

# Feasibility Study of A Direct-to-Earth Mars Sample Return Architecture Using a Dragon-Derived Mars Lander

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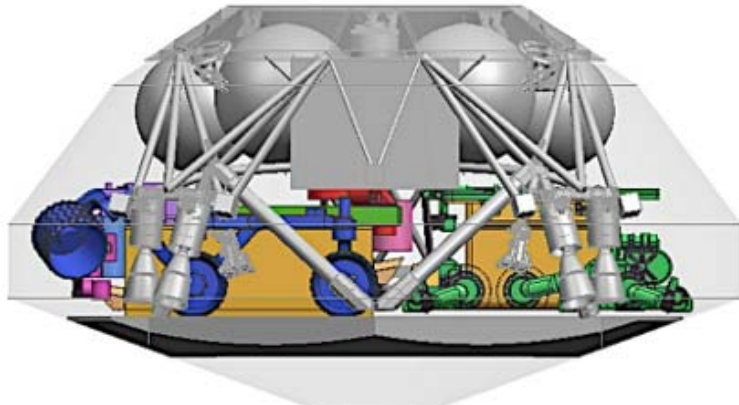
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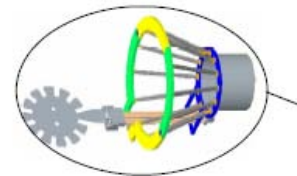
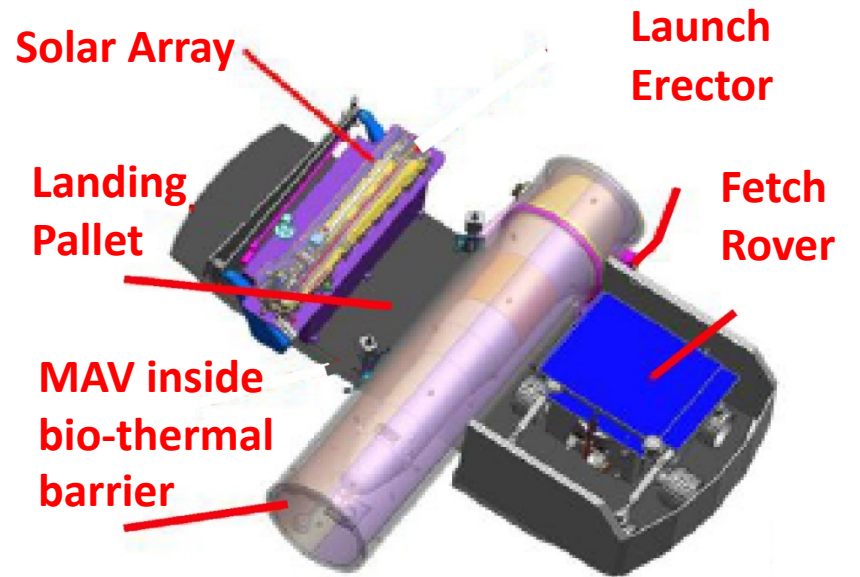
# Problem Statement

- MSR is highest priority in SMD Mars exploration program.
- MSR is high priority in HEOMD exploration roadmap.
- MSR is practically the most complex robotic Mars mission plannable.
- Current MSR architecture of record has high cost, high cost risk.
- Three heavy launches, 10 mission elements, three launch opportunities.
- Direct-to-Earth MSR architecture has potential to reduce cost, cost risk by  $\approx 50\%$ .
- Requires ability to land all Earth-return components in single lander.
- Previous studies showed fundamental feasibility of landing modified SpaceX Dragon capsule (“Red Dragon”) on Mars.
- Can a Direct-to-Earth MSR architecture be enabled by Red Dragon?
  - Getting There: how much mass and volume can a Red Dragon deliver?
  - Getting Back: How much mass and volume is needed for a Direct-to-Earth launch stack?

# Decadal Survey MSR Architecture

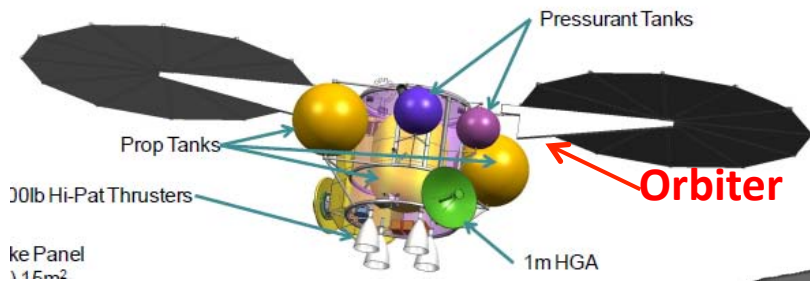


Mission 1 Sample Collection Rover

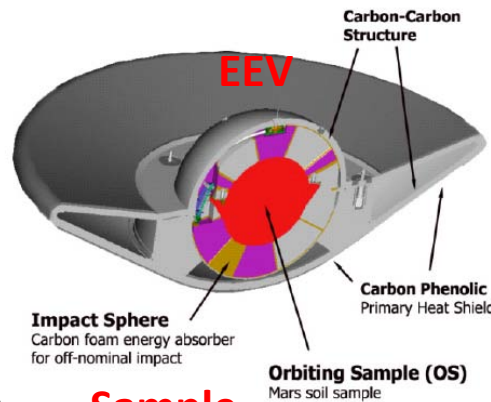


Capture Basket

Mission 2 Fetch sample and launch to Mars orbit



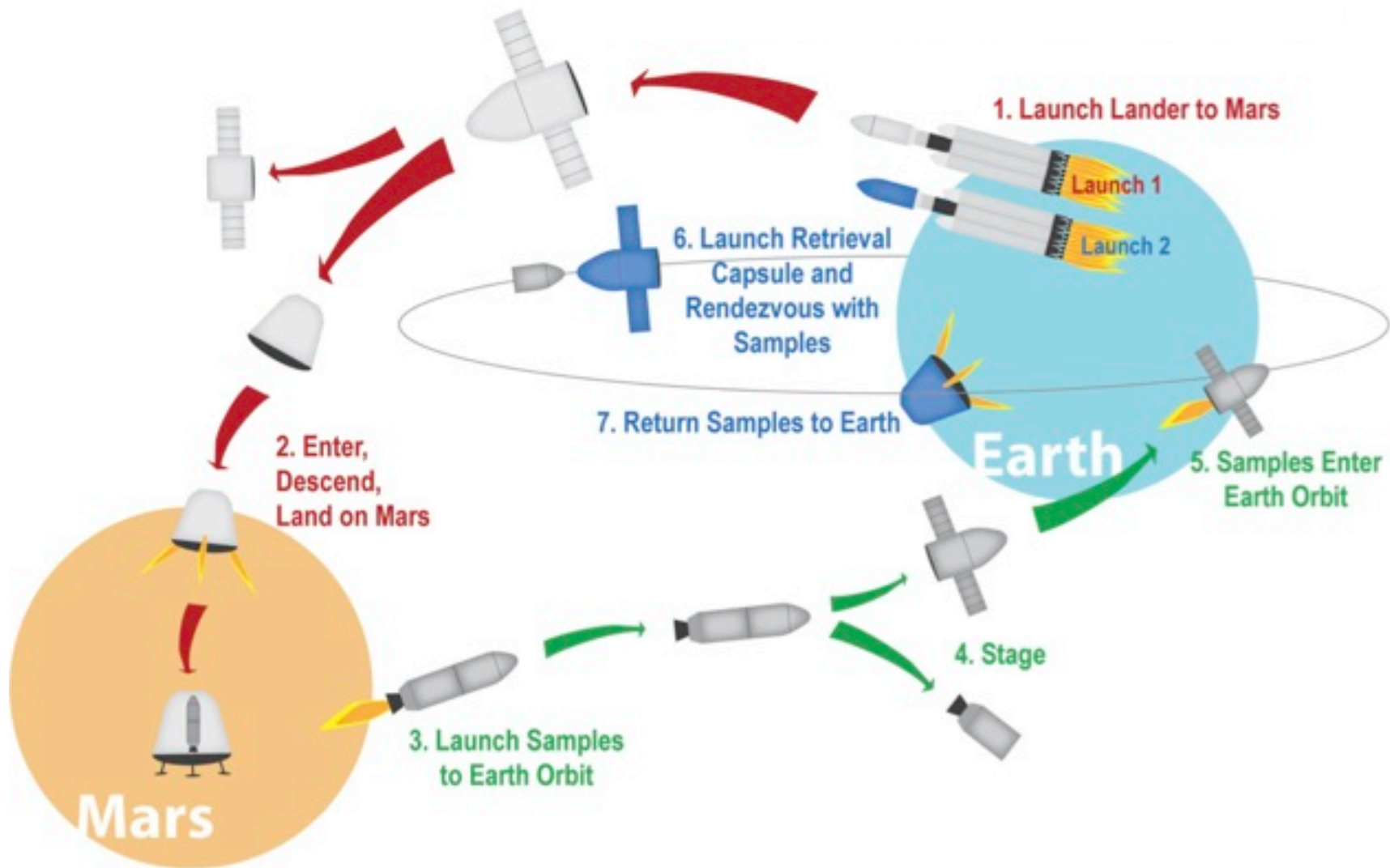
Orbiter



Sample Container

Mission 3 sample container rendezvous and capture in Mars orbit, launch to Earth, direct entry of sample canister in an entry cone shell

# Study Architecture Diagram

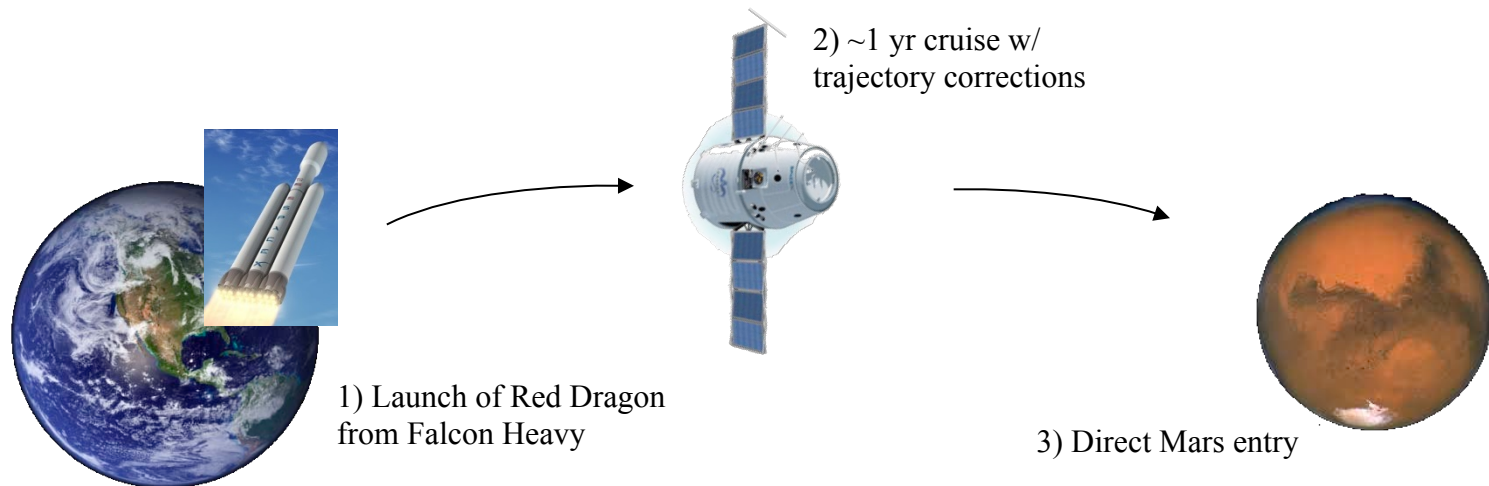


# Earth-Mars Transfer

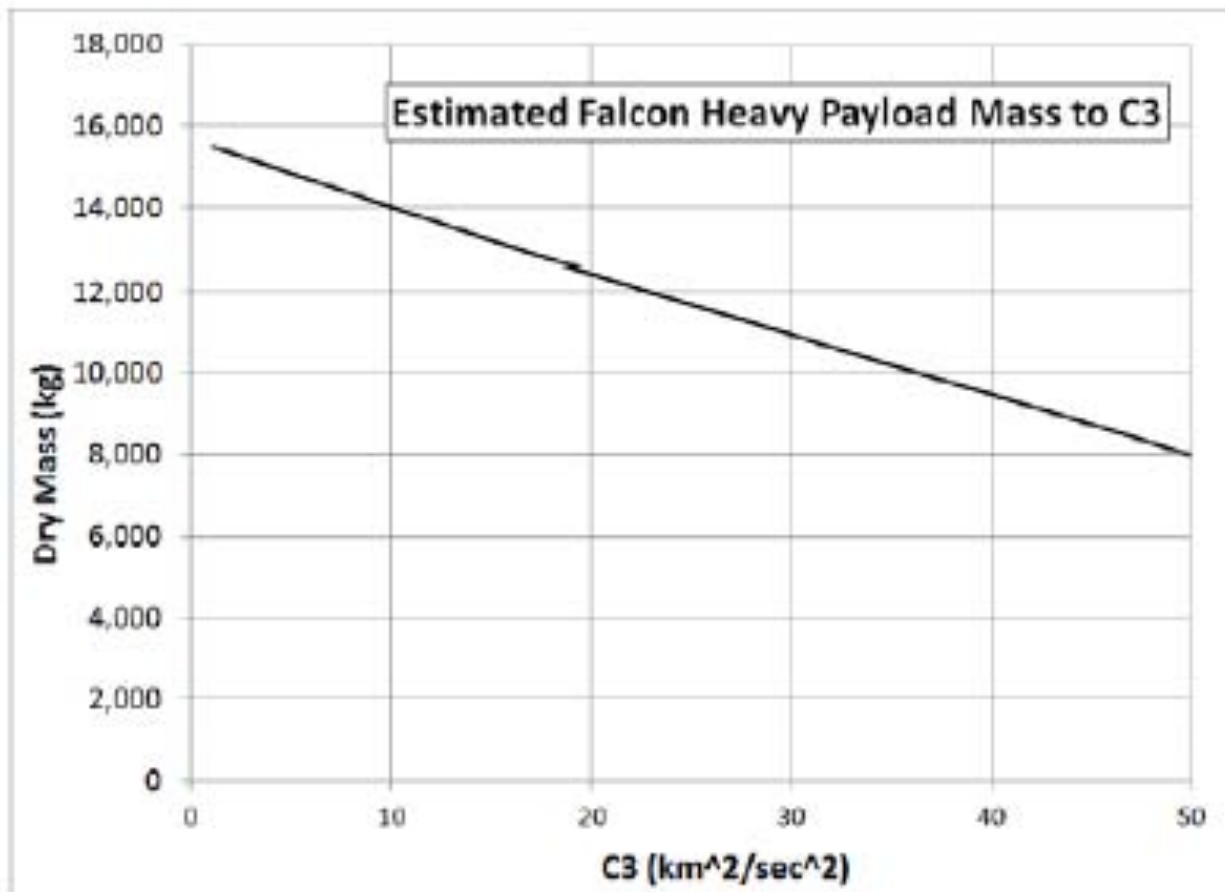
<b>Earth Launch Date</b>	Sep-16-2022	Oct-04-2024	Oct-31-2026
<b>Mars Arrival Date</b>	Oct-08-2023	Sep-12-2025	Aug-19-2027
<b>Transit time</b>	387 days	344 days	292 days
<b><math>L_s</math> at arrival</b>	130°	139°	148°
<b>Earth Launch C3</b>	13.2 km <sup>2</sup> /s <sup>2</sup>	10.5 km <sup>2</sup> /s <sup>2</sup>	8.5 km <sup>2</sup> /s <sup>2</sup>
<b>Mars Entry speed @ 125 km altitude</b>	5.84 km/s	5.52 km/s	5.61 km/s

**Note:**

Trajectories optimized for lowest launch C3.

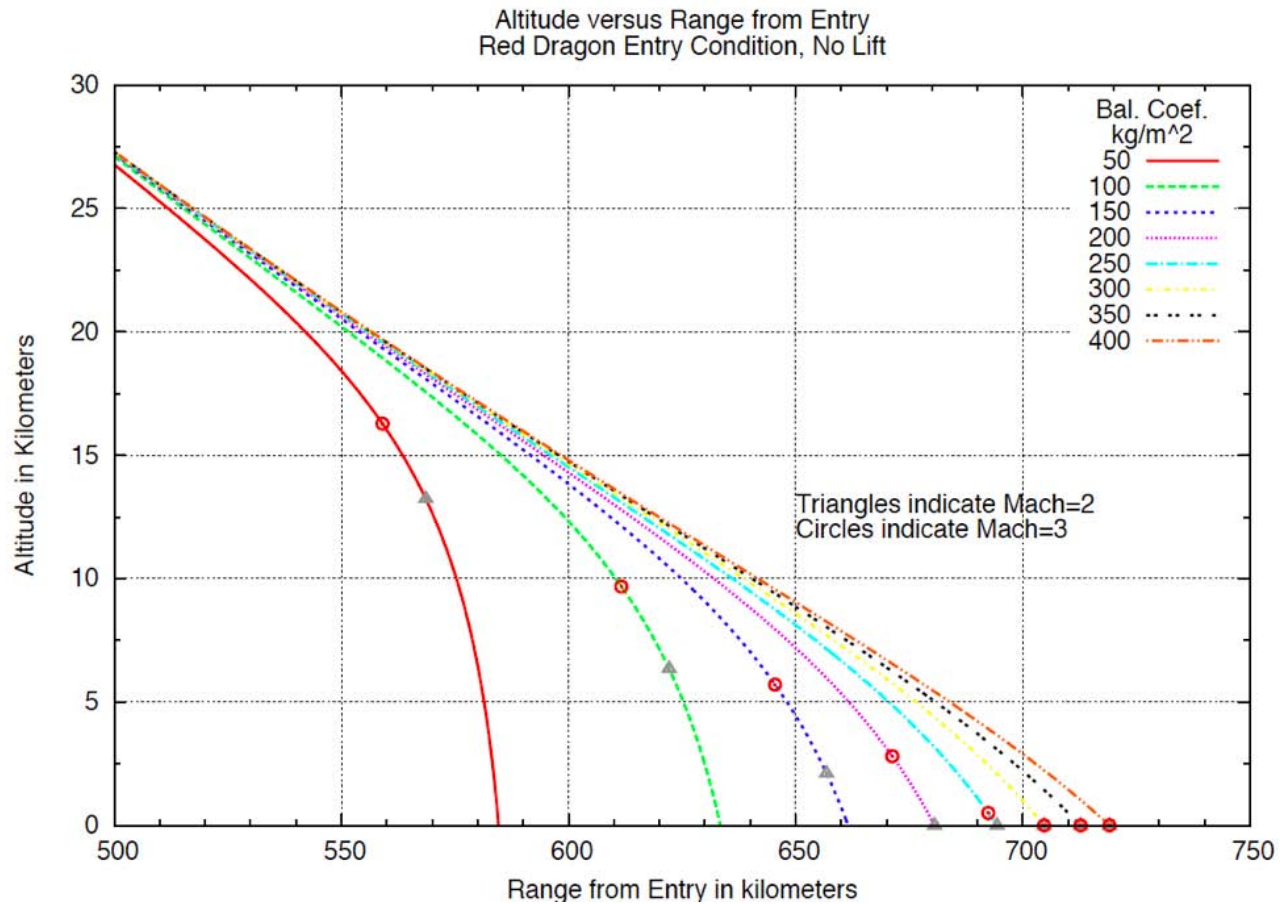


# How Much Can a Falcon Heavy Throw?



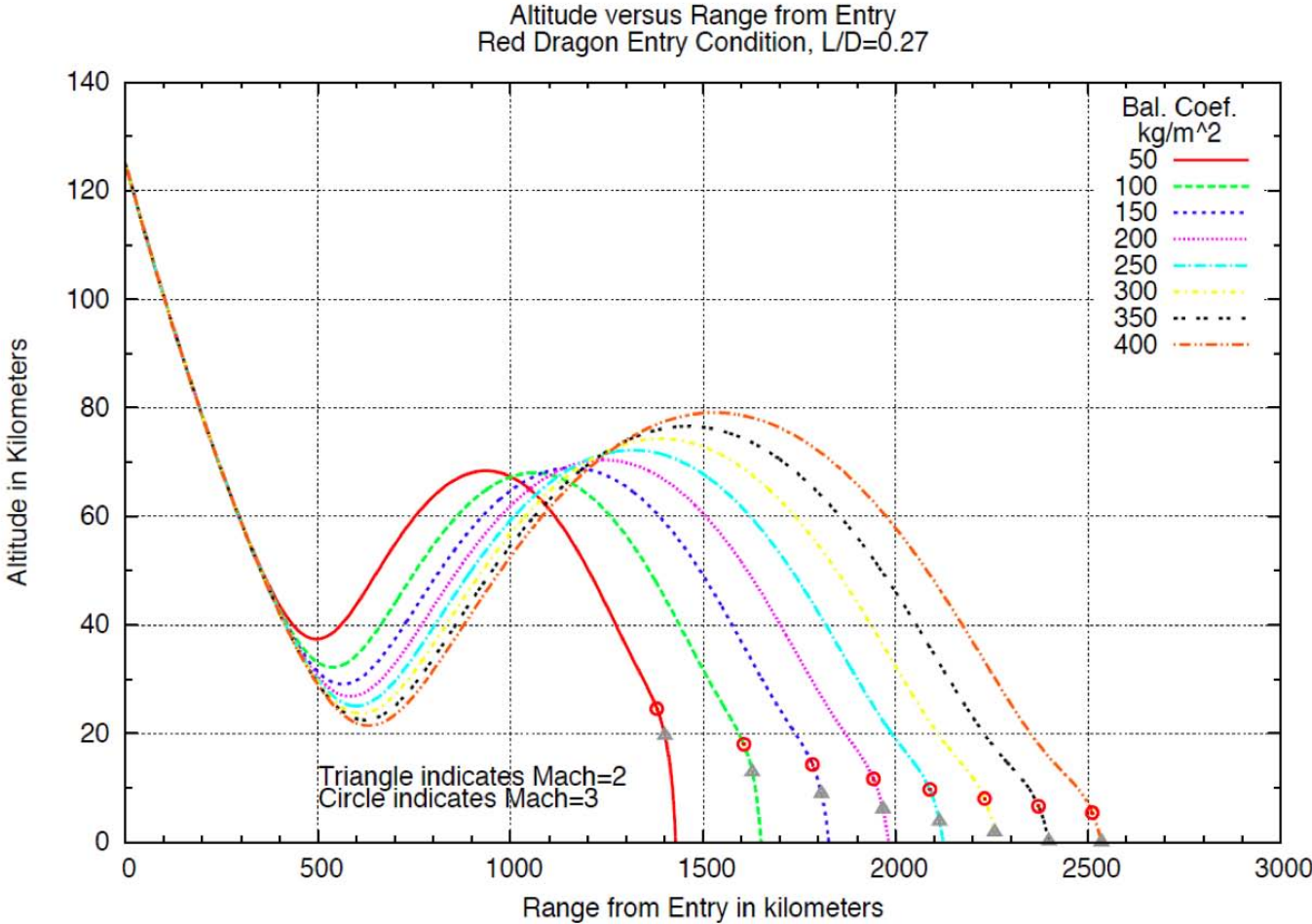
From “Feasibility Analysis for a Manned Mars Free-Return Mission in 2018”, Tito, et. al., IEEE Aerospace Conference, March 2-9, Big Falls, Montana.

# Why Red Dragon Needs Hypersonic Lift for EDL



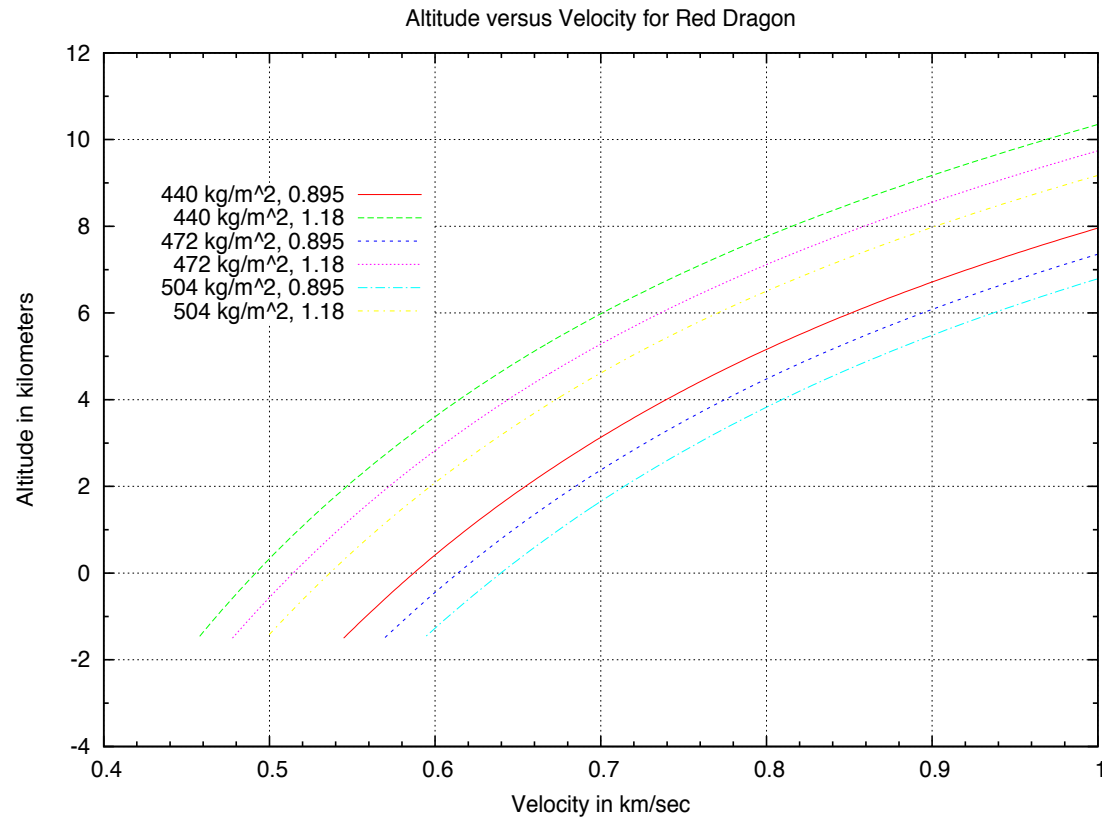
Altitude and Range to M=3 and M=2 Conditions for Non-lifting Trajectories, for Ballistic Coefficients Between 50 and 400 kg/m<sup>2</sup>  
Purely ballistic entry not feasible for High Ballistic Coefficients.

# How Hypersonic Lift Transforms Red Dragon EDL



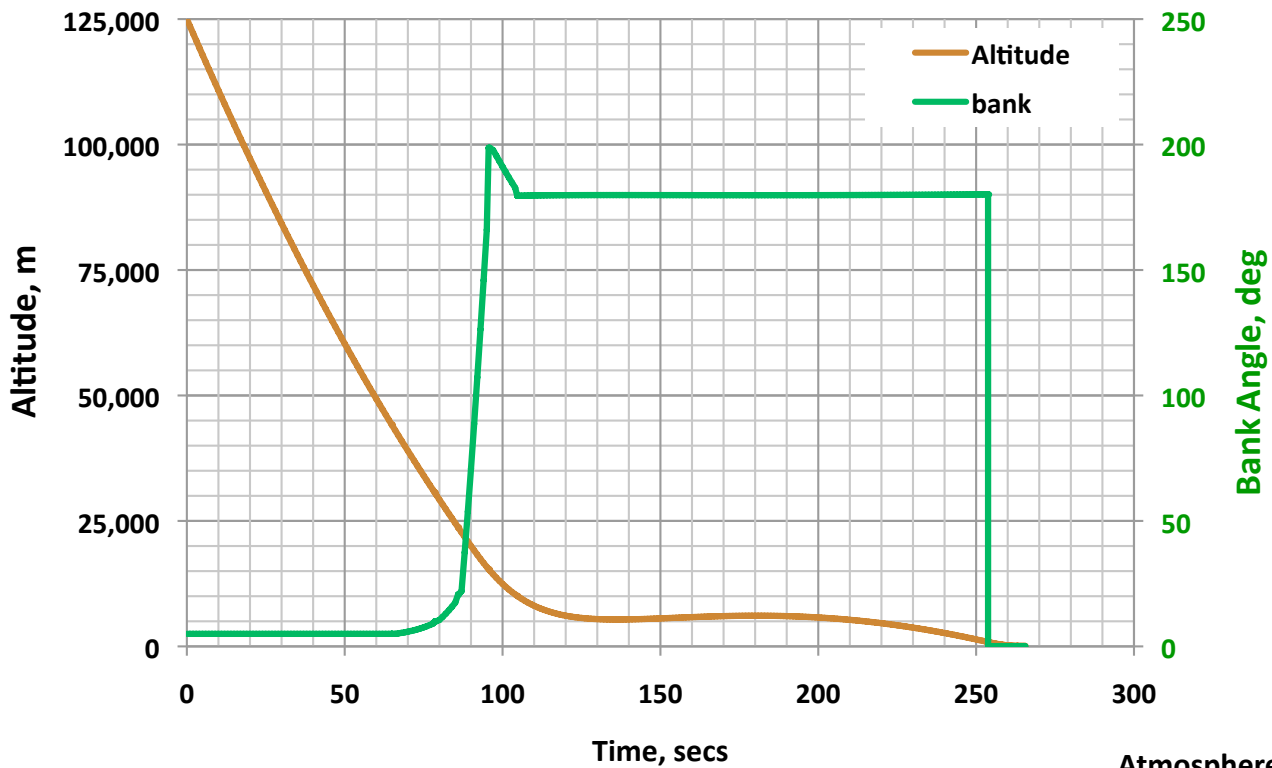


# Why Parachutes Won't Work for Red Dragon Supersonic Deceleration



Plot of terminal velocity vs b. Parachutes not viable; Supersonic retropropulsion required.

# Optimizing Propulsive Landing Performance



Atmosphere: Marsgram 2010, Ls 180  
Entry Mass = 7200 kg  
Entry Velocity = 6.0 km/s  
Entry Flight Path =  $-14^\circ$   
Landing Altitude = 0.0 m  
Landing Latitude =  $0^\circ$

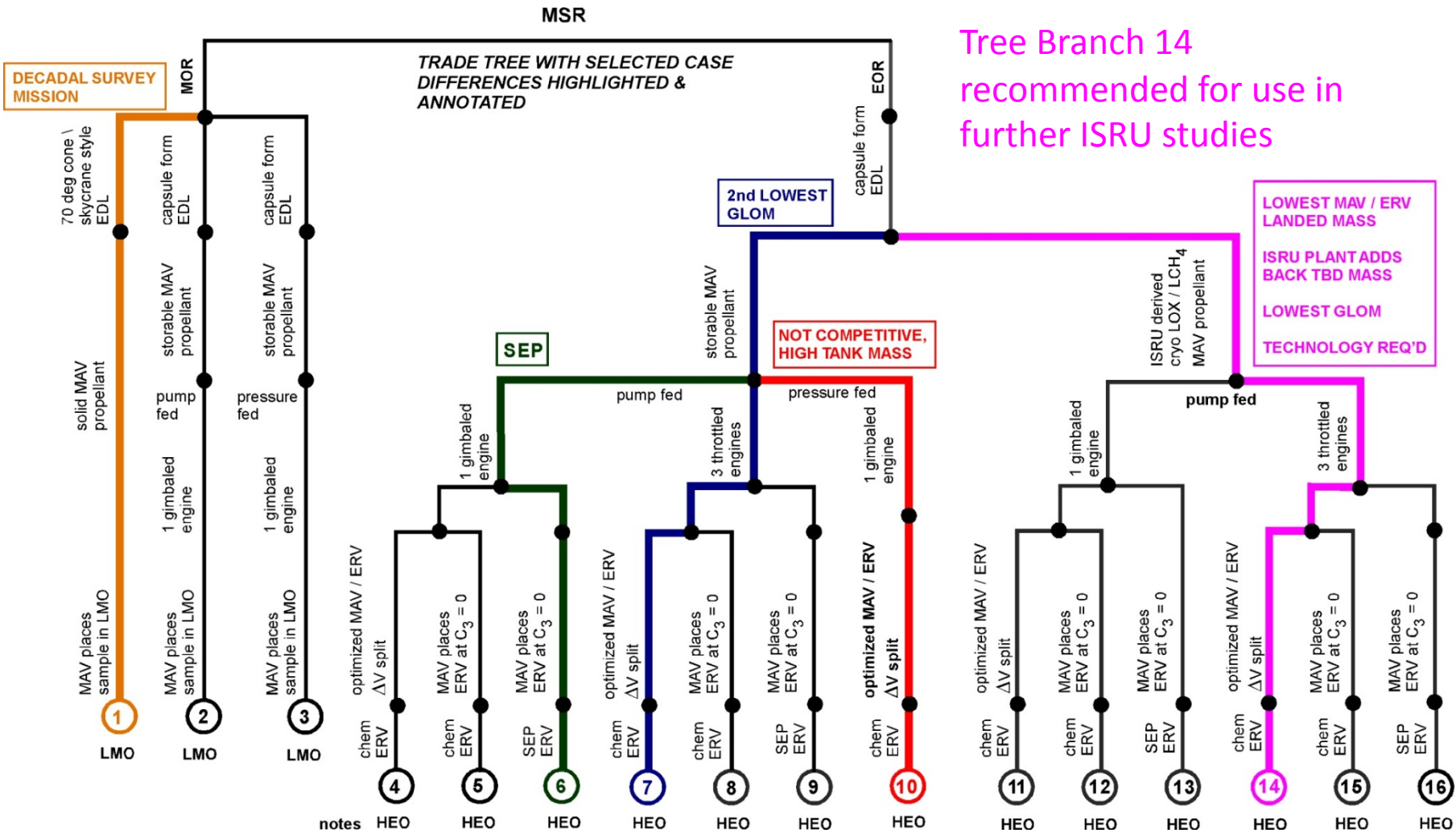
# Sensitivity of Landing Performance to Entry Parameters

- **Trajectory:** using POST II 3DOF , landing at 0m altitude, 0° latitude, the trajectory has 3 phases
  - **Aero entry and descent:**
    - Manipulate the lift vector from 125km to about 800m above landing
  - **Powered descent:** from about 800m to 100m above landing
    - Vacuum thrust = 533,800N (8 engines; 66,725N/engine)
    - Engine cant angle = 20°
    - Isp = 265.3 secs
    - Throttle setting = 80%

## •Conclusions:

- A 9700 kg Entry mass can land close to 6600 kg on Mars surface near Ls = 180 ( $\approx$  32% propellant mass fraction).
- Higher atmospheric density can help gain  $\sim$ 100kg of the landed mass.
- Improving L/D from 0.2 to 0.25 can help gain  $\sim$ 100kg of the landed mass.
- Landing 2000m below MOLA can add 100kg to the landed mass.
- Flight Path angle has very little effect on landed mass but reduces max. G-load.

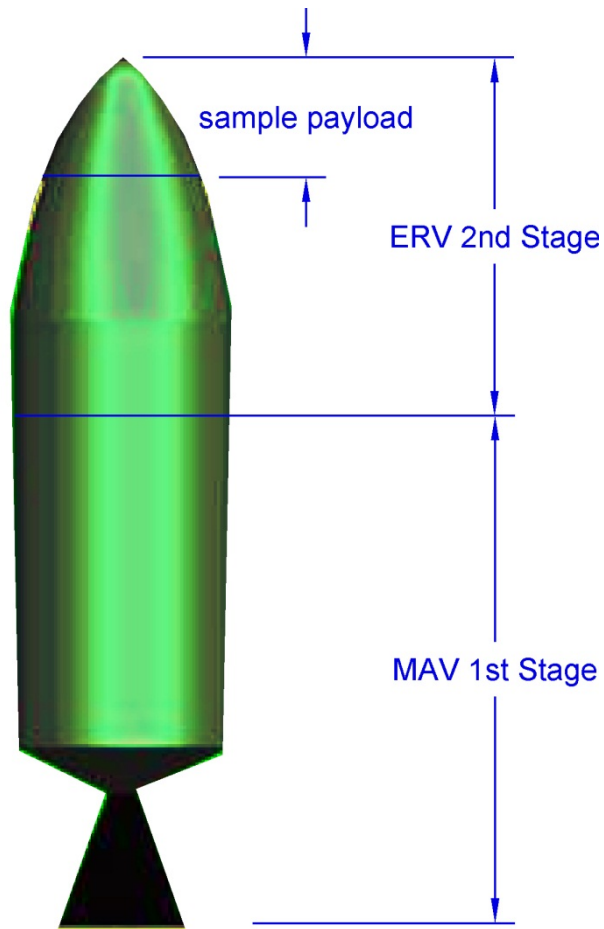
# MAV Trade Tree



## MSR Launch Stack Design Trade Study Early Findings

- Overall Mission  $Dv \geq 7$  km/s.
- Minimum  $Dv$  for first stage is 4200 m/s.
- Minimum 2-stage design (MAV-ERV) required.
  - 3-stage design desirable if volume constraints allow.
- Pump-fed propulsion system required on MAV.
- Nested bulkhead tank design required.
- Ascent aero not a major factor in design.

# Earth Return Stack Notional Staging Split



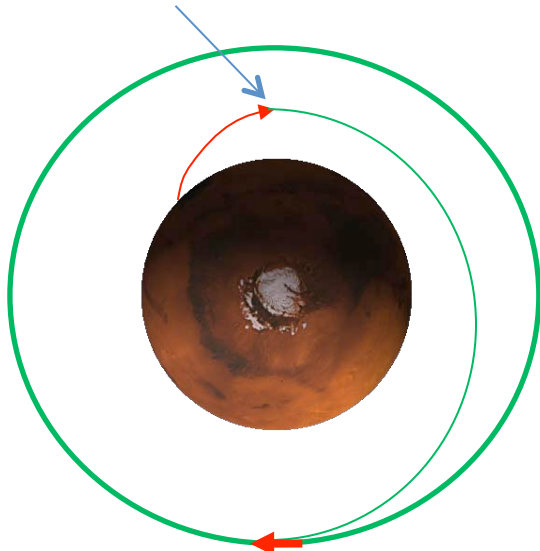
## Trade Tree Branch 14

DV split optimized:

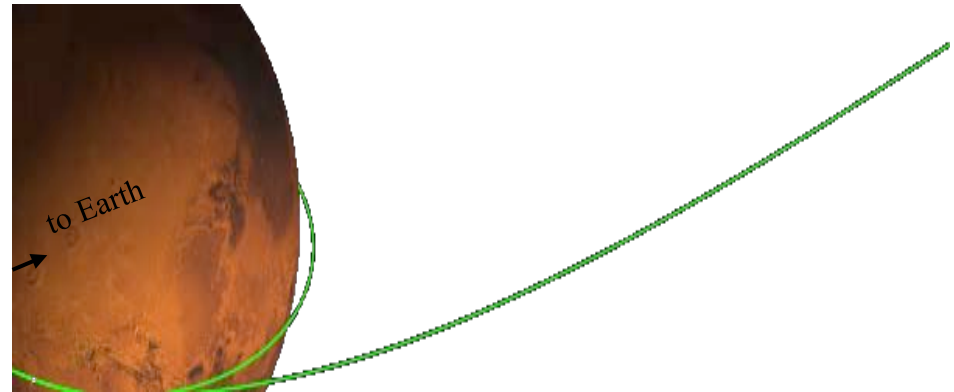
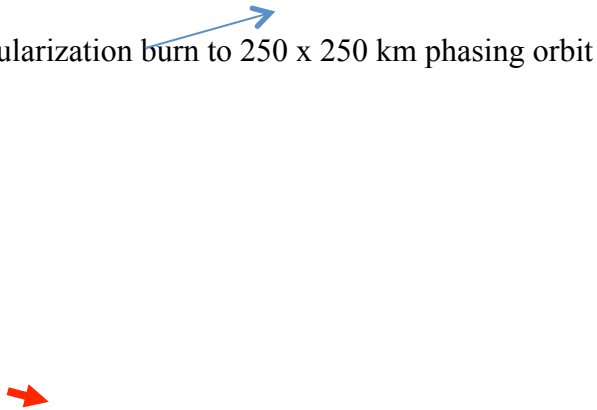
- Cryogenic propellant Mars Ascent Vehicle (MAV) 1st stage delivers Earth Return Vehicle (ERV) 2nd stage + sample payload to beyond Low Mars Orbit but short of Mars Escape
- Storable Propellant ERV 2nd stage delivers itself + sample payload to a High Earth Orbit

# Departing Mars

1) MAV delivers ERV to a 100 x 250 km orbit



2) Circularization burn to 250 x 250 km phasing orbit



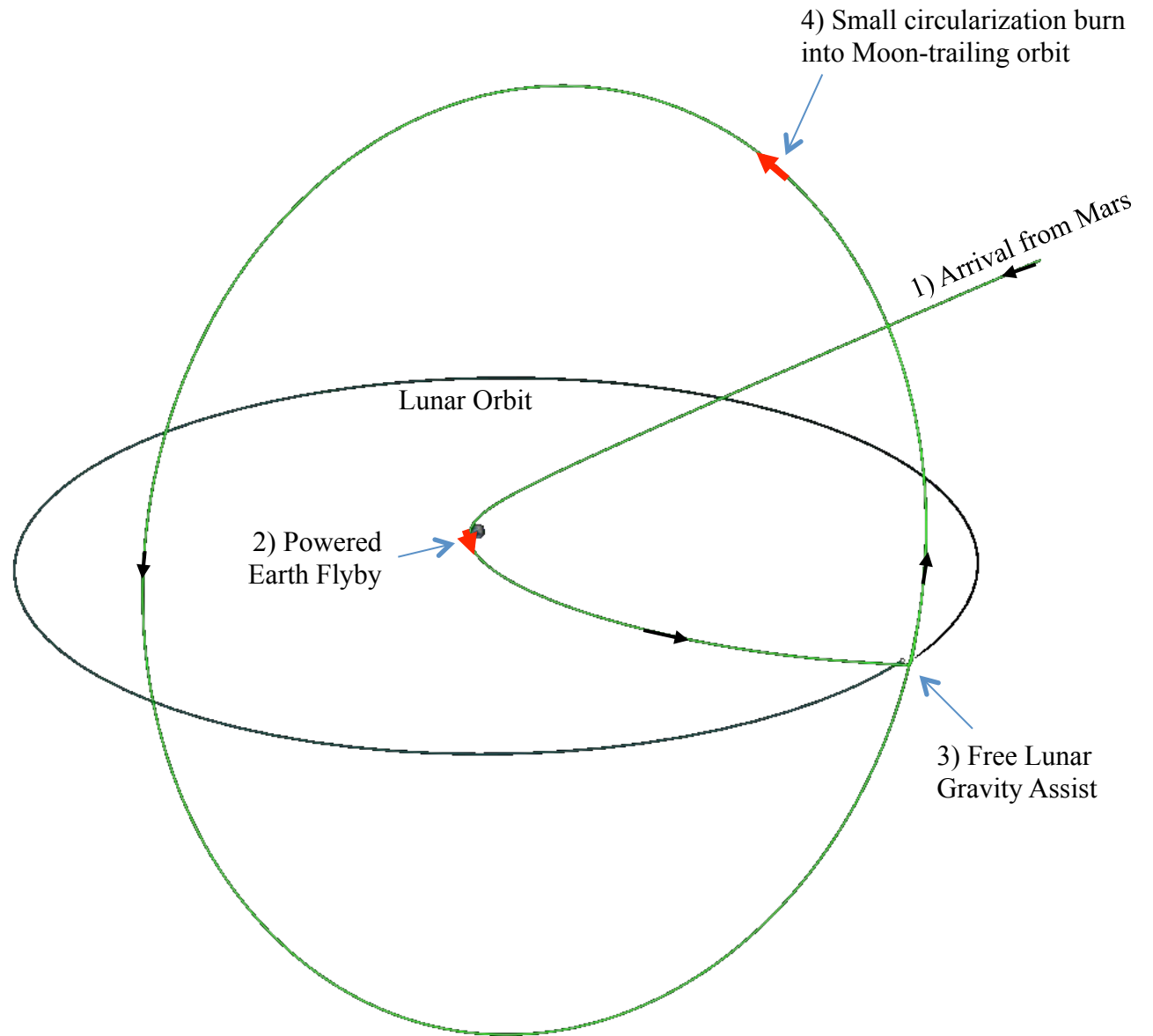
3) Trans-Earth Injection burn

# Earth Arrival and Orbit Insertion

Upon arrival from Mars, the ERV performs a powered Earth flyby at 1200 km altitude for capture into the Earth-Moon system ( $\Delta V = \sim 550$  m/s).

Earth flyby geometry is picked such that the ERV will then coast towards the Moon for a free lunar gravity assist that places the ERV in a Moon-trailing orbit.

A final small circularization burn completes insertion into the ERV's final parking orbit where it awaits a subsequent mission to retrieve the Mars sample.





# Summary ERV $\Delta V$ Budget

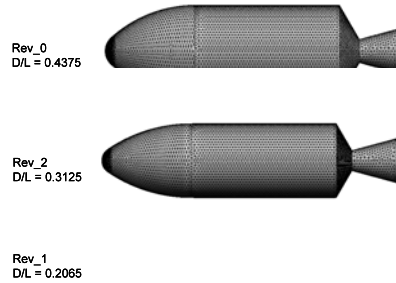
<b>Mars Departure Date</b>	Jul-24-2024	Jul-23-2026	Jul-20-2028
<b>Earth Arrival Date</b>	May-25-2025	Jun-05-2027	Jul-11-2029
<b><math>\Delta V</math> Circularization to 250x250 km Mars orbit</b>	37 m/s	37 m/s	37 m/s
<b><math>\Delta V</math> Trans-Earth Injection</b>	2,253 m/s	2,123 m/s	2,135 m/s
<b><math>\Delta V</math> Trajectory Correction Maneuvers</b>	75 m/s	75 m/s	75 m/s
<b><math>\Delta V</math> Powered Earth Flyby</b>	491 m/s	513 m/s	642 m/s
<b><math>\Delta V</math> Circularization to Moon-trailing orbit &amp; long-term care</b>	25 m/s	25 m/s	25 m/s
<b>Subtotal <math>\Delta V</math></b>	2,881 m/s	2,773 m/s	2,914 m/s
<b>8% <math>\Delta V</math> Contingency</b>	230 m/s	222 m/s	233 m/s
<b>Total <math>\Delta V</math></b>	<b>3,111 m/s</b>	<b>2,995 m/s</b>	<b>3,147 m/s</b>

**Notes:**

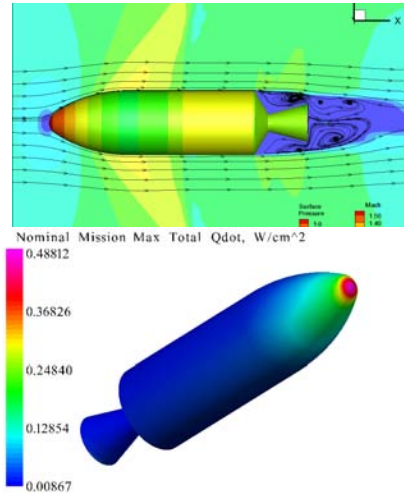
Trajectories optimized for lowest total  $\Delta V$  per 2.2-yr Earth-Mars synodic period  
 $\Delta V$ 's include gravity losses

# MSR MAV Technical Analysis Disciplines

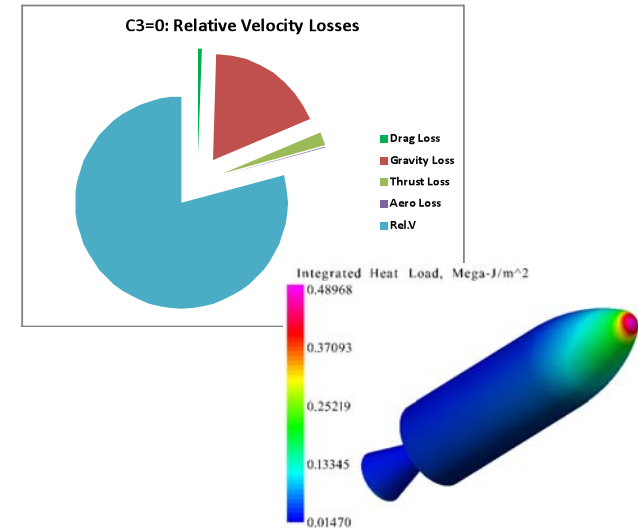
## Geometry Modeling



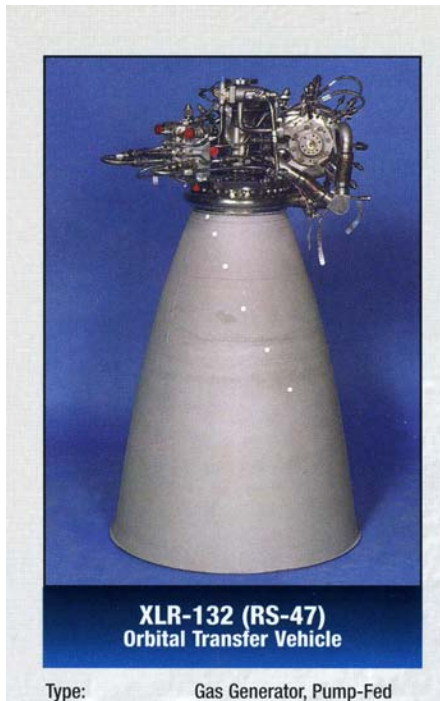
## Aero/Aerothermal



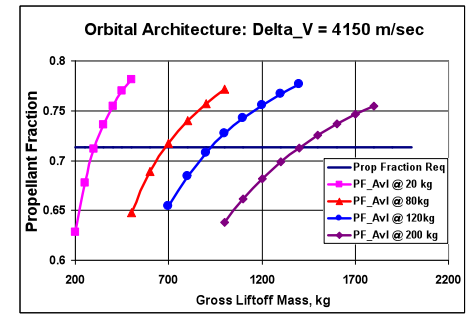
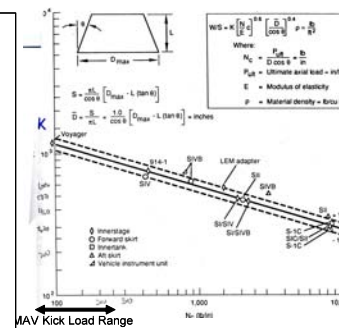
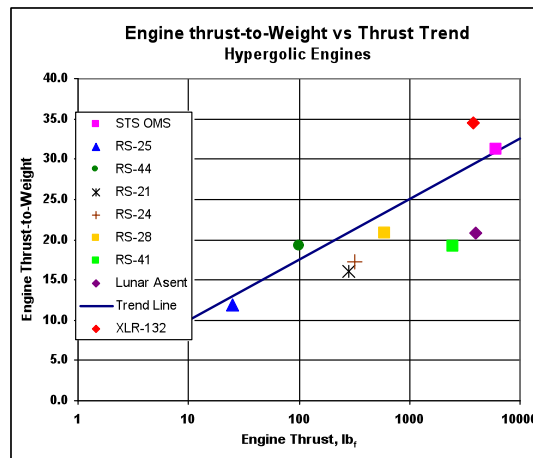
## Trajectory



## Propulsion



## Weights & Sizing



## Characteristics of Key Configurations—Early Results

ERV Propulsion	Chemical	Chemical	Chemical	SEP
$\Delta V_{\text{Total}} / \text{ERV Mass}$	4250 / 230 kg	4250 / 230 kg	4250 / 230 kg	5500 / 110 kg
Propellant/Engine Feed	Hypergolic/Pump Feed	Hypergolic/Press Feed	Cyro/Pump Feed	Hypergolic/Pump Feed
Tank Pressure	5.0 psi	250 psi	25.0 psi	5.0 psi
Tanks	24.4 (17.2% Dry)	92.1 kg (24.2% Dry)	37.9 kg (21.1% Dry)	33.0 kg (25.9% Dry)
Structure	36.1 kg (33.1% Dry)	121.9 kg (41.6% Dry)	48.5 kg (35.1% Dry)	43.7 kg (35.4% Dry)
Main Engine	43.3 kg (39.7% Dry)	88.3 kg (30.1% Dry)	40.0 kg (28.9% Dry)	47.2 kg (38.1% Dry)
Pressurization	2.86 kg (2.6% Dry)	22.6 kg (7.7% Dry)	3.94 kg (2.9% Dry)	3.77 kg (3.0% Dry)
Main Propulsion	47.0 kg (43.1% Dry)	122.2 kg (41.6% Dry)	50.6 (36.6% Dry)	58.4 (47.2% Dry)
Dry Mass	141.8 (8.8% GLOW)	381.3 (12.7% GLOW)	179.7 (11.2% GLOW)	161 (8.2% GLOW)
Propellant Fraction	72.2%	74.6%	69.7%	80.9%
GLOW, kg	1620	3002	1599	1968
Length	3.47 m	5.72 m	3.82 m	4.38 m
Diameter	0.890 m	1.23 m	1.08 m	1.00 m

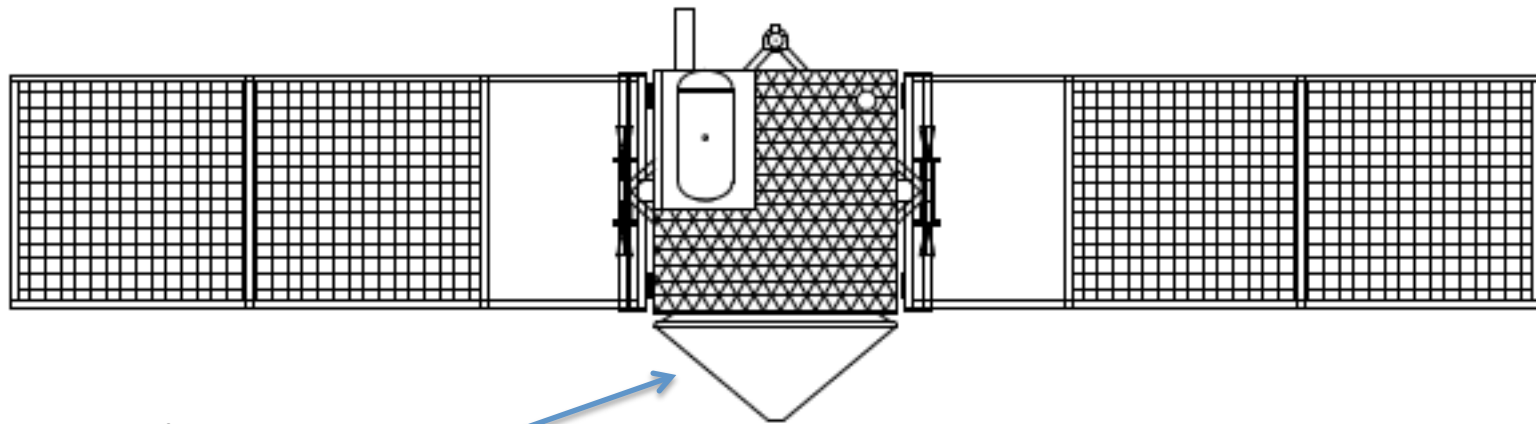
## Mars Ascent Vehicle Closure Summary—Late Results

	ERV	MAV
<b>Structure Mass</b>	<b>39.5 kg (37.2% Dry)</b>	<b>42.1 kg (41.3% Dry)</b>
<b>Primary</b>	<b>7.62 kg (15.2% Dry)</b>	<b>2.74 kg (1.8% Dry)</b>
<b>Tanks</b>	<b>0.96 kg (1.9% Dry)</b>	<b>18.67 kg (18.3% Dry)</b>
<b>Aeroshell</b>	<b>0 kg (0% Dry)</b>	<b>3.03 kg (3.0% Dry)</b>
<b>Induced Environments</b>	<b>2.92 kg (5.8% Dry)</b>	<b>2.49 kg (2.4% Dry)</b>
<b>Auxiliary System</b>	<b>4.06 kg (8.1% Dry)</b>	<b>16.77 kg (16.4% Dry)</b>
<b>Main Propulsion</b>	<b>3.48 kg (6.9% Dry)</b>	<b>35.88 (35.2% Dry)</b>
<b>Engine</b>	<b>2.27 kg (4.5% Dry)</b>	<b>33.1 kg (32.4% Dry)</b>
<b>Prime Power</b>	<b>9.0 kg (18.0% Dry)</b>	<b>0.4 kg (0.4% Dry)</b>
<b>Power Conversion/Dist</b>	<b>4.45 kg (8.9% Dry)</b>	<b>3.27 kg (3.2% Dry)</b>
<b>DHCC</b>	<b>15.0 kg (29.9% Dry)</b>	<b>1.0 kg (0.8% Dry)</b>
<b>Contingency</b>	<b>13.34 kg (26.6% Dry)</b>	<b>30.58 kg (18.0% Dry)</b>
<b>Dry Mass</b>	<b>63.5.8 kg (30.9% GLOW)</b>	<b>132.5 kg (10.5% GLOW)</b>
<b>Propellant Fraction</b>	<b>62.4%</b>	<b>71.8%</b>
<b>Payload</b>	<b>8.5 kg (16.6% GLOW)</b>	<b>205.5 kg (5.3% GLOW)</b>
<b>GLOW</b>	<b>205.5 kg</b>	<b>1170 kg</b>
<b>Length</b>	<b>0.56 m</b>	<b>2.9 m</b>
<b>Diameter</b>	<b>0.927 m</b>	<b>1.02 m</b>

# Earth Return Vehicle Design Considerations

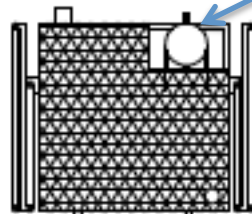
- ERV Provides all power, data, comm, attitude control, and navigation services for entire Earth return stack.
- Controls entire trajectory from Mars' surface to Earth orbit.
  - Commands all 5+ propulsive burns.
- Keeps Mars samples in temperature controlled environment.
- Remains active in Earth orbit for cooperative rendezvous with sample retrieval spacecraft.
- Must be built to Class A mission standards.
- Must be high performance.
  - 1 kg of mass on ERV = 50 kg launched from Earth.
- ERV is Challenging Small Spacecraft Design Problem.

# Getting Back--ERV General Design Concept



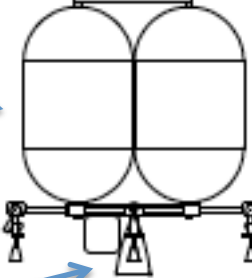
High Gain Antenna

Sample Canister



Propellant Tanks (4)

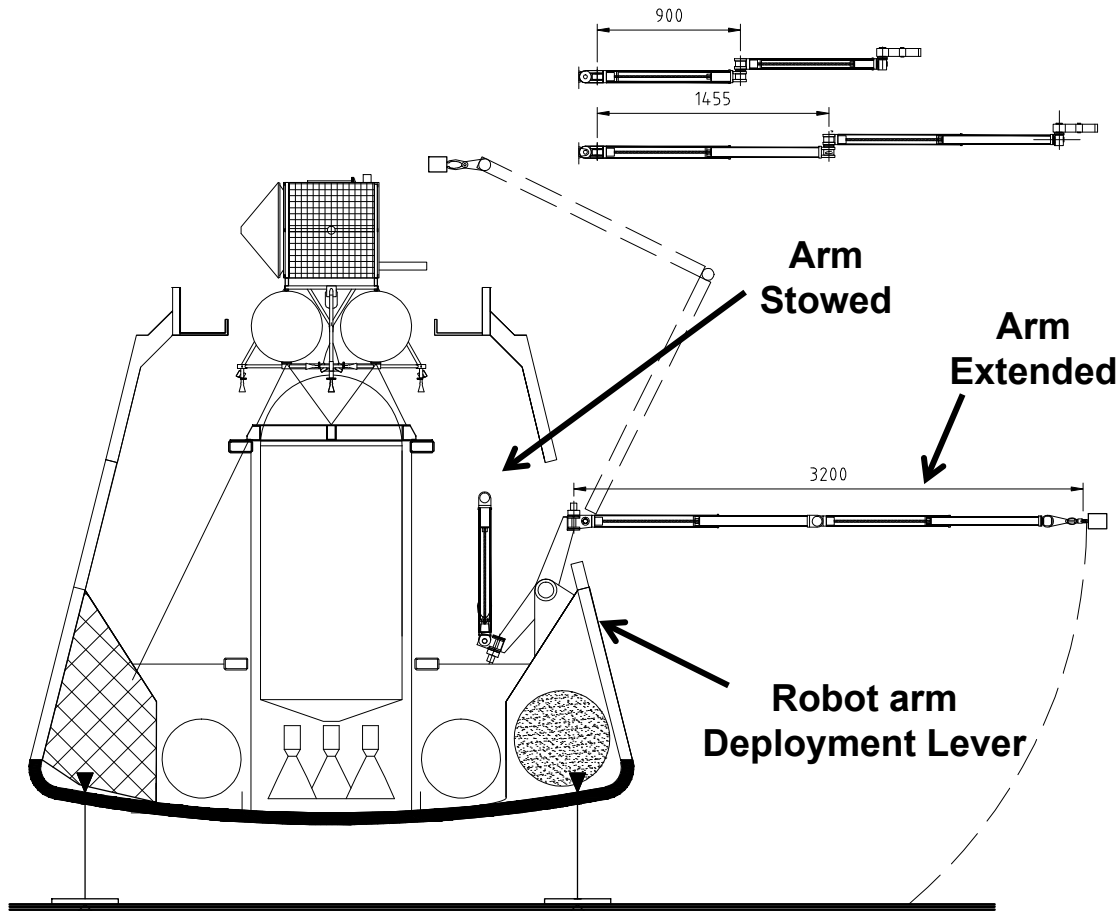
ACS Thrusters (8)



Main Rocket Motor



# Placing Samples in Earth-Return Stack

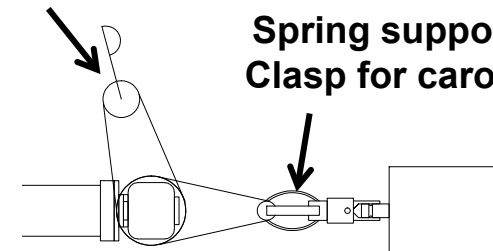


## Robot Arm solution

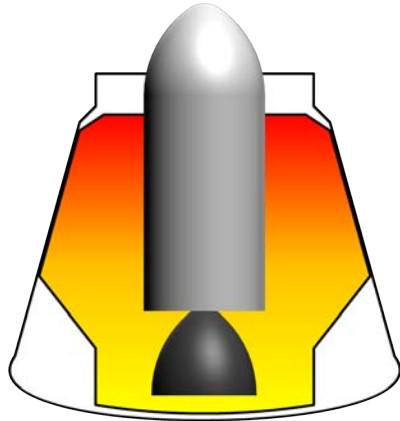
- 4 DOF jointed Robot arm with extendable segments
- Extension 3 meters
- End effectors: Female coupling and Spoon

Spoon for regolith Grab

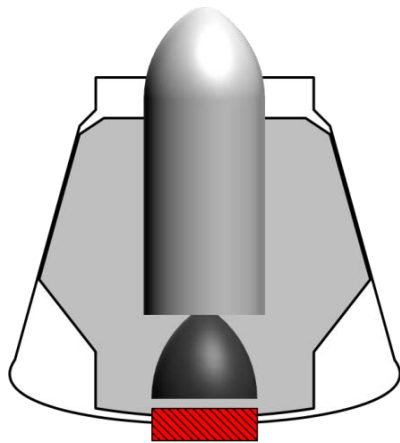
Spring supported Clasp for carousel



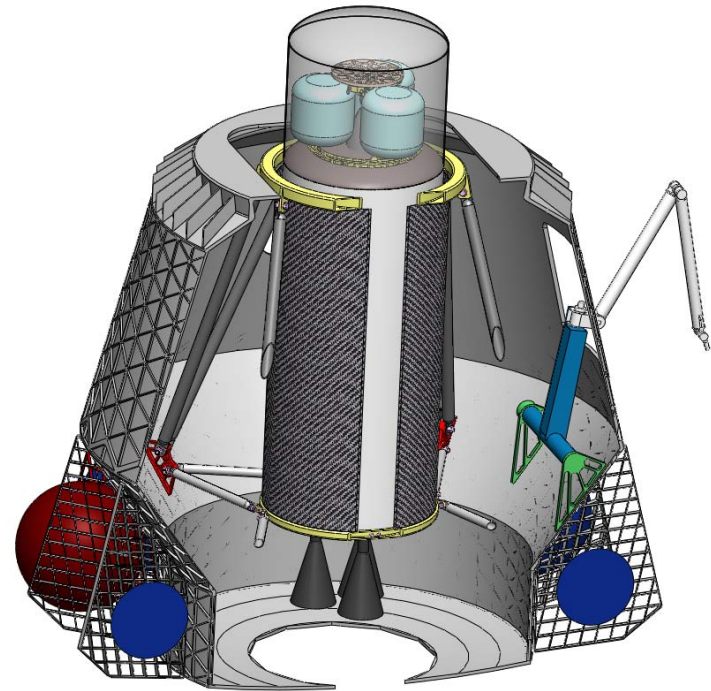
# Accommodating MSR Unique Elements



Exhaust Gas of MAV Needs Exhaust Route to Prevent Destruction of Capsule



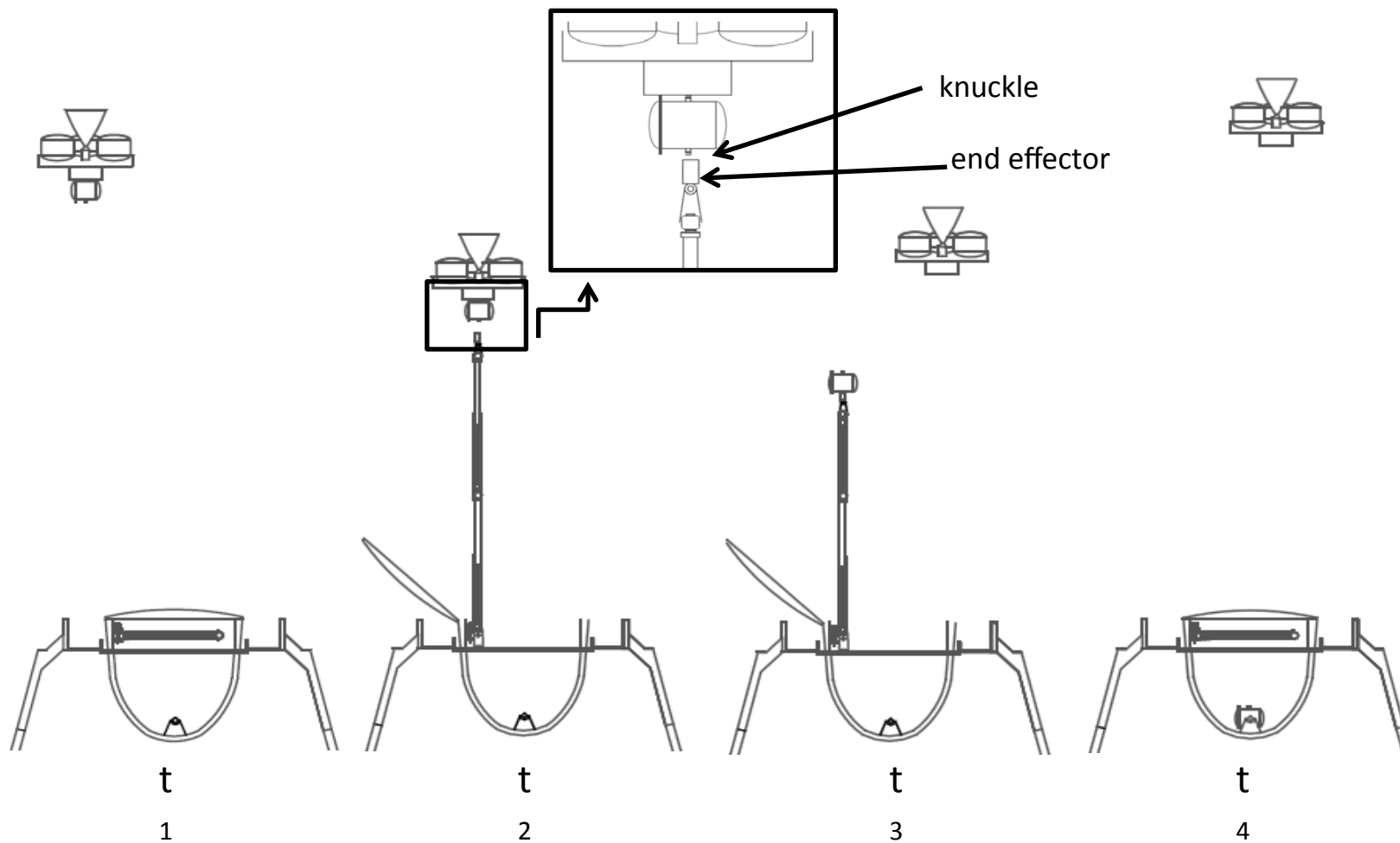
Preferred Approach is to Locate Vents in Floor Underneath MAV



MAV Needs Mission Unique Support Structure inside Capsule to Accommodate Landing and Launch Loads



# Earth Orbit Rendezvous Operations



# Mission Summary MEL

Earth Launch Date 9/16/2022	Mars Arrival Date 10/8/2023	Ls = 130	C3 Required, Km <sup>2</sup> / m <sup>2</sup>	Falcon Heavy Launch Capability, mt
Mars Return Date 7/25/2024	Earth Orbit Date 6/1/2025	Thin Atmosphere	13.2	13.4
			Falcon Heavy Launch Margin	25%
		Configuration	Description	Estimated Mass, mt
		Earth Launch	S/C Injected from Earth to Mars	10.7
		Mars Entry	W/O Trunk	9.7
		Mars Landed	Empty of Propellant, Post EDL	6.6
		Total Useful Payload	MAV + ERV + Mission Unique Equipment	1.9
		MAV + ERV	Return Vehicle w/ Onboard Propellant	1.3
		Mission Unique Equipment	Red Dragon Modifications + Support Equipment	0.7