnE calculated minimum-ΔV trajectories targeted to future encounters with Mercury. The conditions of the first arrival at Mercury following a failed MOI attempt are never suitable for satisfying the Mercury orbital goals, so this encounter must be a flyby that puts MESSENGER into a one-Mercury-year return trajectory. There is a continuum of such return trajectories, a "circle" of solutions where a combination of the heliocentric inclination to the ecliptic and flight path angle can usually be found that will achieve the inclination (82.5° to Mercury's equator) and node (such that the Mercury-centered orbit is nearly perpendicular to the direction of the Sun) where a new MOI maneuver might be accomplished to achieve the planned science orbit. The new MOI must satisfy the constraints listed in the Contingency Overview section. If the new MOI maneuver will not have good visibility from the Earth, a flyby must be used instead to enter another one-Mercury-year return loop to reach Mercury again and possibly repeated until an MOI is found that satisfies all of the goals. There are two additional constraints on the added Mercury flybys:

- The pass distance at the flyby must be above Mercury's surface by a comfortable margin; a distance of 1.05 Mercury radii from Mercury's center is adequate if communication with the spacecraft is possible around the time of the flyby, but at least 1.50 Mercury radii is needed if the flyby occurs during a solar conjunction, that is, if the solar elongation is less than 3.0°.
- If there is an eclipse of the Sun during the flyby, its duration must be less than 68 minutes to satisfy the maximum battery depth of discharge.

Once a suitable Mercury arrival is achieved, the hyperbolic periapse state is entered into a Swingby program mission file. Swingby can propagate (numerically integrate) the trajectory backwards in time from periapsis, then propagate the trajectory forward, applying a finite burn thrust with parameters that adequately model the behavior of MESSENGER's LVA and other thrusters. After this new MOI maneuver, the now-captured orbit is propagated forward one revolution to the next periapsis, and the Mercury-centered orbital elements are evaluated there. Swingby can then target those orbital elements by varying the back-propagation time from periapsis, the LVA thruster burn duration, and the fraction of the burn applied in the orbit plane perpendicular to the velocity direction (of course, most of the burn is applied in the Mercury-centered anti-velocity direction) to achieve the following goals at the next periapsis: period of 12.0 hours, periapse altitude equal to 200 km, and periapse latitude of 60°. The MESSENGER science team would be satisfied with a southern periapsis orbit, if that is the only viable alternative; if there is ice in the north polar craters, south polar craters could also have ice on their permanently shadowed floors. Perihelion arrivals favor southern arrivals. However, for the aphelion arrivals that are used for all of the heliocentric return cases, as described below, all of the arrivals have northern periapse latitudes, like for the nominal MOI.

The MAnE-calculated new MOI burns don't take into account the extra ΔV needed to achieve the desired periapse latitude, so the ΔV penalty (total ΔV needed to achieve the desired science orbit minus the nominal MOI ΔV) calculated with MAnE is always less, and less realistic, than the penalties calculated with Swingby. As noted before, a penalty of > 224 m/s is not desirable since it would use up all of the fuel (and possibly achieve an orbit with a period considerably longer than the desired 12 hours), leaving none for the OCMs that are needed to maintain the science orbit. This situation with no ability for OCMs after MOI applies to the 60% MOI ΔV case shown in Table 7. A penalty < 134 m/s would just use up the available fuel margin, leaving enough for the OCMs to complete the full one (Earth) year science mission. Penalties between 134 and 224 m/s, while not desirable, would allow the early OCMs to be performed for a partial science mission.

There are two possibilities for returning to Mercury from the heliocentric orbit:

1. Perform the heliocentric (C1) ΔV as soon as possible for a direct transfer to Mercury, generally arriving at the planet about one Mercury year (87.969 d) after the C1 ΔV.
2. Perform a small C1 ΔV as soon as possible, but targeting Mercury after several revolutions, as close as possible to the beat, or resonant, period. The spacecraft's period, slightly different from a Mercury year, allows the spacecraft to complete one orbit of the Sun more or one orbit less than Mercury completes.

In both cases, the "as soon as possible" date for the C1 ΔV must be no earlier than 28 March 2011 since the MESSENGER team will need a minimum of 10 days to figure out why MOI underperformed, design the C1 ΔV, and safely implement it. It may take much longer for the team to be comfortable with performing another maneuver, in which case it is possible to wait a Mercury year and perform the maneuver then, in June 2011. For direct transfers, that might increase the ΔV, but that value can be decreased by performing the maneuver at a more optimum location than is possible in late March. A maneuver in June 2011 has an additional complication of needing to avoid a solar conjunction a few days in length. Unless the C1 ΔV is 2 m/s or less, so that it can be performed with two mode-1 components, the spacecraft Z-axis must be aligned with the ΔV direction so that it can be performed with the C thrusters or the LVA thruster (mode 2 or 3). This imposes another constraint:

- If the C1 ΔV is more than 2 m/s, the ΔV-Sun angle must be 90° or 270° ± 12°.

Table 6 lists information about the heliocentric trajectory at the Astrogator-computed 900,000-km distance from Mercury following the different large underburns that preclude immediate capture into Mercury orbit. It lists the spacecraft's heliocentric period and the beat period with Mercury so that one can tell if the flight times involved with option 2 above are reasonable. The table shows that longer flight times are needed as the achieved MOI % ΔV increases, up to 33.8%. The table also shows that as the spacecraft's period approaches that of Mercury the beat (or resonance) period with Mercury increases to infinity.

Table 6. Heliocentric periods and osculation dates for large MOI underburns.

Achieved MOI ΔV (%)	Orbital Period (days)	Arrival Date at 900,000 km Distance from Mercury (dd/mm/yyyy)	Beat Period with Mercury (Earth years)	Beat Period with Mercury (Mercury years)
0.0	91.64	22/3/2011	6.02	24.98
10.0	90.45	23/3/2011	8.76	36.39
20.0	89.35	23/3/2011	15.62	64.87
30.0	88.33	24/3/2011	59.33	246.32
33.8	87.97	25/3/2011	315691.72	1310733.76
40.0	87.43	26/3/2011	38.79	161.05
50.0	86.70	29/3/2011	16.51	68.56
60.0	86.34	5/4/2011	12.79	53.11

At the start of Section III (Five Mercury Gravity-Assist Strategy), it was described how an arrival and insertion near the aphelion of Mercury's orbit could decrease the insertion ΔV by about 200 m/s. This was found to be the case also for the heliocentric contingency recoveries, so unless otherwise indicated, all of the recovery scenarios described below involve aphelion arrivals. In some cases, there are substantial negative penalties, that is, the overall ΔV cost is markedly lower than for the nominal MOI. It was often possible to achieve the aphelion arrival directly by completing n.5 revolutions from the C1 ΔV to the arrival rather than n revolutions, where "n" is an integer. In other cases, the initial arrival following the C1 ΔV is near perihelion. In that case, a half-Mercury-year loop is added, but since those loops have high inclinations (the spacecraft travels almost directly above or below Mercury), the flybys are usually below the surface at either the start or end (or both). To overcome that problem, the initial loop is a 1-Mercury-year loop where the inclination can be increased so that the next Mercury flyby can lead to the next Mercury flyby one half-Mercury-year later. Similarly, following this half-Mercury-year loop, a 1- Mercury-year loop can be added to decrease the inclination while remaining compliant with the minimum Mercury distance constraint specified above. This "indirect" approach adds at least 2.5 Mercury years, or just over 7 months, to the mission, a strategy that offers substantial ΔV savings. The ΔV saving often allows selecting a return time less than the optimum beat period. At least two Earth years can often be saved with that approach, more than offsetting the 7-month delay that might be needed for arrival near Mercury's aphelion.

All of the heliocentric recoveries described above involve recoveries from orbits close to Mercury's orbit, with aphelion distances less than 0.50 AU. For all of these arrivals, in order to satisfy the 82.5° inclination constraint, the argument of periapse was always either near 60° or (for southern arrivals) near 240°, unlike the nominal MOI arrival value near 120°. In these cases, with argument of periapse near 60° or 240°, the Mercury orbits evolved in the opposite way as for the nominal MOI, that is, the periapse altitude decreases and the periapse latitude moves towards the equator. This requires insertion into a high-altitude (500 km rather than 200 km) periapsis orbit, and also into a higher-latitude initial periapse (±65°) to avoid long, battery-draining eclipses at periapse latitude near ±55° one year after MOI. Then, during the (Earth)-year-long science phase, the OCMs raise the periapse altitude, to prevent impact as well as to keep altitude above the approximately 150 km minimum needed for effective coverage with MESSENGER's instruments. Following the one-year science orbit for the nominal MOI, an extended mission is possible since the periapse altitude will increase and the periapse latitude moves towards the north pole. After a few years, after periapse passes near Mercury's north pole, the altitudes and latitudes will decrease. However, for the heliocentric recoveries, an extended mission will either not be possible, or will be short, because either the spacecraft will impact the planet when there's no propellant left to raise periapse height, or the spacecraft will see overly long eclipses near apoapse when the apoapse and periapse latitudes become too close to Mercury's equator.

The different heliocentric contingency options are tabulated, described, and illustrated below. If MOI is missed altogether (0% achieved), there are two useful recovery options. As shown in Table 7 and in order, the beneficial, distinguishing characteristics are:

- the first 0%-achieved MOI has the lowest ΔV penalty (best margin) of the 0% MOI cases,
- the second 0%-achieved MOI provides the shortest flight time possible with a ΔV penalty under 134 m/s,
- the third 0%-achieved MOI has the shortest flight time with a full-year science mission, with final altitude below the 200 km lower limit since less ΔV is available for the final OCM. This is also the case for the second 10%-achieved MOI and the 51.4%-achieved MOI cases that have finite ΔV penalty >134 m/s.

The 0% cases, and the 33.8% and 50% cases, are described in further detail in Table 8, and the final Mercury arrival for the second 0% case is illustrated in the lower left panel of Figure 7. Panel 7a is an ecliptic-plane view of the 50% case. Panel 7b, the view from the Earth, shows that the entire MOI maneuver will be visible from that perspective. All of the trajectories in this paper have 100% of MOI visible from the Earth. Table 7 also lists the number of Mercury flybys that occur between the anomalous and final MOI.

The 33.8%-achieved MOI ΔV maneuvers provided the largest negative penalties (or ΔV savings), with 153 m/s more margin than provided by the nominal MOI. More details are given in Table 8. Another case that is not shown in Table 7, the 0% completed MOI with long-duration, 6.14-year delayed MOI, has even more ΔV margin with over 214 m/s savings versus the nominal MOI.

While the 60%-achieved MOI ΔV is undesirable with greater than 224 m/s penalty, an MOI that would use the remaining propellant and leave the spacecraft in an orbit with an apoapse altitude (and period) not too much greater than the nominal orbit, for a mission that would last about 4 months that would achieve partial mission success.

Table 8 provides more information about the two 0%-achieved MOI cases and the 33.8% and 50% MOI cases. The Earth (⊕) distance varies between 0.7 and 1.3 AU. For the 0% cases, the S/C-⊕-⊙ (spacecraft-Earth-Sun, or solar elongation) angle for the first ΔV should be at least 3.0° to ensure good communications even during major solar activity. With normal quiet solar activity, adequate communication might be achieved even down to 1.5°. Thus, 2.0° S/C-⊕-☉ angle is allowed to minimize both the flight time and the integrated ΔV penalty. Mercury flyby solar elongations below 3.0° are allowed because they are not associated with a propulsive event. The first 0%-achieved MOI burn has the lower integrated ΔV penalty but at the cost of an increased flight time. The S/C-⊕-☉ angles for propulsive events are all above 2.0°, and the flyby distances are sufficiently above the surface. In Table 8, only the 0% cases have eclipses. For the first listed case (lowest ΔV penalty), the first Mercury flyby has a 26-minute eclipse and for the second listed case (earliest arrival), the second Mercury flyby has a 29-minute eclipse; there are no eclipses at the other flybys.

If possible, it would be better to achieve a heliocentric recovery MOI that would have an argument of periapse near 120° (or, for southern arrivals, near 300°) so that the orbit about Mercury would evolve in the same way as for the nominal MOI, that is, with both the height and latitude of periapse increasing after the MOI, enabling a longer extended science mission. This can be achieved only from a larger heliocentric orbit than the ones considered so far. The nominal MOI occurs at the end of a resonant orbit that completes five revolutions in six Mercury years and has an aphelion distance of 0.57 AU, much larger than those for the cases considered above. Such orbits can be achieved for the 0% MOI contingency case, but with higher MOI percentages, the hyperbolic excess velocity relative to Mercury decreases and only longer resonance orbits with longer beat periods are possible. For example, for the 30.0% MOI case, an argument of periapse near 120° can be achieved with an eight-revolutions-in-nine-Mercury-years orbit with more information given in Table 7 (30.0* case). However, to set up the departure for that scenario requires a sequence of five one-Mercury-year loops to keep eclipses at the flybys short enough, and then another two one-Mercury-year loops are needed to achieve robust visibility of the new MOI from Earth. This sequence results in an operationally complex trajectory with seven additional Mercury flybys and arrival at Mercury in late April 2015 with a ΔV penalty of about 67.4 m/s. This compares with the 33.8% MOI trajectory above that arrives over three years earlier (with a flight time of only 0.85 Earth years) and a very robust ΔV penalty of -153 m/s. The MESSENGER team prefers the quicker return with the less complex trajectory; with the large ΔV margin, providing

Table 7. Recovery options for large MOI underburns.

Achieved MOI (%)	# of New ☿ Fly-bys	First Recovery ΔV Date (dd/mm/yyyy)	First Recovery ΔV ΔV (m/s)	First Recovery ΔV S/C-⊕-☉ Angle (deg)	New MOI Maneuver Date (dd/mm/yyyy)	New MOI Maneuver ΔV (m/s)	New MOI Maneuver S/C-⊕-☉ Angle (deg)	Penalty Time (years)	Penalty Patched Conic ΔV (m/s)	Penalty Finite ΔV (m/s)
0.0	3	19/06/2011	49.1	2.5	10/05/2017	619.7	24.0	6.15	-215.4	-206.6
0.0	3	18/06/2011	180.3	2.0	23/05/2016	624.3	18.5	5.18	-79.8	-70.8
0.0	3	18/06/2011	388.1	2.2	06/06/2015	637.7	10.4	4.22	138.6	150.4
10.0	3	17/06/2011	254.7	2.7	11/02/2017	560.6	17.0	5.91	31.3	27.4
10.0	3	17/06/2011	359.4	2.7	23/05/2016	573.0	18.4	5.18	141.2	144.5
20.0	4	16/06/2011	249.2	3.0	02/07/2013	481.6	11.6	2.29	44.3	30.4
30.0	3	15/06/2011	109.2	2.7	18/04/2012	467.2	27.5	1.09	-46.8	-18.6
30.0*	7	15/06/2011	115.4	3.0	21/04/2015	564.7	12.2	4.09	91.6	67.4
33.8	3	28/03/2011	0.9	16.5	21/01/2012	425.1	10.9	0.85	-134.5	-153.5
40.0	1	08/04/2011	193.2	3.0	24/10/2011	437.9	16.4	0.60	123.1	105.9
50.0	1	07/06/2011	201.1	5.3	18/08/2016	351.3	27.4	5.42	132.3	114.7
51.4	1	07/06/2011	213.9	5.1	18/08/2016	351.5	27.4	5.42	151.8	140.0
60.0	1	05/06/2011	260.5	7.1	29/10/2017	334.5	13.1	6.62	249.0	**244.8**

Unlike all other Table 7 cases, this case arrives at perihelion with argument of periapse near 120° - see text above for more information. The number in* ***bold* *indicates insertion into Mercury orbit, but no ability to adjust the orbit.*

more propellant to keep raising the periapse long after the end of the nominal one-year science mission. A near-120°-argument-of-periapse case was also computed for the 0% MOI trajectory, but the spacecraft does not return to Mercury until late February 2019, almost eight years after the failed March 2011 MOI and over three years after the second 0% MOI case shown in Table 7.

Table 8. Details of selected large-underburn options.

Achieved MOI (%)	Des-crip-tion	Event	Date (dd/mm/yyyy)	⊕ Dist. (AU)	S/C-⊕-⊙ Angle (deg)	Incl. (deg)	☿ Flyby Dist. (R_M)	ΔV (m/s)	Penalty Finite ΔV (m/s)
0	Lowest Penalty	First ΔV	18/06/2011	1.323	2.0	-	-	180.3	-70.8
		☿ Flyby	14/10/2015	0.922	17.9	5.6	3.00	0.0	
		☿ Flyby	10/01/2016	0.708	9.5	6.0	2.51	0.0	
		☿ Flyby	25/02/2016	1.237	20.5	5.5	58.73	0.0	
		New MOI	23/05/2016	0.625	18.5	5.5	-	624.3	
0	Earliest Arrival	First ΔV	18/06/2011	1.323	2.2	-	-	388.1	150.4
		☿ Flyby	27/10/2014	0,848	17.0	5.6	4.00	0.0	
		☿ Flyby	23/01/2015	0.757	13.8	5.5	9.40	0.0	
		☿ Flyby	10/03/2015	1.153	23.6	5.5	56.64	0.0	
		New MOI	06/06/2015	0.571	10.4	5.5	-	637.7	
33.8	Earliest Arrival	First ΔV	28/03/2011	0.755	16.5	-	-	0.9	-153.5
		☿ Flyby	13/06/2011	1.322	1.4	5.9	20.18	0.0	
		☿ Flyby	09/09/2011	1.103	16.0	5.9	35.02	0.0	
		☿ Flyby	25/10/2011	1.318	16.8	5.9	125.43	0.0	
		New MOI	21/01/2012	1.393	10.9	5.9	-	425.1	
50	Lowest Penalty	First ΔV	07/06/2011	1.308	5.3	-	-	201.1	114.7
		☿ Flyby	22/05/2016	0.615	17.7	6.2	127.92	0.0	
		New MOI	18/08/2016	0.885	27.4	6.2	-	351.3	

Note: For each flyby, the periapse distance is in terms of Mercury radii, R_M = 2439.7 km.

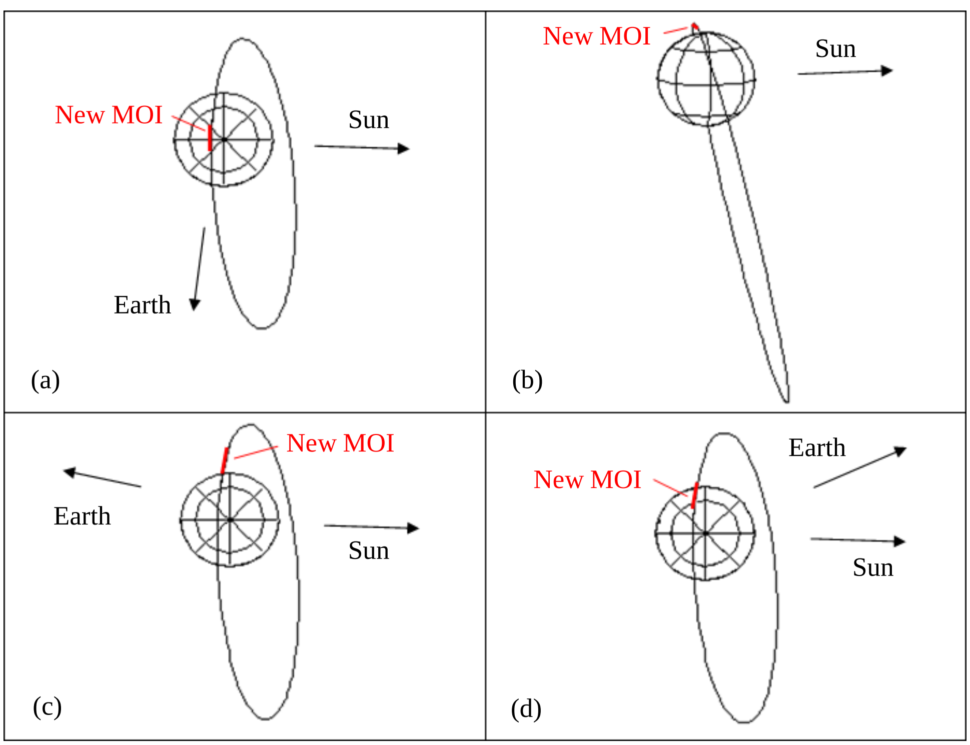

Figure 7. MOI views from the north ecliptic pole or from Earth. *(a) Ecliptic-plane view of 50%-achieved MOI. (b) View from the Earth, with ecliptic north up, for 50%-achieved MOI. (c) Ecliptic-plane view of 0%-achieved MOI (2nd case from Table 7). (d) Ecliptic-plane view of 33.8%-achieved MOI.*

VII. Conclusion

The possibility of recovering a full science mission for MESSENGER following a wide range of underburns for the Mercury orbit insertion maneuver has been demonstrated. Robust plans have been developed for the most likely MOI contingency scenarios, including large partial burns from 70% to 100% of the nominal MOI ΔV, and also for cases where the MOI is entirely or almost entirely missed. For partial burns around 34% of MOI ΔV, the period of the heliocentric orbit is nearly the same as Mercury's orbit period. In these cases, the ΔV costs for a quick (less than one year) return to Mercury can be small, making these recoveries attractive relative to the other heliocentric recoveries, most of which have been shown to also have viable recovery possibilities. Figure 8 offers an effective graphical summary of the recovery potential from all levels of MOI under burn. Plans for future work include the generation of integrated trajectories from anomalous MOI through recovery MOI for both the 0% MOI complete minimum 4.22-year delay to final MOI and the quickest heliocentric recovery option – the 40% MOI complete case with 0.60-year delay to final MOI. Priority for these two cases is based on a higher likelihood of 0% MOI completed on 18 March 2011 than nearly every feasible underburn scenario, and the need for an early (within three weeks of the initial partial MOI) recovery maneuver.

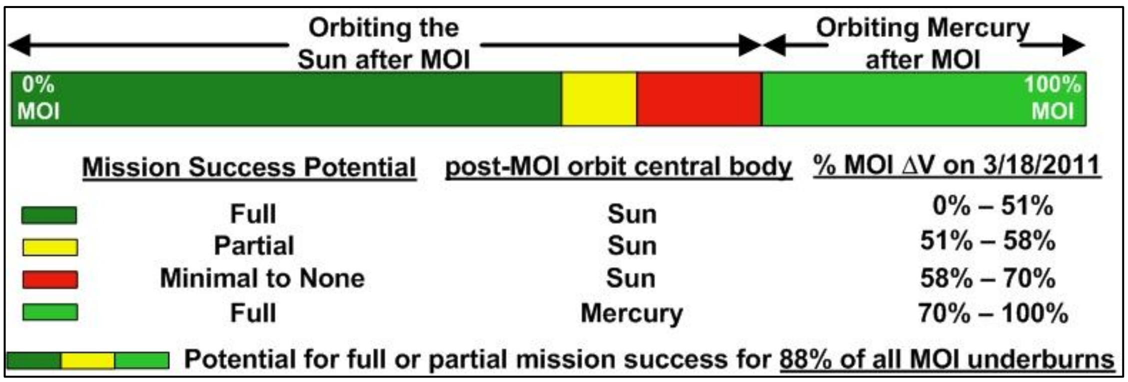

Figure 8. Recovery outlook for all Mercury orbit insertion underburn options. ΔV margin is used to reduce time until final MOI. Partial recovery potential indicates use of all ΔV margin with potential loss of ability to implement post-MOI maneuver(s).

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