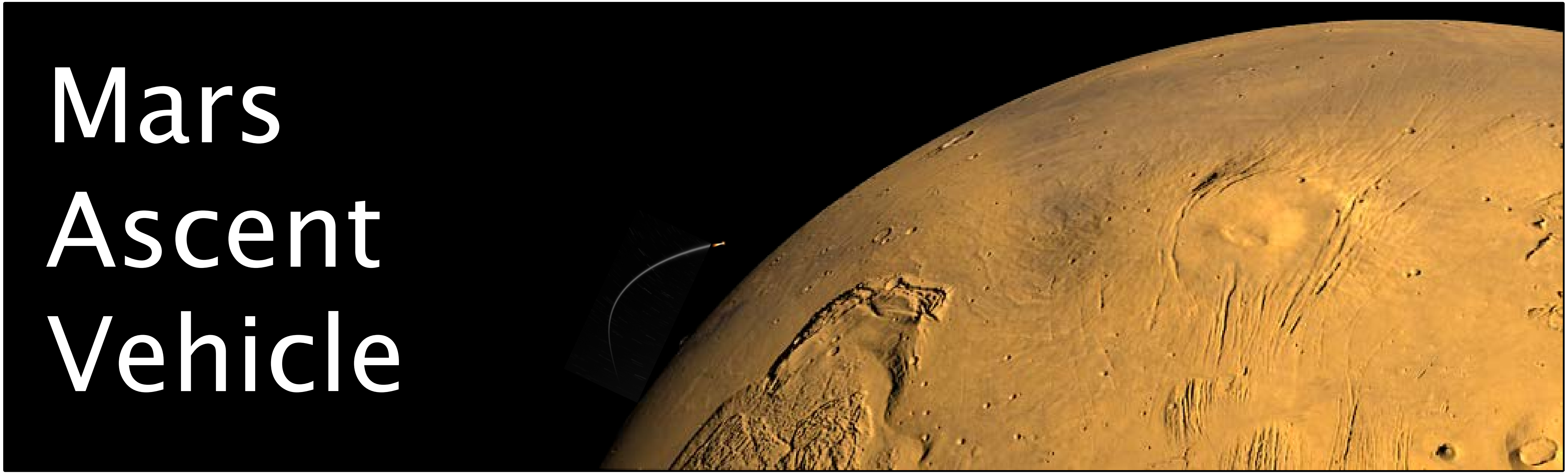

Mars Ascent Vehicle

Jet Propulsion Laboratory
California Institute of Technology

MARSHALL
SPACE FLIGHT CENTER

A Design for a Two-Stage Solid Mars Ascent Vehicle

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Timothy Kibbey, Jacobs/NASA Marshall Space Flight Center
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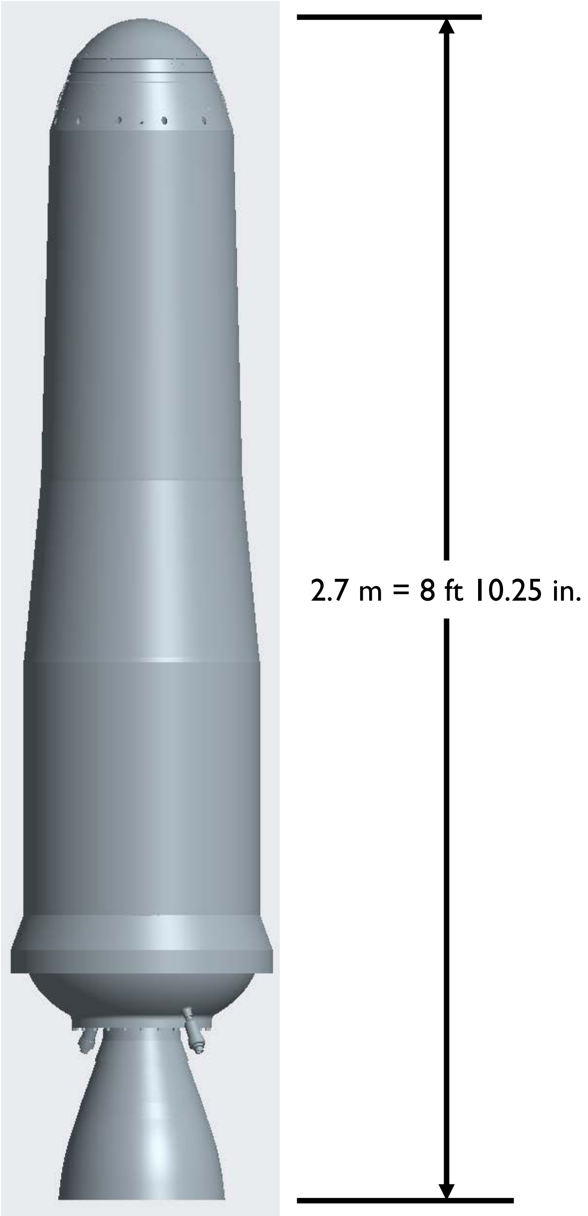
Mars Ascent Vehicle (MAV)

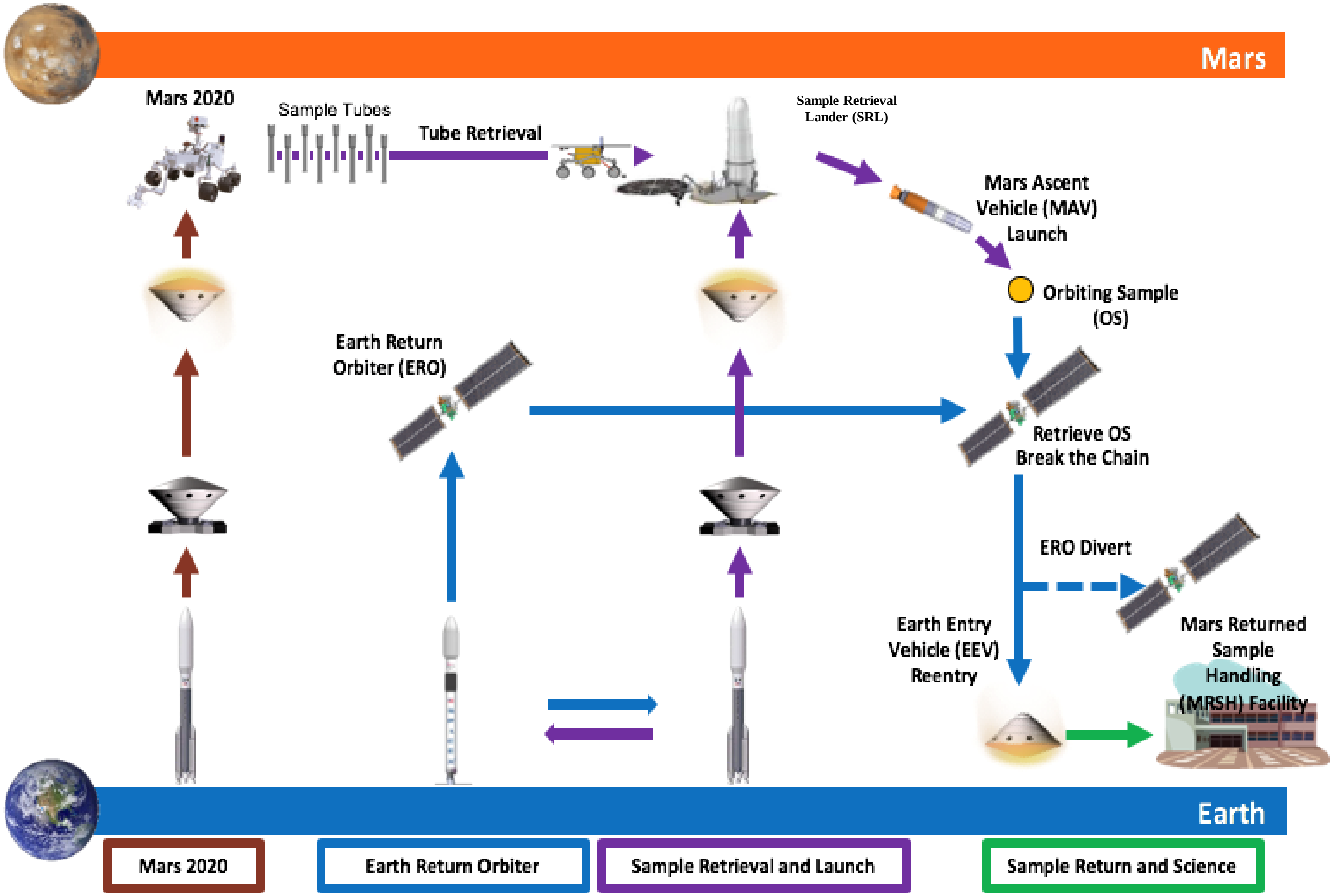
- Marshall Space Flight Center (MSFC) and the Jet Propulsion Laboratory (JPL) are developing the MAV as part of a potential robotic Mars Sample Return campaign
- One option for MAV is a solid propulsion vehicle
- This paper outlines development of the propulsion system for that vehicle

- The solid propulsion design steps outlined were completed concurrently with the remainder of the vehicle
  - Design methodology
  - Optimization trades
  - Motor development refinements
  - Propellant and motor testing



394 kg = 868.6 lbs

Mars Sample Return (MSR)

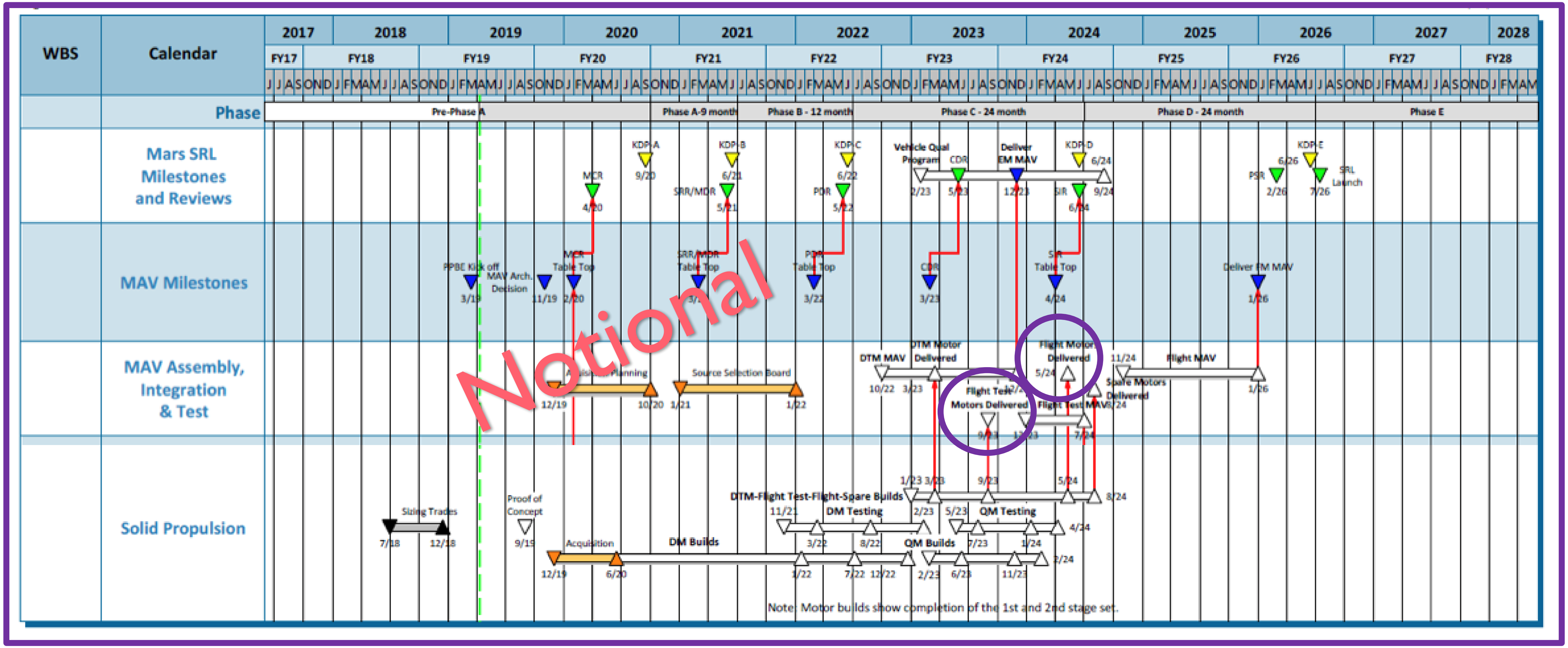


> *“While neither NASA nor the European Space Agency has yet to give formal approval, or funding, for missions to return samples from Mars, both agencies are taking steps to refine plans for what those missions will be.*
>
> *Those plans, discussed at a Mars science conference and working group meeting last week, would involve two launches in 2026 to send spacecraft to fetch samples collected by NASA’s Mars 2020 rover and return them to Earth in 2031.”*

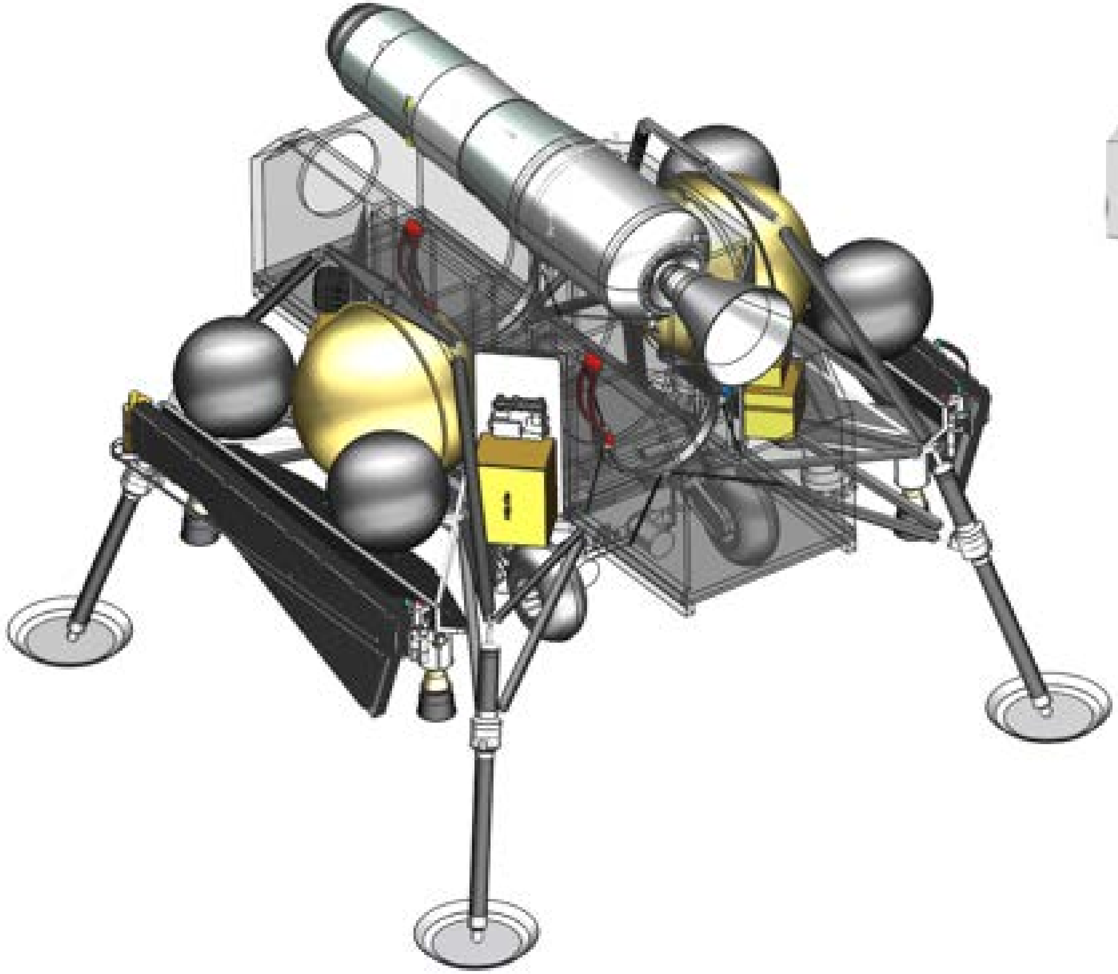
- Space News, July 28 2019

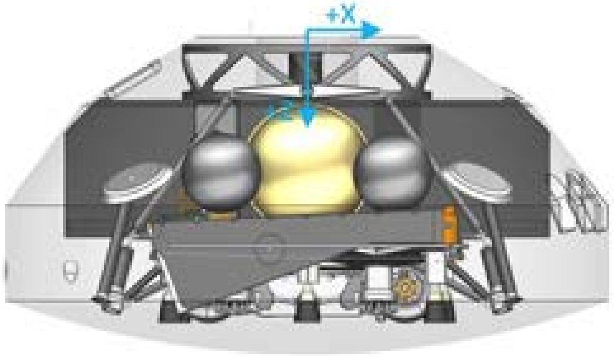
MAV Draft Schedule

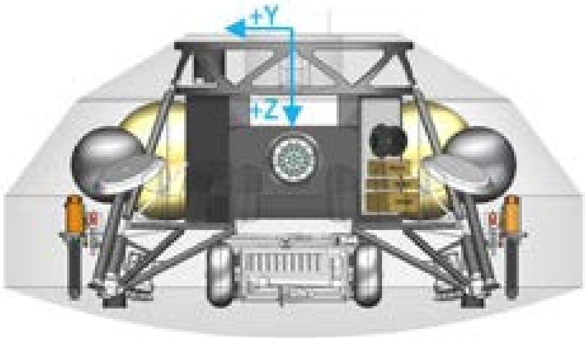
- Time is potentially short

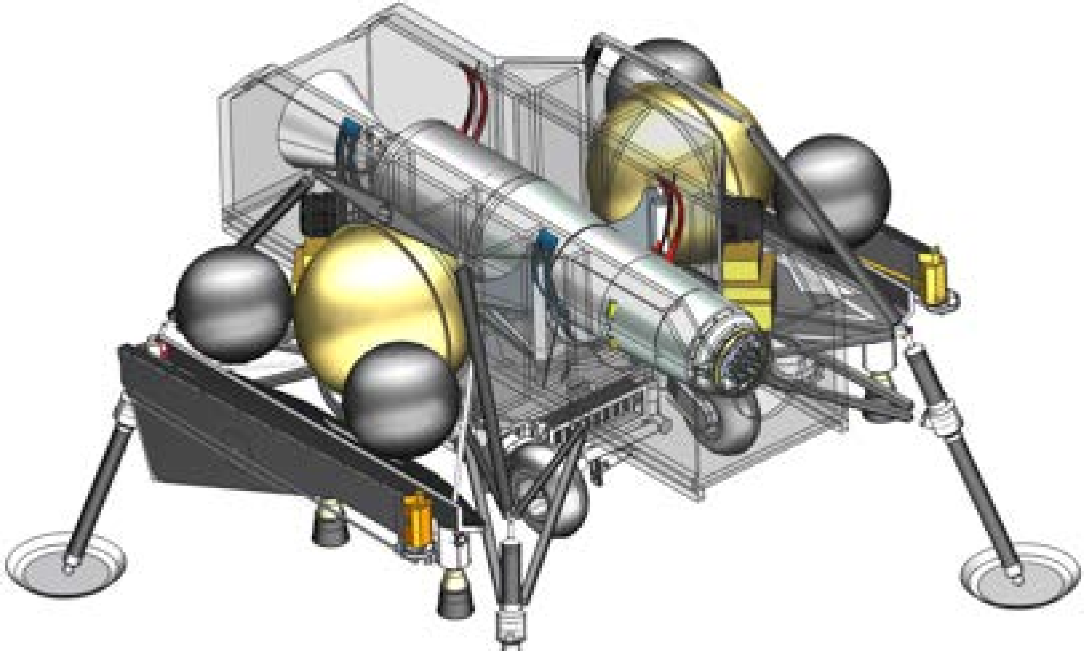


MSR Lander Concept



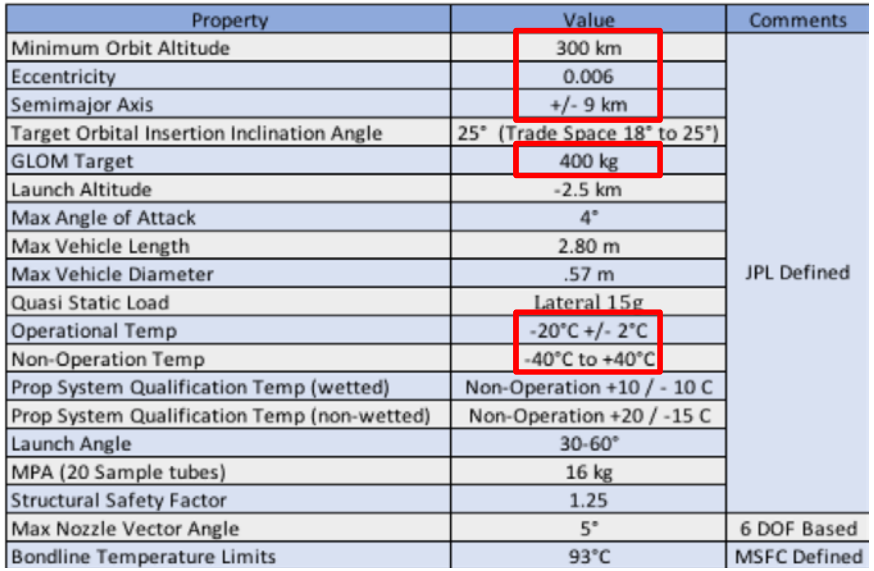




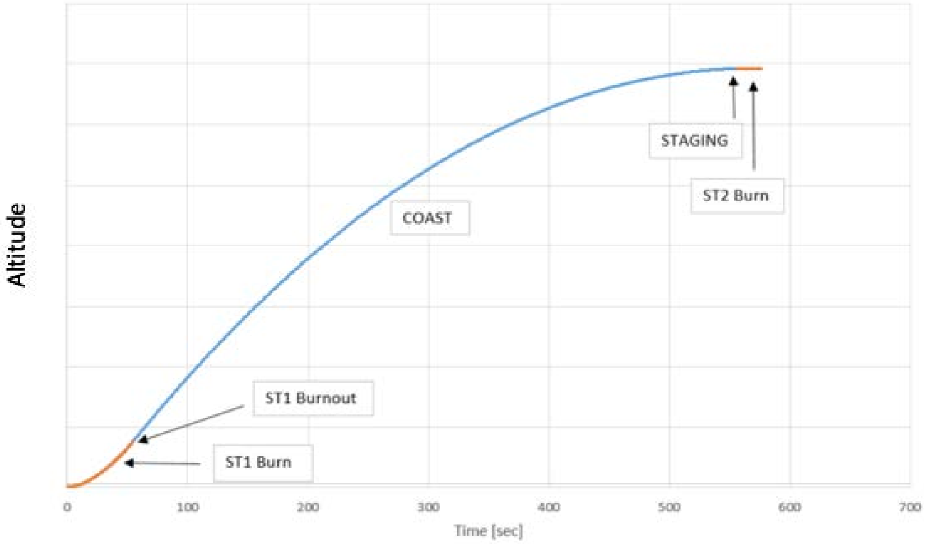


Ground Rules and Assumptions (GR&A)

- The design centered on a set of GR&A
  - Vehicle Gross Lift-Off Mass (GLOM), temperature extremes, and orbital dispersions are the most significant challenges
- Mission design includes two nearly instantaneous burns separated by a long coast
  - Stage 1 (ST1) puts the vehicle into a highly elliptical orbit with an apoapsis at the desired altitude of the circular orbit, but with a negative periapsis.
  - Once the vehicle has coasted nearly to apogee, Stage 2 (ST2) fires to circularize the orbit

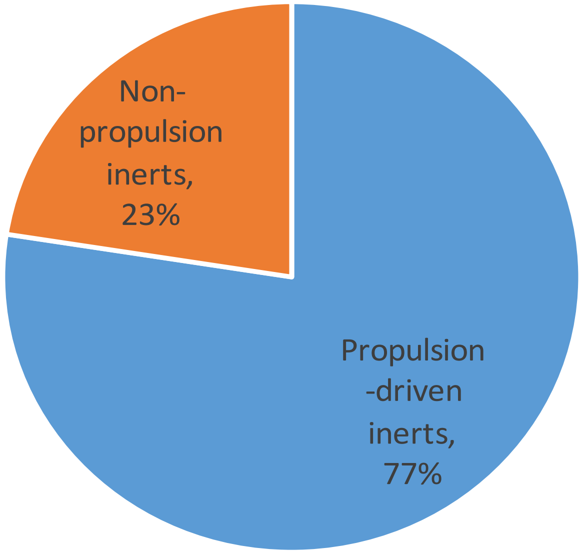


Property	Value	Comments
Minimum Orbit Altitude	300 km	JPL Defined
Eccentricity	0.006	
Semimajor Axis	+/- 9 km	
Target Orbital Insertion Inclination Angle	25° (Trade Space 18° to 25°)	
GLOM Target	400 kg	
Launch Altitude	-2.5 km	
Max Angle of Attack	4°	
Max Vehicle Length	2.80 m	
Max Vehicle Diameter	.57 m	
Quasi Static Load	Lateral 15g	
Operational Temp	-20°C +/- 2°C	
Non-Operation Temp	-40°C to +40°C	
Prop System Qualification Temp (wetted)	Non-Operation +10 / - 10 C	
Prop System Qualification Temp (non-wetted)	Non-Operation +20 / -15 C	
Launch Angle	30-60°	
MPA (20 Sample tubes)	16 kg	
Structural Safety Factor	1.25	
Max Nozzle Vector Angle	5°	6 DOF Based
Bondline Temperature Limits	93°C	MSFC Defined

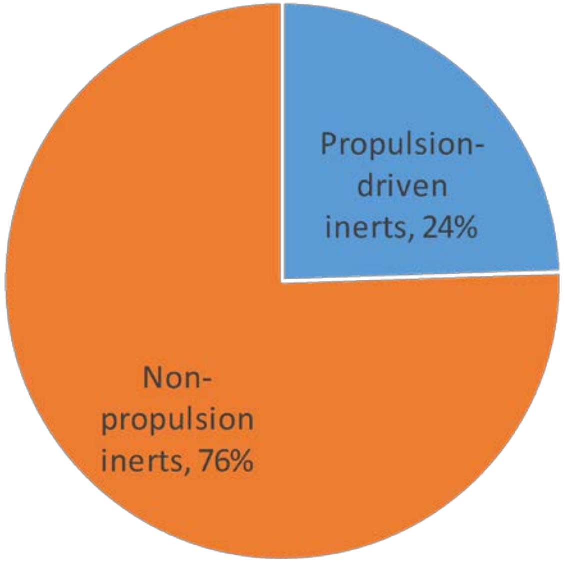


MAV Idiosyncrasies

- The small payload and stage sizes of MAV drove unconventional sizing interactions
- In larger vehicles like SLS most of the stage’s inert mass is driven by propulsion choices allowing other systems to be designed separately.
- Conversely, the MAV second stage **non-propulsion** inert mass is approximately 75% of the mass (avionics, RCS, thermal control systems, and the structure) This causes MAV performance optimization to be more linked across systems.



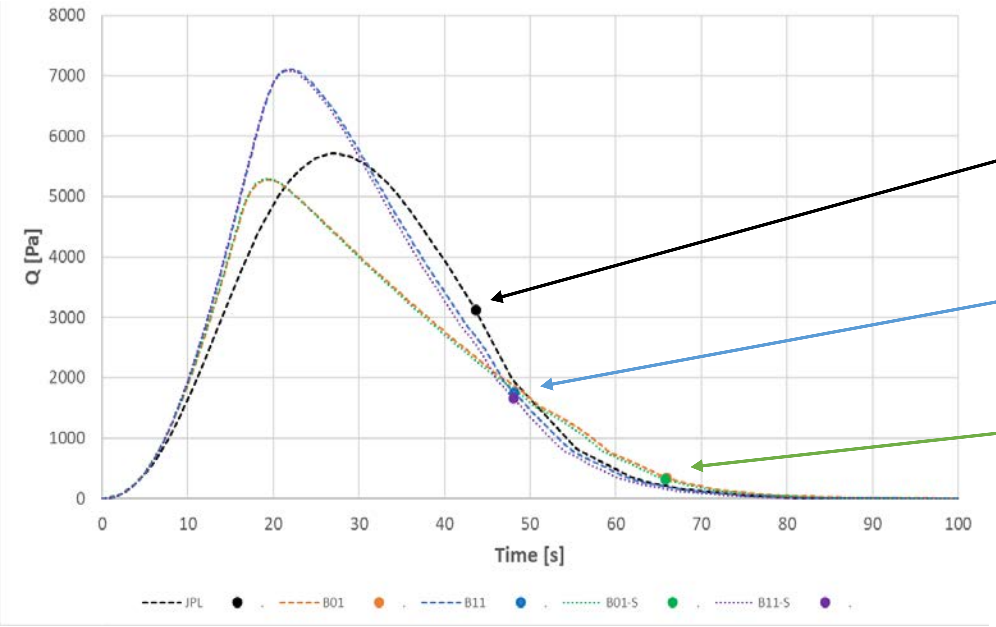
Sample Large-Stage Mass Proportions



MAV Second Stage Mass Proportions

Minimize RCS

- RCS must conduct control maneuvers during the long coast between stages.
  - Aerodynamic forces at stage 1 burnout can significantly drive RCS propellant usage and thruster mass.
  - A longer first-stage burn time results in a lower dynamic pressure at burnout reducing the disturbances RCS must counteract. First estimates were that 65 s was long enough to keep RCS propellant at a tolerable level and thus set as nominal.



ST1 Burnout:

JPL Original

burn time trade case 'short'

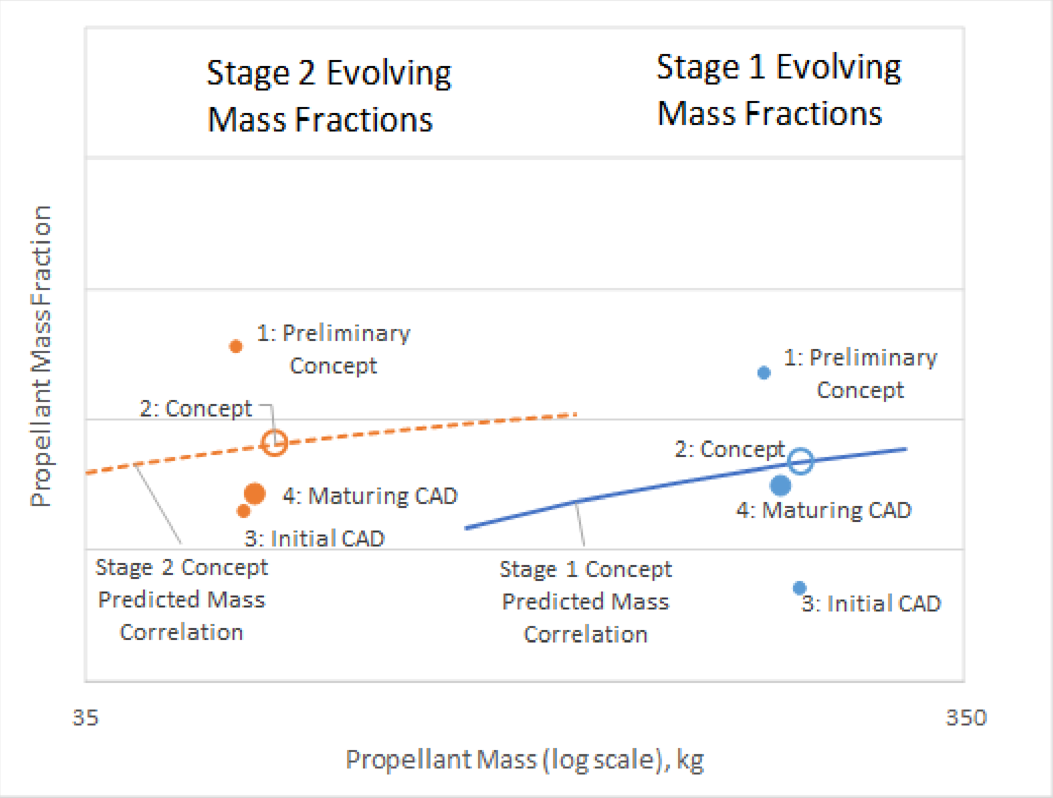
burn time trade case 'long'

Second Stage Sensitivities

- GNC and propulsion teams each performed trade studies on second stage performance and found that impulse-conserving burn time variation, due to propellant burn rate, caused very little variation in orbit.
- However, I_{sp} variation of the upper stage led to a variation of tens of km in apoapsis or periapsis altitude.
- This led to an increase in the target orbit in order to keep any lower-performing vehicles above 300 km periapsis.

Motor Mass Fractions

- A previous study[1] on this MAV concept showed correlations of propellant mass fraction to predict motor masses at the concept phase
  - Preliminary estimates were optimistic prior to considering the issues and trades discussed here
  - Nevertheless, maturing CAD models have allowed motor masses to recover closer to model estimates.



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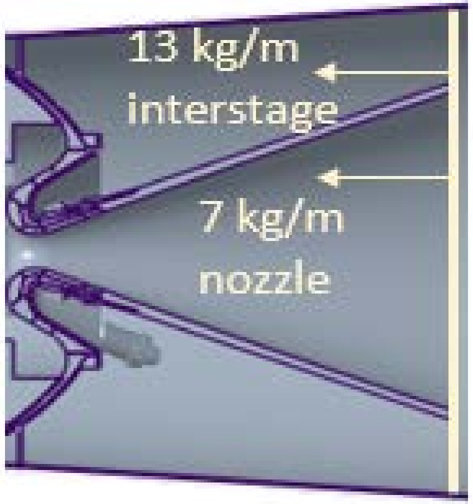
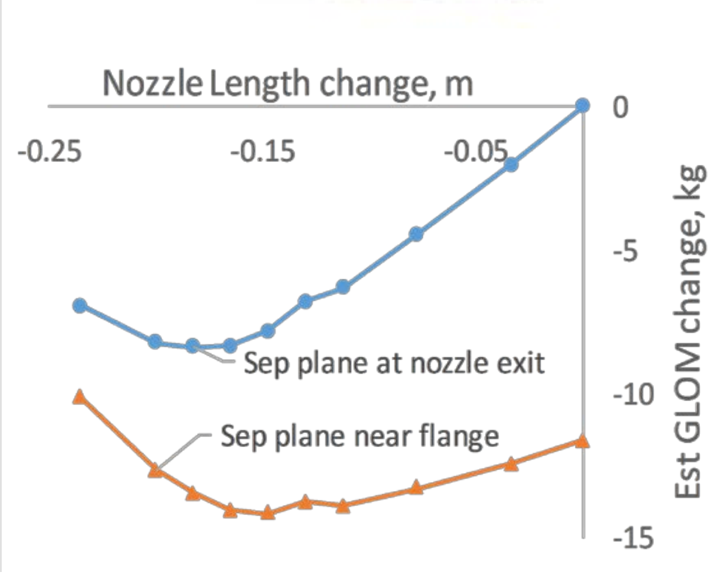
[1] Prince, A.; McCauley, R.; Kibbey, T.; McCollum, L.; Oglesby, B.; Stefanski, P.; “Mars Ascent Vehicle Propulsion System Solid Motor Technology Plans,” Conference Paper, IEEE Aerospace Conference (AeroConf 2019); Mar. 2019; Big Sky, MT; United States.

Optimization Trades

- The second-stage nozzle led to increased performance by trading Isp for nozzle length.
  - The reference motor assumed a nozzle expansion ratio of 81 and an Isp of 293 s
  - The initial CAD showed that truncating the nozzle would save about 7 kg per meter (or 0.4 lbm per inch)
  - inter-stage mass traded at 13 kg per meter (or 0.7 lbm per inch)
- Partial derivatives from trajectory analysis were used to estimate a series of vehicle performance values as a function of nozzle and inter-stage length
- This led to a convergence point that provided a significantly shorter inter-stage and nozzle with predicted mass savings, despite an I_{sp} reduction of approximately 10 seconds
- An opportunity to move the plane of separation was also employed





Optimization Trades, continued

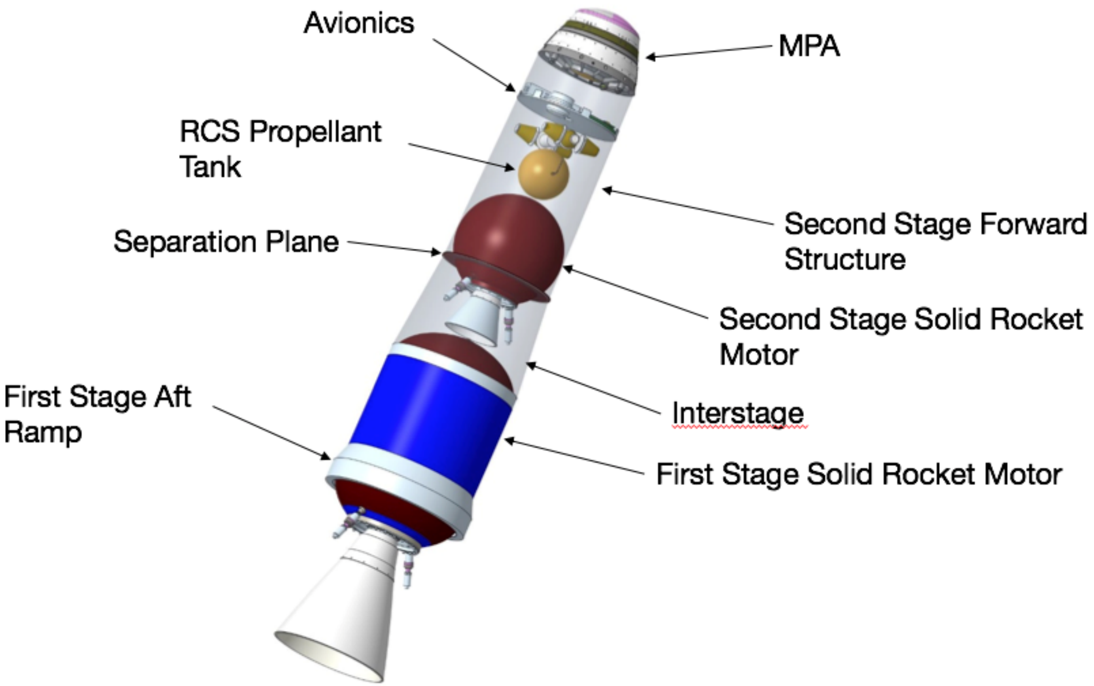
- Guided System vs. Unguided
  - An unguided system would reduce the mass of the RCS and accompanying structure
  - In this case a spin-stabilized, unguided upper stage increased orbital variations to about 300 km.

- Metallic Stage 1 vs. Composite Case
  - Savings of 5+ kg (11 lbs)

- 1500 psi vs. 1000 psi Maximum Operating Pressure (MOP)
  - The lower pressure was realized by increasing the nozzle throat diameter at the same nozzle exit size resulting in a minor 4-5 second I_{sp} reduction
  - Case insulation scales with pressure allowing additional mass to be captured for operating at a lower pressure
  - Even with composite, the case mass savings due to lower pressure is significant

Optimization Trades, continued

- Stage 1 Length, Diameter, and Aero Ramp vs. Stability
  - Preliminary 6 Degree of Freedom (DoF) showed first stage burn time of 65 s burn time still required a significant amount of RCS propellant
  - Two possible solutions
    1. Increase the size and effectiveness of the aft aerodynamic surface by reducing the first-stage motor diameter making it harder to maintain thrust levels in sustain phase
    2. Further extend the burn time of the first-stage motor to reduce burnout dynamic pressure with reduced chamber pressure. (Bolstered by insulation mass savings discussed previously)
- Updated trajectory analysis showed that 72 s of burn time reduced the dynamic pressure to one third of the value of the 65 s trajectory reducing RCS propellant usage by 32% based on 6 DoF results



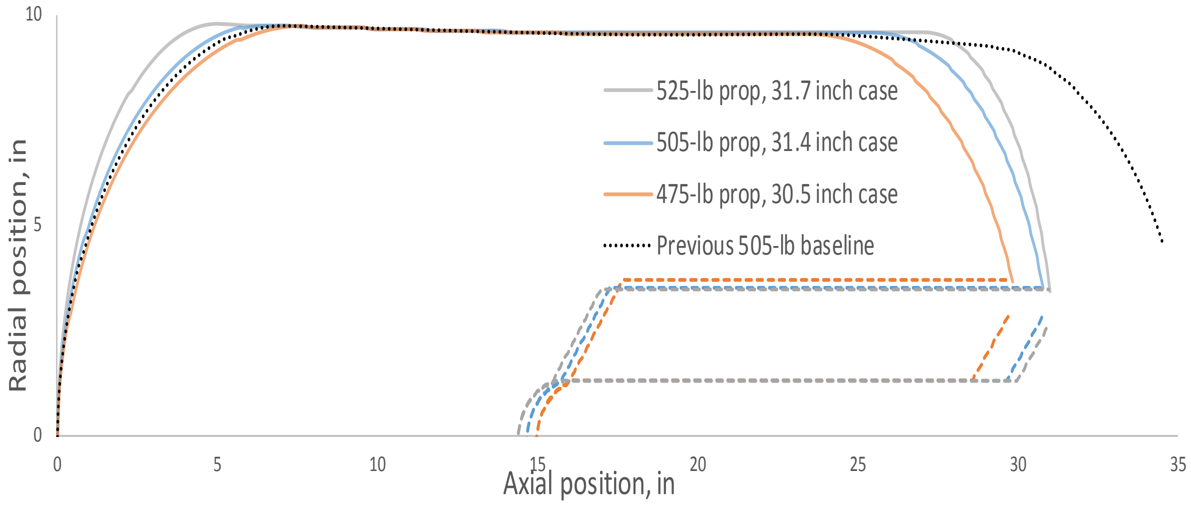
Motor Development Refinements, cont.

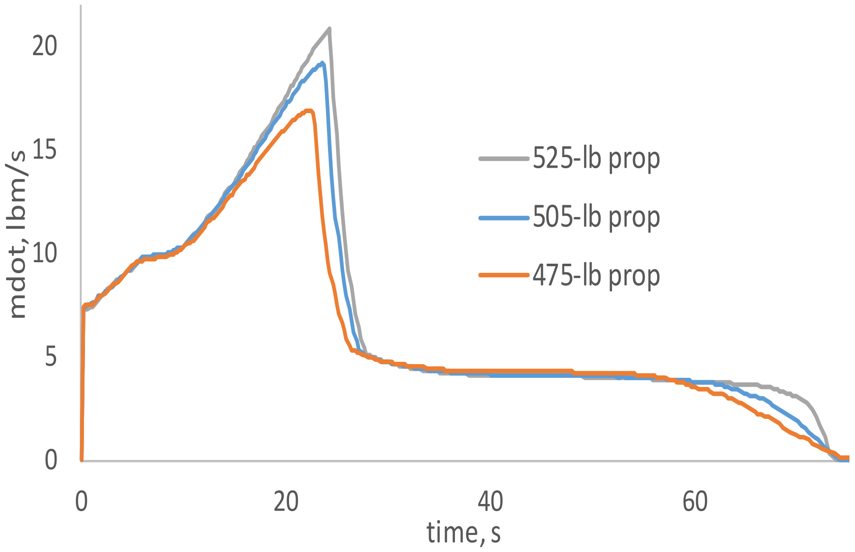
- Motor Grain Optimization[2] - Reduce inert mass and length
  - Geometric parameters that controlled the pressure and thrust trace and insulation exposure times were examined
  - A set of constraints such as burn time and fraction of impulse in the “boost” phase were levied to limit solutions to the desired class of thrust traces
  - The Solid Performance Program (SPP)12 code was used over this design space to create surrogate models to predict motor performance.
    - Initially, minimizing length was selected as the optimization objective but this incentivizes large throat diameters leading to an overly reduced I_{sp}
    - The ΔV relationship between the two stages was alternatively selected as an objective which included the effects of insulation and case mass as well as nozzle I_{sp}
    - The optimization was able to reduce motor chamber length by about 4 inches and reduce insulation mass by about 10 pounds.
    - Additional details of this effort are to be shared in an upcoming AIAA forum by Robert Hetterich.

2) Hetterich, Robert. “Using Advanced Design Methods to Optimize the Mars Ascent Vehicle First Stage Solid Rocket Motor.” AIAA Next Gen Technical Symposium, 9 September 2019, Huntsville, AL. Symposium Presentation.

Motor Grain Optimization

- Model results for three difference propellant mass inputs

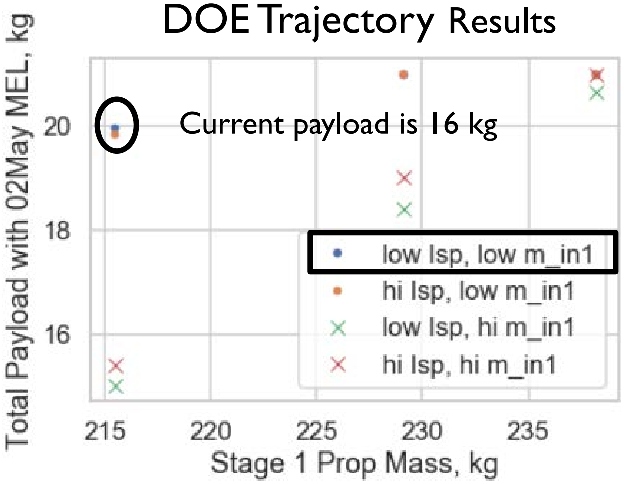




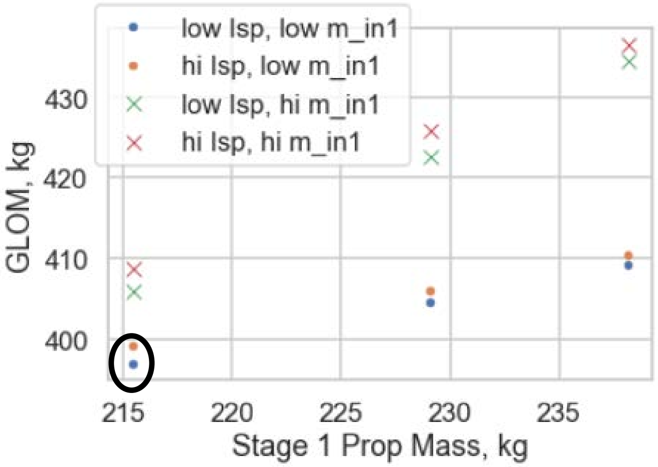
Trajectory Design of Experiments

- Given the MAV is preliminary and changes are occurring a wider design space of vehicle and propellant masses were explored
- A 12-run matrix Design of Experiments (DoE) was developed considering the following three Stage 1 variables:
  - SRM1 propellant mass – 3 levels, from the Motor Grain Optimization output
  - Stage 1 inert mass – 2 levels, a range of 14 kg to cover structural assumptions as well as the titanium or composite case trade
  - Stage 1 Isp – 2 levels, representing a nominal or a 4-inch-extended nozzle
- Stage 2 mass margin was computed for each of these cases and if it was more than 5 kg the Stage 2 motor was offloaded instead, moving ΔV and propellant to the first stage.
  - The figures show results with assumptions that accomplish the mission <400 kg GLOM highlighted
  - Maturing CAD models have shown that Stage 1 motor inert masses were very close to these low inert mass points.

DOE Trajectory Results



Current payload is 16 kg



Analog Testing Propellant Testing

- A candidate propellant was tested to determine the effect of grain geometry on structural capability of propellant at low temperatures
  - End-burning analog samples
  - Center Perforated (CP) analog samples (Strain Evaluation Cylinders)
  - Various web fractions
  - Conditioned to increasingly cold temperatures levels
  - Inspected and measured

Web Fraction (%)	Quantity
40	3
50	3
60	3
70	3
80	3

Strain Evaluation Cylinders

Web Fraction (%)	Quantity
40	3
80	3
Reserve	3

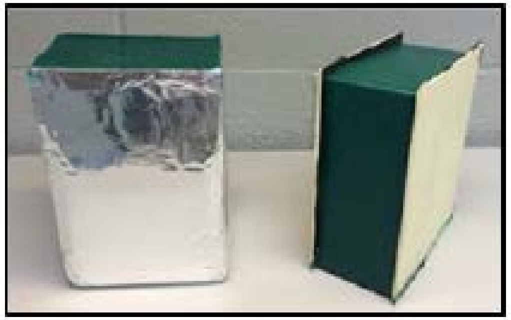
End-Burning Logs

Tensile and PLI – Mechanical Data

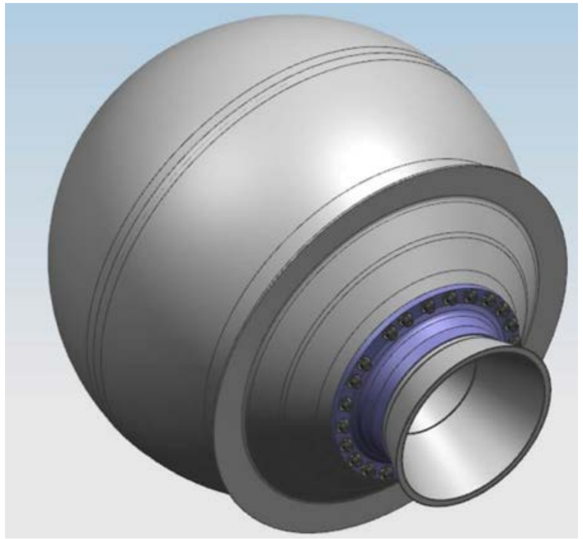
- SRM 2 analog hot fire test scheduled for October 15
  - Cold soak to -50 ˚C (qualification low temperature)
  - Fire at -20 ˚C (launch temperature)
- Mechanical testing is also taking place on a candidate propellant
  - Propellant and bondline tensile
  - Peel
  - Strain endurance

Bondline Tensile

Peel



Propellant Liner Insulation (PLI)



Test Motor Model

Data has strain capability at the lower temperature bounds expected on Mars

Summary

- A set of solid propulsion motors were designed based on a given set of GR&A for MAV
- Once sized initially a series of trades were performed tuning interactions with the vehicle to fine tune masses and ΔV
- The motors inert masses were further optimized based on an optimized grain design
- A trajectory DOE was performed investigating reasonable mass trades between the stages for the optimum payload based on potential GLOM changes.
- Testing is going on in parallel to understand the effect of temperature on propellant mechanical properties as well as motor operation