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

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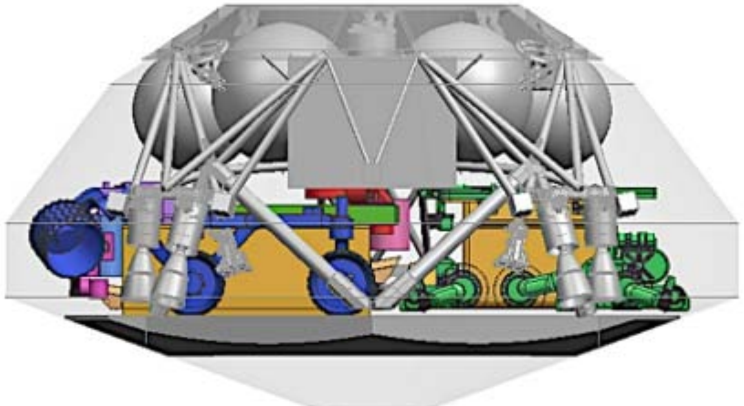
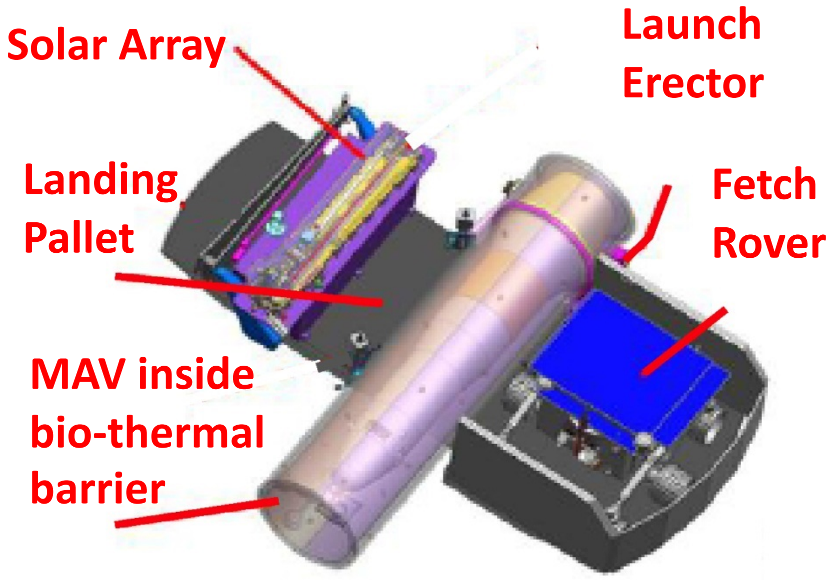
Problem Statement

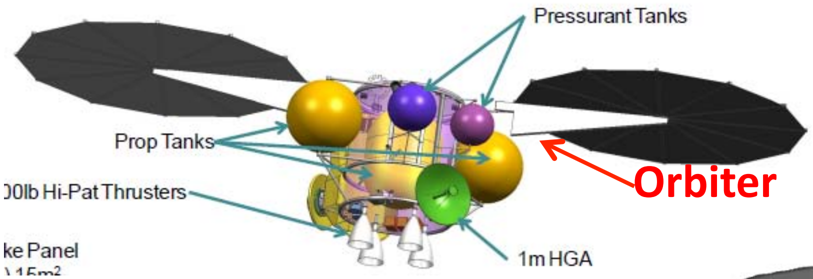
- MSR is highest priority in SMD Mars exploration program.
- MSR is high priority in HEOMD exploration roadmap.
- MSR is practically the most complex robotic Mars mission plannable.
- Current MSR architecture of record has high cost, high cost risk.
- Three heavy launches, 10 mission elements, three launch opportunities.
- Direct-to-Earth MSR architecture has potential to reduce cost, cost risk by ≈ 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?

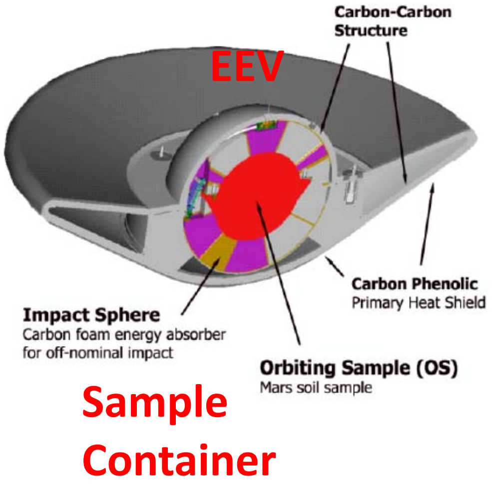
Decadal Survey MSR Architecture



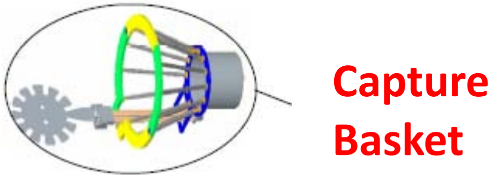
Mission 1 Sample Collection Rover





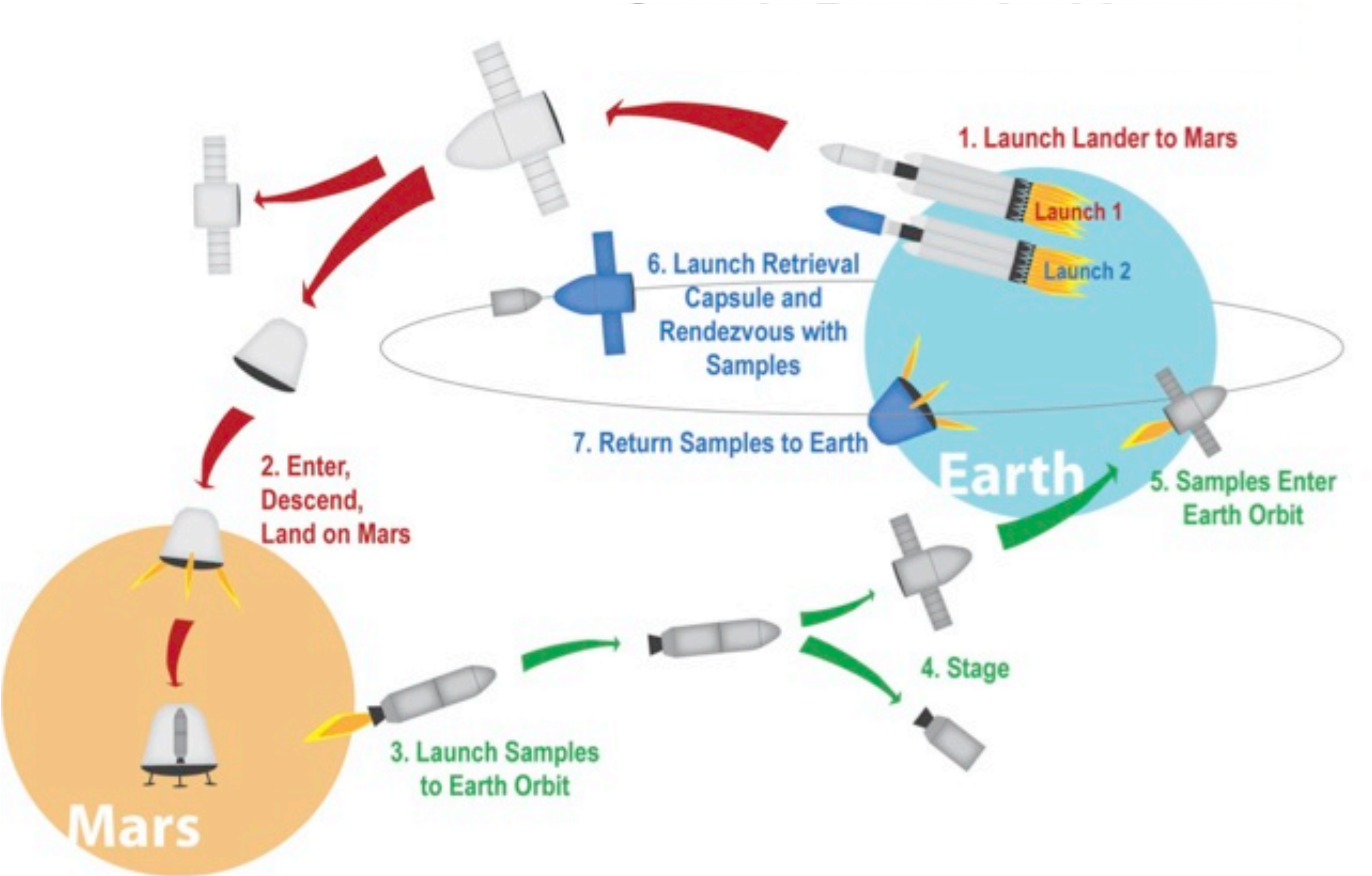


Mission 3 sample container rendezvous and capture in Mars orbit, launch to Earth, direct entry of sample canister in an entry cone shell



Mission 2 Fetch sample and launch to Mars orbit

Study Architecture Diagram

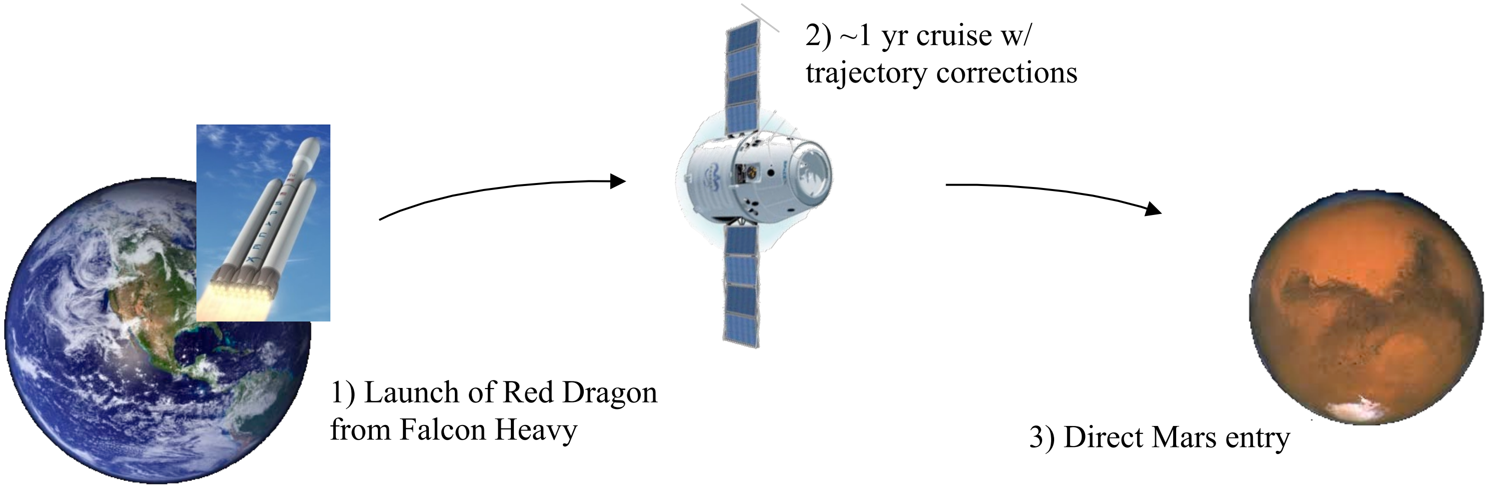


Earth-Mars Transfer

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

Note:

Trajectories optimized for lowest launch C3.

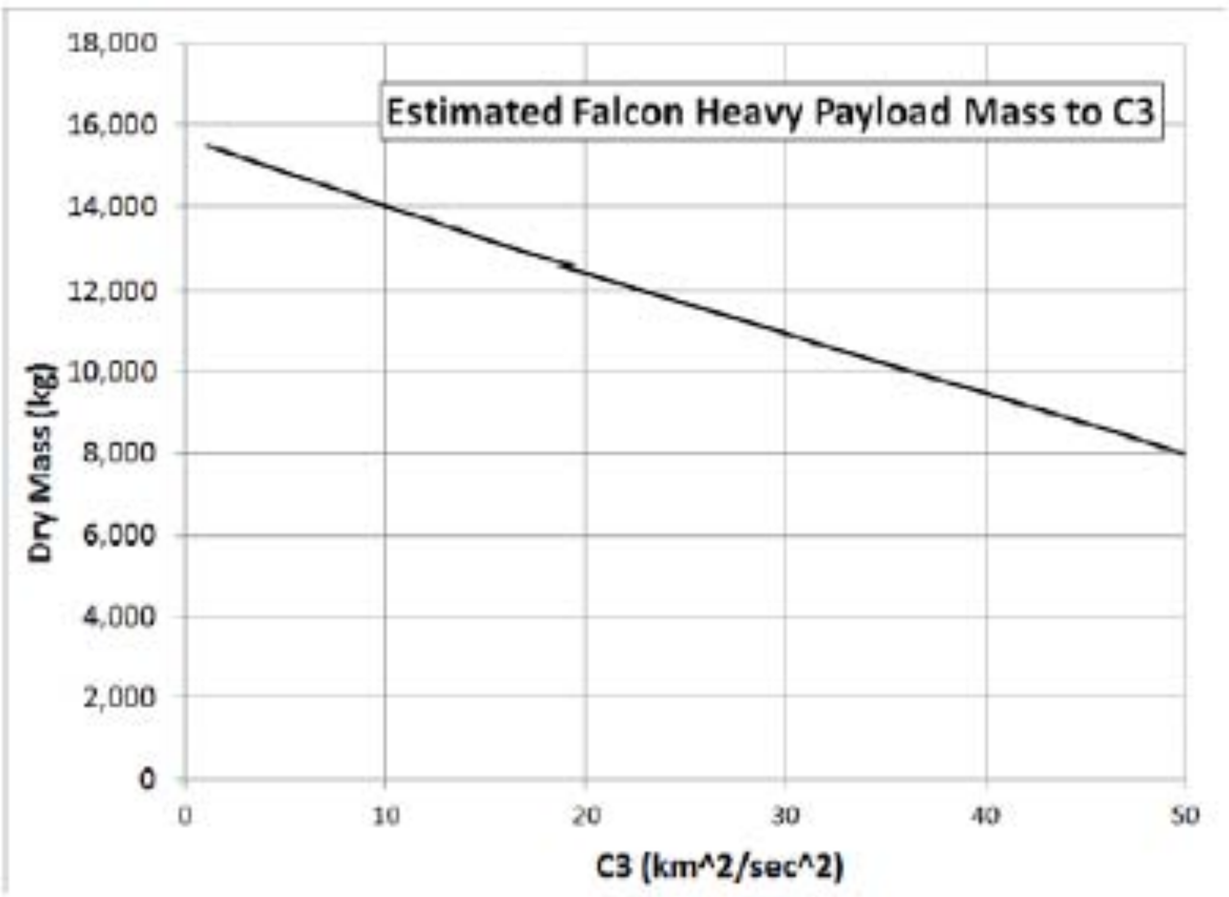


1) Launch of Red Dragon from Falcon Heavy

2) ~1 yr cruise w/ trajectory corrections

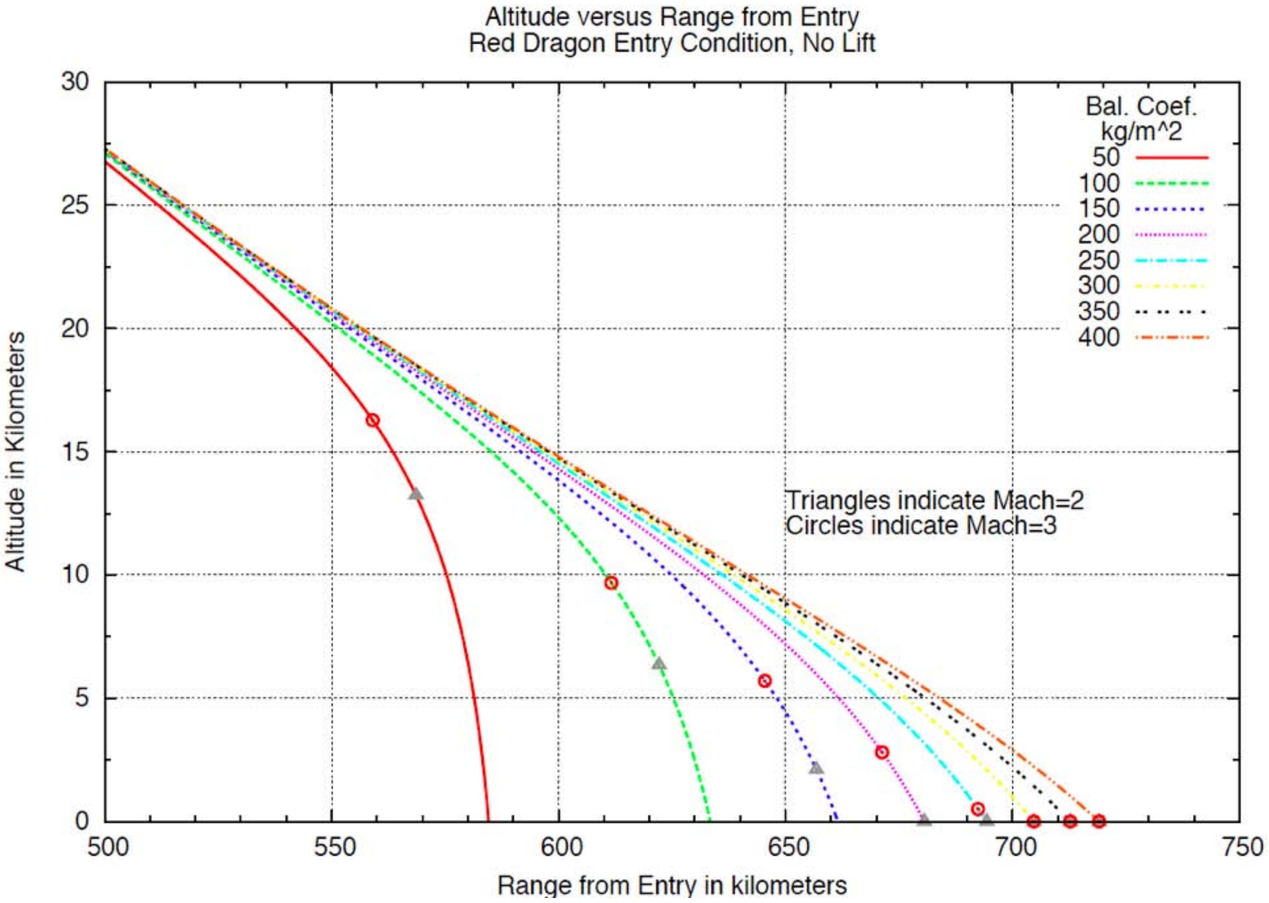
3) Direct Mars entry

How Much Can a Falcon Heavy Throw?



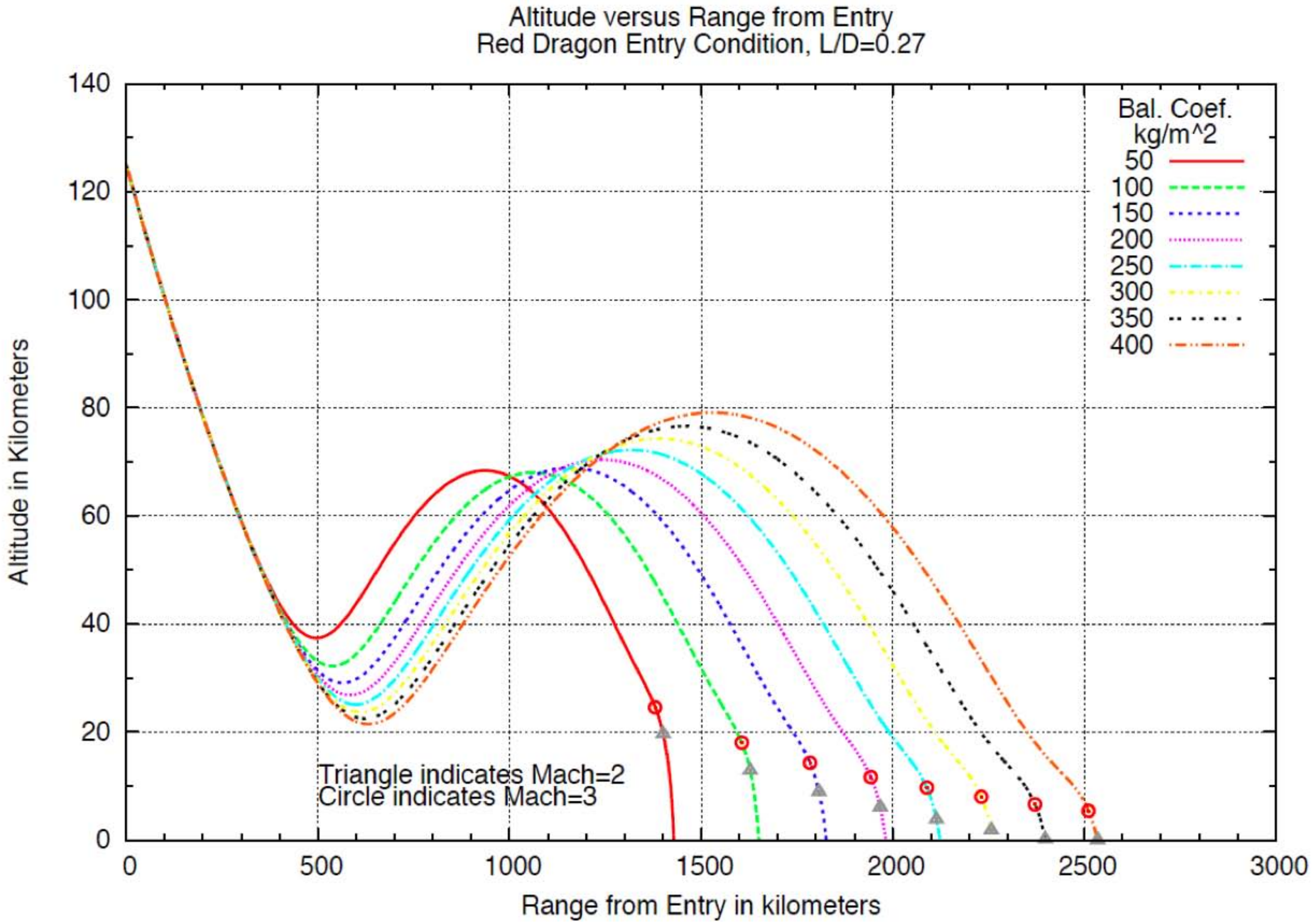
From “Feasibility Analysis for a Manned Mars Free-Return Mission in 2018”, Tito, et. al., IEEE Aerospace Conference, March 2-9, Big Falls, Montana.

Why Red Dragon Needs Hypersonic Lift for EDL

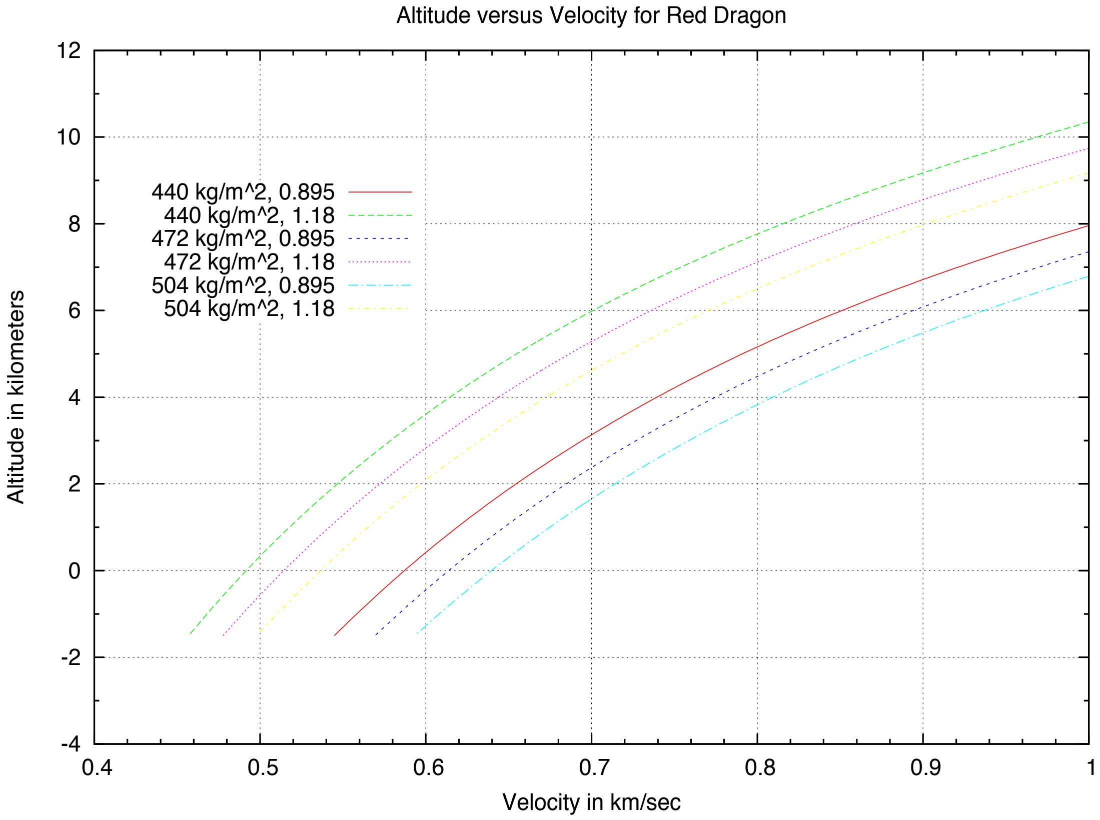


Altitude and Range to M=3 and M=2 Conditions for Non-lifting Trajectories, for Ballistic Coefficients Between 50 and 400 kg/m^2
Purely ballistic entry not feasible for High Ballistic Coefficients.

How Hypersonic Lift Transforms Red Dragon EDL

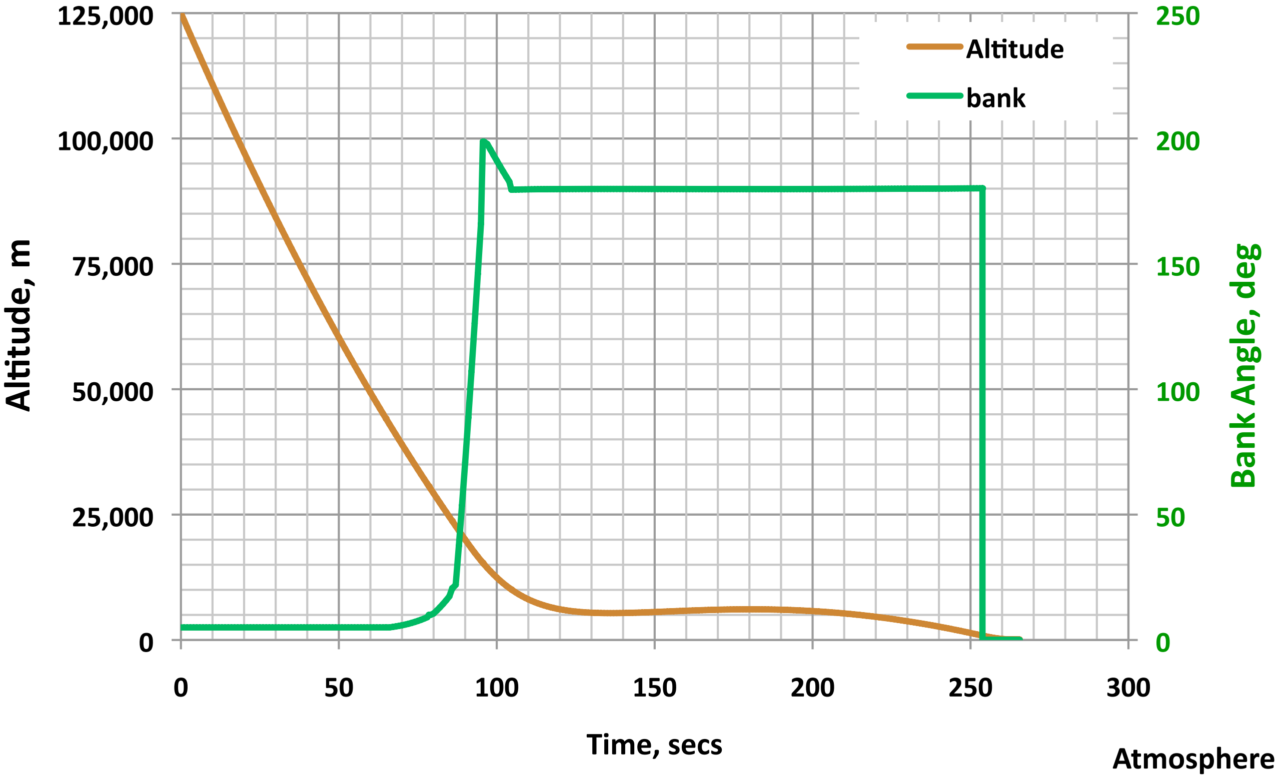


Why Parachutes Won't Work for Red Dragon Supersonic Deceleration



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°
Landing Altitude = 0.0 m
Landing Latitude = 0°

Sensitivity of Landing Performance to Entry Parameters

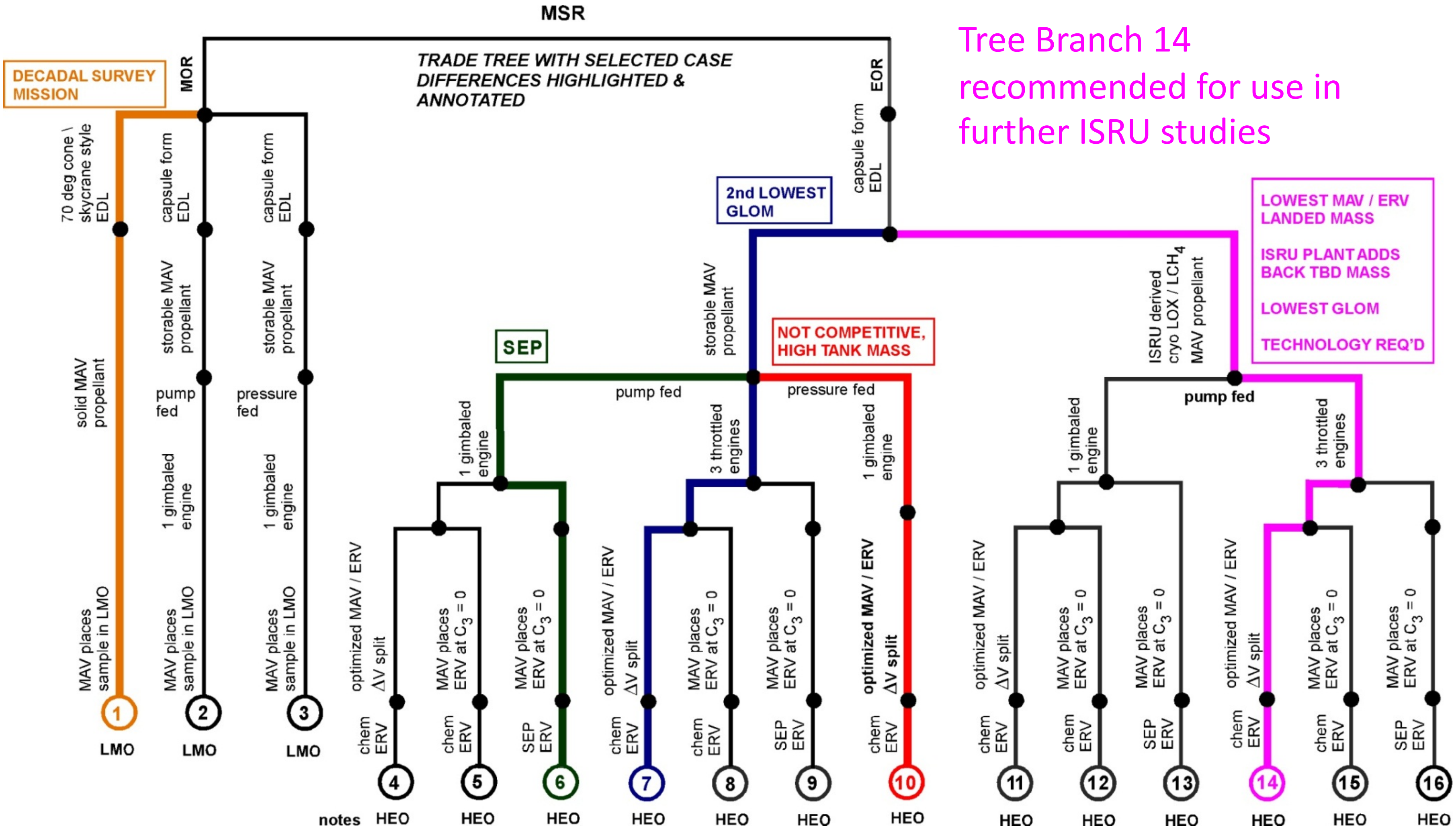
- **Trajectory**: using POST II 3DOF , landing at 0m altitude, 0° latitude, the trajectory has 3 phases
  - Aero entry and descent:
    - Manipulate the lift vector from 125km to about 800m above landing
  - Powered descent: from about 800m to 100m above landing
    - Vacuum thrust = 533,800N (8 engines; 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 (≈ 32% propellant mass fraction).**
- **Higher atmospheric density can help gain ~100kg of the landed mass.**
- **Improving L/D from 0.2 to 0.25 can help gain ~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

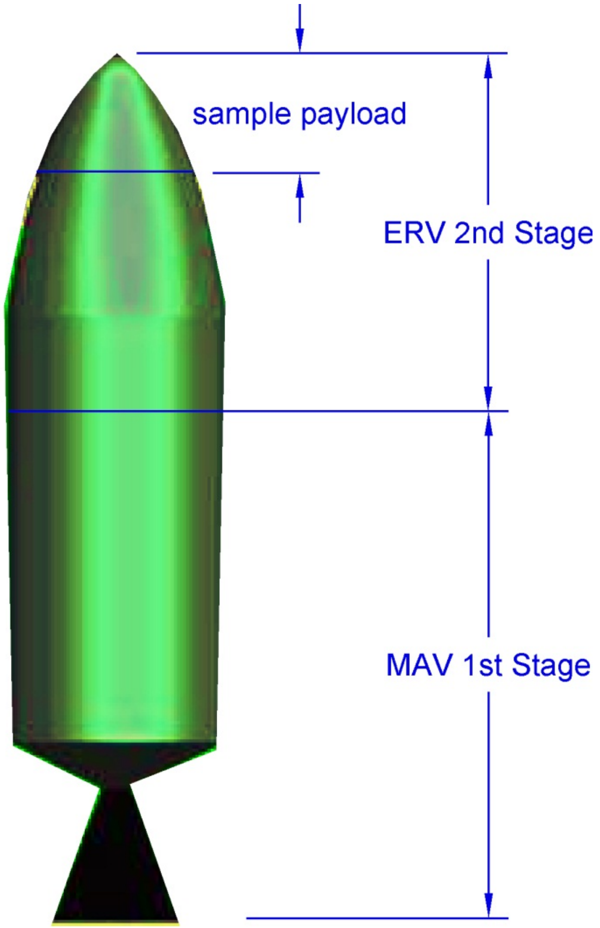
Tree Branch 14 recommended for use in further ISRU studies



MSR Launch Stack Design Trade Study Early Findings

- Overall Mission Dv ≥ 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

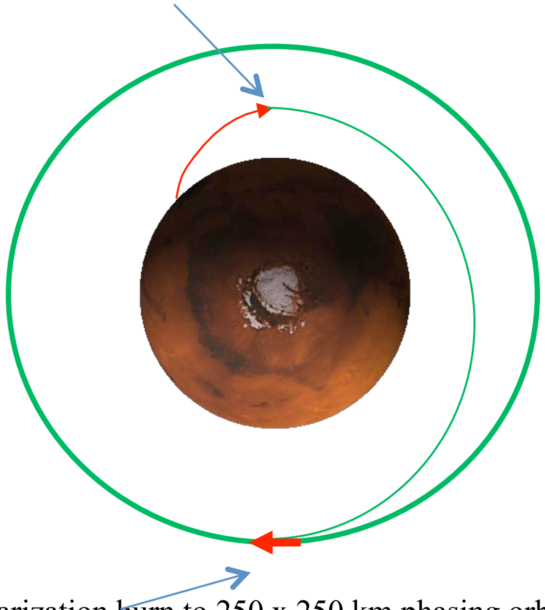
DV split optimized:

- 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

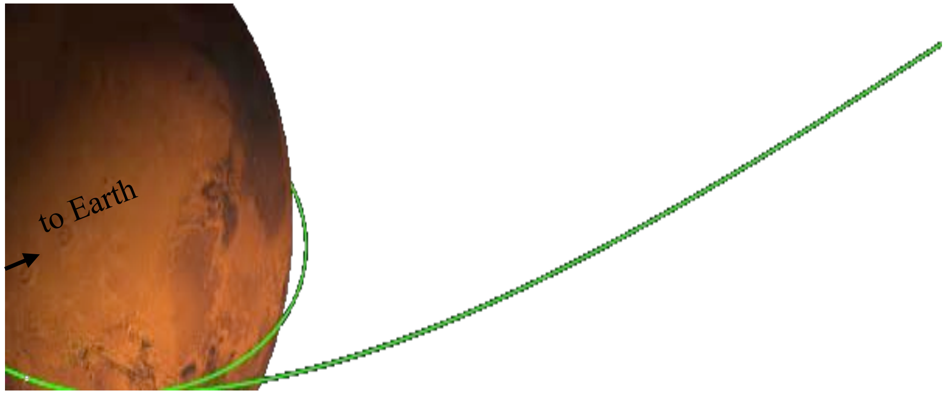
- Storable Propellant ERV 2nd stage delivers itself + sample payload to a High Earth Orbit

Departing Mars

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



2) Circularization burn to 250 x 250 km phasing orbit



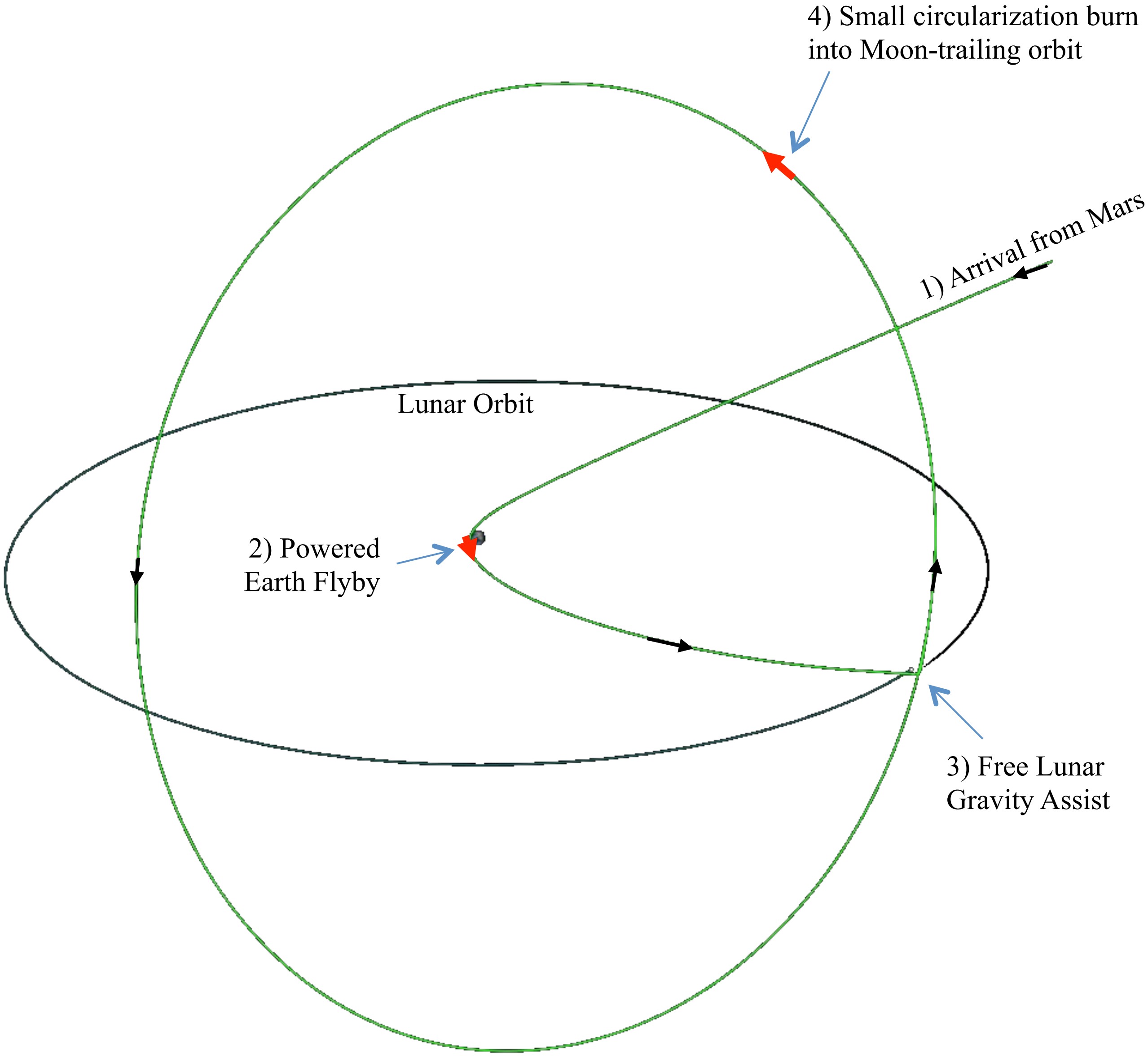
3) Trans-Earth Injection burn

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 (ΔV = ~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 ΔV Budget

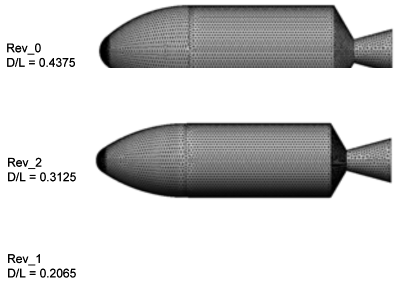
Mars Departure Date	Jul-24-2024	Jul-23-2026	Jul-20-2028
Earth Arrival Date	May-25-2025	Jun-05-2027	Jul-11-2029
ΔV Circularization to 250x250 km Mars orbit	37 m/s	37 m/s	37 m/s
ΔV Trans-Earth Injection	2,253 m/s	2,123 m/s	2,135 m/s
ΔV Trajectory Correction Maneuvers	75 m/s	75 m/s	75 m/s
ΔV Powered Earth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

Notes:

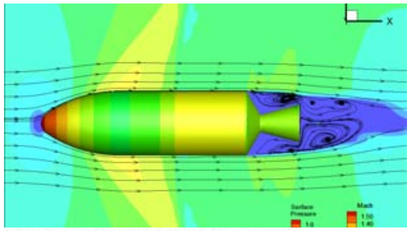
Trajectories optimized for lowest total ΔV per 2.2-yr Earth-Mars synodic period
ΔV's include gravity losses

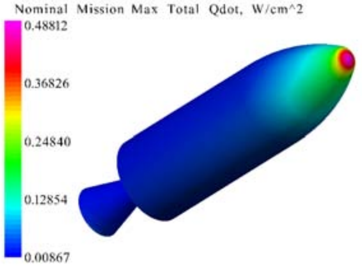
MSR MAV Technical Analysis Disciplines

Geometry Modeling

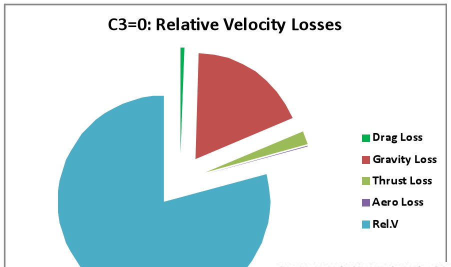


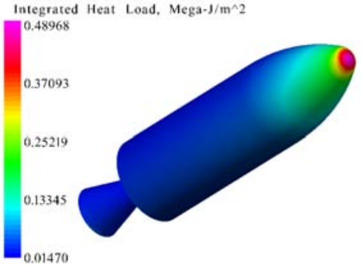
Aero/Aerothermal





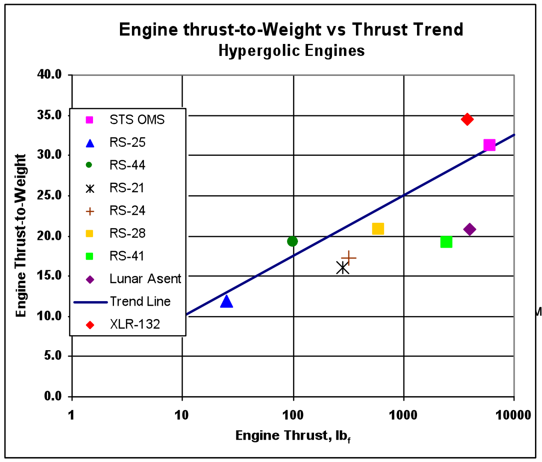
Trajectory

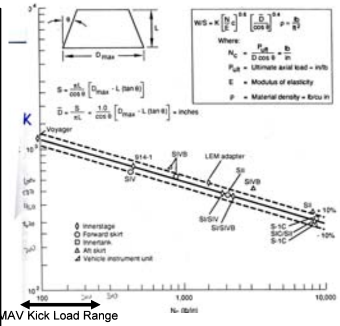


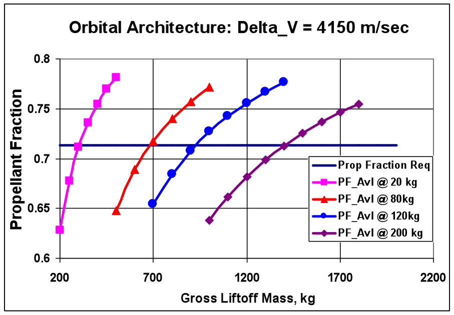


Propulsion

Weights & Sizing







Characteristics of Key Configurations—Early Results

ERV Propulsion	**Chemical**	**Chemical**	**Chemical**	**SEP**
ΔV_{Total} / 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**

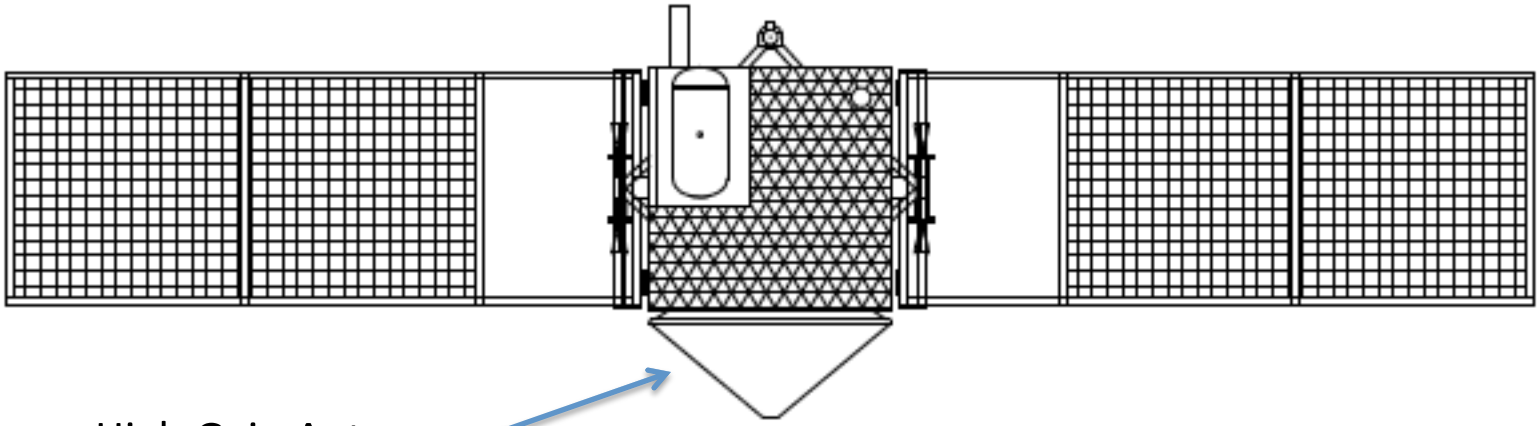
Mars Ascent Vehicle Closure Summary—Late Results

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

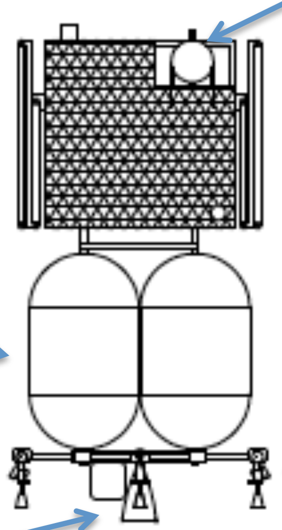
Earth Return Vehicle Design Considerations

- 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



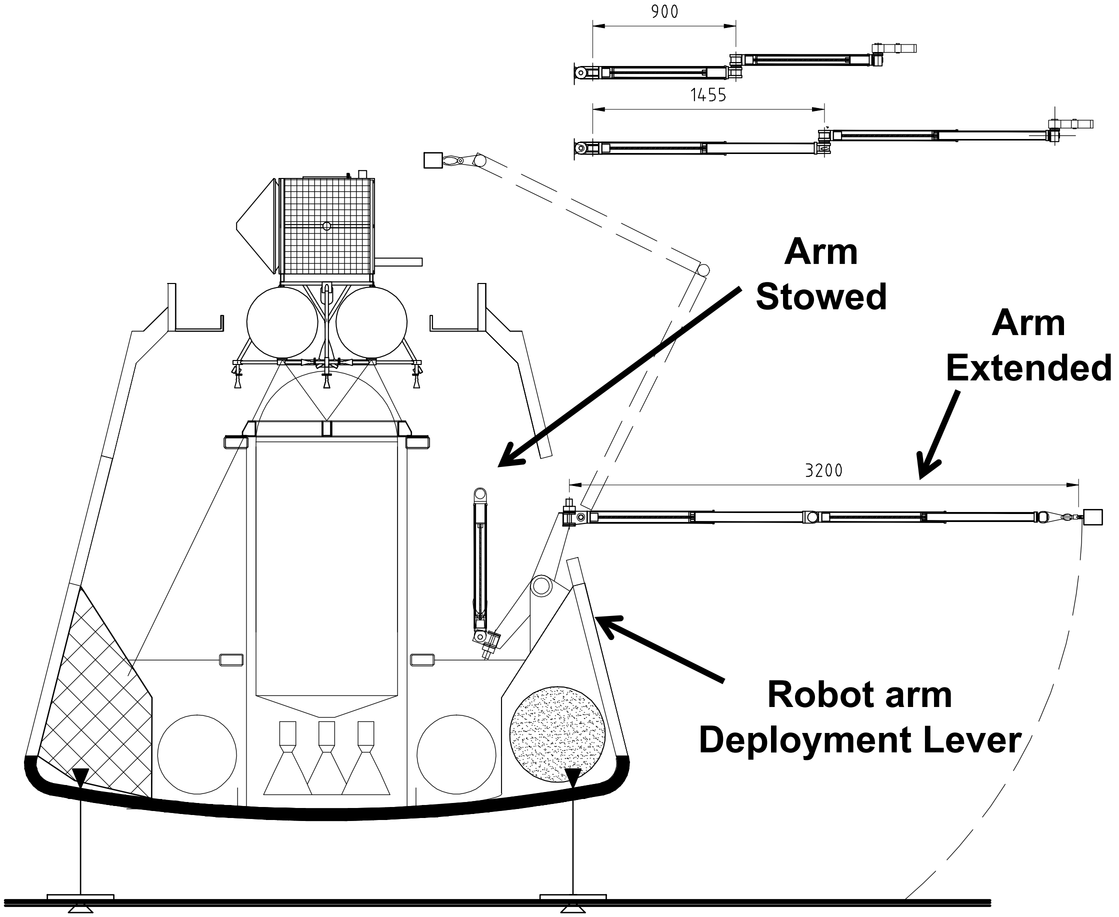
Sample Canister

Propellant Tanks (4)

ACS Thrusters (8)

Main Rocket Motor

Placing Samples in Earth-Return Stack



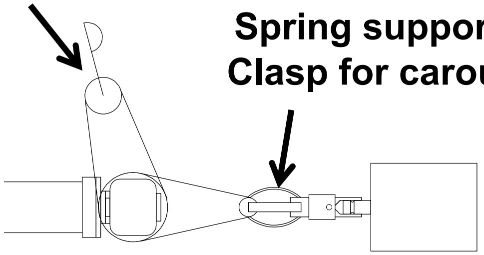
Arm Stowed

Arm Extended

Robot arm Deployment Lever

Robot Arm solution

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

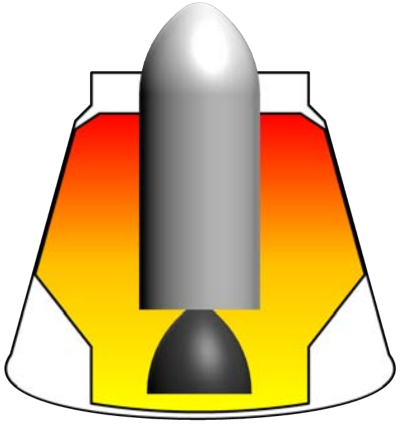


Spoon for regolith Grab

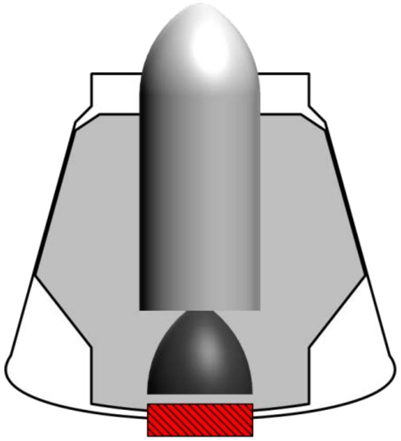
Spring supported Clasp for carousel

End effectors

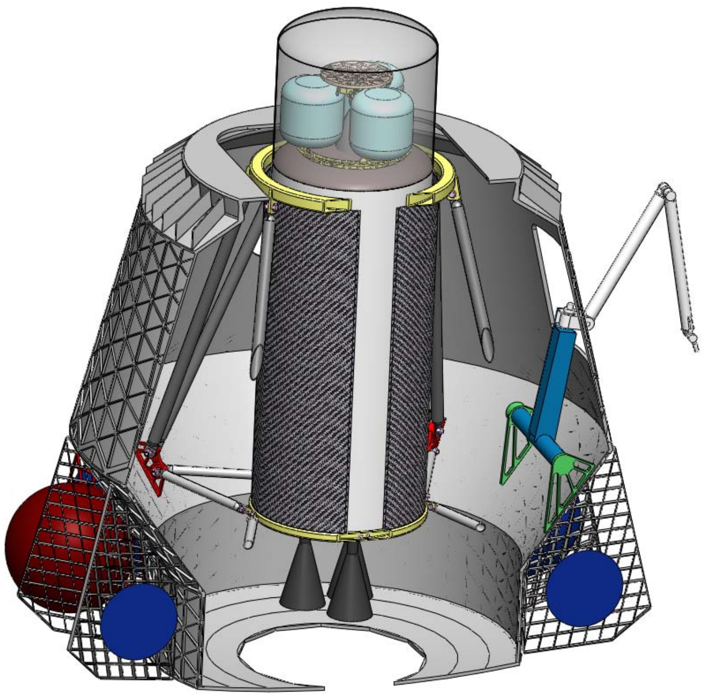
Accommodating MSR Unique Elements



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

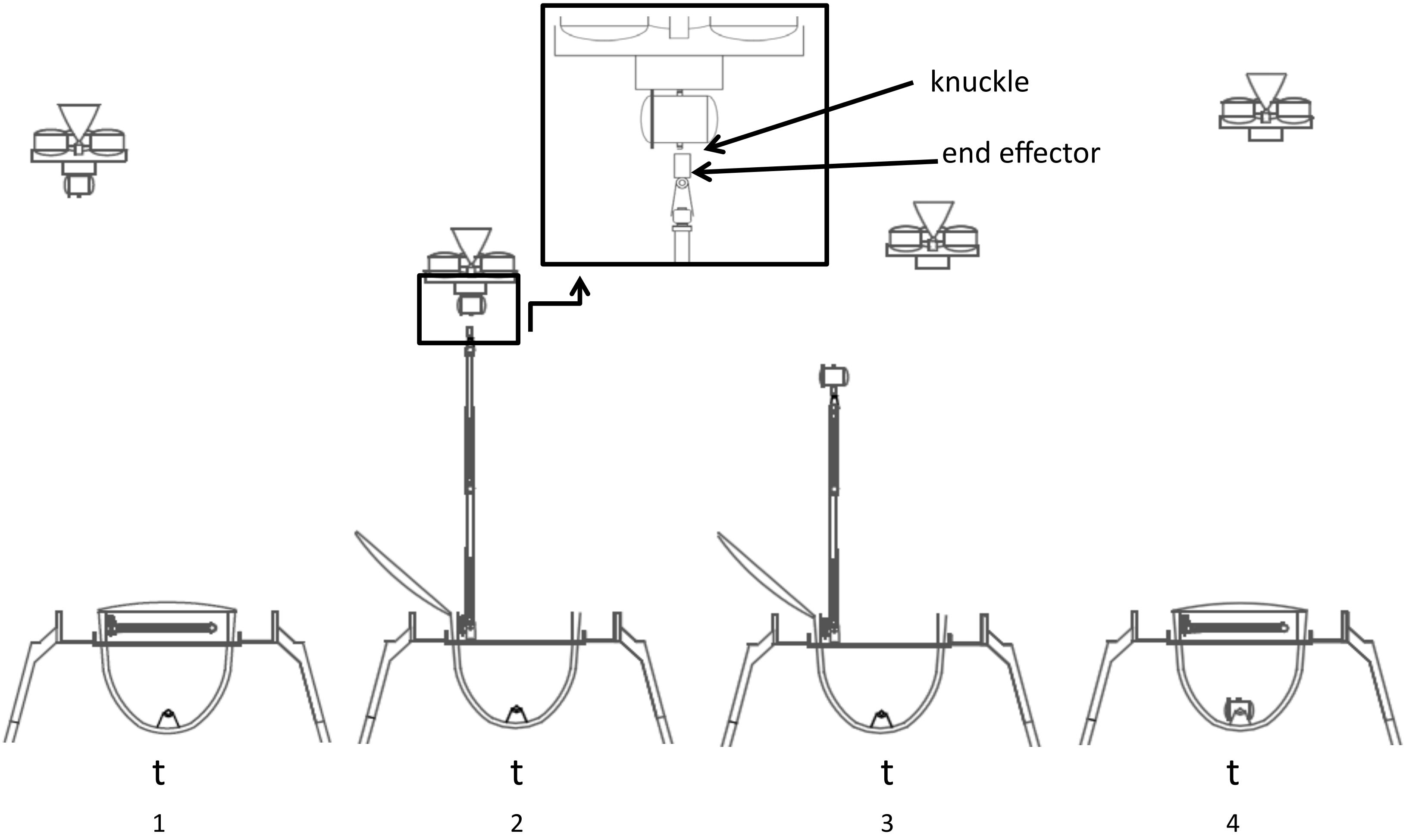


Preferred Approach is to Locate Vents in Floor Underneath MAV



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, Km²/m²	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