Cryogenic Propulsive Stage (CPS) Mission Sensitivity Studies
Earth-Moon L1 Departure Results

Rev B | 4 October 2012 | Atlanta, GA

Mark Schaffer
Senior Aerospace Engineer, SpaceWorks Engineering
mark.schaffer@sei.aero | 1+202.503.1752

Brad St. Germain, Ph.D.
Director, Advanced Concepts Group, SpaceWorks Engineering
brad.stgermain@sei.aero | 1+770.379.8010

John E. Bradford, Ph.D.
Principal Engineer, SpaceWorks Engineering
john.bradford@sei.aero | 1+770.379.8007

- This presentation summarizes the results of a parametric study to characterize the influence of **four design parameters** on the design of Cryogenic Propulsion Stages (CPSs) for **three candidate missions** starting at the Earth-Moon L1 Lagrangian point.

Design Parameters
Propellant Mass Fraction (PMF)
Engine Specific Impulse (Isp)
Boil-Off Rate
LEO Duration (loiter time)

Candidate Missions
Lunar Surface
Near Earth Object (NEO)
Mars Orbit

- These missions are representative of **future human exploration missions** in the 2020 to 2030 timeframe. Masses for the stage payloads (i.e. MPCV and habitation elements) for this study were taken from ongoing NASA studies.

- The ranges of values selected for the design parameters span currently available conservative values to realistic achievable, near-term technology advancement goals

- The primary **figure of merit for this study is initial mass in L1**. Other systems-level design factors, such as cost or reliability, were not considered in this study

Introduction: Study Overview

Study Background

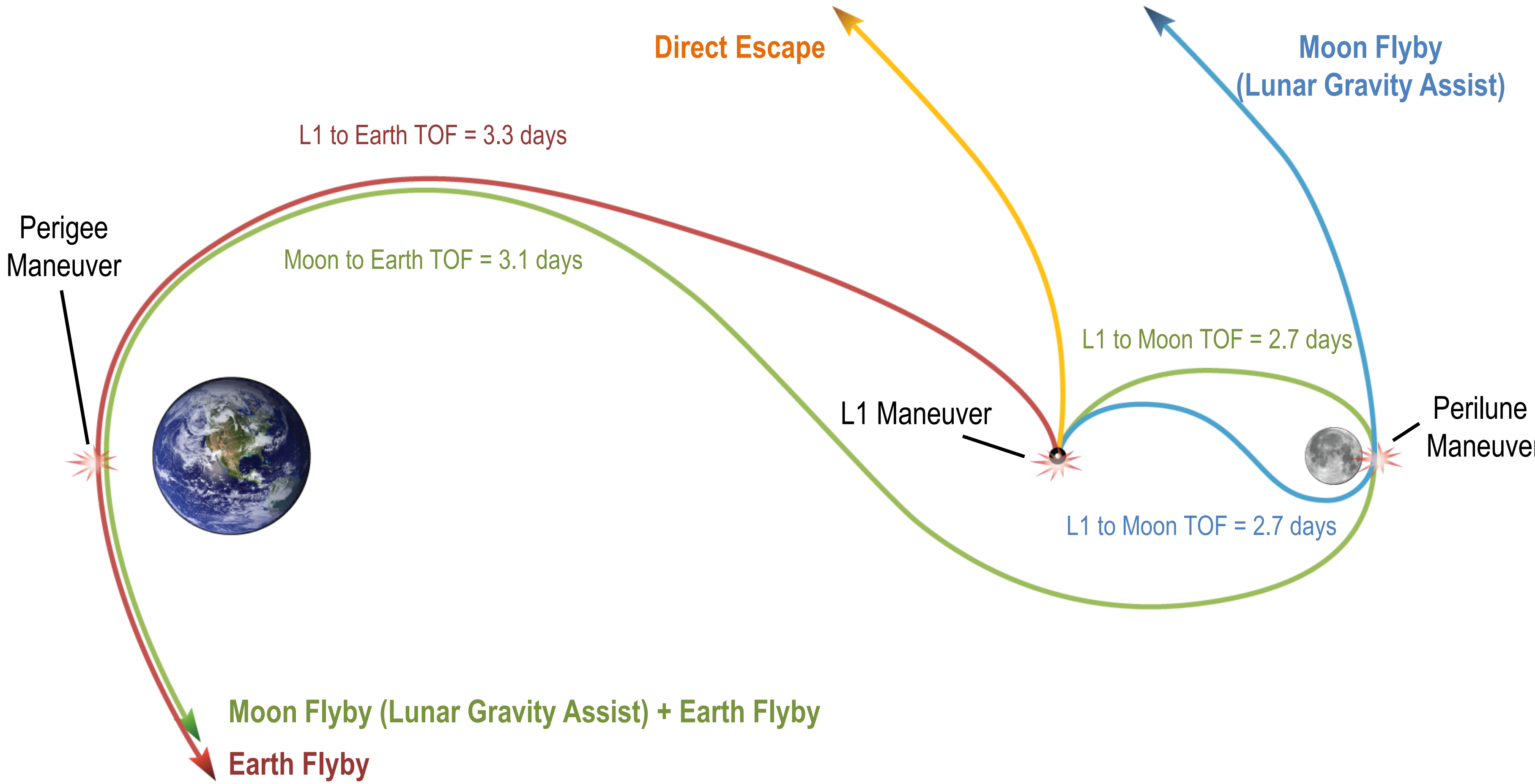
- 6 month study from June through December 2011
- Sponsored by United Launch Alliance
- Performed by SpaceWorks with technical support from United Launch Alliance

About SpaceWorks

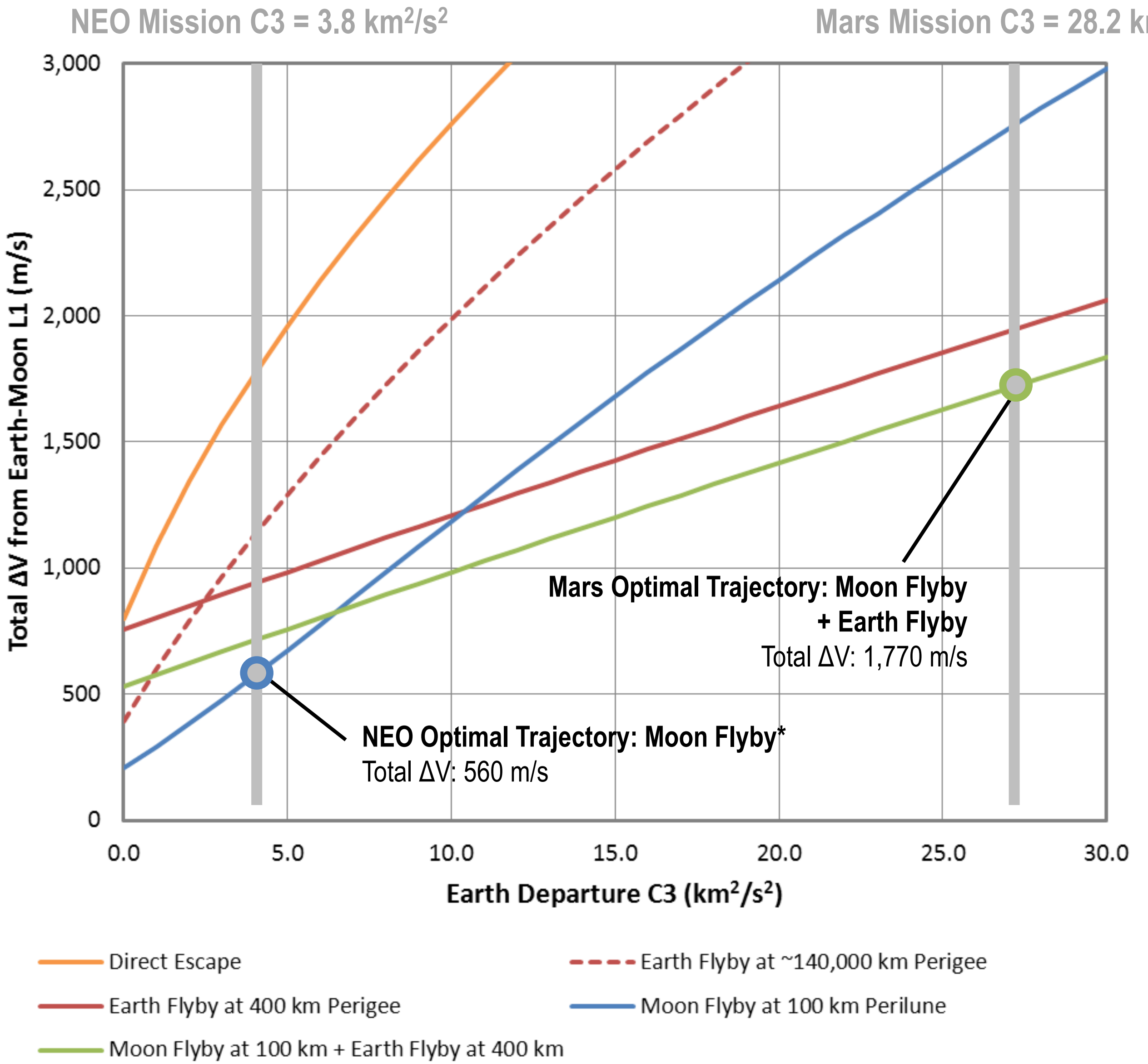
- Aerospace engineering services and space systems analysis firm founded in 2000
  - A responsive and nimble multidisciplinary engineering team focused on independent concept analysis and design, technology assessment, and life cycle analysis at fidelity levels suitable for concept initiation through PDR
  - Over a decade of experience supporting advanced design and long range planning activities for customers in private industry, NASA, DoD, DARPA, and entrepreneurial space organizations
- Three primary operating divisions: Engineering, Commercial, and Software.
- Two partner companies: Generation Orbit Launch Services, Inc. and Terminal Velocity Aerospace, LLC.

L1 Departure Options

- SpaceWorks identified four possible departure paths for deep space missions departing from Earth-Moon L1 into a heliocentric orbit
- These options were compared at different required Earth escape C3 values to determine the optimal mission path and total departure ΔV for each option using in-house cis-lunar trajectory tools



Delta-V Requirements: L1 Departure Options



* Departure trajectory without Earth flyby may significantly limit the departure heliocentric inclination available

Assumptions

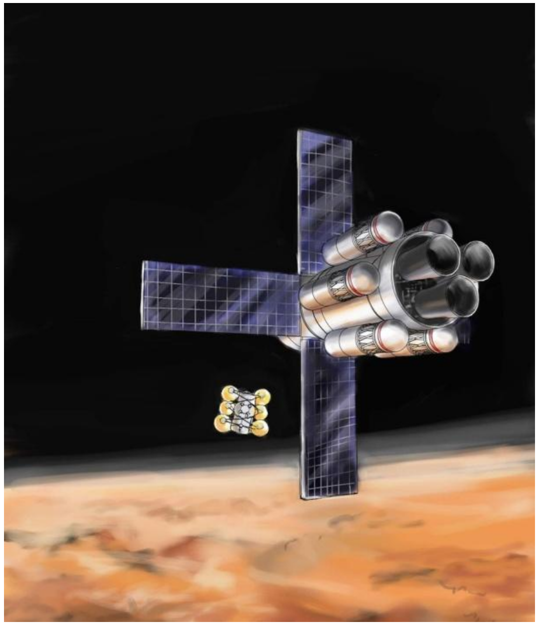
- Model uses two-body equations and patched conic method to determine position, velocity, and time of flight
- Heliocentric declination of Earth departure velocity vector is always assumed to match that required to for the particular mission, i.e. the Earth-Moon orientation at L1 departure is optimal
- Heliocentric inclination of the Earth departure velocity vector is not considered. Minor adjustments to the spacecraft velocity vector before the flyby maneuvers should allow for an appropriate range of heliocentric inclinations to be achieved.
- All maneuvers assumed to be instantaneous changes in velocity with no gravity losses

Delta-V Requirements: L1 Departure Results

- SpaceWorks determined the following delta-Vs for each mission for the CPSs:

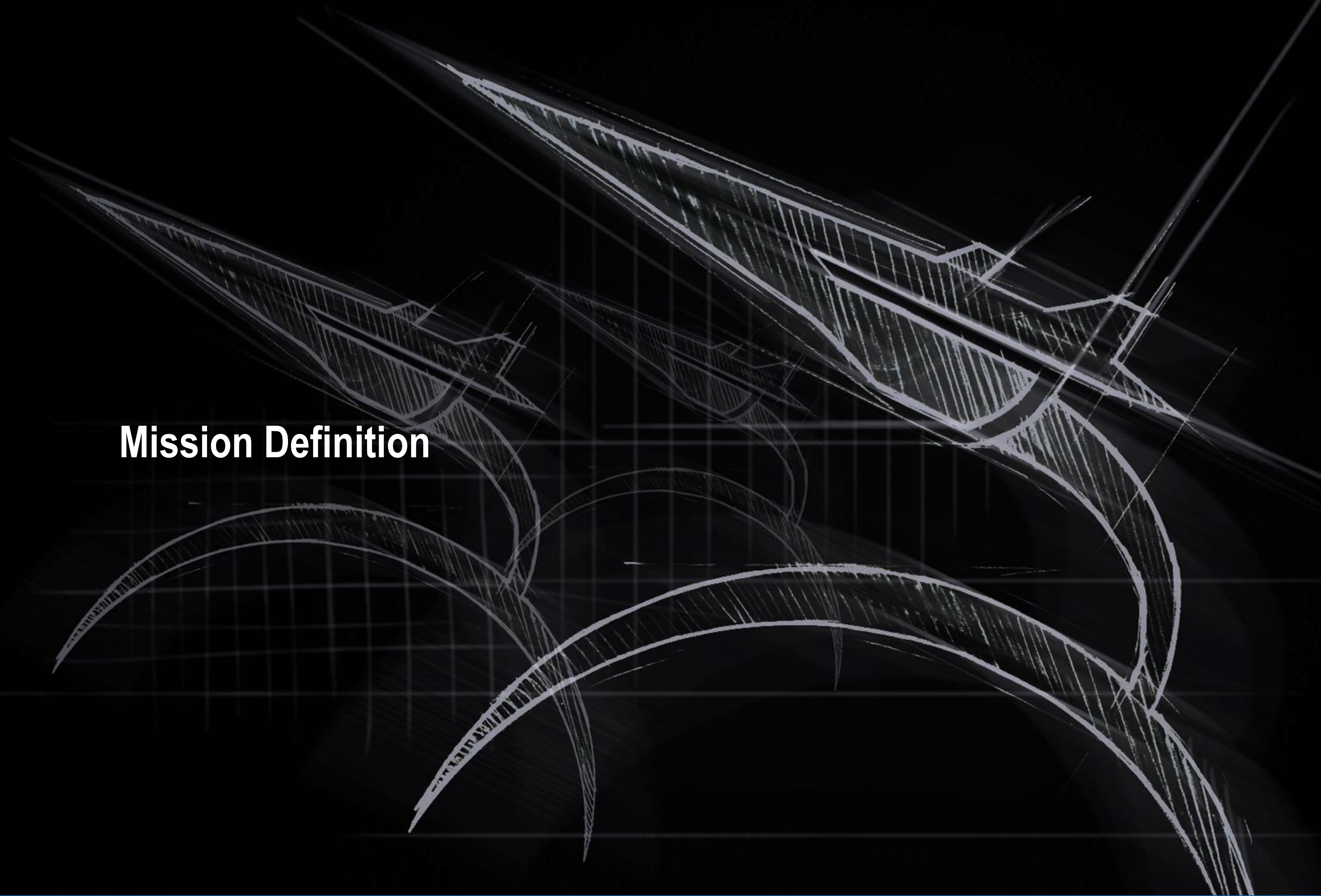
Mission	Mission Segments				
	L1 ΔV (m/s)	Perilune ΔV (m/s)	Perigee ΔV (m/s)	Arrival ΔV (m/s)	Departure ΔV (m/s)
Low Lunar Orbit	85	640	-	-	-
NEO Encounter	85	475	-	2,000	2,150*
Mars Orbit	230	230	1,310	2,200	2,550*

* Maximum second burn delta-V represents a conservative estimate for boil-off

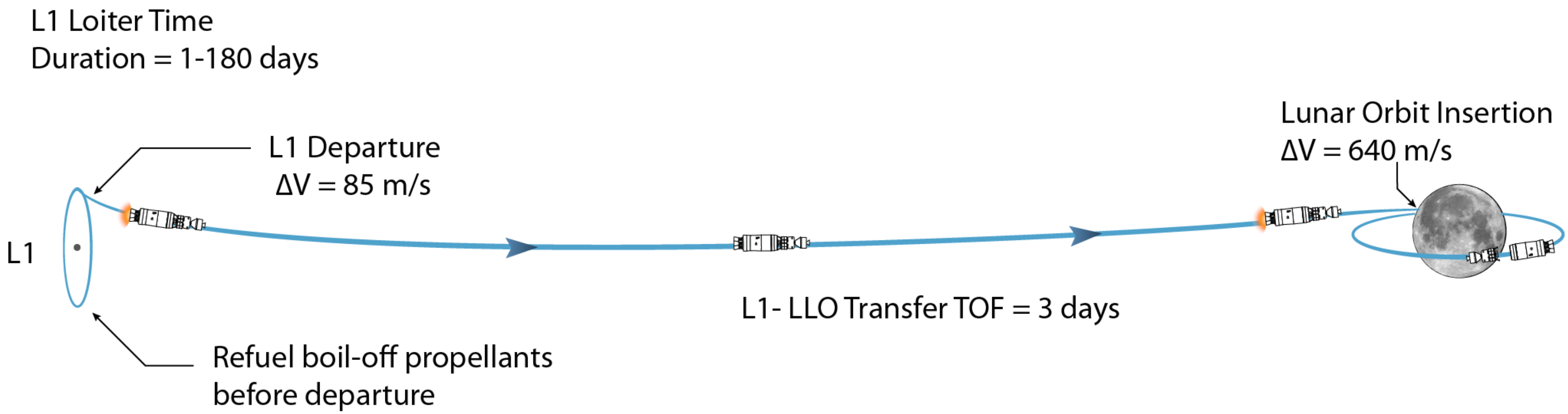


Delta-V Requirements: Summary

Image Credit: SpaceWorks Enterprises, Inc.

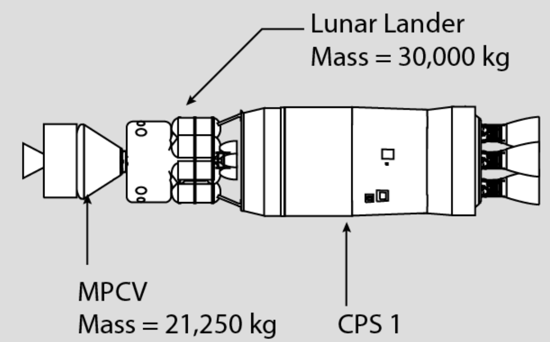


Mission Definition

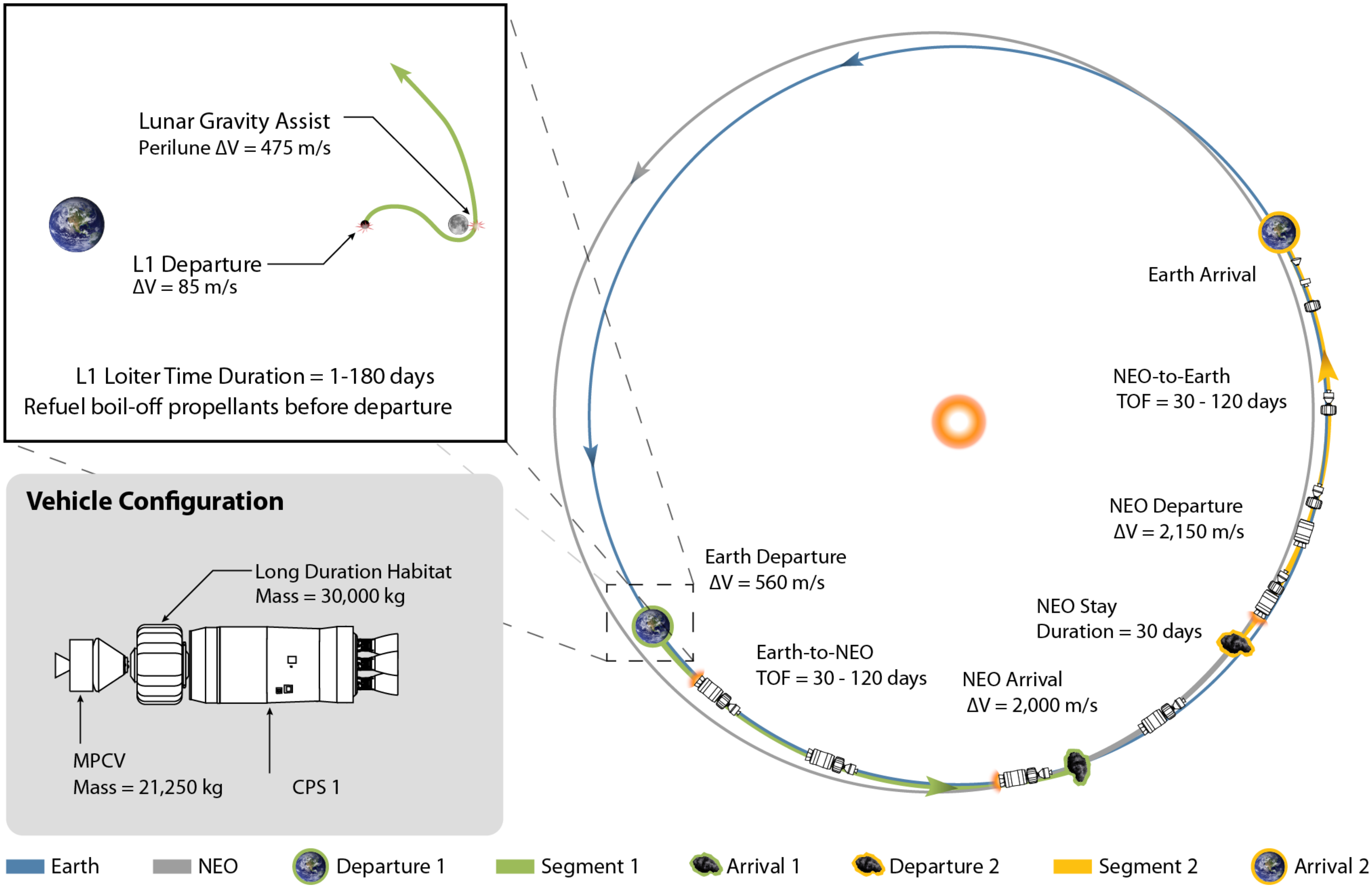


- Assume lunar lander performs descent to lunar surface and ascent to LLO
- Assume Low Lunar Orbit (LLO) departure / Trans-Earth Injection (TEI) return to Earth maneuver performed by propulsion component of MPCV

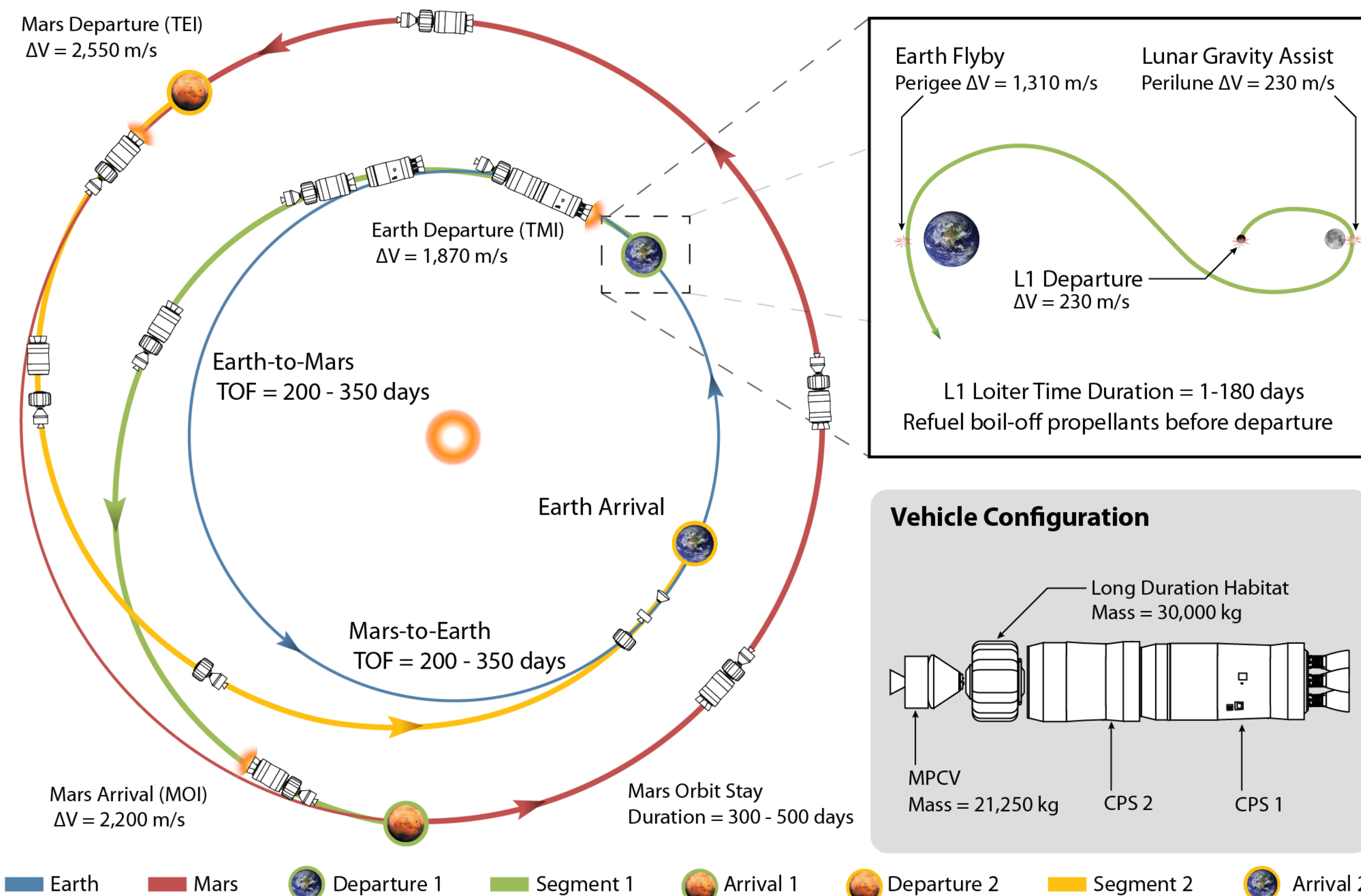
Vehicle Configuration



Mission Definition: Lunar Surface



Mission Definition: Near-Earth Object (NEO)



Mission Definition: Mars Orbit

Assumptions and Methodology

- Four design parameters were identified for this study:

Variable A: Propellant Mass Fraction	
0.75	Low-end CPS mass fraction
0.85	Ares V EDS-like (Earth Departure Stage) mass fraction
0.90	Centaur-like mass fraction
0.95	High-end CPS mass fraction

Variable B: Engine Specific Impulse (Isp)	
448 sec	J2-X
451 sec	RL10-A4-2
465 sec	RL10-B2 or Next Generation Engine

Variable C: Boil-off Rate	
0.1%/day	Centaur boil-off rate achievable via already reviewed modifications
0.05%/day	Reasonable near-term boil-off rate with passive thermal protection
0.01%/day	Aggressive boil-off rate with passive thermal protection
0.001%/day	Requires active cooling

Variable D: L1 Duration	
1 day	Constellation approach requiring same day launch
30 days	One month provides reasonable time to enable launch of two vehicles
180 days	Provides time to launch multiple vehicles

Assumptions and Methodology: Design Variables

- SpaceWorks has developed a **parametric sizing model** to size the CPSs required for each mission

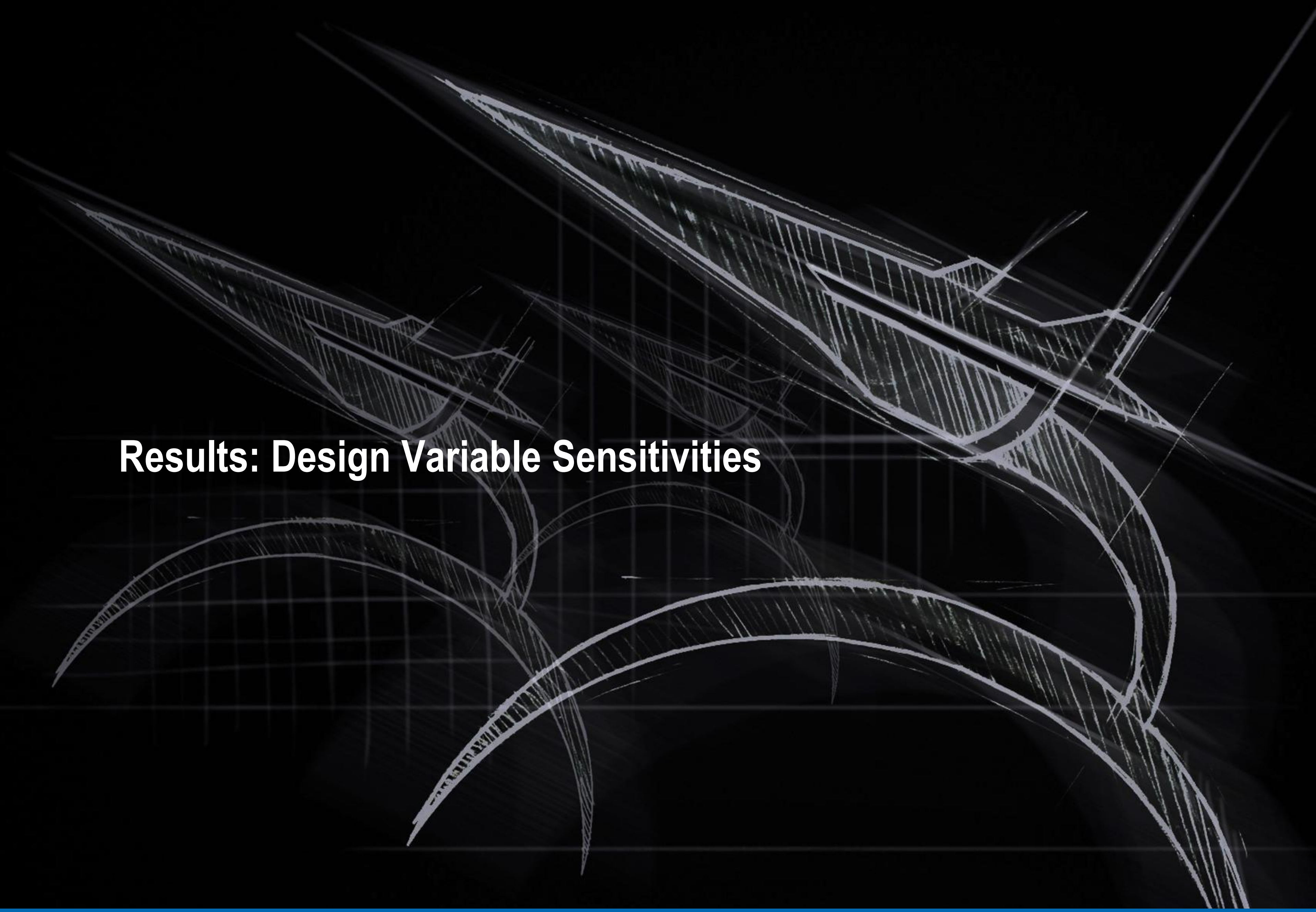
- This sizing model is implemented in Microsoft Excel and uses the built-in circular reference functionality to accomplish **vehicle closure** using the rocket equation automatically whenever a new set of design variables is selected

- VBA macros are used to sweep through **all combinations of the design variables** and determine the inert and propellant masses, initial mass in L1, and additional boil-off propellant for each case

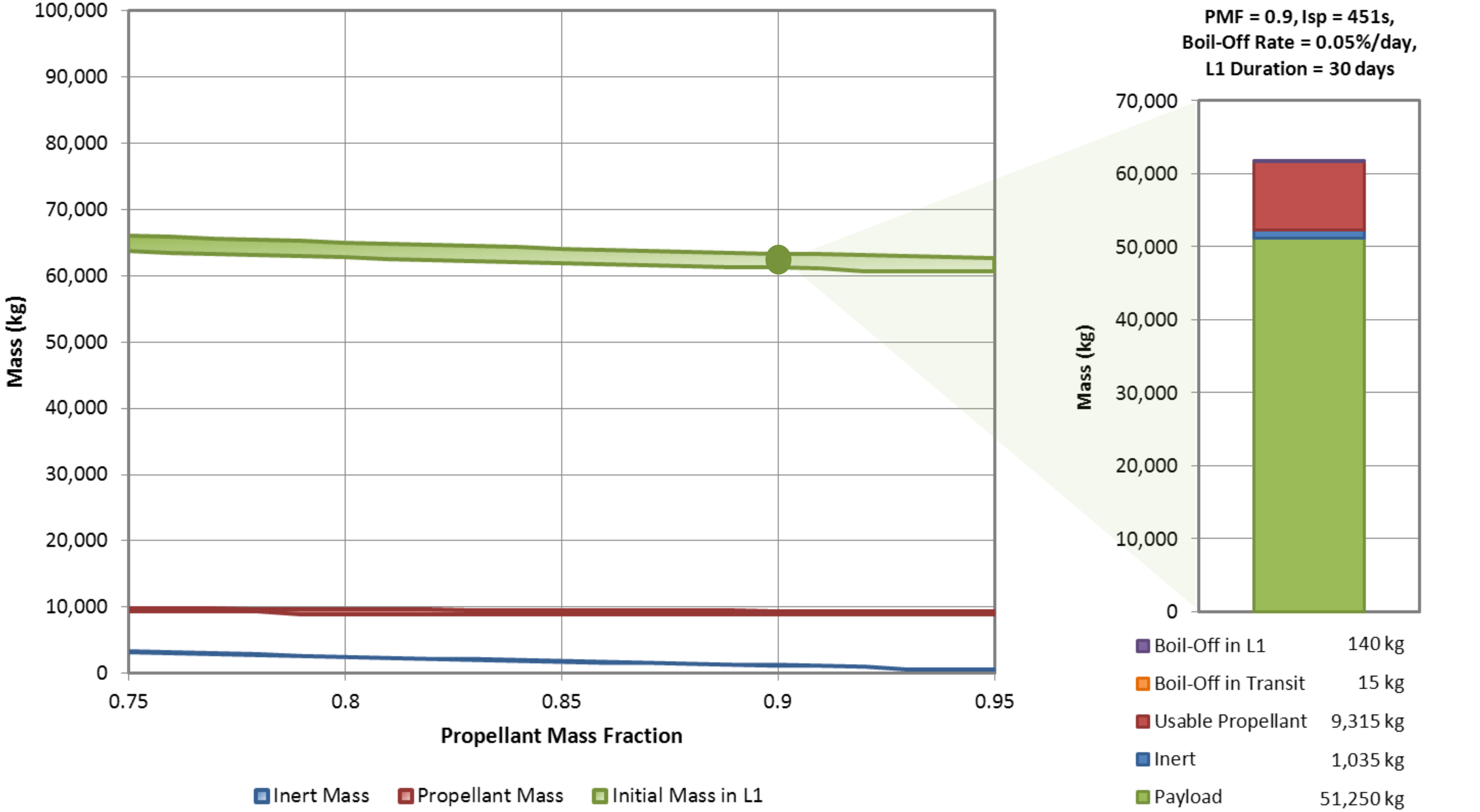
- Boil-Off Assumptions:
  - CPSs are refueled of any lost boil-off propellants during the L1 stay time immediately before the mission begins
  - Boil-off losses are based on a %/day loss of total propellant mass at the start of the mission. A fixed daily mass loss rate is determined from the %/day input and is held constant throughout the mission.
  - It is assumed that the boil-off propellant mass generated before any particular maneuver is vented before that maneuver occurs

Assumptions and Methodology: Parametric Sizing Model

Results: Design Variable Sensitivities

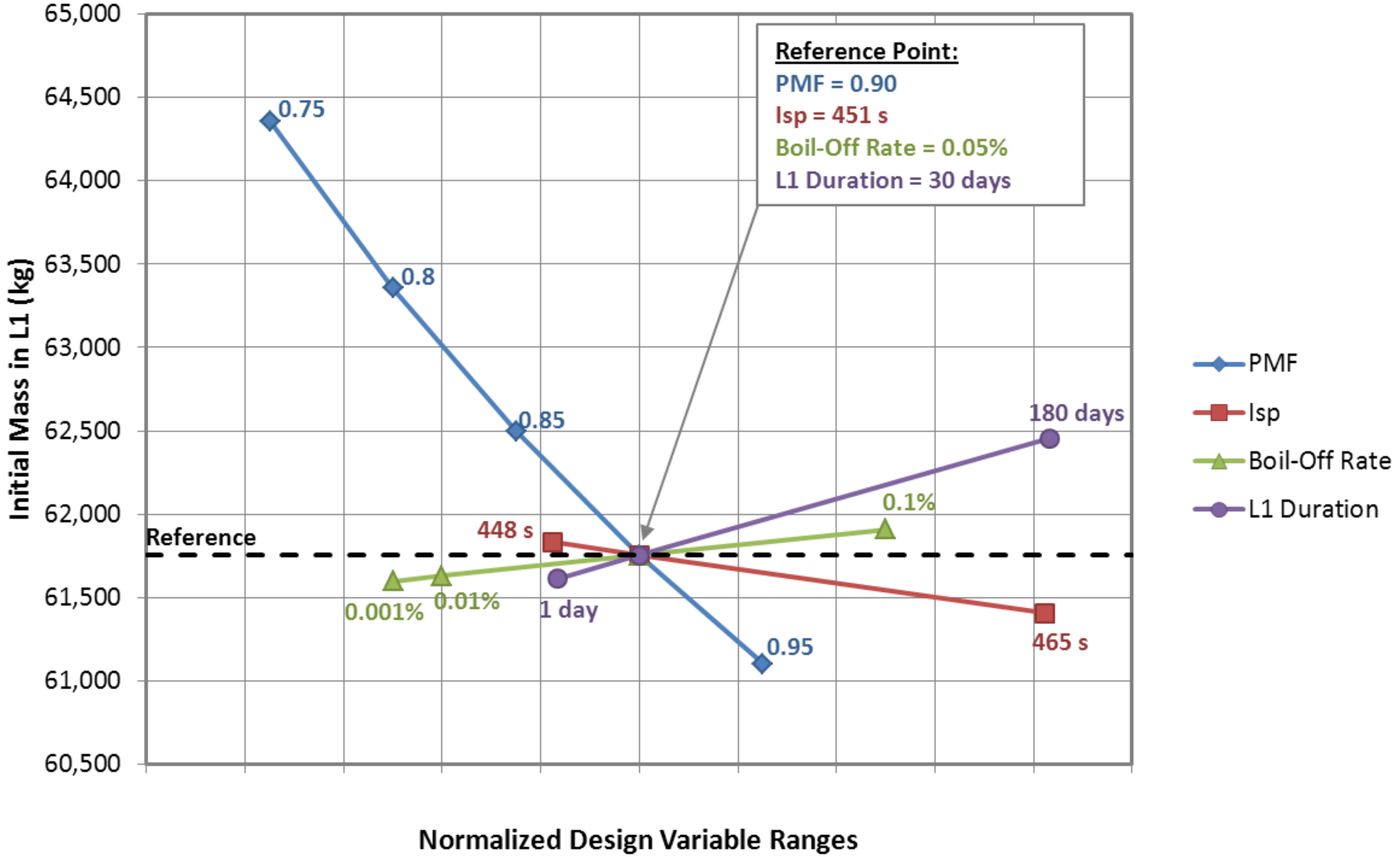


Lunar Surface Mission



- Results for all combinations of design variables shown above

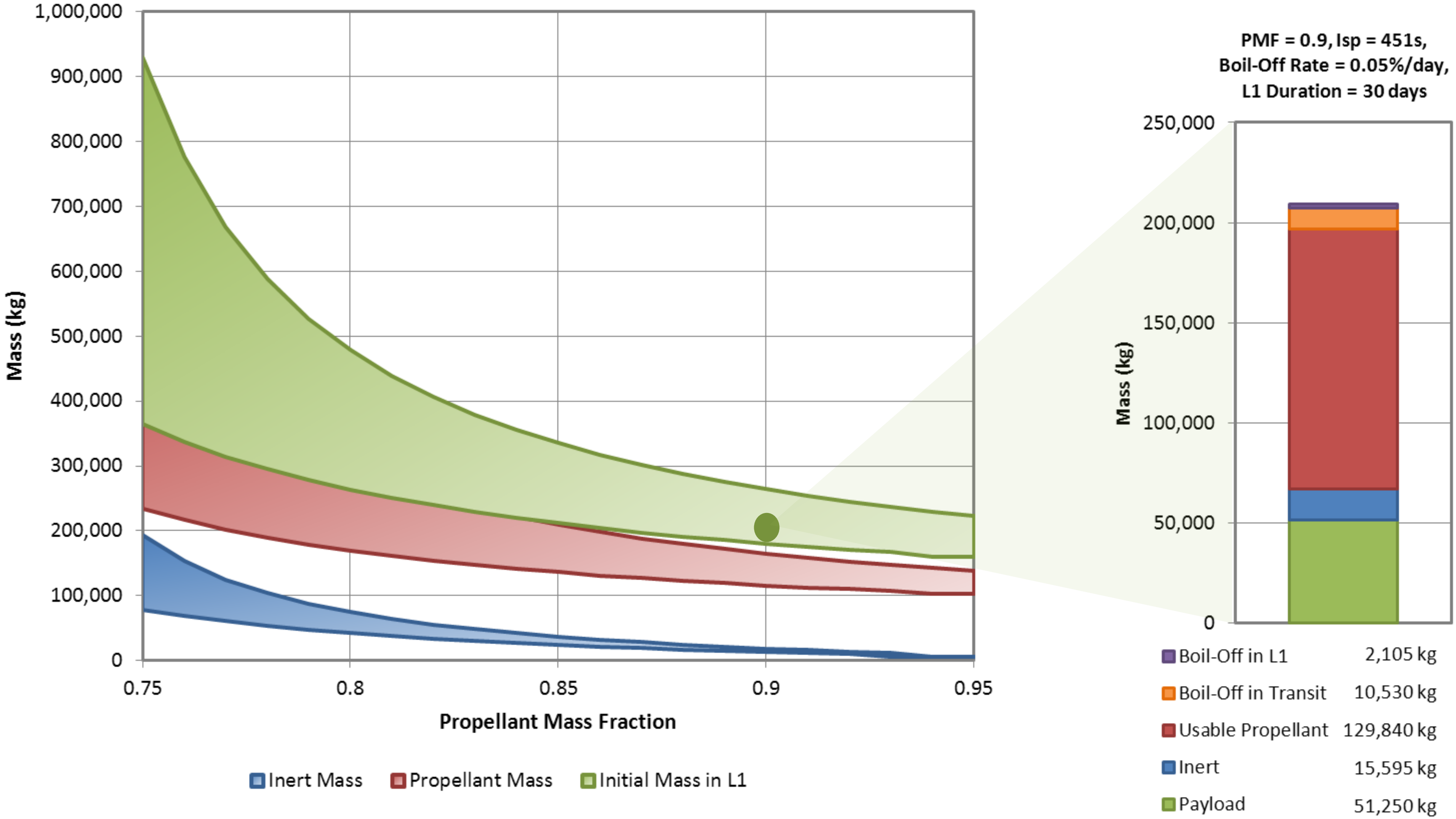
Lunar Mission Results: Design Variable Sweeps



- **Propellant Mass Fraction** has the largest impact on initial mass in L1 and is the dominant design variable for this mission
- All other design variables have very little impact

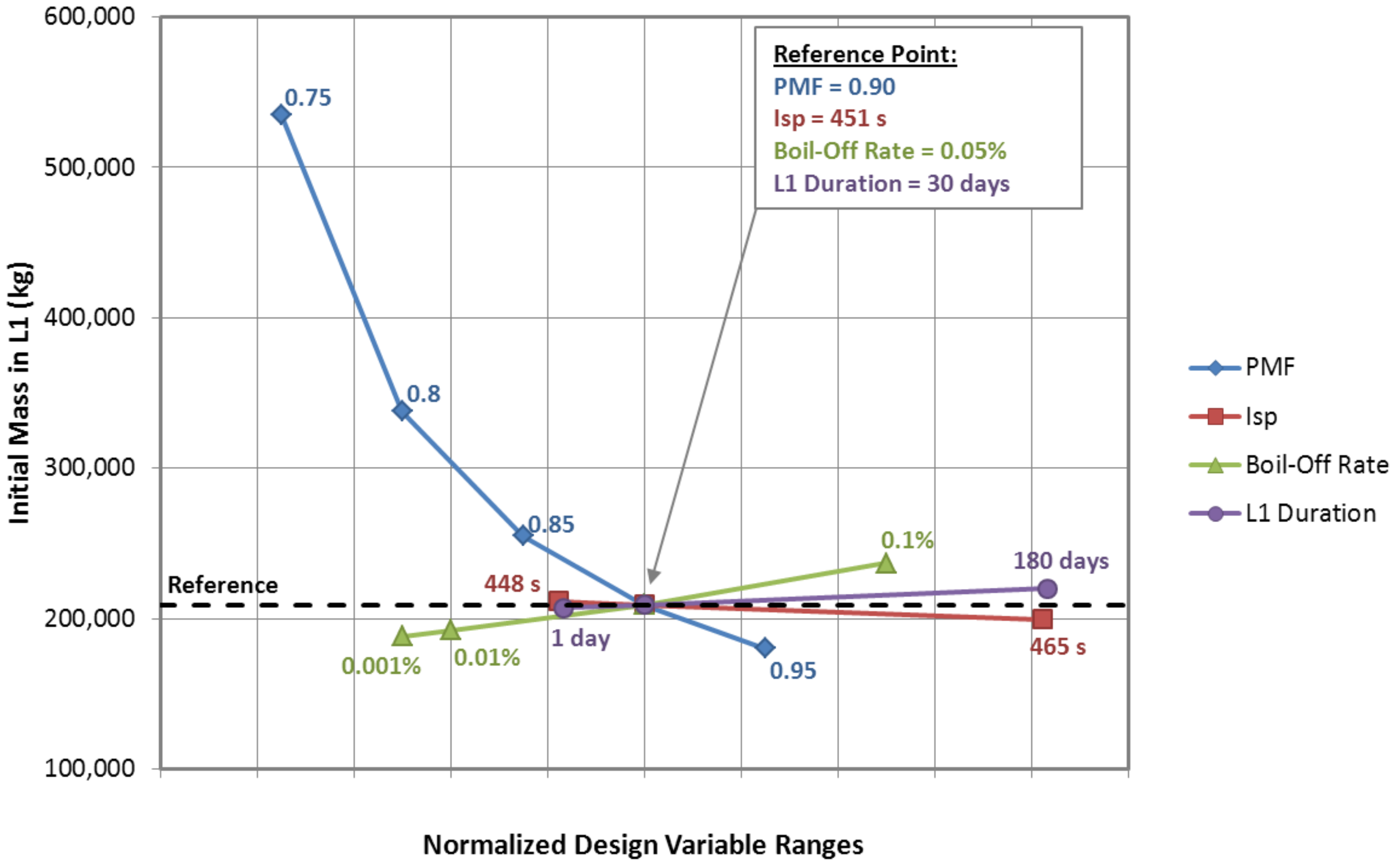
Lunar Mission Results: Design Variable Impacts

Near Earth Object (NEO) Mission



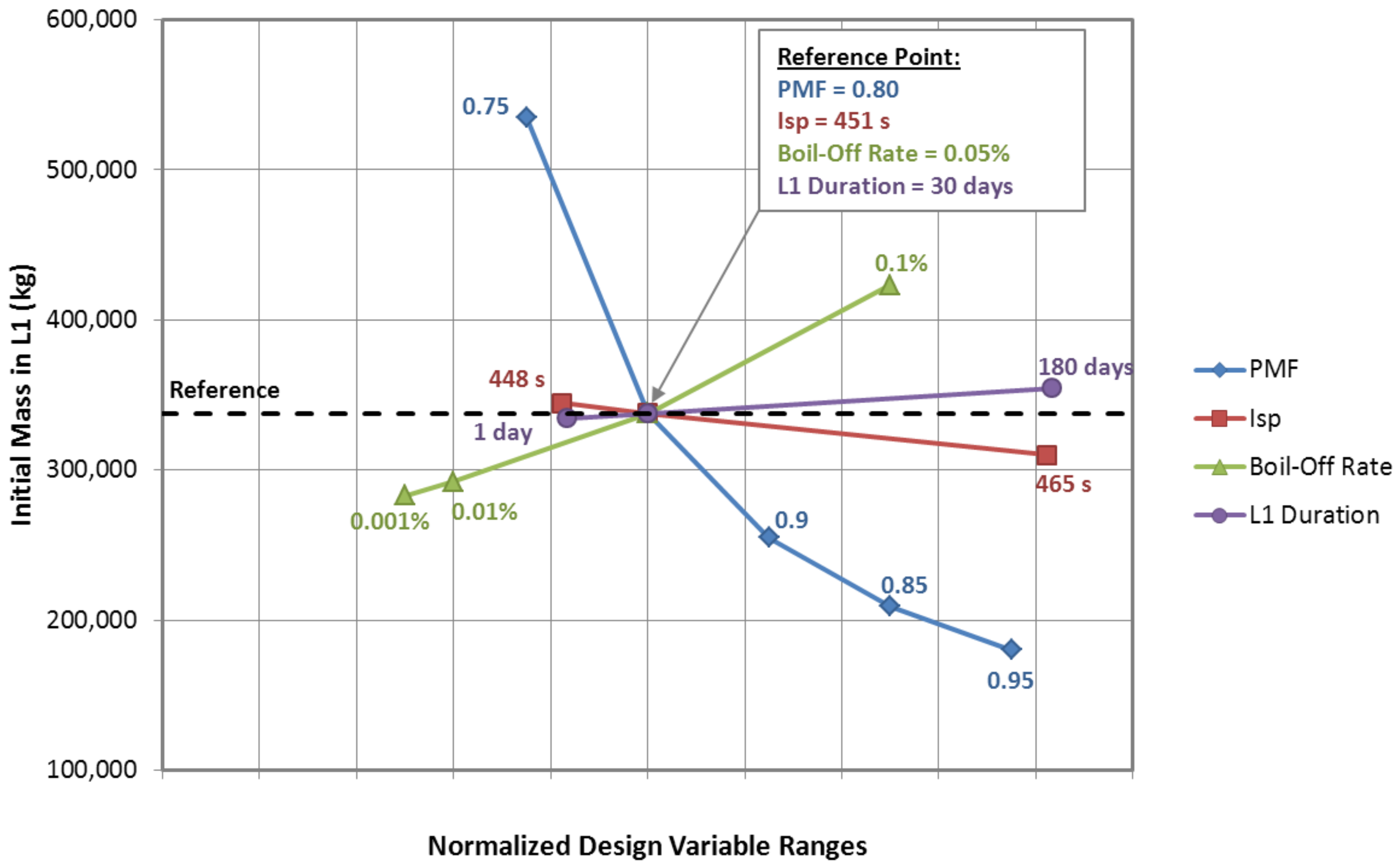
- Results for all combinations of design variables shown above
- At low propellant mass fractions, the system sensitivity to the other design variables increases significantly

NEO Mission Results: **Design Variable Sweeps**



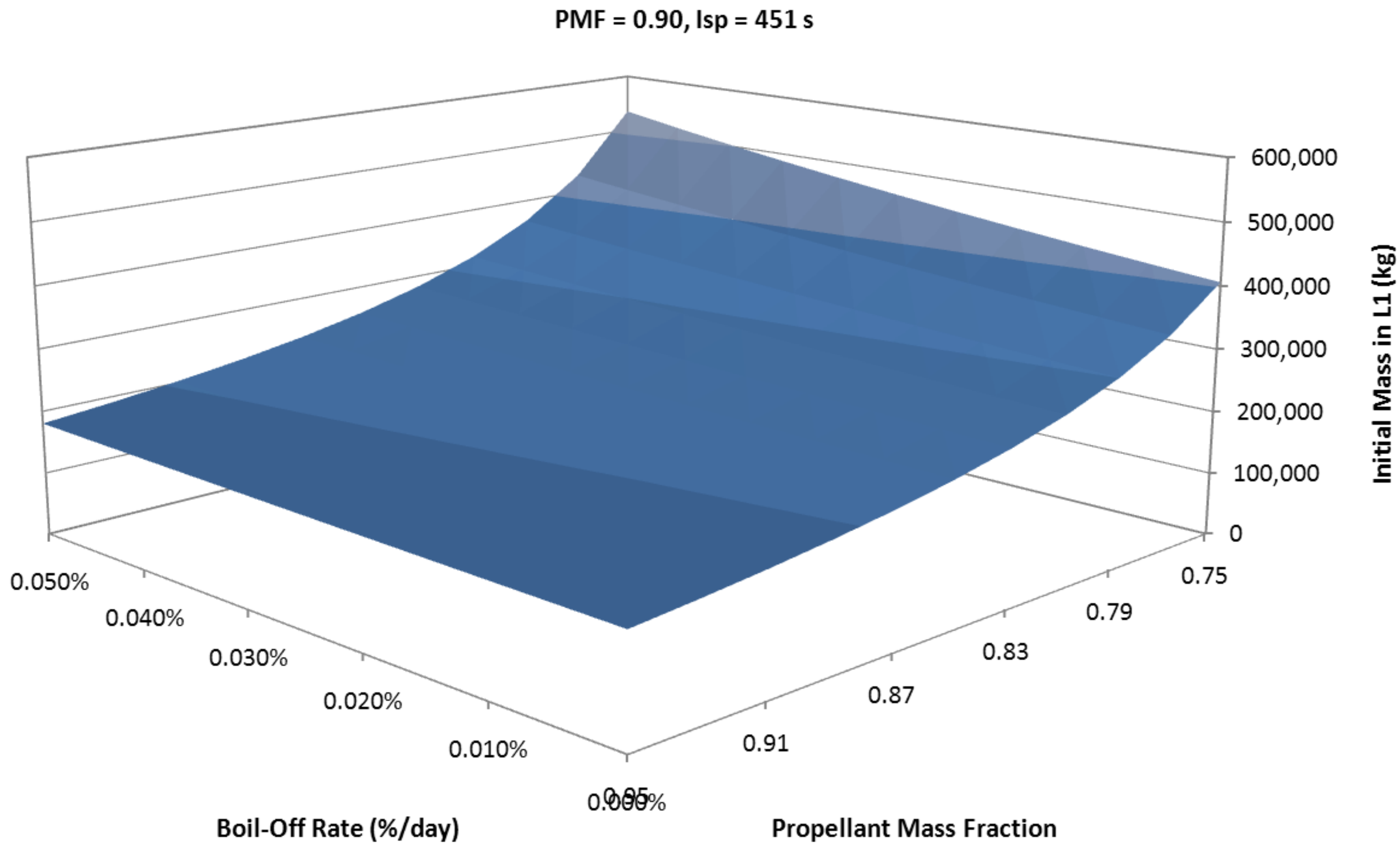
- **Propellant Mass Fraction** has the largest impact on initial mass in L1
- As seen on the previous chart, the impact of the other design variables is small at high propellant mass fractions, but significantly increased at lower propellant mass fractions

NEO Mission Results: Design Variable Impacts



- At a lower reference propellant mass fractions, the impact of boil-off rate is increased substantially
- The other design variable impact are exaggerated as well

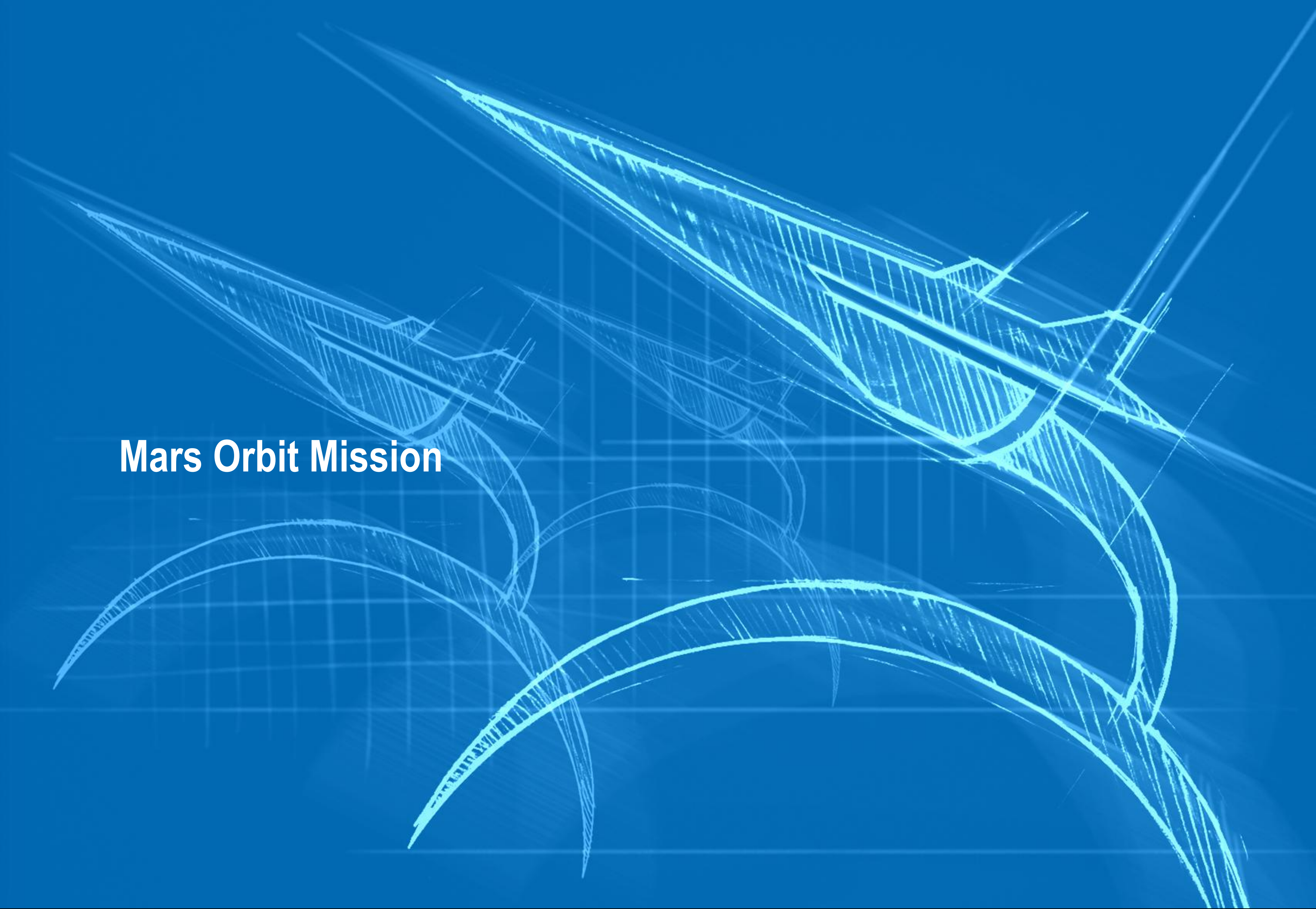
NEO Mission Results: Design Variable Impacts

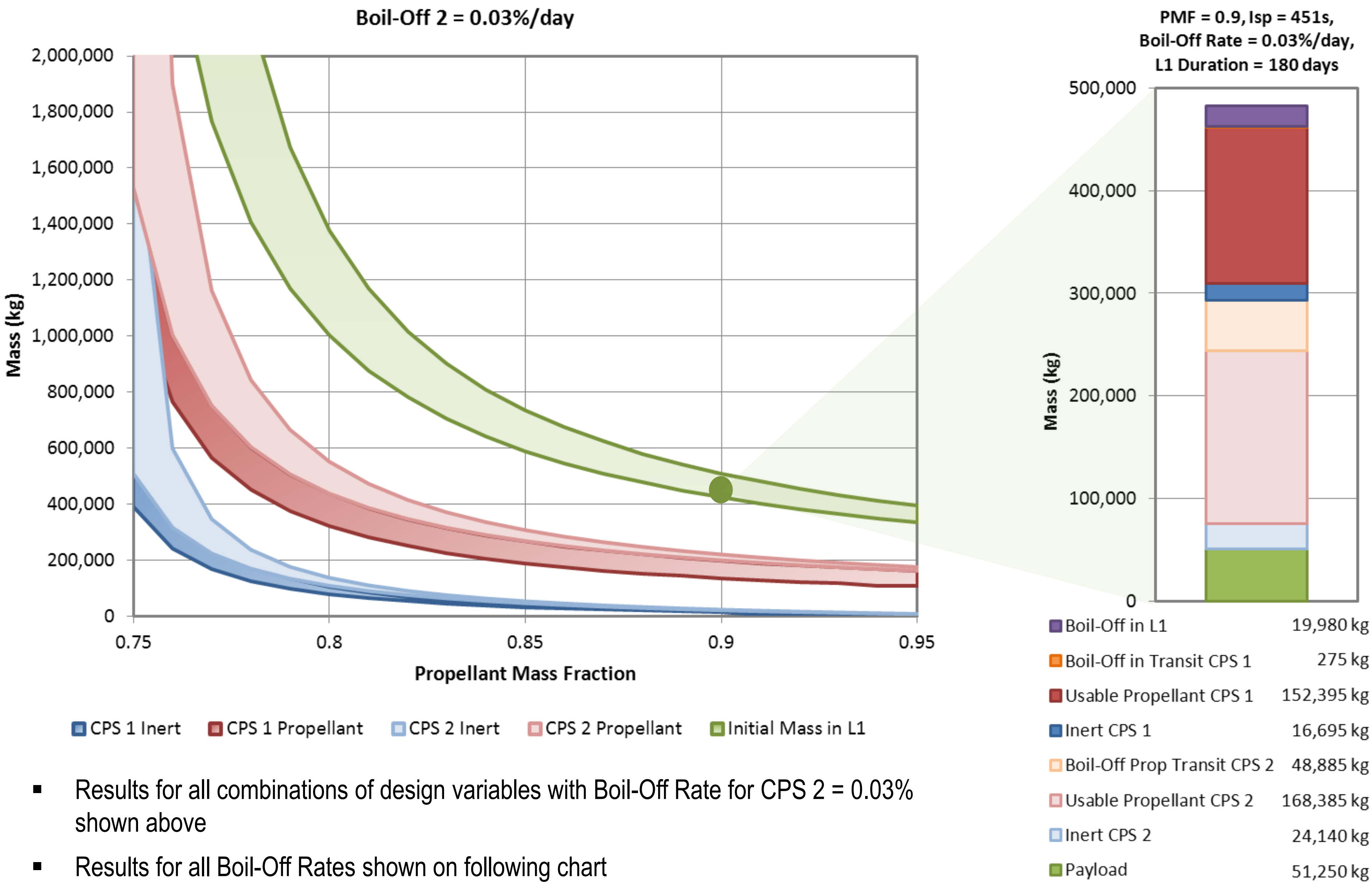


- Little coupling between Boil-Off Rate and Propellant Mass Fraction

NEO Mission Results: Design Variable Coupling

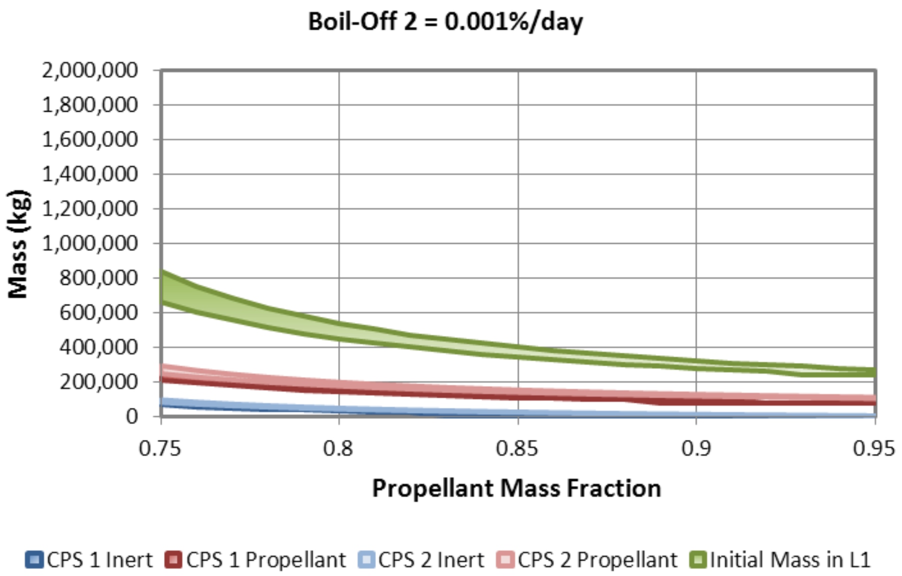
Mars Orbit Mission

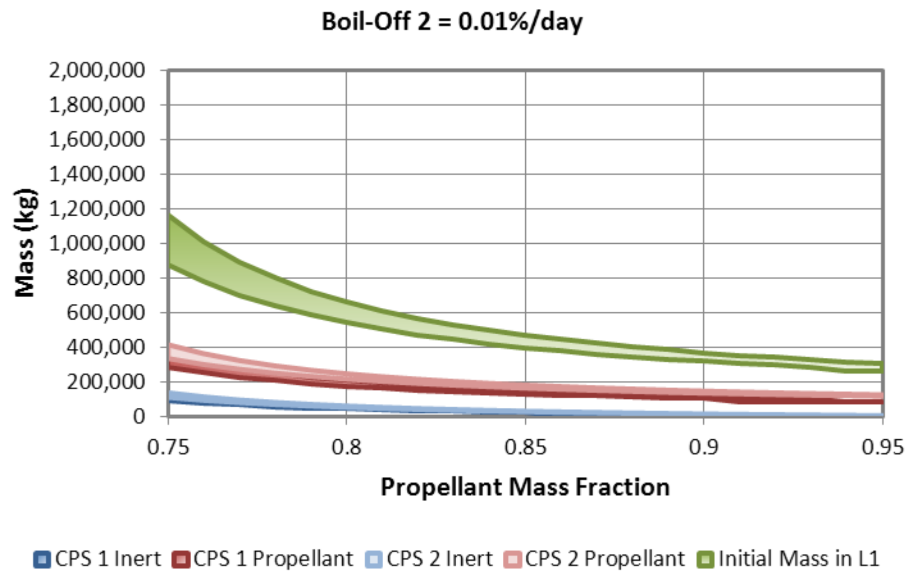


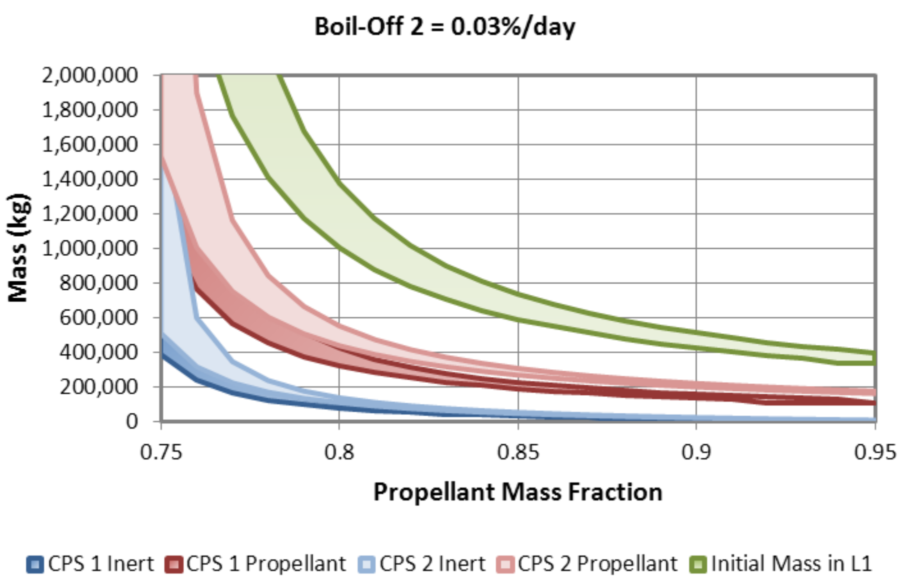


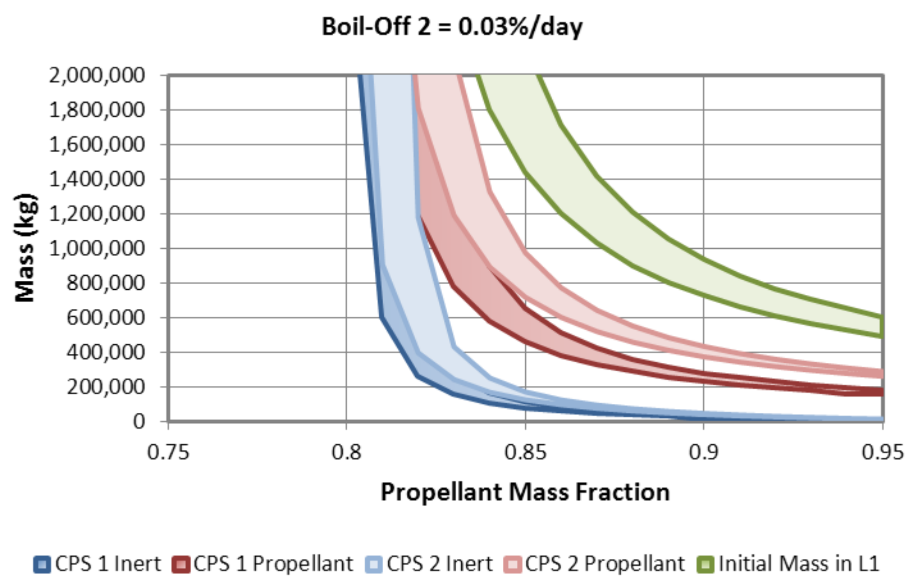
- Results for all combinations of design variables with Boil-Off Rate for CPS 2 = 0.03% shown above
- Results for all Boil-Off Rates shown on following chart

Mars Orbit Mission Results: Design Variable Sweeps (1 of 2)

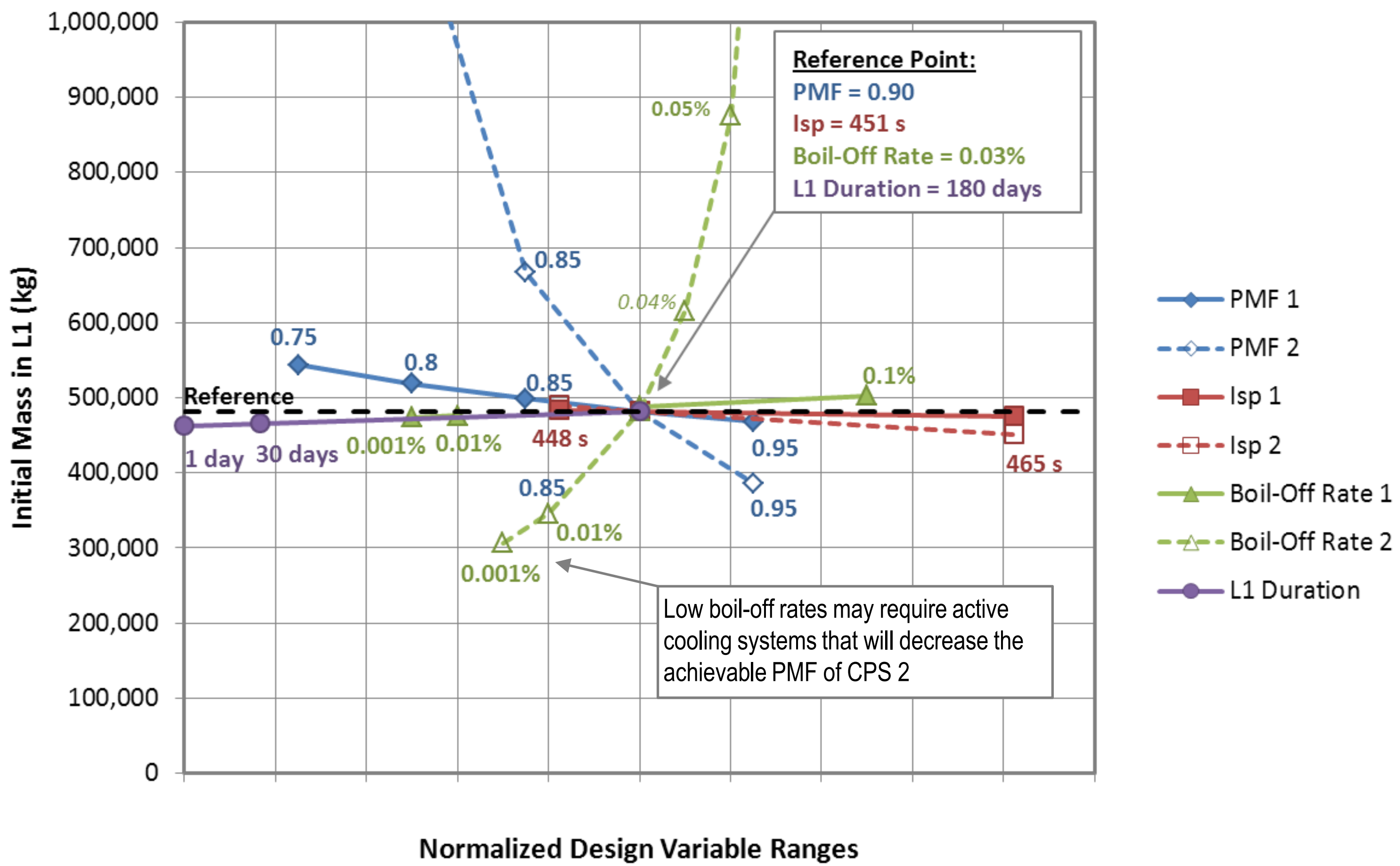






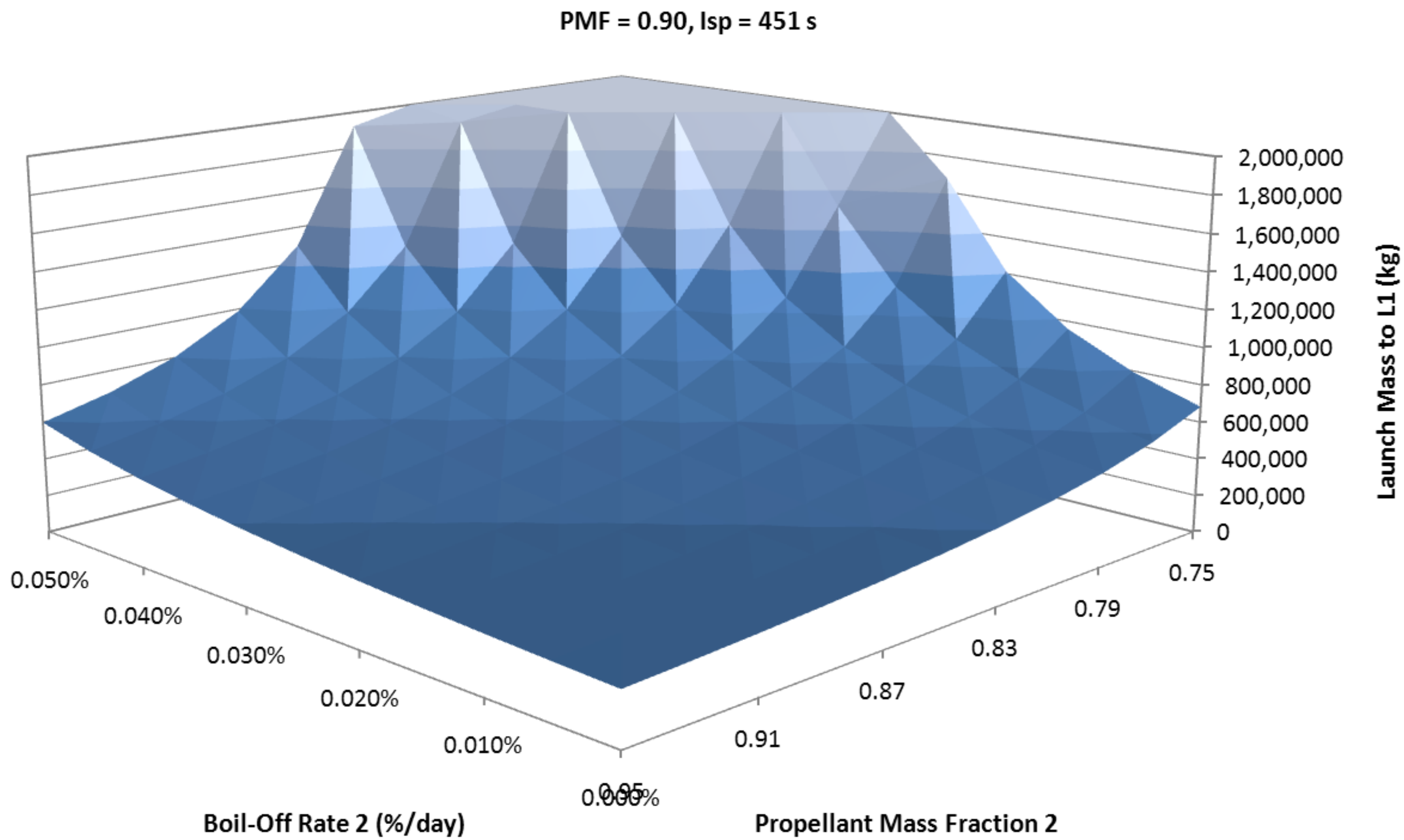


Mars Orbit Mission Results: Design Variable Sweeps (2 of 2)



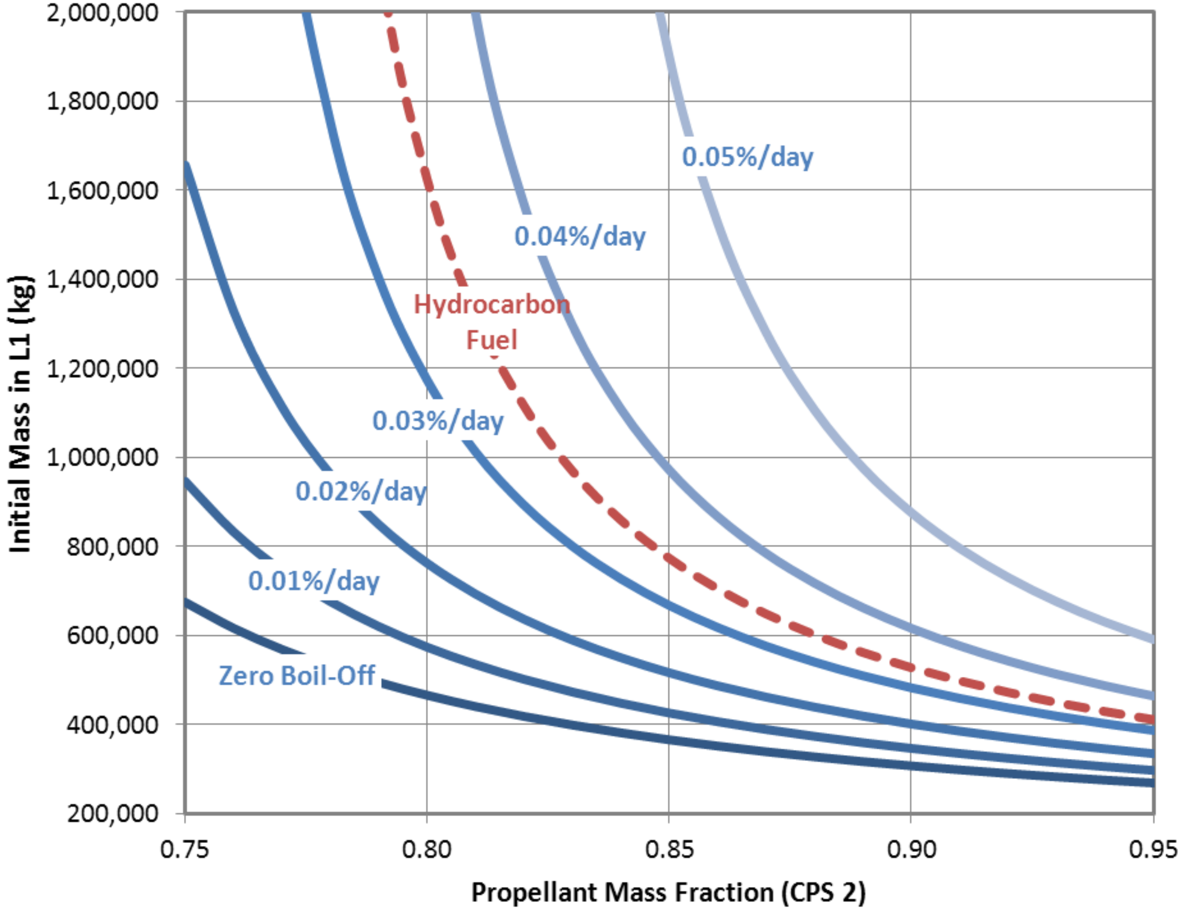
- **Propellant Mass Fraction** and **Boil-Off Rate** for CPS 2 have the largest impact on initial mass in L1
  - Conservative choices for these variables lead to systems that do not close
  - Reducing boil-off rate below 0.05%/day on CPS 2 yields the largest reduction in launch weight from the reference point; however it may not be possible to achieve these gains and maintain the reference PMF

Mars Orbit Mission Results: Design Variable Impacts



- Strong coupling between Boil-Off Rate for CPS 2 and Propellant Mass Fraction for CPS 2
- Conservative values for both variables can quickly lead to unclose-able cases

Mars Orbit Mission Results : Design Variable Coupling



Assumptions

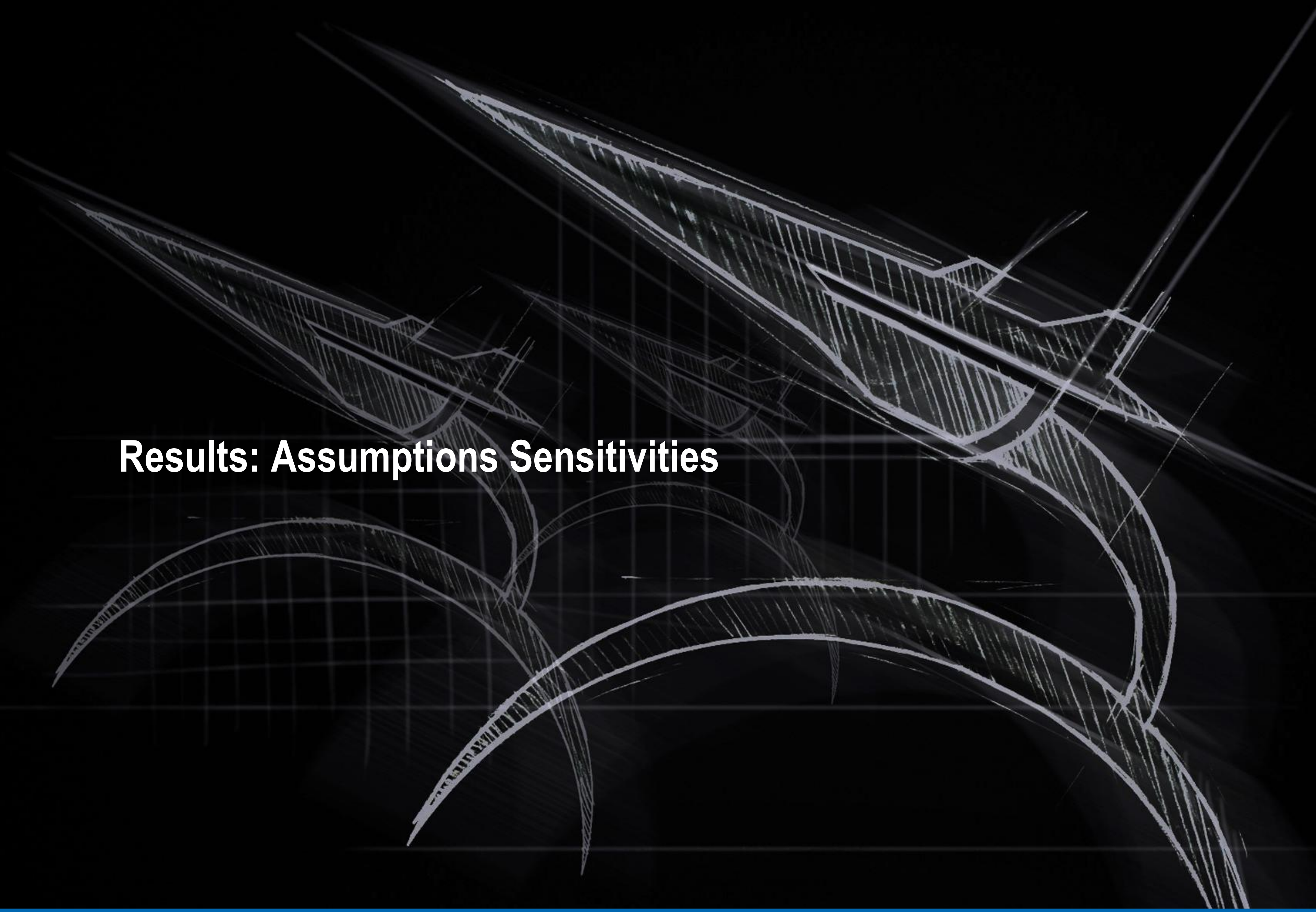
CPS 1
- **PMF = 0.9**
- **Isp = 451 s**
- **Boil-Off Rate = 0.03%/day**

CPS 2
- PMF = Variable
- Boil-Off Rate = Variable
- **Cryo Fuel Isp = 451 s**
  or
- **Hydrocarbon Fuel Isp = 340 s**

L1 Duration = 180 days

- Reducing boil-off rate by increasing stage dry mass, through the addition of passive or active cooling systems, may reduce total initial mass in L1 at the expense of propellant mass fraction
- If boil-off rates cannot be improved on CPS 2, the use of a **storable hydrocarbon fuel** can reduce total initial mass in L1

Mars Orbit Mission Results: Cryogenic vs. Storable Fuels

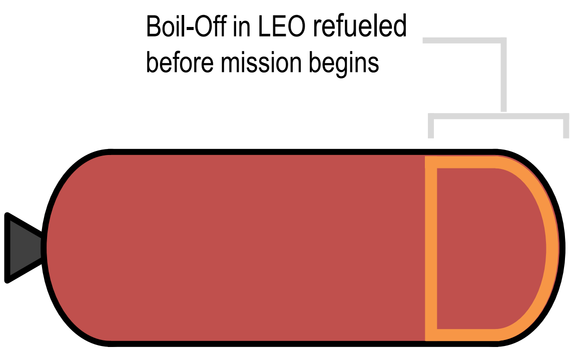


Results: Assumptions Sensitivities

L1 Refuel Sensitivity: Options

CPS Refueled Prior to Departure (baseline)

- It is assumed that this **boil-off propellant is replenished** before the mission commences.
- The boil-off propellant lost during the L1 Duration period **is not included** in the CPS propellant mass fraction when the inert mass of the CPS is being determined (i.e. not included in stage sizing).
- The boil-off propellant lost during the mission away from L1 and in transit **is included** in the propellant mass fraction when the inert mass is being determined.



Start of Mission

No Refueling (alternative)

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- The boil-off propellant lost during the L1 Duration period **is included** in the CPS propellant mass fraction when the inert mass of the CPS is being determined (i.e. included in stage sizing).
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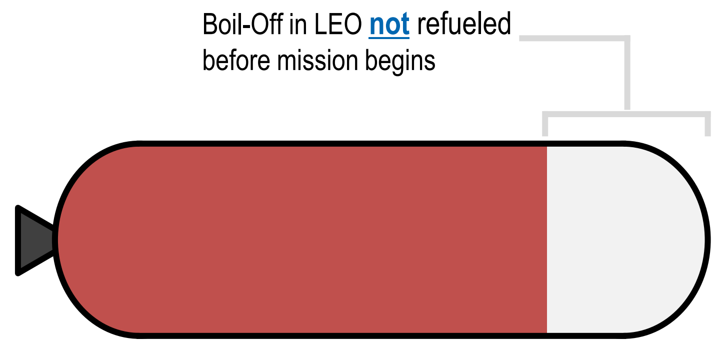
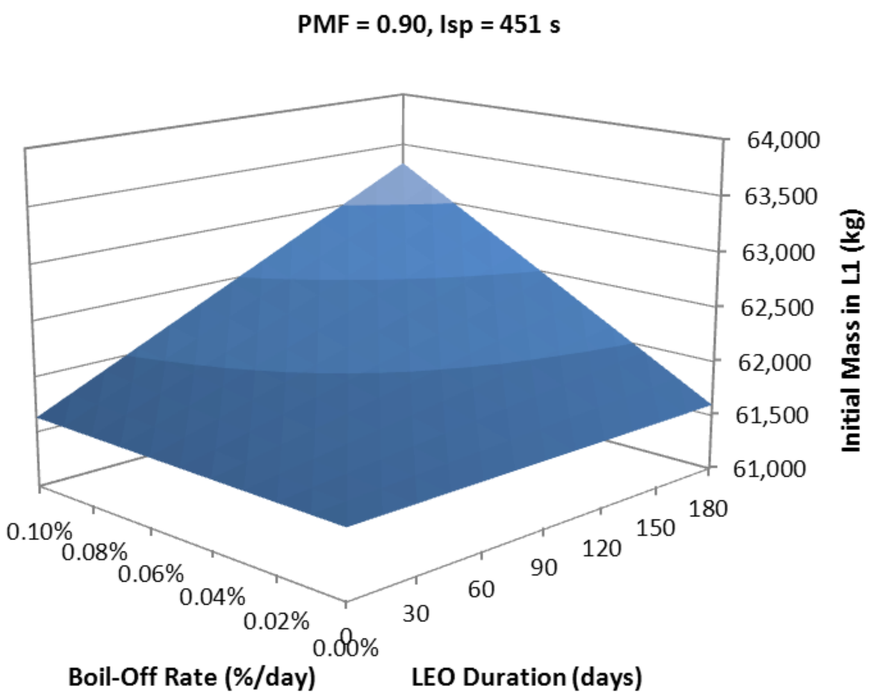
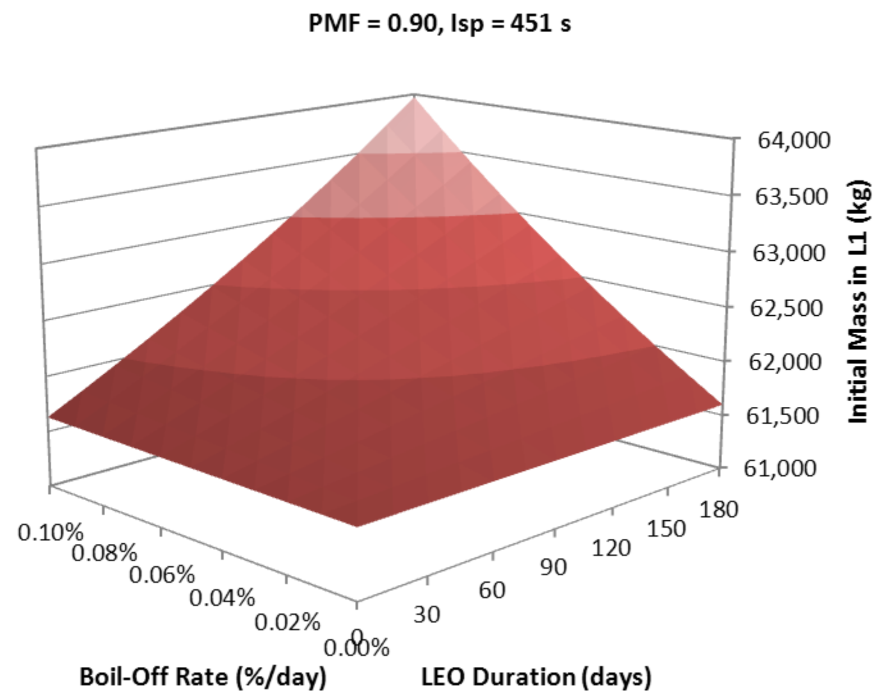


Start of Mission

CPS Refueled Prior to Departure (baseline)



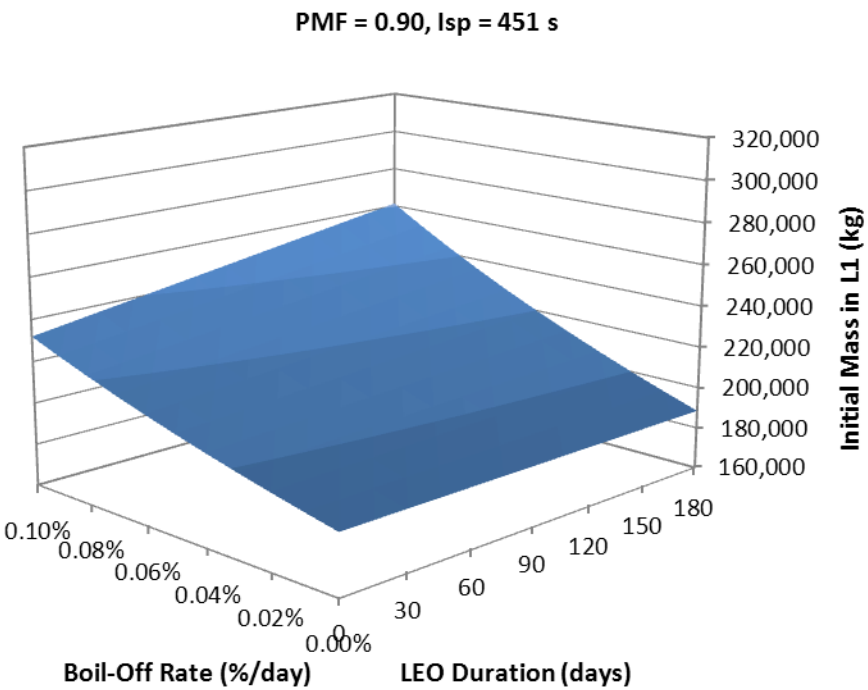
No Refueling (alternative)



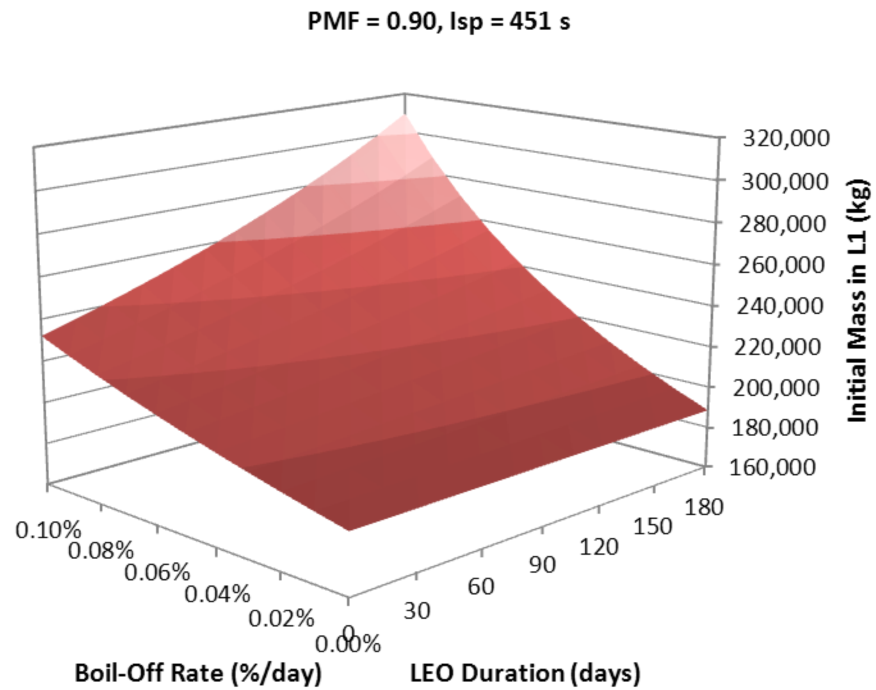
For the mission to LLO, refueling before departure can only save 1% in initial mass in L1

L1 Refuel Sensitivity: Lunar Mission Results

CPS Refueled Prior to Departure (baseline)



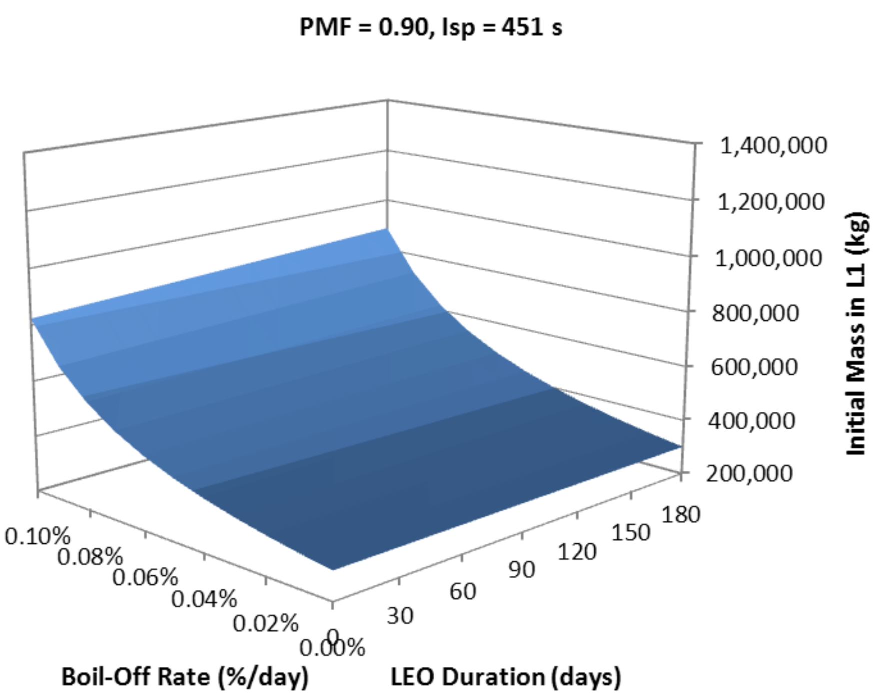
No Refueling (alternative)



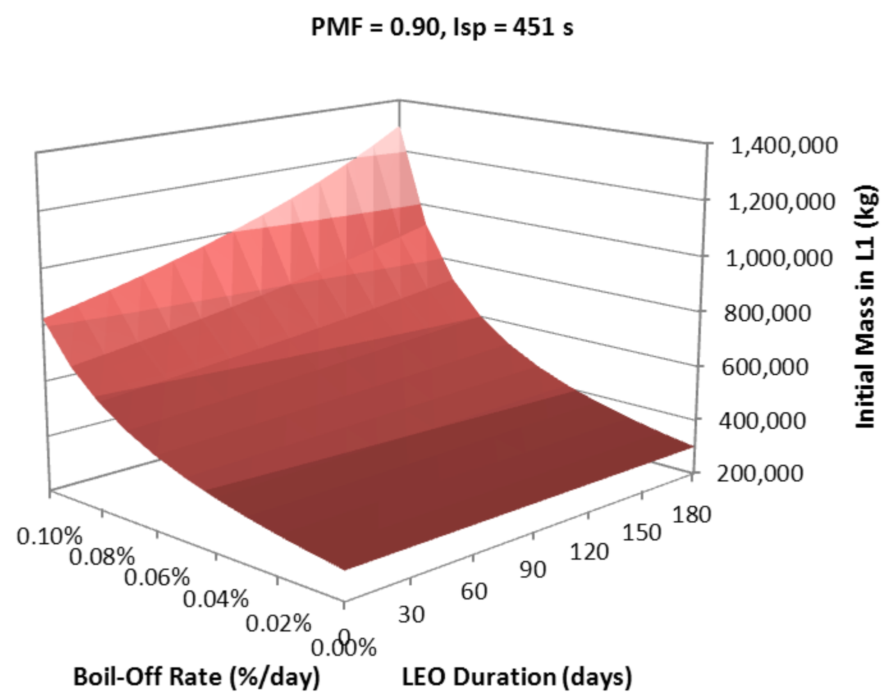
For the mission to a NEO, refueling before departure can only save up to 15% in initial mass in L1

L1 Refuel Sensitivity: Mars Orbit Mission Results

CPS Refueled Prior to Departure (baseline)



No Refueling (alternative)



For the mission to a Mars, refueling before departure can only save up to 30% in initial mass in L1

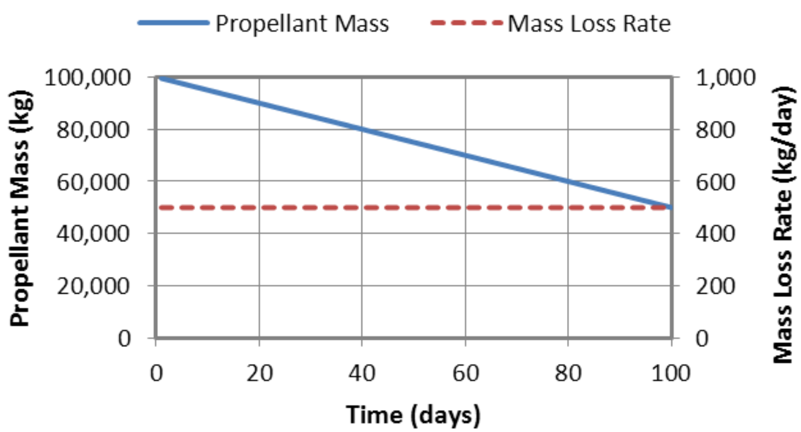
L1 Refuel Sensitivity: Mars Orbit Mission Results

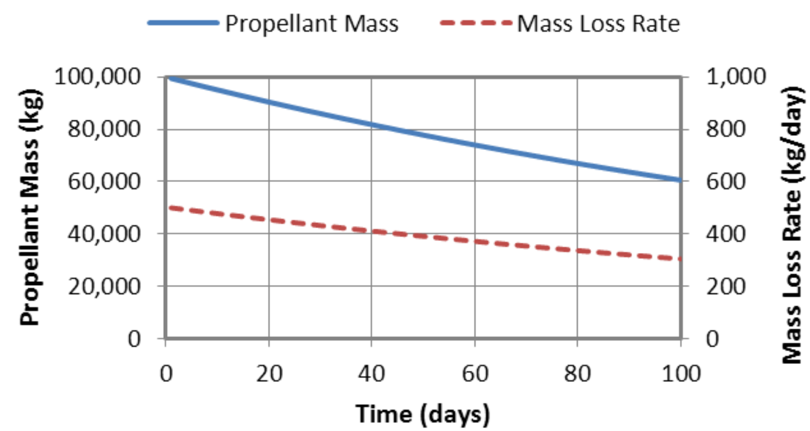
Total Initial Propellant Method (baseline)

- Boil-off rates are measured as a percent of **total initial** propellant mass lost per day
- A fixed mass loss rate is calculated at the beginning of the mission and held constant throughout the mission
- Analogous to worst case scenario for unsettled zero-g propellants

Remaining Propellant Method (alternative)

- Boil-off rates are measured as a percent of **current remaining** propellant mass lost per day
- Each day of the mission, a percent of propellant mass is assumed lost to boil-off. As the mission progresses, the amount of remaining propellant decreases, so the effective mass loss rate decreases.
- Analogous to best case scenario for settled propellants

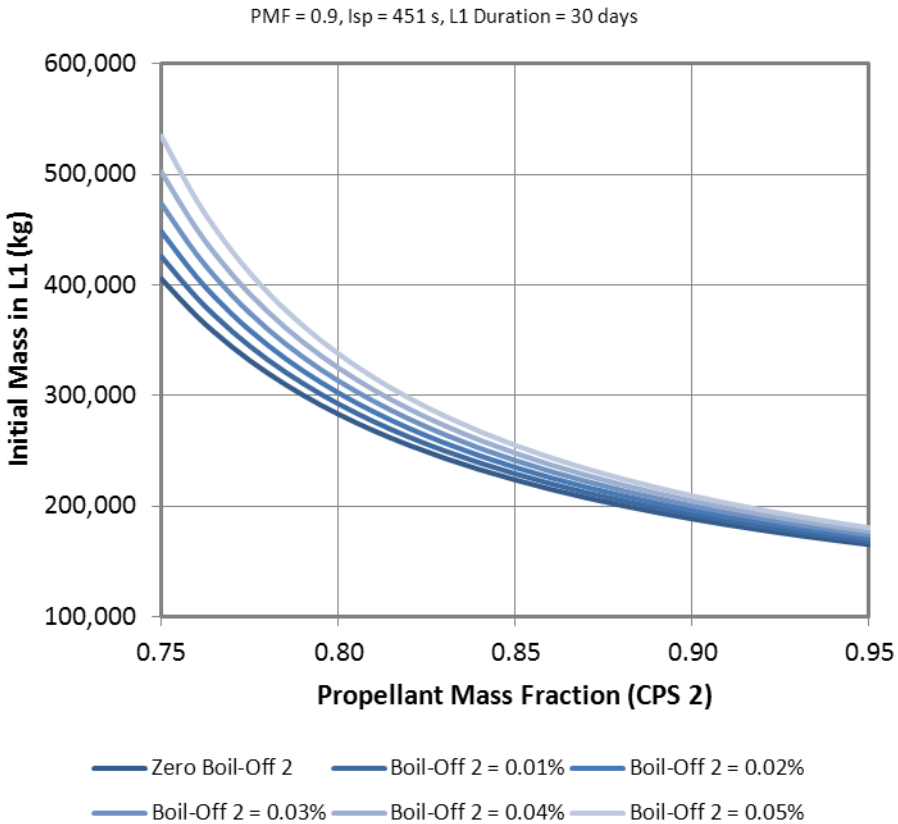




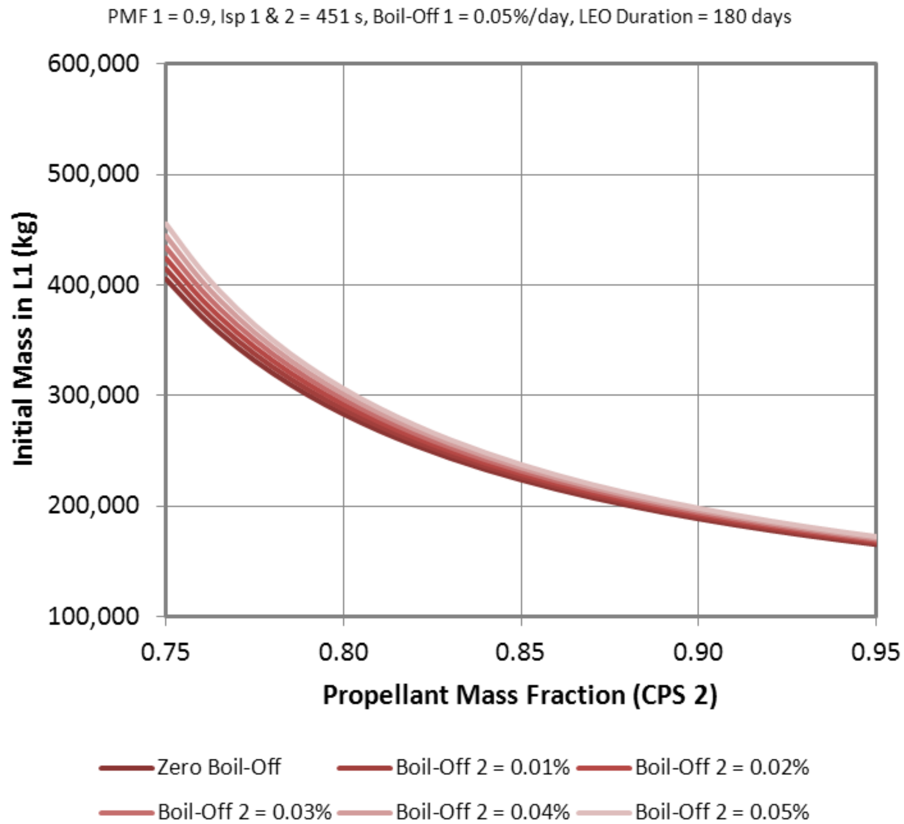
Boil-Off Method Sensitivity: Options

Boil-Off Method Sensitivity: NEO Mission Results

Total Initial Propellant Method (baseline)

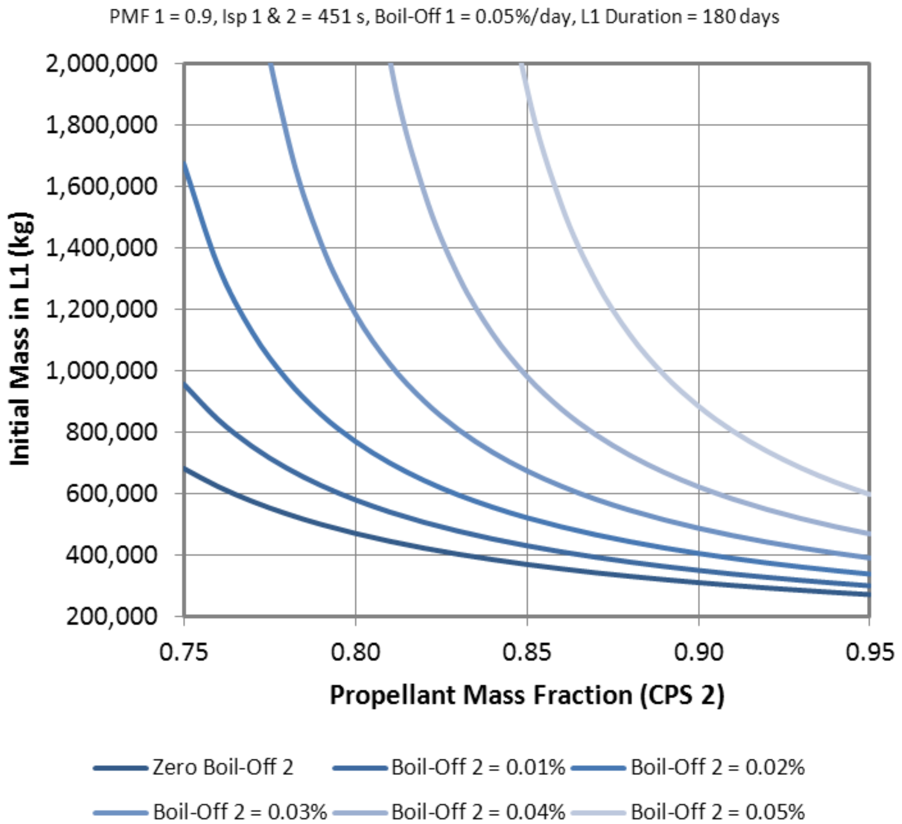


Remaining Propellant Method (alternative)

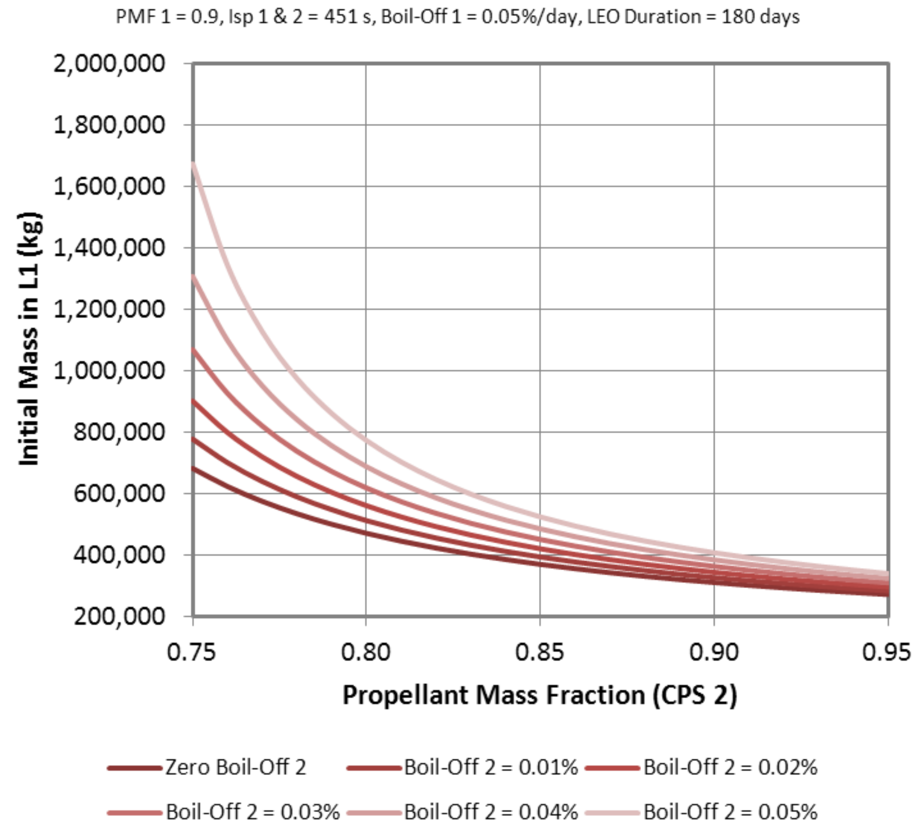


For NEO missions with only 30 days at the NEO with a partially full CPS, there is only a small between the two methods

Total Initial Propellant Method (baseline)

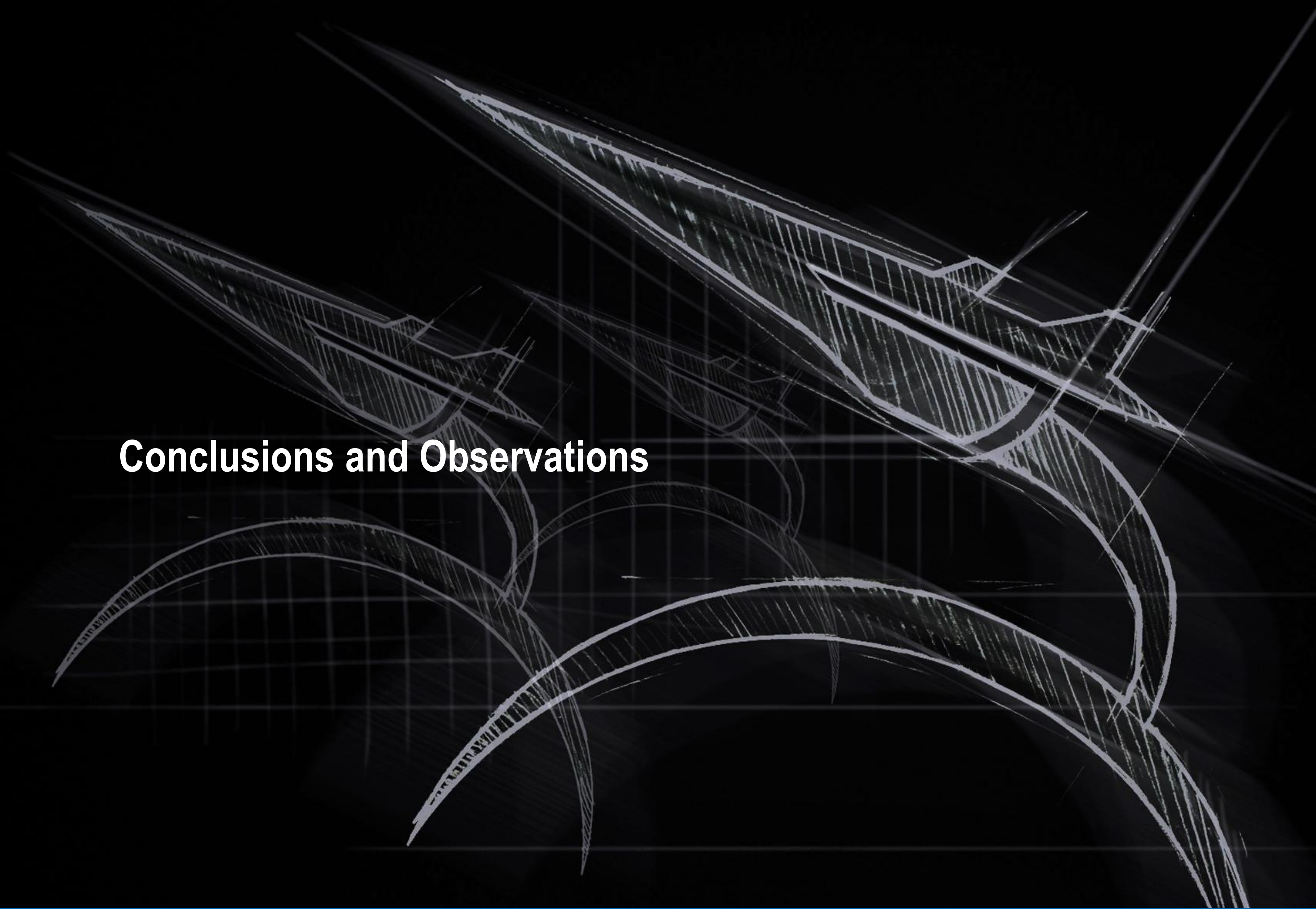


Remaining Propellant Method (alternative)



For Mars mission with 550 days in Mars orbit with a partially full CPS 2, there is a significant difference between these two methods

Boil-Off Method Sensitivity: Mars Orbit Mission Results



Conclusions and Observations

- **Propellant Mass Fraction** is the single largest design driver based on the range of values chosen for the design variables for all missions, particularly for the upper stages of multistage vehicles.
- **Specific Impulse** has a much smaller impact than Propellant Mass Fraction for the ranges considered but can still be a significant driver
- **Boil-Off Rate** has varying impact based on the mission requirements
  - For short, single stage missions (L1 and Lunar Surface), boil-off rate has little impact on the system
  - For relatively short, multi-stage missions (NEO), boil-off rate has a small impact on the system
  - For long, multi-stage missions (Mars), the boil-off rate on the second CPS has a very large impact on the missions
    - Improvements in boil-off rate on this stage can significantly reduce initial mass in L1 for this mission
    - If boil-off rate cannot be reduced, storable hydrocarbon fuels are a viable option
- If the CPSs can be refueled prior to departure, **LEO Duration** will have a small impact on the total initial mass in L1 because the propellant lost to boil-off during this phase will not impact the size of the CPSs
- Refueling the CPS in LEO before the mission begins reduces Initial Mass in L1 required

Design variable sensitivities are identical to those for missions starting in Low Earth Orbit

Conclusions

- The orientation of the Earth-Moon system with respect to the sun results in **~4 day wide launch windows** from L1 to heliocentric transfer orbits occurring approximately **once per month**
  - To launch outside of this launch window, the change in the declination of the heliocentric departure velocity vector required imparts a significant penalty on total ΔV required
  - The long gap between launch windows may have **serious implications** on missions to NEOs or Mars, where a missed launch opportunity can significantly alter the total required mission ΔVs.

- Departing from L1 introduces several days of **additional flight time** to leave the Earth-Moon system, increasing consumables requirements and boil-off losses

- Because spacecraft must change velocity at apogee to achieve a stable L1 orbit, and change velocity again to leave L1, any mission starting from L1 incurs a total ΔV penalty compared to missions starting in LEO, when the trip from LEO to L1 is included.
  - In all the following results, the **energy required** to reach L1 from the Earth is **not considered**

Earth-Moon L1 has both advantages and disadvantages as a starting point for deep space missions to NEOs or Mars

Observations

SPACE IS GO

SpaceWorks Enterprises, Inc.

SpaceWorks Enterprises, Inc. | 1040 Crown Pointe Parkway | Suite 950 | Atlanta, GA 30338 | 1+770-379-8000 (Office) | 1+ 770-379-8001 (Fax) | www.sei.aero | info@sei.aero