National Aeronautics and
Space Administration

Design of a Family of Mars Chemical Transportation Elements

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Entry, Descent, Landing, & Ascent Lead

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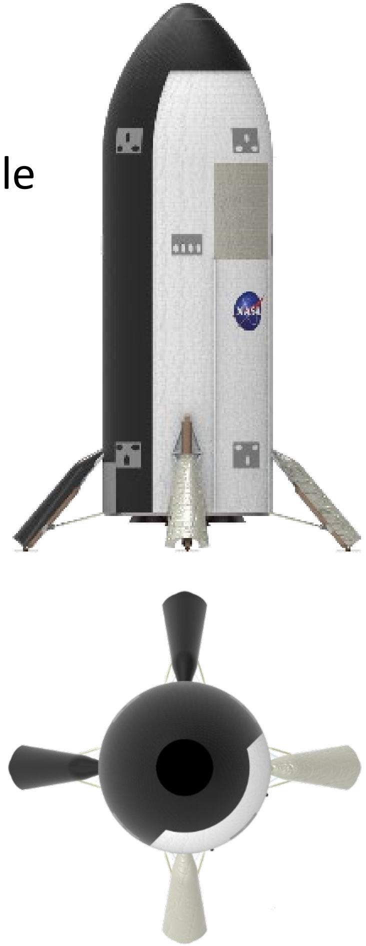
Motivation

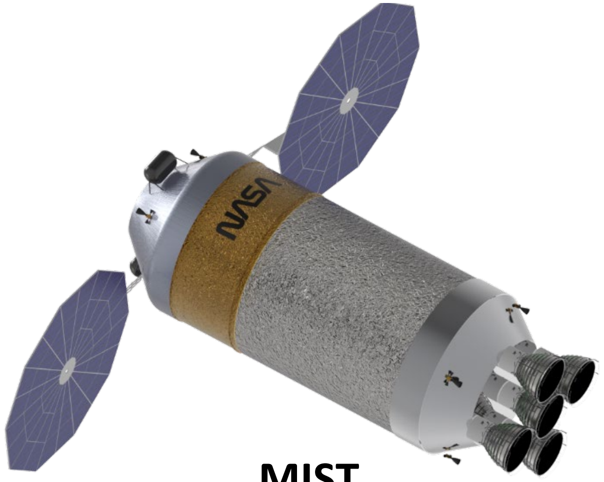
- NASA's Mars Architecture Team (MAT) is assessing the capabilities and constraints presented by architectures incorporating large-scale Mars In-Situ Resource Utilization (ISRU) propellant production
  - A collection of transportation vehicle, ISRU, and surface systems concepts were developed to support this assessment
- The work presented here details the efforts developing a dual role lander/ascent vehicle and an in-space transporter
  - Two companion papers detail the ISRU and surface systems concepts
    - *Kiloton Class ISRU Systems for LO2/LCH4 Propellant Production on the Mars Surface*
    - *Assessment of a Surface Water Transportation System Concept for ISRU Operations on Mars*
- The primary objective of the concept design was to estimate a reasonable bound for propellant production such that ISRU and supporting surface systems could be designed
  - Resulted in a feasible end-to-end all-chemical-based Mars transportation architecture for assessment with other transportation architectures alternatives

Transportation System Overview

MACHETE
Mars Chemical Transportation Elements

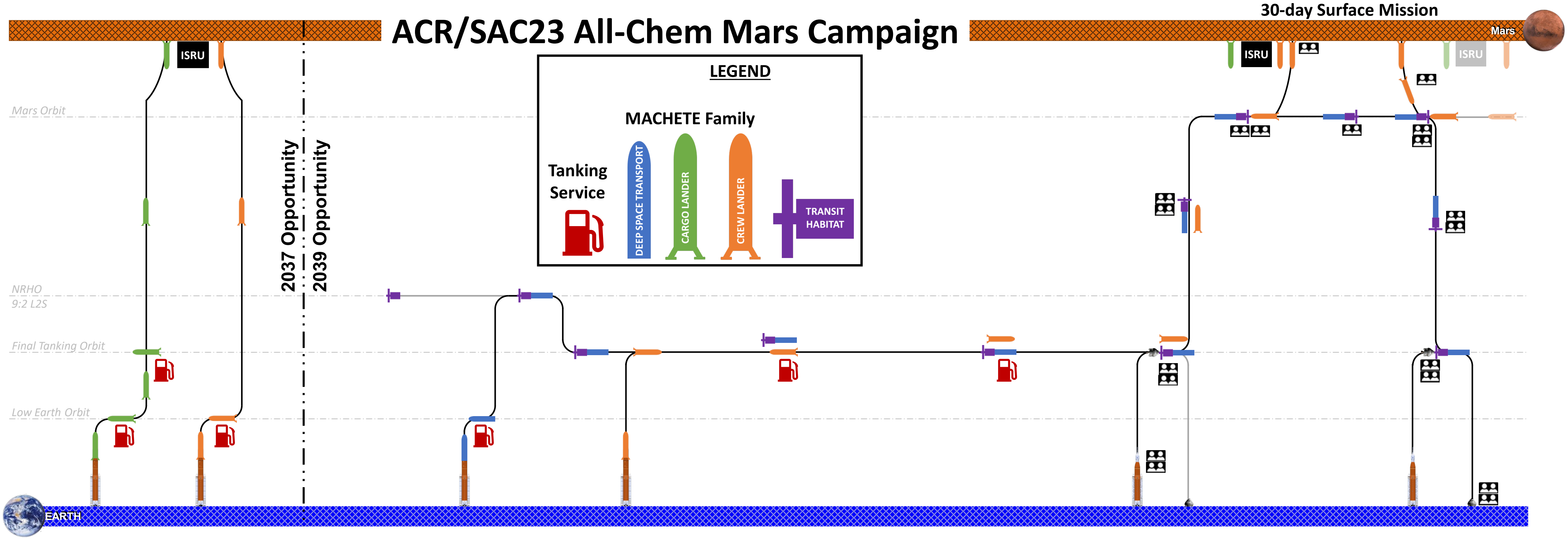


MALV
Mars Ascent/Lander Vehicle



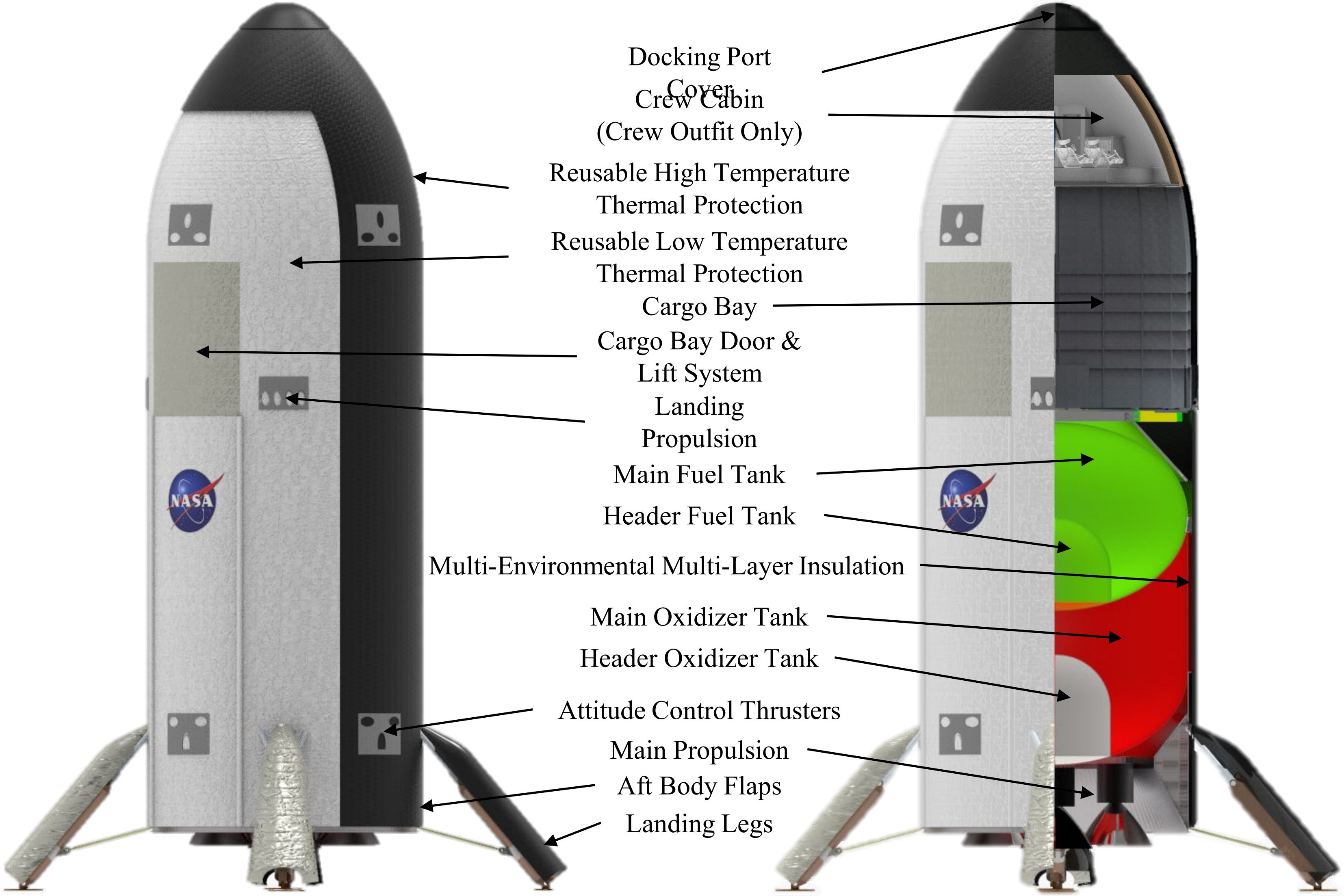
MIST
Mars In-Space Transport

Campaign Concept



**Earth launch and pre-Earth departure propellant resupply is future work*

Configuration - MALV



Docking Port Cover

Crew Cabin (Crew Outfit Only)

Reusable High Temperature Thermal Protection

Reusable Low Temperature Thermal Protection

Cargo Bay

Cargo Bay Door & Lift System

Landing Propulsion

Main Fuel Tank

Header Fuel Tank

Multi-Environmental Multi-Layer Insulation

Main Oxidizer Tank

Header Oxidizer Tank

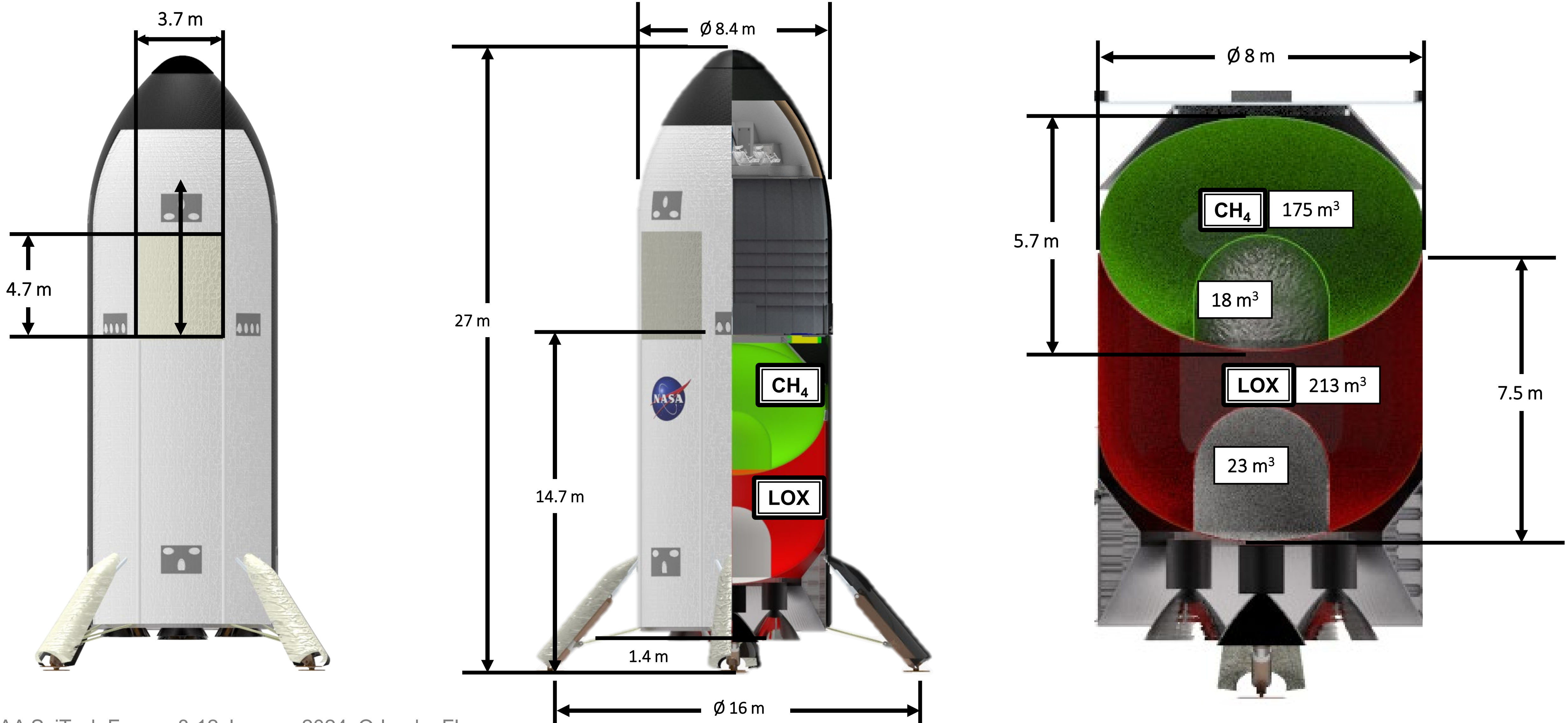
Attitude Control Thrusters

Main Propulsion

Aft Body Flaps

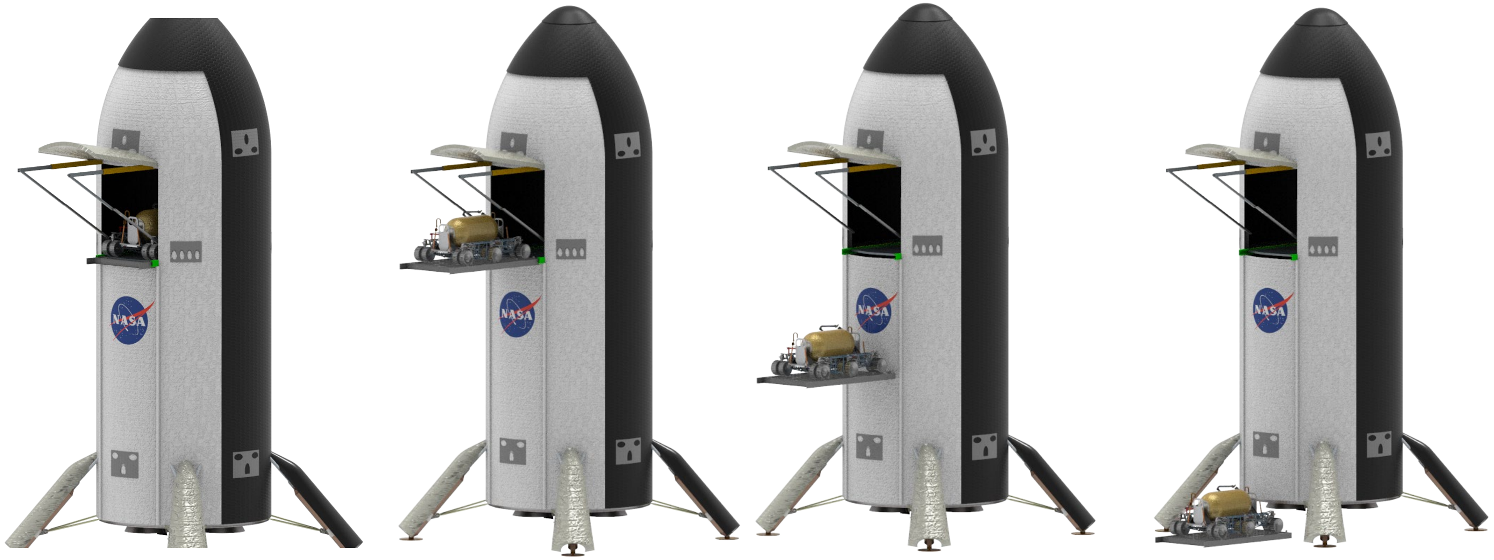
Landing Legs

Configuration - MALV



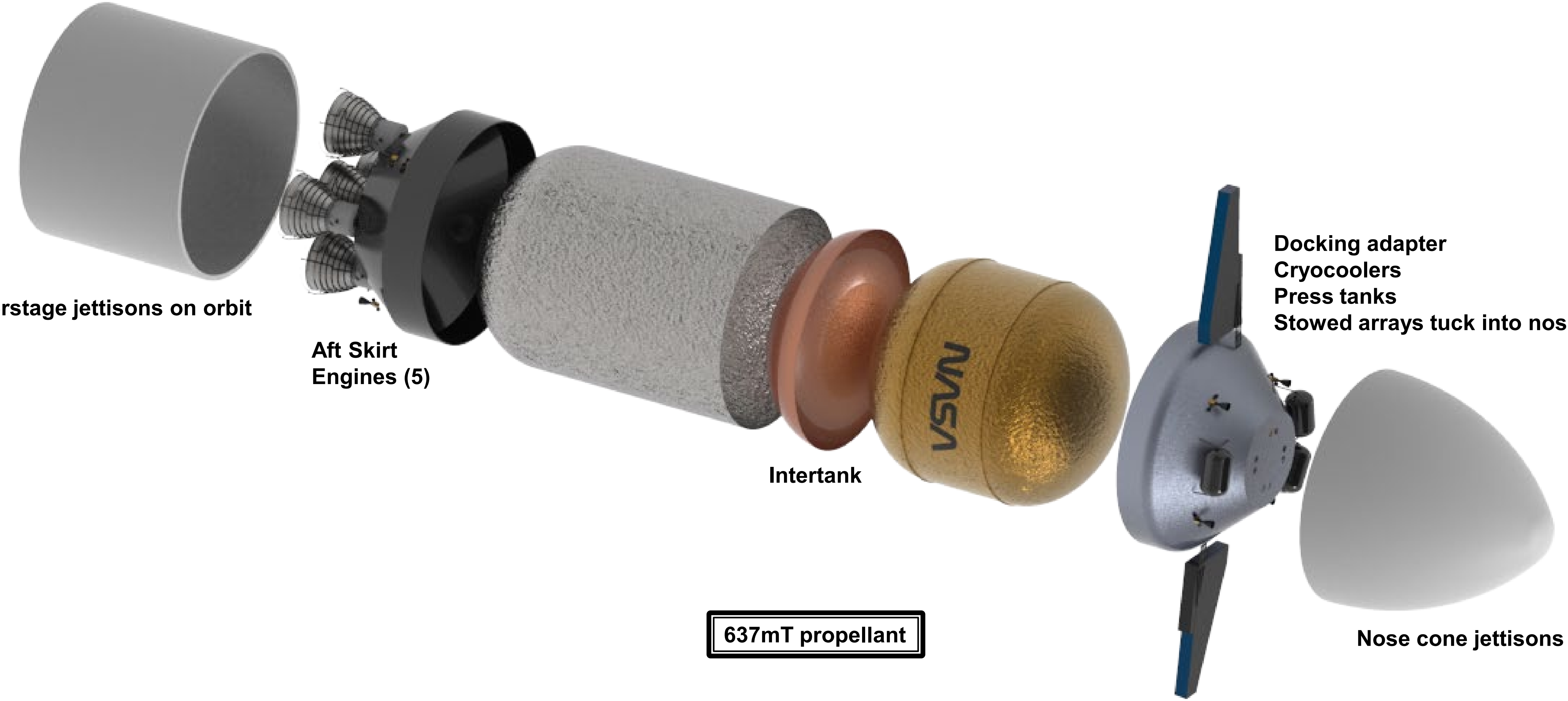
Configuration - MALV

EDL Body Flap Deployment



Surface Payload Deployment

Configuration - MIST



Interstage jettisons on orbit

Aft Skirt
Engines (5)

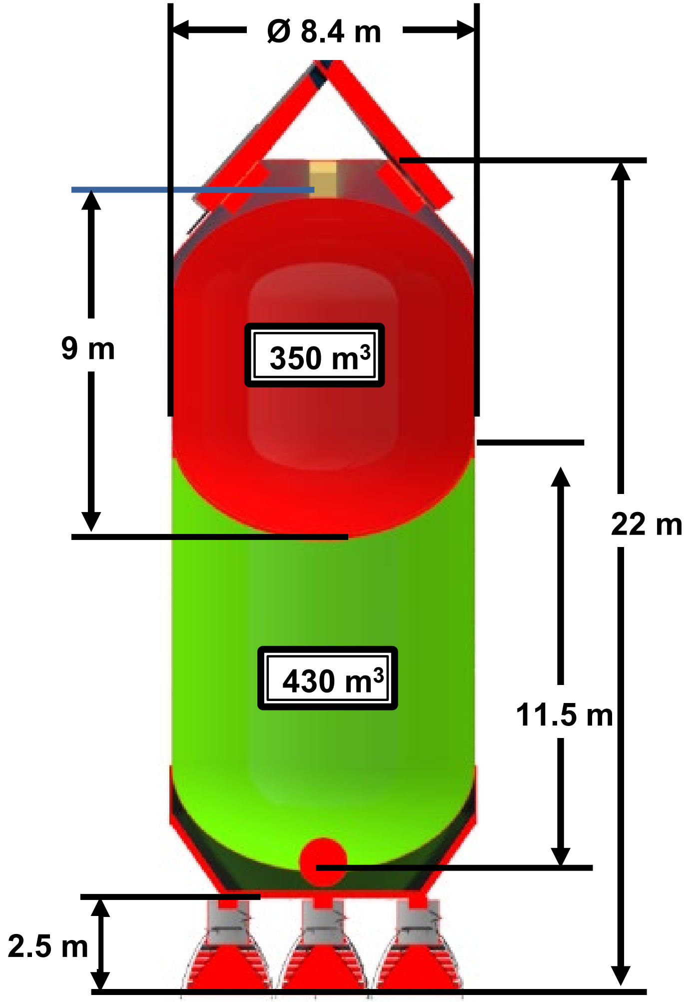
Intertank

637mT propellant

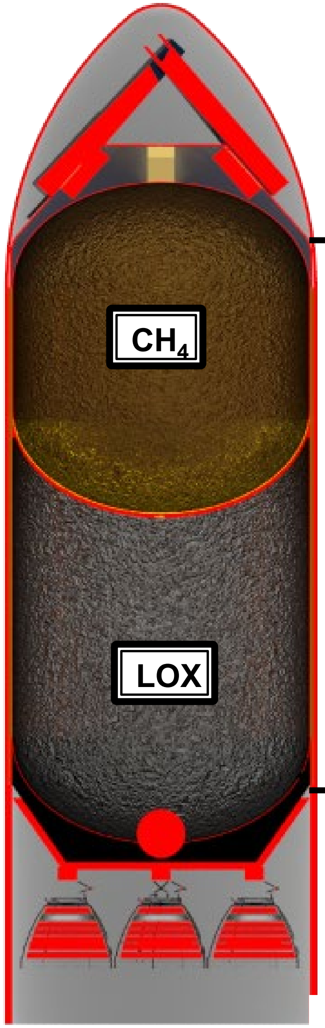
Docking adapter
Cryocoolers
Press tanks
Stowed arrays tuck into nose

Nose cone jettisons on orbit

Configuration - MIST



637mT propellant



Stowed arrays tuck into nose

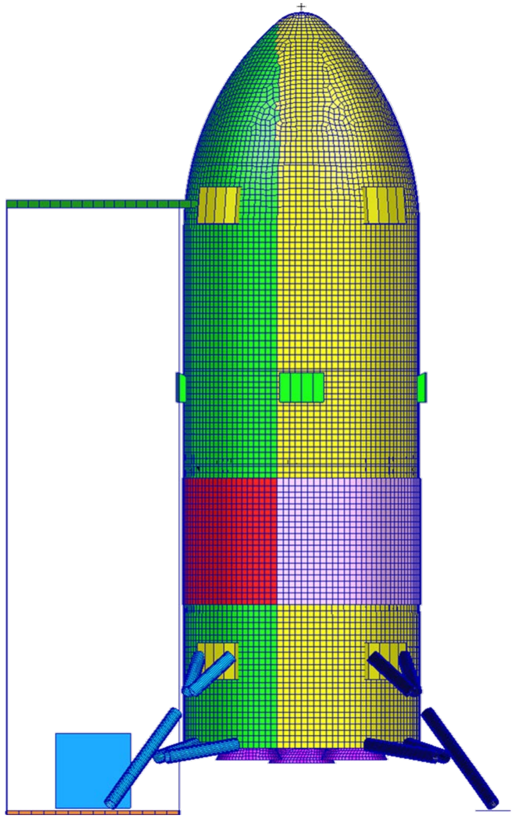
Nose cone jettisons on orbit

Interstage jettisons on orbit

SLS Shroud OML (unchanged)

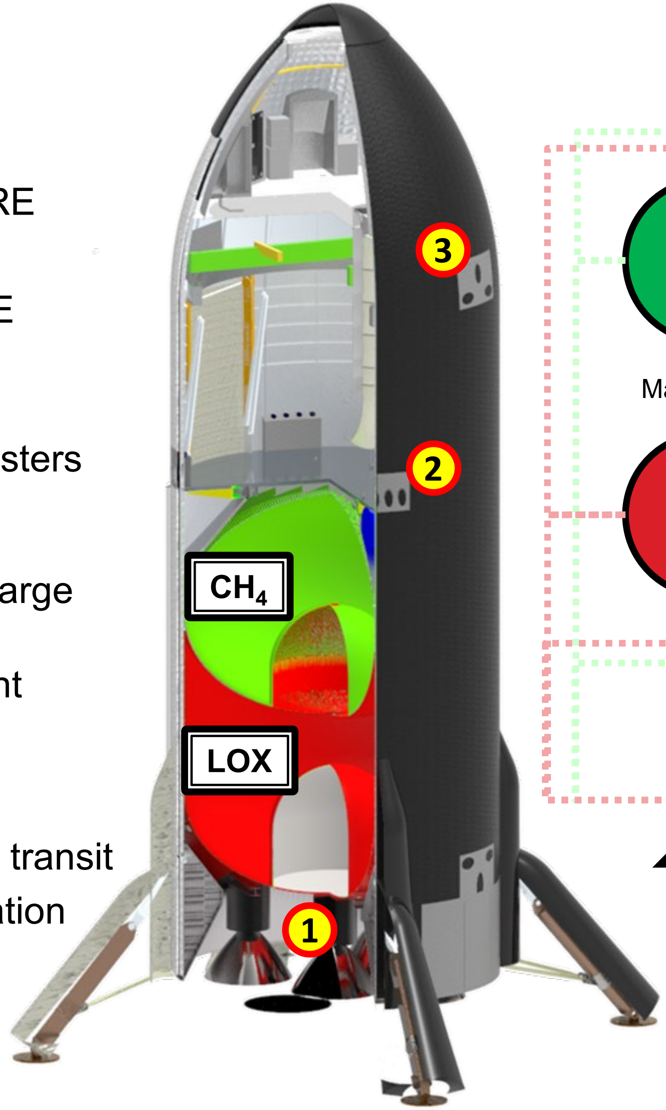
Structures

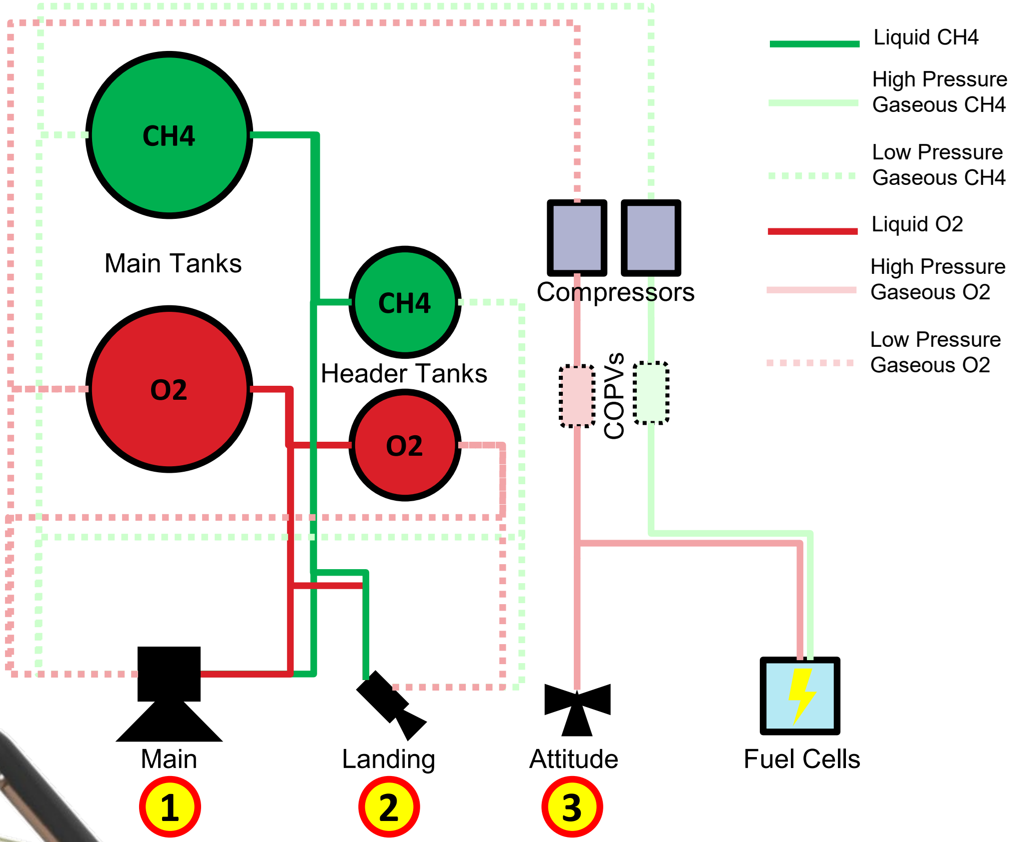
- Performed preliminary FEA using NX Patran, NX Nastran, and HyperSizer
  - All metallic aluminum primary structure with a 1.4 ultimate strength factor of safety
  - Additional analyses may have led to alternative material selections
    - aerothermal structures
    - manufacturability
    - life cycle cost
- A total of 19 load cases across three vehicle configurations were evaluated covering a broad range of flight environments including Earth ascent, Mars descent, Mars ascent, and in-space propulsion
- Preliminary analysis of a payload lift system with a 15,000 kg lift capacity



Propulsion

- Three Integrated Propulsion Systems
  - Main Propulsion System ①
    - 5 x 165,000 lbf O_2/CH_4 pump-fed GG RDRE
  - Landing Propulsion System ②
    - 4 x 48,000 lbf O_2/CH_4 pump-fed GG RDRE (4-chamber)
  - Attitude Control System ③
    - 24 x 28 lbf pressure-fed CH_4 cold gas thrusters
- Two sets of tanks
  - Main tanks provide bulk propellant storage for large in-space burns and ascent from Mars
  - Header tanks provide more controlled propellant storage environment for EDL
- Ullage Gas Recouperation
  - Electric compressor captures ullage gas during transit
  - Provides stored gas for ACS and power generation

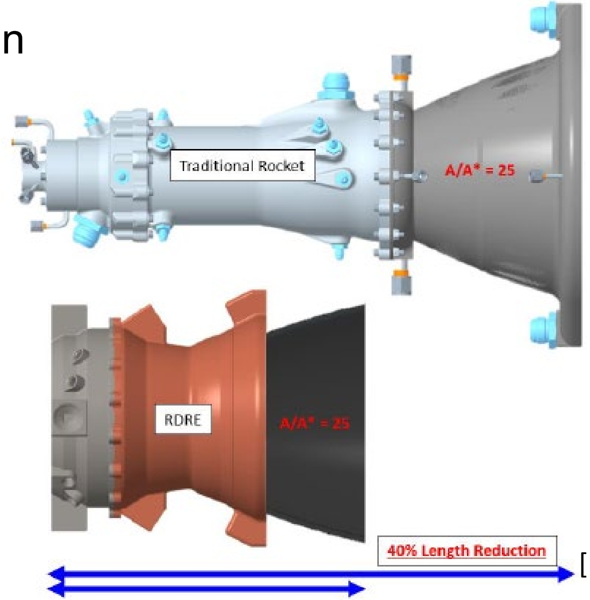




Enabling Technology - RDRE

Fig 19. High speed images of liquid/liquid LOX/LCH4 co-rotating waves. Images show from left to right a frame-by-frame capture of the wave movement.

- RDRE = Rotating Detonation Rocket Engine
  - No moving/rotating parts; the detonation wave is what is rotating
- Detonation process results in increased theoretical combustion pressures and temperatures compared to traditional constant pressure deflagration
  - increased work extraction, ultimately leading to increasing engine performance
- Increased temperature and pressure drive increased reaction rates, resulting in shorter combustors
- Combustor exit conditions are already supersonic, so no need for converging flow section
- Annular combustion chamber results in much reduced nozzle length for the same aspect ratio constant pressure combustors
- Benefits
  - Improved performance, Isp (10-15%) <- due to higher combustion temperatures and pressures
  - Reduced Length (~40%) <- due to detonation cycle and subsequent combustor geometry
  - Reduced Weight (~30%) <- due to combustor/nozzle length reduction
- Challenges/Drawbacks
  - Detonation stability
    - Rotating Detonation Bifurcation Wave Collapse
  - Increased Cooling due to higher heat rates



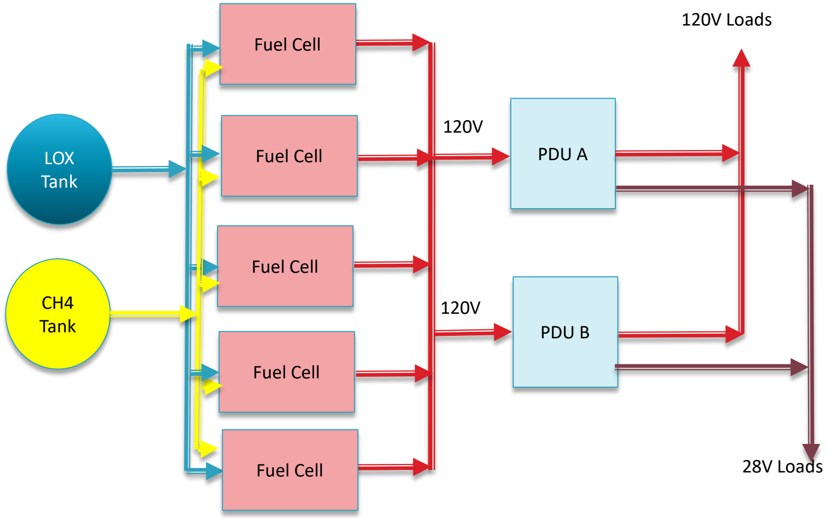
[1]

Fig 3. From left to right, NASA CP WHALE engine (top) and V2 RDRE (bottom).

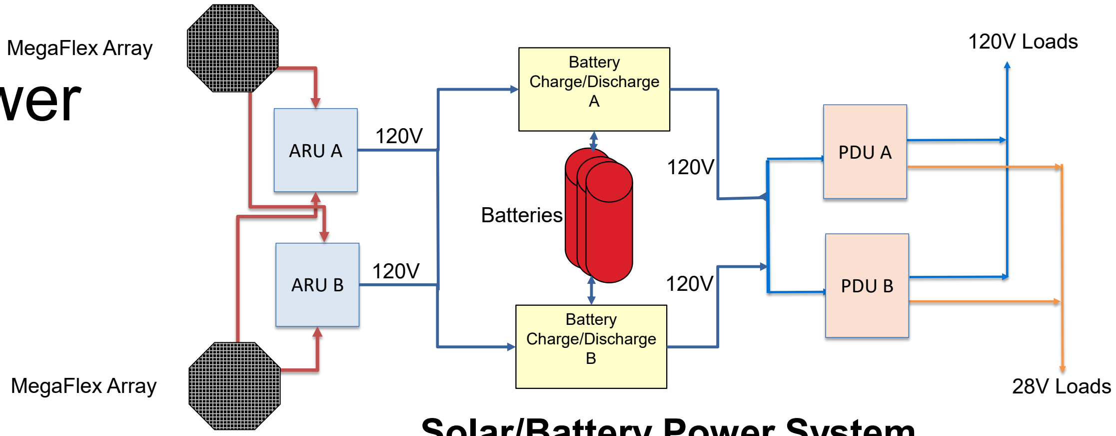
[1] Teasley, T., Fedotowsky, T., Gradl, P., Austin, B., Heister, S., *“Current State of NASA Continuously Rotating Detonation Cycle Engine Development*”, AIAA SciTech Forum, National Harbor, MD, January 2023

Power

- MALV consists of an Oxygen/Methane fuel cell power system
  - 6 parallel fuel cells to provide 12,644 Watts peak power output
  - 22,000 kg of reactants for outbound transit
  - 700 kg of reactants for Mars ascent
- MIST consists of a solar/battery power system
  - 2 x 11-meter diameter MegaFlex Arrays
  - Supports additional 12,000 Watts of power for crew habitat at Mars distance
- Both systems provide 120-volt and 28-volt outputs for vehicle systems operation



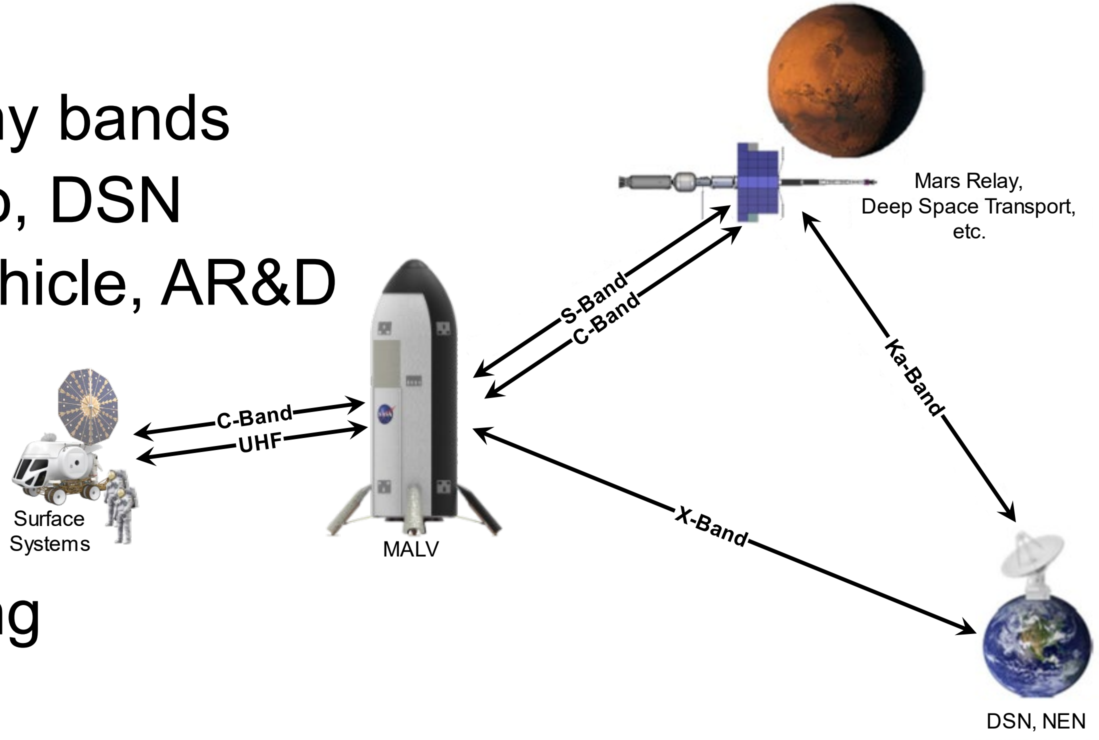
Fuel Cell Power System



Solar/Battery Power System

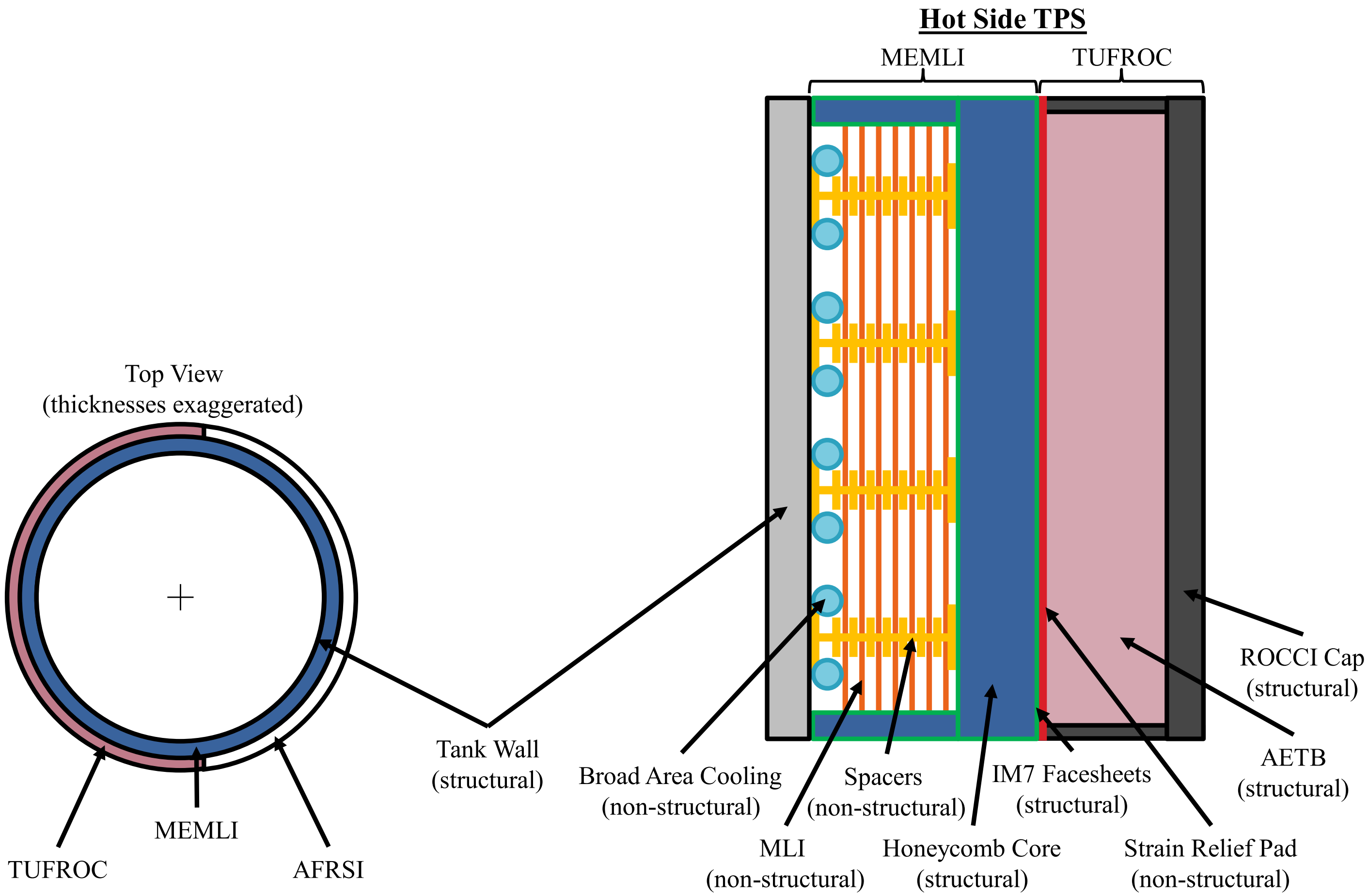
Avionics

- Leverages heritage design derived from Orion flight systems
- Does not support direct-to-Earth communication during Mars descent/ascent
- Complex communication system covering many bands
  - X-band: high data rate telemetry and video, DSN
  - S-band: surface-to-orbit, telemetry, intervehicle, AR&D
  - C-band: range safety, AR&D
  - UHF: surface systems
- Terrain relative navigation similar to that flown on Mars 2020 to support precision landing
  - Lidar altimeter
  - Lander vision system
  - Hazard avoidance



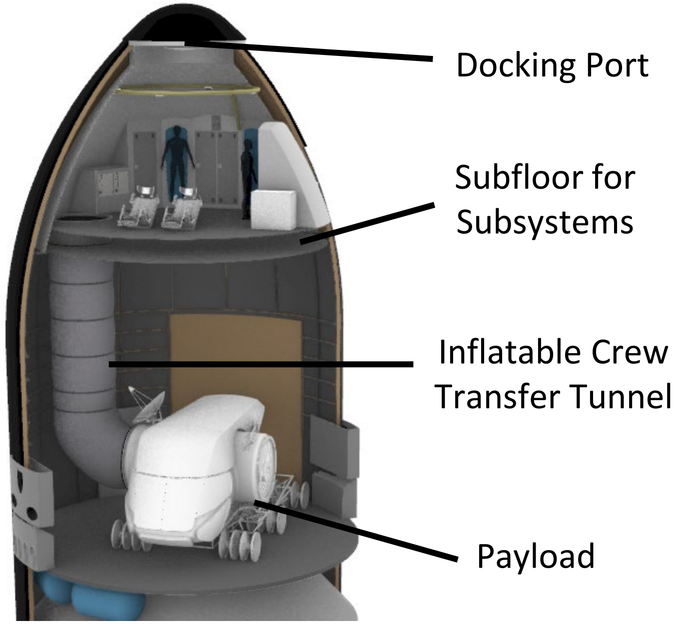
Thermal Protection and Management

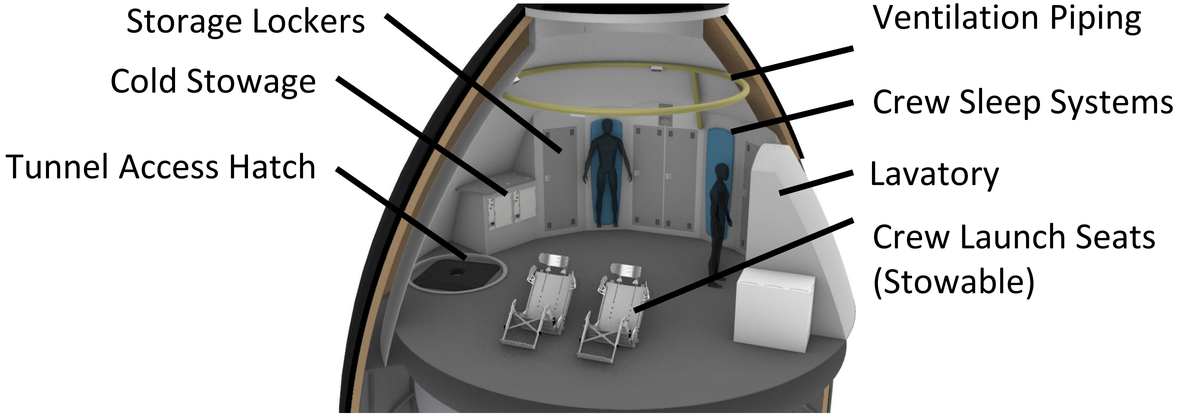
- Multi-functional thermal subsystem
  - Boiloff mitigation
  - EDL aerothermal protection
  - Propellant liquefaction support
- Minimal cryocoolers provided to mitigate boiloff in-space
  - Broad area cooling on tanks are fed by external cryocooler systems for surface propellant liquefaction
- MEMLI supports outer TUFROC aerothermal protection layer



Crew Support

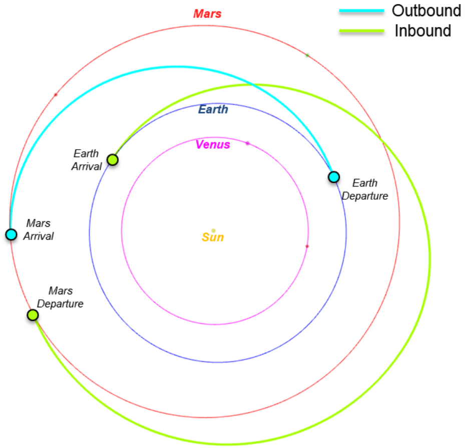
- Integrated crew cabin capable of supporting up to six crew with minimal impact to vehicle design
- Pressurized access to integrated payload through an inflatable transfer tunnel
  - Helps mitigate transfer of uncontained Martian material
- Forward docking port in the nose for docking and crew ingress/egress with other architectural elements
- Short duration cabin (84 hours nominal)
  - No exercise equipment
  - Basic waste management system
  - Open loop ECLSS





In-Space Trajectories

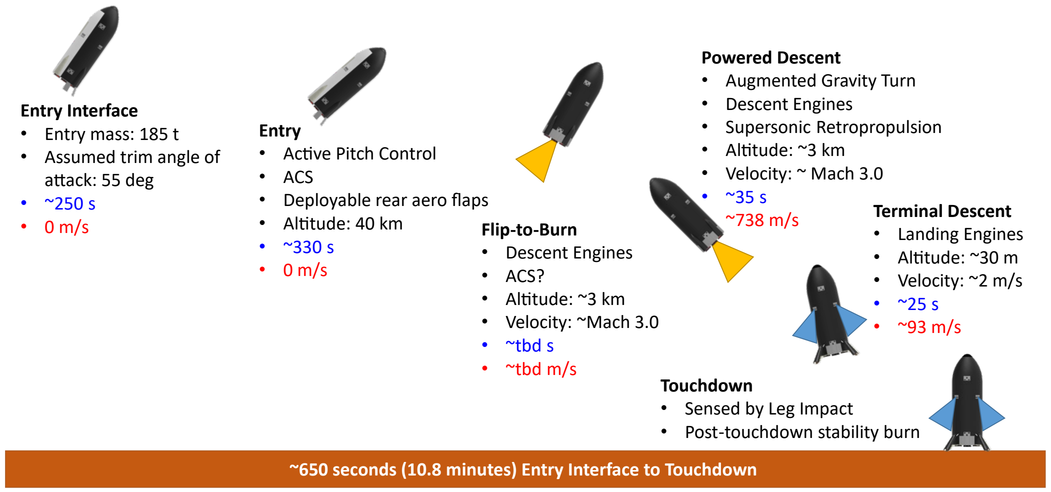
- Set of high thrust, 850-day total duration, trajectories were calculated over an Earth-Mars synodic cycle
  - 2037 & 2039 were selected as the reference trajectories, as they represent a compromise between minimum and maximum total delta-V over the Earth-Mars synodic cycle
- Trajectories assume roughly 51 days in Mars vicinity, with 10 days of orbital operation after arrival and before departure, resulting in roughly a 30-day crew surface mission
- Cargo must arrive prior to crew and is delivered to Mars one opportunity before the crew
  - Time required to deliver ISRU equipment and manufacture Mars ascent propellant



Reference Type A	High Thrust Ballistic 850d EME	High Thrust Ballistic 850d EME	
	2037	2039	
Earth Departure	09/01/2037	10/20/2039	
Deep Space Maneuver	11/20/2037	03/11/2040	
Mars Arrival	04/05/2038	07/06/2040	
Mars Departure	05/26/2038	08/27/2040	
Deep Space Maneuver	03/06/2039	05/22/2041	
Earth Arrival	11/23/2039	02/16/2042	
Outbound	216.0	260.5	Days
Stay	51.0	51.7	
Inbound	546.0	538.4	
Total	**813.0**	**850.6**	
Crew Launch Window	90	90	Days
Pre-Departure	10	10	
Post-Arrival	10	10	
Total Off Earth	923.0	960.6	
Trans-Mars Injection	928.20	1,230.45	m/s
Deep Space Maneuver	0.00	0.00	
Mars Orbit Insertion	916.10	857.63	
Trans-Earth Injection	733.30	844.18	
Deep Space Maneuver	2,309.30	2,841.20	
Earth Orbit Insertion	801.50	626.35	
Total DV	**5.6884**	**6.3998**	km/s

Entry, Descent, Landing, & Ascent

Mars EDL Conop



Entry Interface
- Entry mass: 185 t
- Assumed trim angle of attack: 55 deg
- ~250 s
- 0 m/s

Entry
- Active Pitch Control
- ACS
- Deployable rear aero flaps
- Altitude: 40 km
- ~330 s
- 0 m/s

Flip-to-Burn
- Descent Engines
- ACS?
- Altitude: ~3 km
- Velocity: ~Mach 3.0
- ~tbd s
- ~tbd m/s

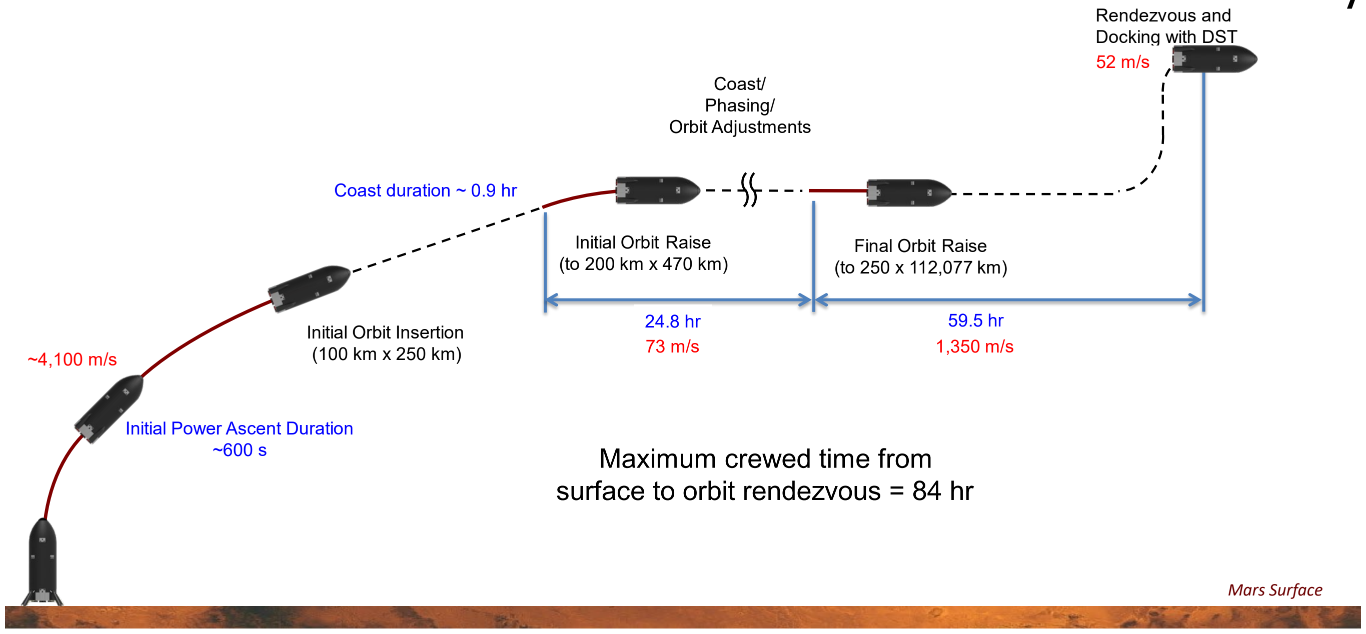
Powered Descent
- Augmented Gravity Turn
- Descent Engines
- Supersonic Retropropulsion
- Altitude: ~3 km
- Velocity: ~ Mach 3.0
- ~35 s
- ~738 m/s

Terminal Descent
- Landing Engines
- Altitude: ~30 m
- Velocity: ~2 m/s
- ~25 s
- ~93 m/s

Touchdown
- Sensed by Leg Impact
- Post-touchdown stability burn

~650 seconds (10.8 minutes) Entry Interface to Touchdown

Mars Ascent Conop



Rendezvous and Docking with DST
52 m/s

Coast/
Phasing/
Orbit Adjustments

Coast duration ~ 0.9 hr

Initial Orbit Raise
(to 200 km x 470 km)

Final Orbit Raise
(to 250 x 112,077 km)

24.8 hr
73 m/s

59.5 hr
1,350 m/s

Initial Orbit Insertion
(100 km x 250 km)

~4,100 m/s

Initial Power Ascent Duration
~600 s

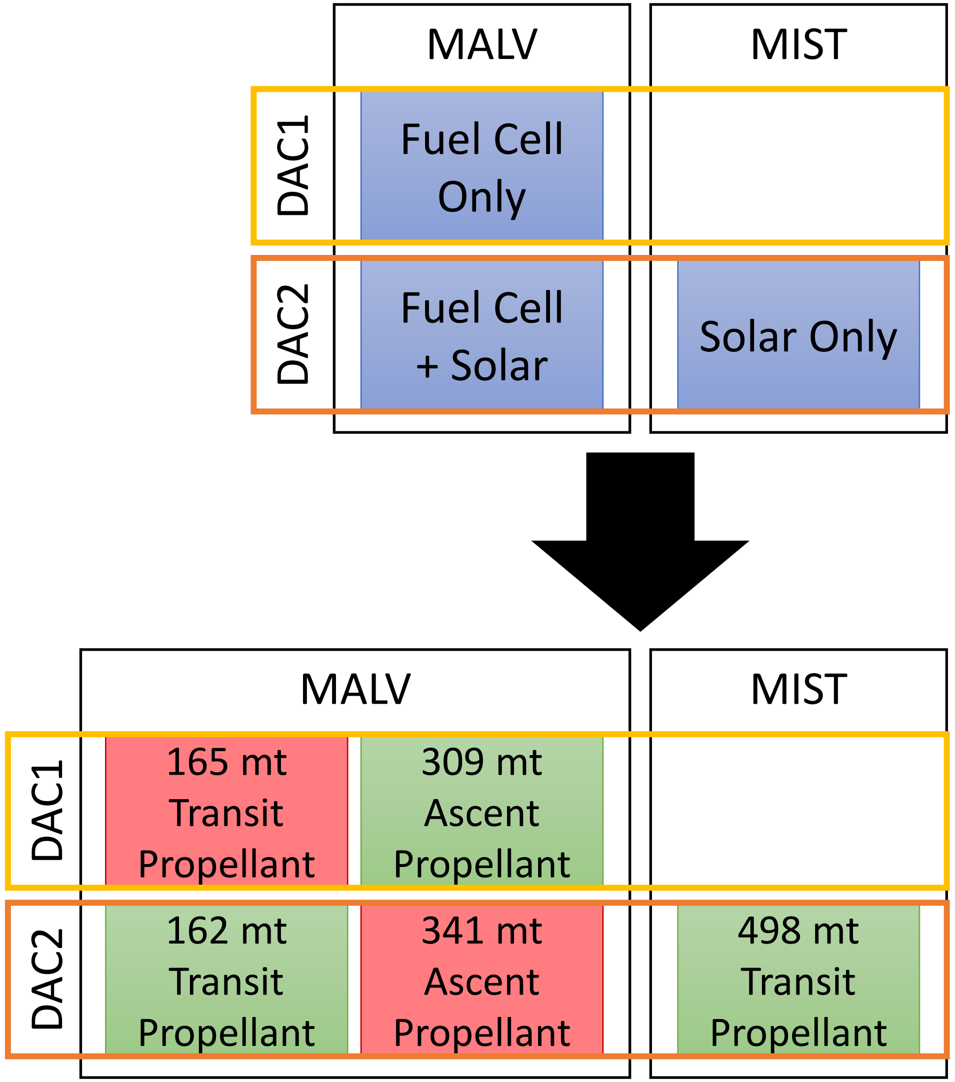
Maximum crewed time from
surface to orbit rendezvous = 84 hr

Mars Surface

- EDL
  - Preliminary 2 DoF model developed to provide initial estimate of descent ΔV
  - Higher fidelity model currently being developed to better understand critical EDL phases such as reorientation and precision landing
- Ascent
  - 84-hour nominal trajectory to 5-sol derived from historical Apollo, Shuttle, and Orion flight operations
  - Target initial ascent thrust-to-weight of 0.75 minimizes ascent ΔV and sets the thrust required for the vehicle design
  - Future work to update and optimize ascent and rendezvous trajectory based on lessons learned from HLS operations

Campaign Performance

- Preliminary campaign performance focused on estimating a required propellant for Mars ascent which must subsequently be manufactured by the ISRU systems
- Two analysis cycles were performed to date
  - First cycle resulted in the initial concept design of the MALV
  - Seconds cycle resulted in the initial concept design of the MIST configuration, as well as refining key subsystems to close the architectural concept
- Initial observations
  - MIST could not close with fuel cell power systems due to high reactant mass over long transient periods, driving the design to a solar-based power system
  - MALV saw increased ascent propellant loads because of increased inert mass for a combined fuel-cell and solar power system, driving the design to a fuel-cell only power system to reduce ISRU demand
- Future analysis will consider architecture performance over a variety of trajectories, Earth launch and refueling operations



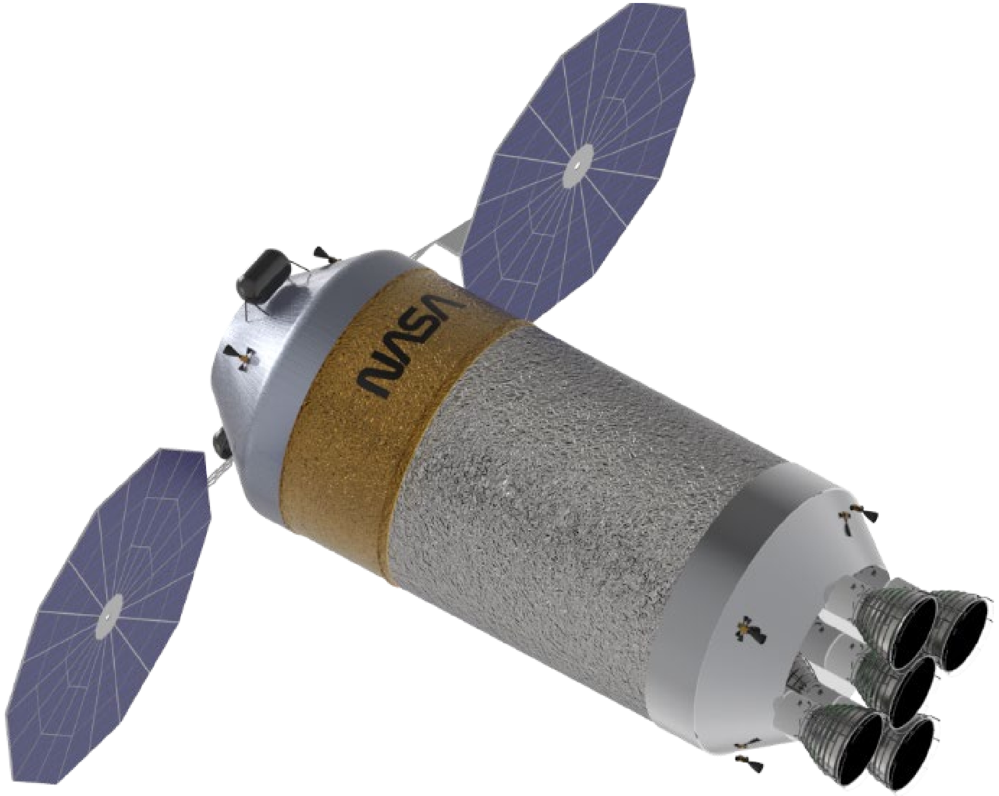
	MALV	MIST
DAC1	Fuel Cell Only	
DAC2	Fuel Cell + Solar	Solar Only

	MALV		MIST
DAC1	165 mt Transit Propellant	309 mt Ascent Propellant	
DAC2	162 mt Transit Propellant	341 mt Ascent Propellant	498 mt Transit Propellant

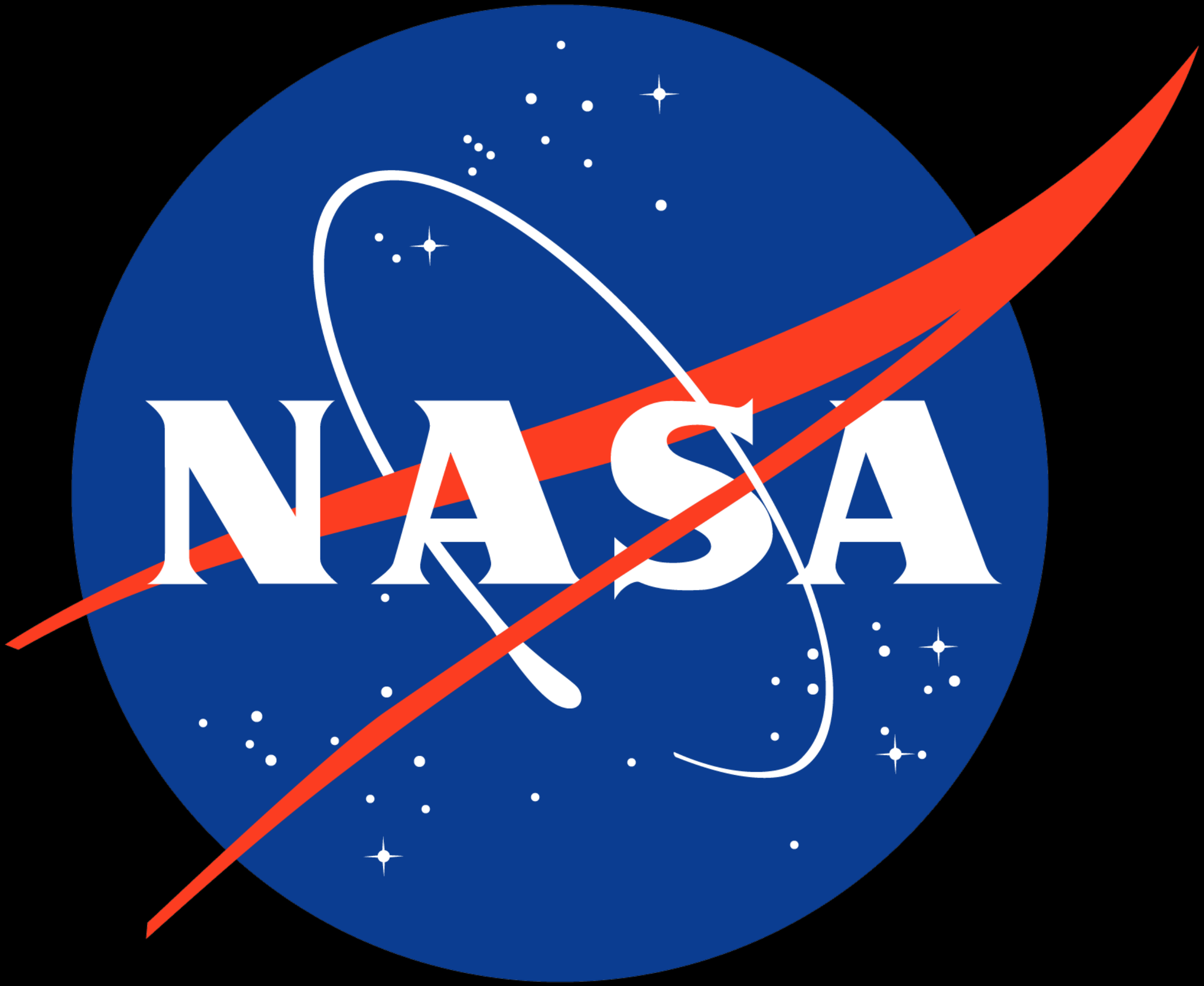
Mass Summary - MALV

MACHETE MALV		Basic Mass (kg)	MGA (%)	Predicted Mass (kg)
Mass Breakdown Structure				
1.0	Structures & Mechanisms	36,672	20.6%	44,245
2.0	Propulsion	11,262	19.6%	13,466
3.0	Power	554	35.1%	748
4.0	Avionics	993	14.5%	1,138
5.0	Thermal	7,337	30.7%	9,587
6.0	ECLSS	568	20.8%	686
7.0	Crew Cabin & Access	961	20.0%	1,153
Dry Mass		58,347	21.7%	71,022
10.0	Cargo			75,000
11.0	Inert Fluids			4,923
12.0	Mass Margin			8,752
Inert Mass				159,697
20.0	Useable Propellant			320,445
Total Stage Gross Mass				480,142

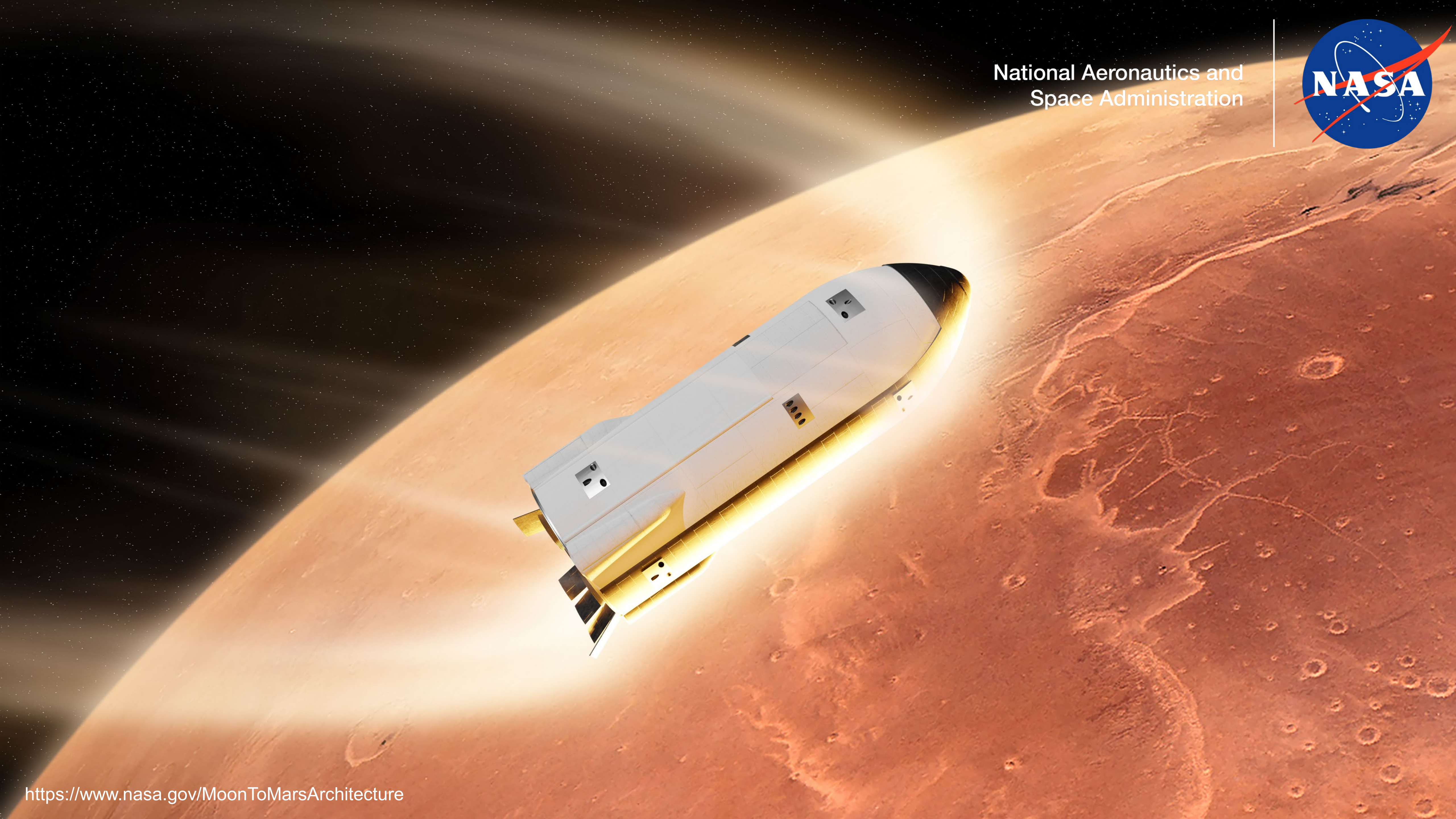
Mass Summary - MIST



MACHETE MIST		Basic Mass (kg)	MGA (%)	Predicted Mass (kg)
Mass Breakdown Structure				
1.0	Structures & Mechanisms	15,232	19.9%	18,256
2.0	Propulsion	8,597	19.4%	10,265
3.0	Power	1,994	26.9%	2,530
4.0	Avionics	763	15.8%	884
5.0	Thermal	1,789	31.9%	2,361
Dry Mass		28,374	20.9%	34,295
10.0	Cargo			55,000
11.0	Inert Fluids			7,838
12.0	Mass Margin			4,256
Inert Mass				101,390
20.0	Useable Propellant			629,224
Total Stage Gross Mass				730,614



https://www.nasa.gov/MoonToMarsArchitecture



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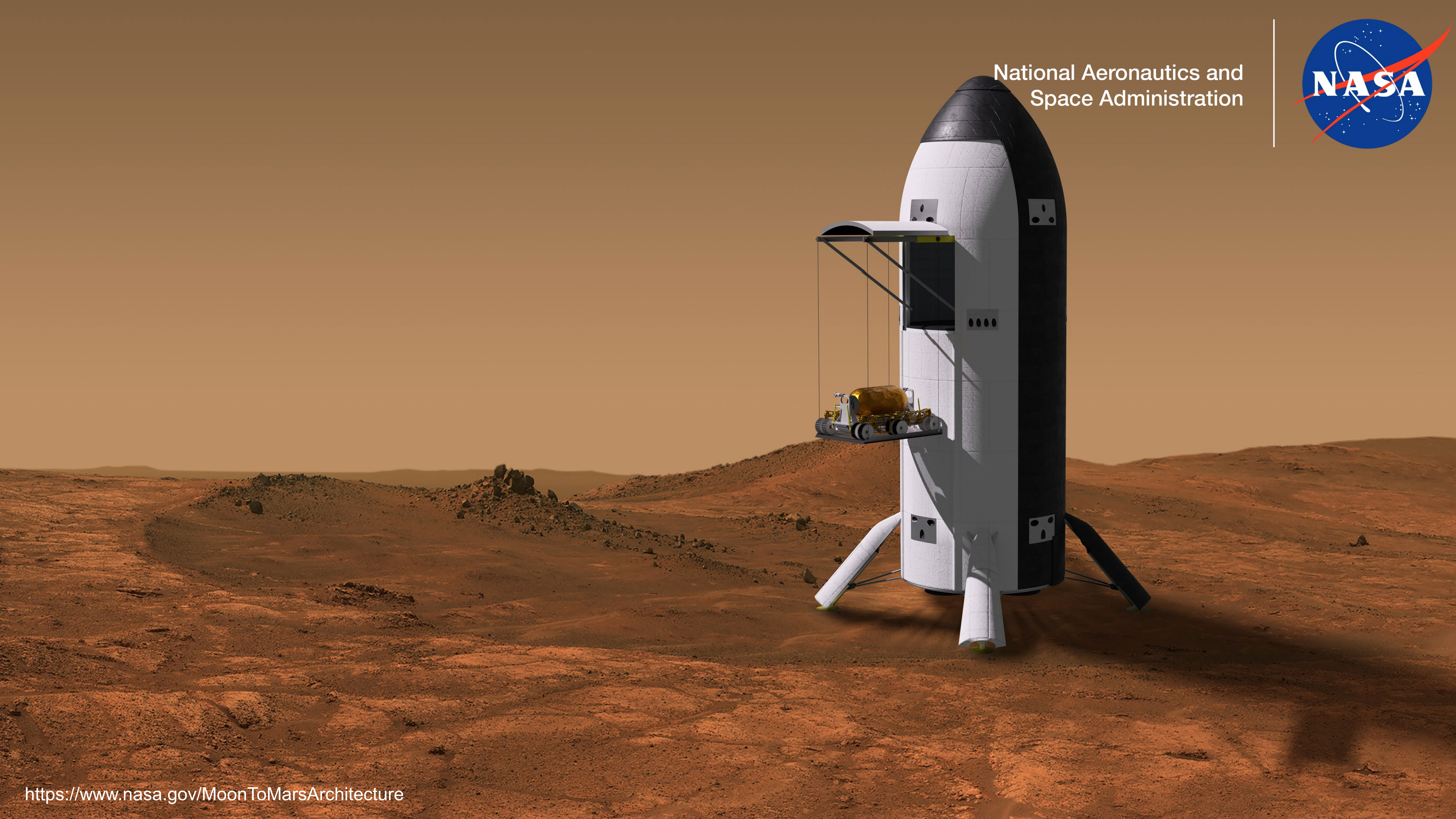

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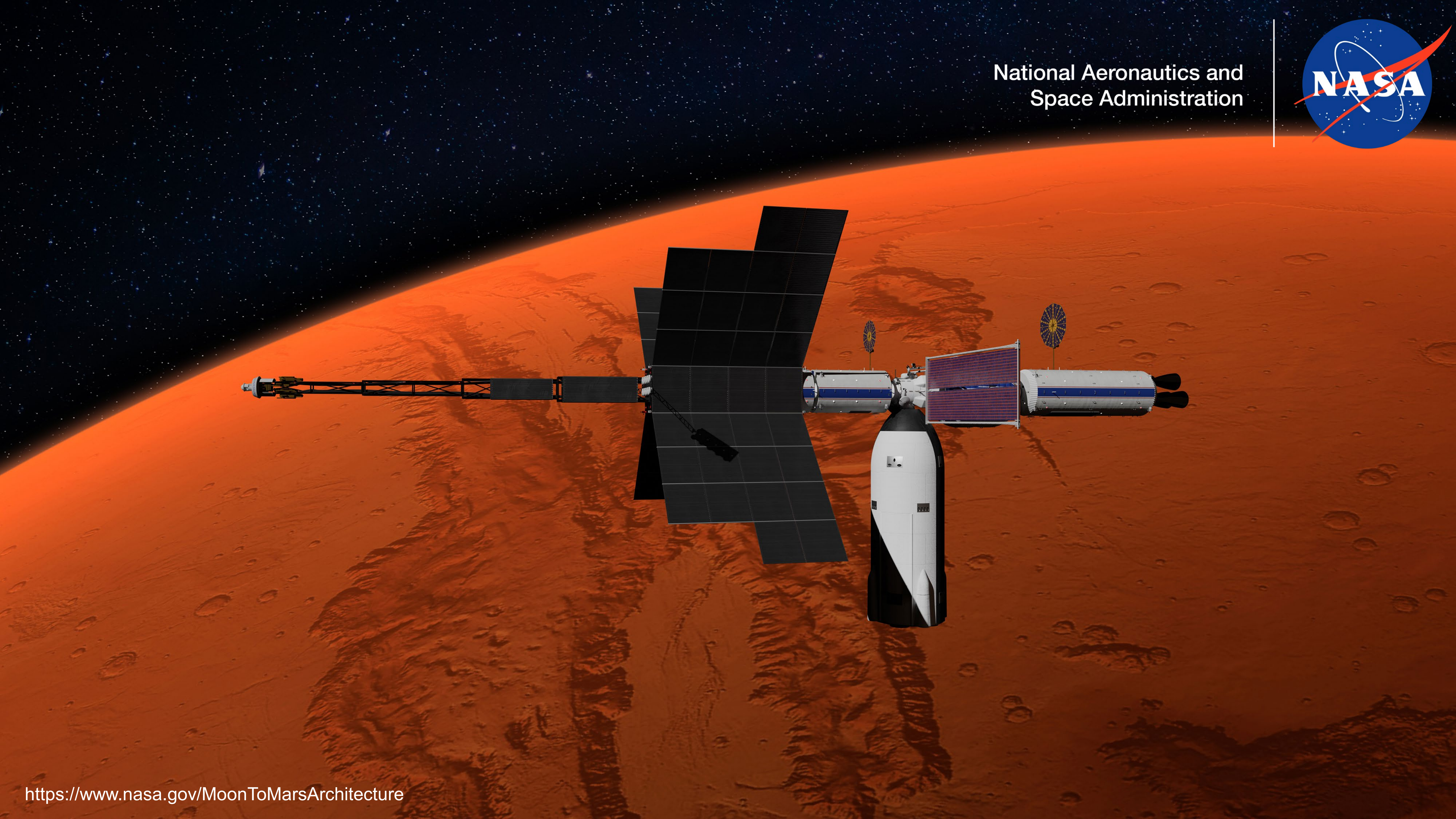

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