ARTEMIS

Advanced Reusable Transport for Exploration Missions

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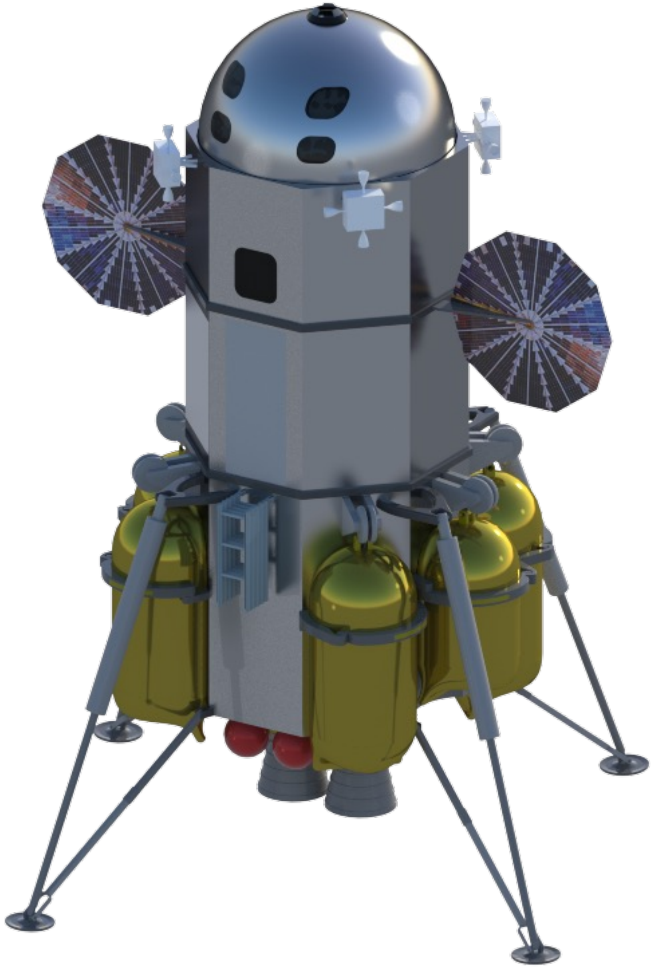
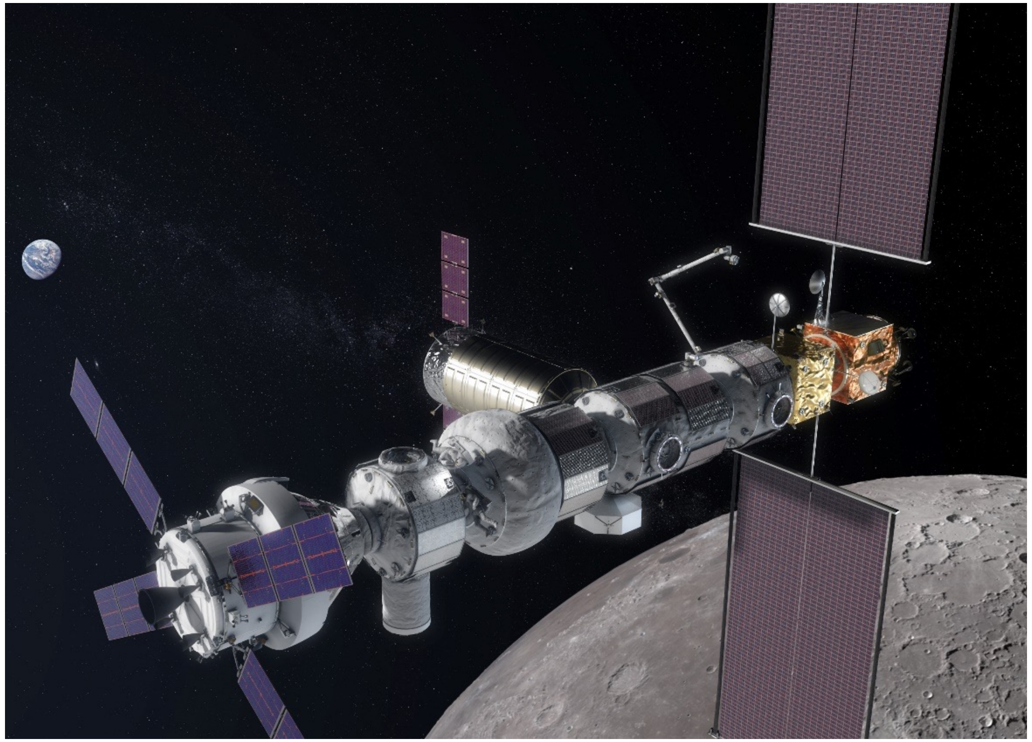


Introduction

Motivation and Background

- Gateway – opportunity to return to the Moon
  - Pre-solicitation for commercial companies to study and prototype reusable landers
- Existence of water-ice in craters near lunar poles
  - In-situ propellant production



Artist's Rendering of Gateway (Credit: NASA)

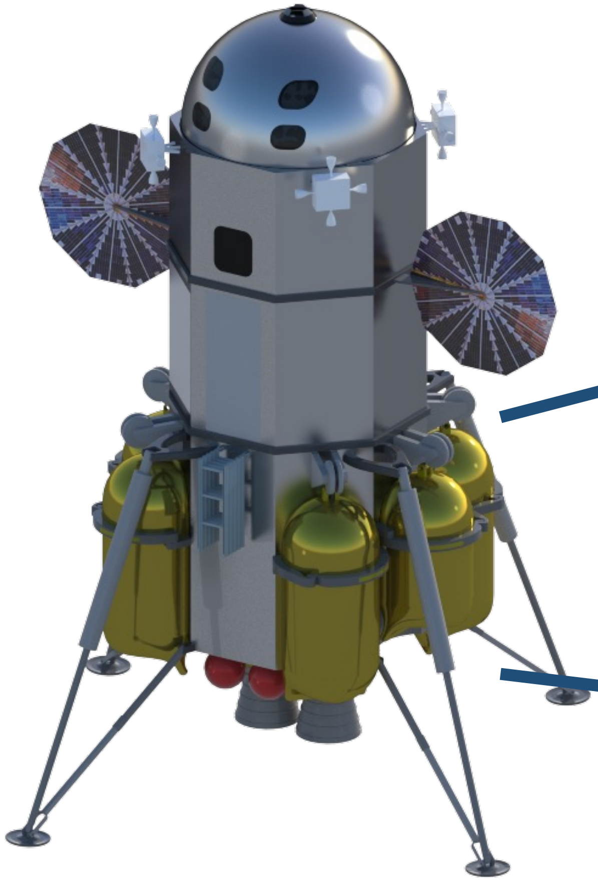
Scope of the Study

- Gateway <---> Lunar Surface by 2028
- Mission Modes
  - 6-day surface stay, 2 crew, 500kg cargo
  - 2-day surface stay, 4 crew, 100kg cargo
- Reusable vehicle
- Cannot depend on pre-deployed infrastructure
- Capability to evolve beyond initial capabilities

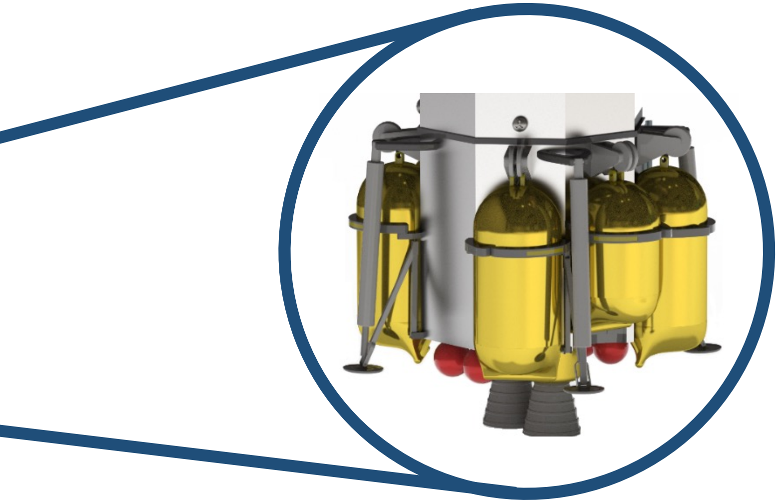
Design Summary

✓ Open for trade: Distribution, number, location, and staging of propulsive elements

Orbiter (13.8 tons)
Reusable, uncrewed



Lander (12.8 tons)
Reusable, crewed



Drop Tanks (9.7 tons)
Repurposed, then matured to full reusability

Concept of Operations

Launch and Validation

✓ Crew is delivered from Earth to the Gateway via NASA's Space Launch System (SLS) and Orion
✓ Crew returns to Earth from Gateway via Orion
✓ Considerations: Number of SLS launches

- ARTEMIS launched via two New Glenn rockets
- Crew launched from and returned to Earth using Orion MPCV
- Two crew validation mission

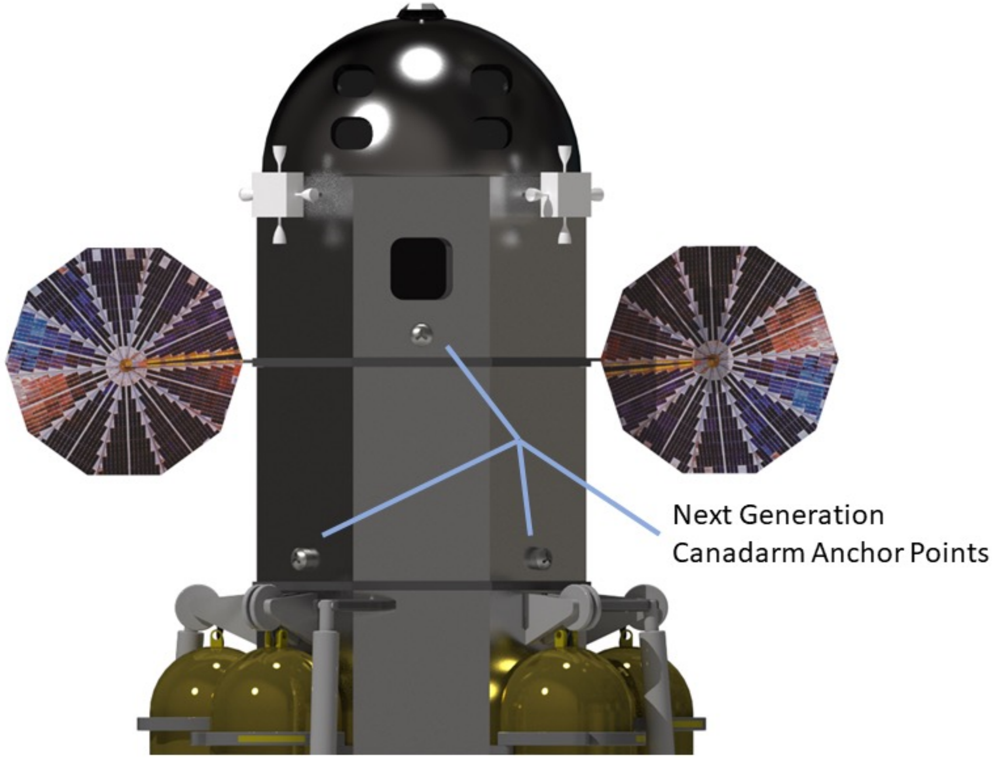
Credit: Blue Origin

Credit: SpaceX

Resupply and Refueling

- Annual resupply and refueling missions starting in 2027
  - Orion MPCV co-manifest for mission supplies
  - Expendable Falcon Heavy for refueling
- New drop tanks for each resupply mission
  - Next-Generation Canadarm on Gateway for attachment to lander

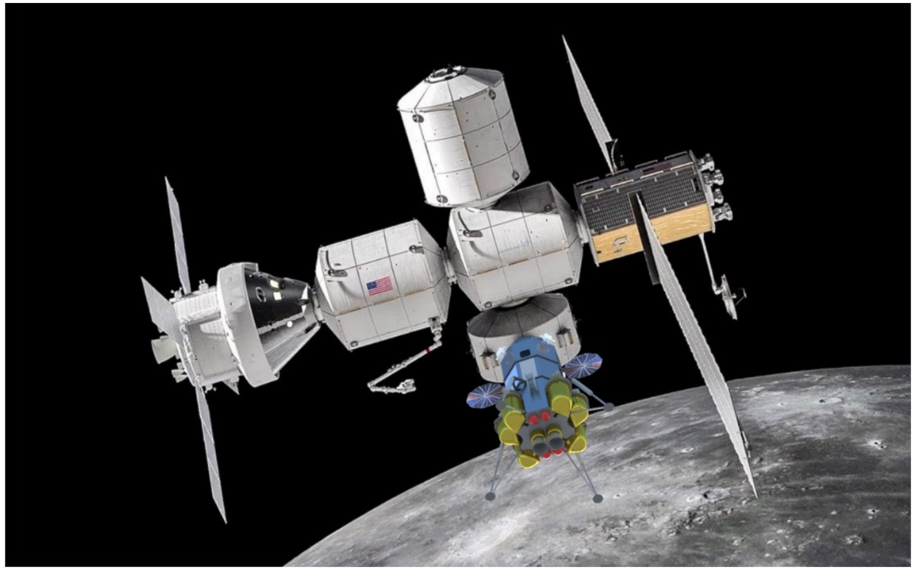
	Orion MPCV resupply	Falcon Heavy refueling
Supplies (t)	1.98	N/A
Fuel (t)	7.02	20.3



✓ Open for trade: Propellant resupply strategy (anticipated launch vehicles, depots, etc.)

Impact on Gateway and Uncrewed Operations

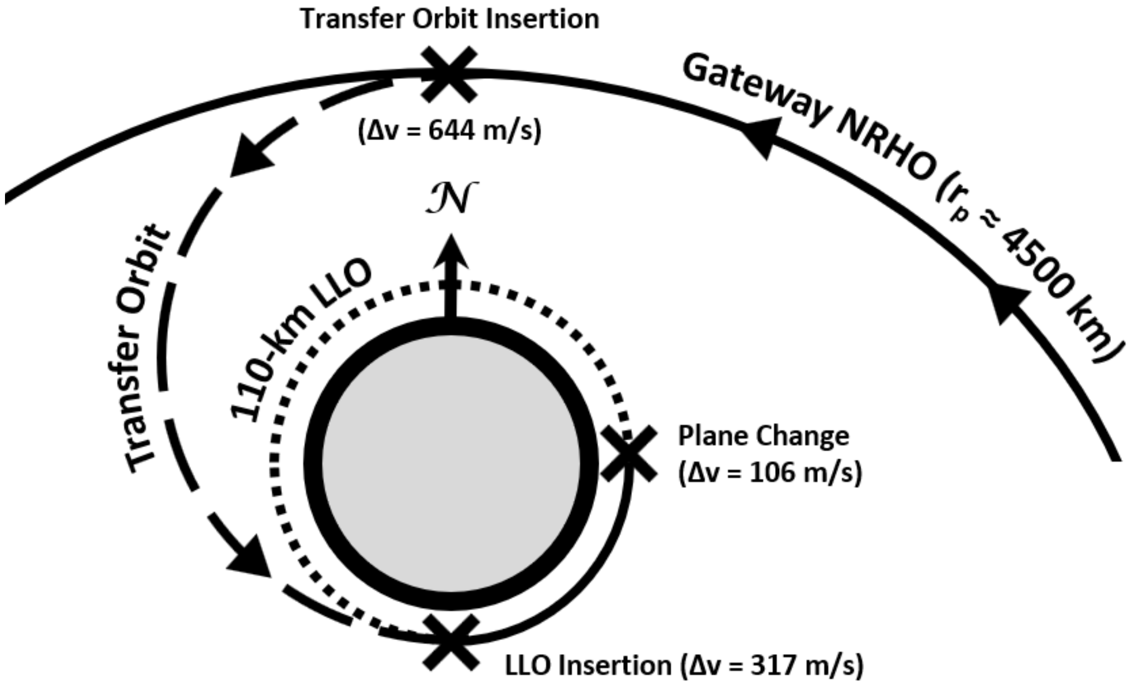
- Impact on Gateway elements
  - NDS ports – lander and orbiter
  - Fully fueled ARTEMIS affects moments of inertia for orbit keeping maneuvers
  - Reduced thermal load when ARTEMIS between the Sun and Gateway
- Uncrewed Operations
  - ARTEMIS in dormant function mode during uncrewed period (11 months)
  - Tests on ECLSS and propulsion systems
  - Fix on resupply mission if anomalies detected



✓ Considerations: Impact of elements on the Gateway

Mission Profile: Gateway-to-LLO Transfer

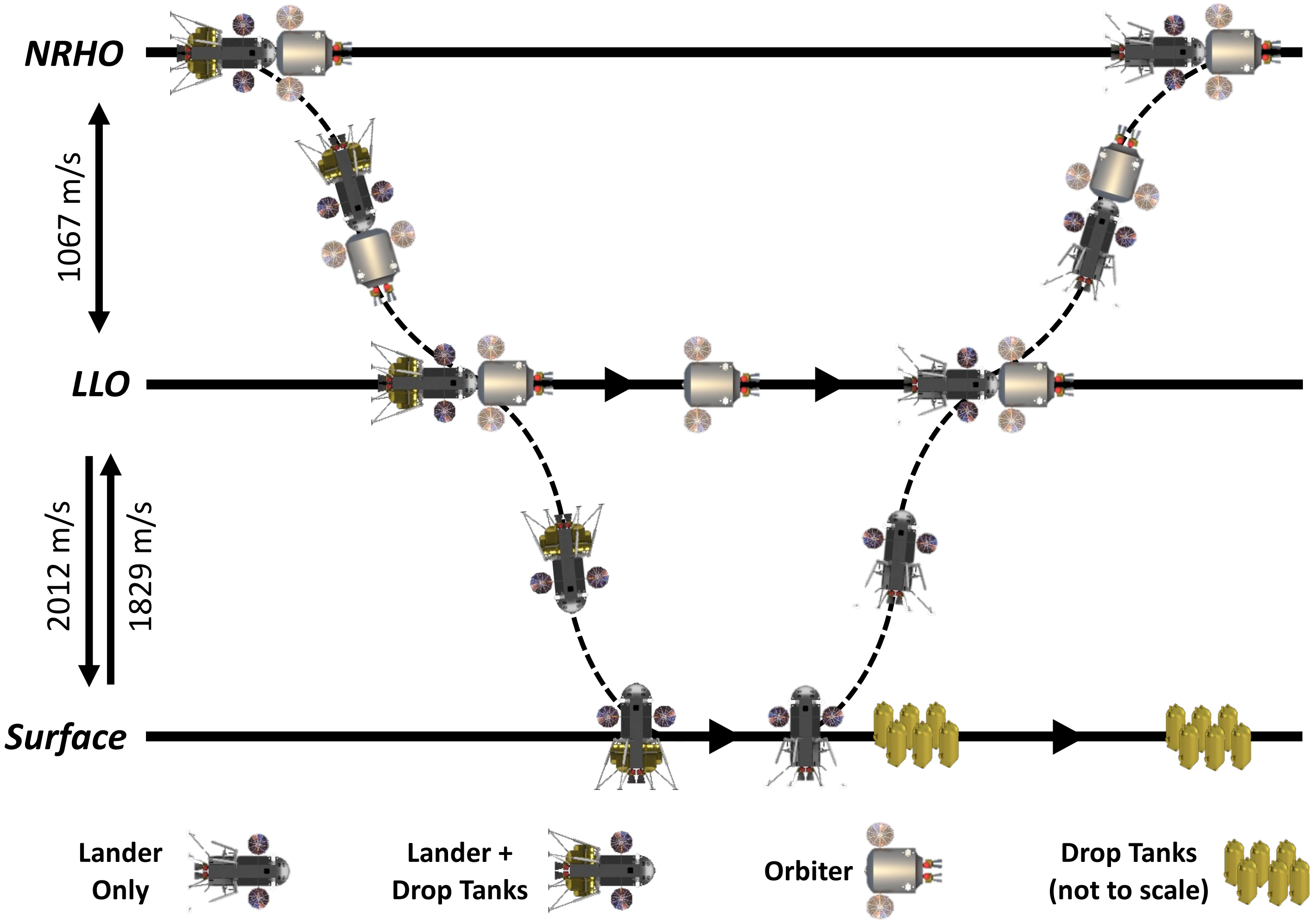
- All stages (orbiter, lander, drop tanks) present at Gateway departure
- Three maneuvers for transfer from NRHO to 110-km lunar staging orbit
  - Transfer Orbit Insertion (TOI)
  - LLO Insertion (LLOI)
  - Plane Change (up to 4°)
- All maneuvers powered by orbiter
- Intermediate LLO provides suitable staging area, where the lander & drop tanks detach from the orbiter prior to descent



✓ A reusable ascent/descent cabin/vehicle is based at the Gateway, where it is resupplied and refueled between lunar missions

Mission Profile: Descent, Landing, & Ascent

- Descent & landing
  - Lander + drop tanks
  - Fuel provided by drop tanks, feeding into the lander's engines
- 6-day surface operations
  - Potential landing site: Amundsen Crater
  - Removal of empty drop tanks
- Ascent
  - Lander only
  - Fuel provided by lander's internal tanks
- Docking with orbiter in LLO, followed by return to Gateway

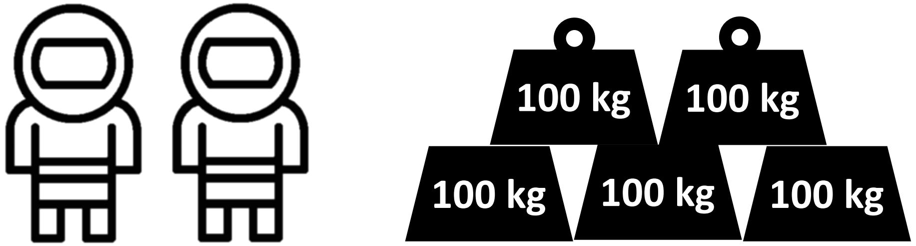


✓ Open for trade: Distribution, number, location, and staging of propulsive elements

Mission Modes and Surface Operations

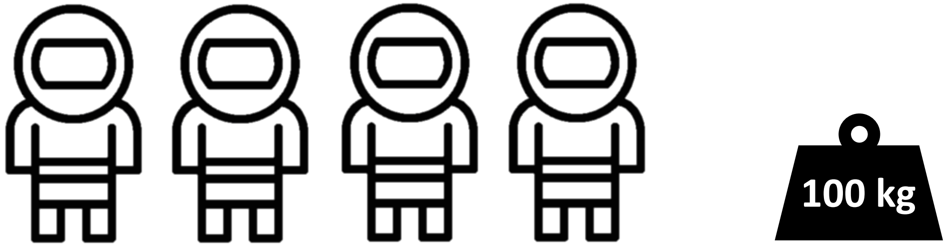
Mission Mode 1

- Two crew on surface for six days with 500kg of cargo
- Seven-day mission in total, including one day for orbital transfers



Mission Mode 2

- Four crew on surface for two* days with 100kg of cargo
- *Four-day extension required, due to Gateway’s one-week orbital period

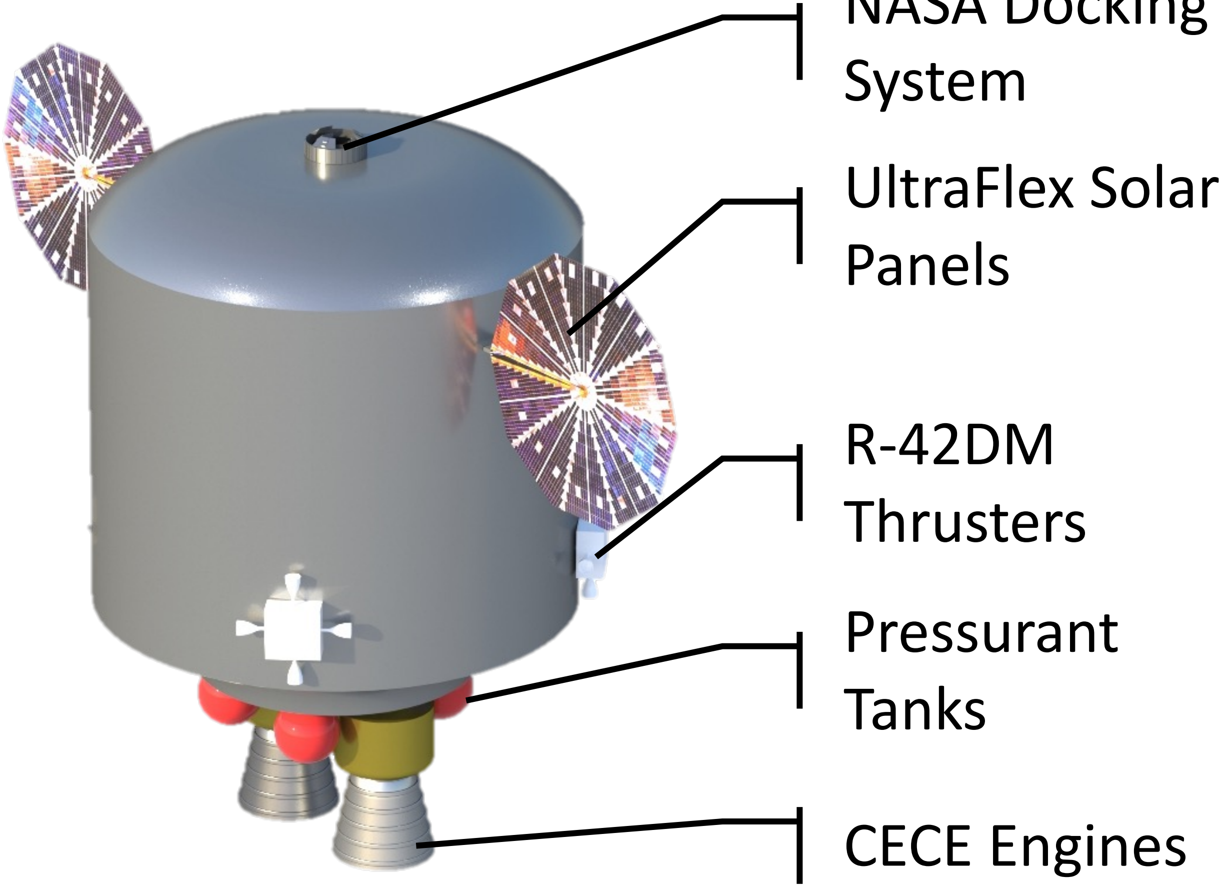


✓ The lander must accommodate two mission modes (near polar location at a minimum)

Vehicle Configuration

Orbiter

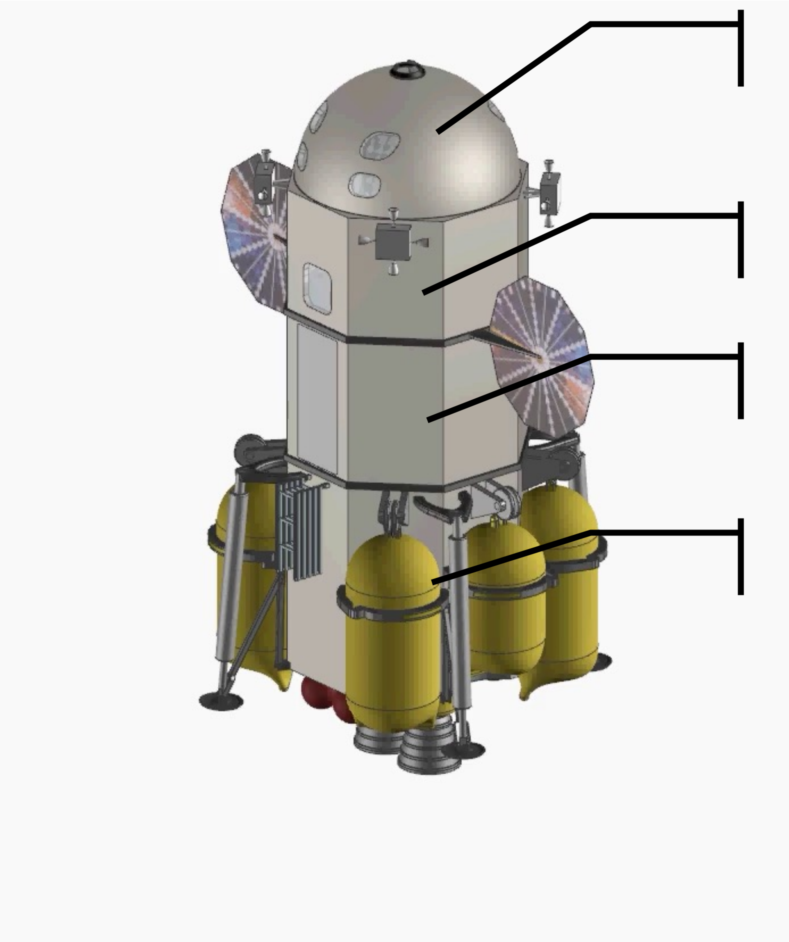
- Simple design based on a Centaur upper-stage.
- All orbiter subsystems designed to be independent of the lander.



✓ A reusable ascent/descent cabin/vehicle is based at the Gateway, where it is resupplied and refueled between lunar missions

Lander

- Outer octagonal hull
  - Provides flat surface to easily mount drop tanks and external payloads
- Inner pressurized volume
  - Crew Quarters
    - 1.84m radius hemisphere
  - Work Area
    - 2.13m height cylinder
  - Egress Section
    - 2.4m height unpressurized cylinder
      - Contains an inner pressurized heptagon



Crew Quarters

Work Area

Egress Section

Propulsion Section

Drop Tanks

- Enables ISRU architecture by providing storage containers for resources.
- Enables lowest overall system mass and cost compared to all other considered configurations.

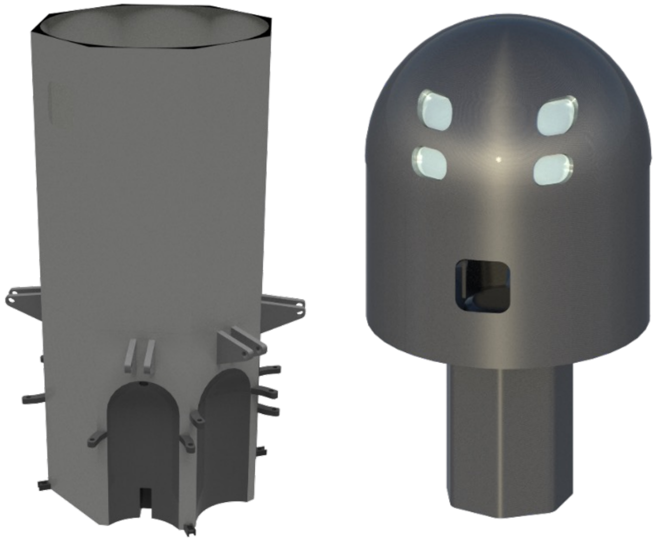
✓ A reusable ascent/descent cabin/vehicle is based at the Gateway, where it is resupplied and refueled between lunar missions

Vehicle Subsystems

Structures

- T-1100G Carbon Fiber Composite from Toray Advanced Composites (TRL 8)
  - Desirable mechanical properties and a lower density result in a lower system mass compared to other materials
  - Used for the outer (unpressurized) hull and the inner pressurized area

Property	T-1100G Carbon Fiber Composite	2195 Aluminum	301 Stainless Steel
Density (kg/m^3)	***1790***	3000	8030
Tensile Strength (MPa)	***3460***	590	515
Elastic Modulus (GPa)	185	69	**212**



Power System

Solar Panels

- UltraFlex Solar Array from Northrop Grumman (TRL 9)
  - High specific power lowers overall system mass
- Power degradation rate of 3% per year included in size calculations

Solar Panel	Specific Power (W/kg)	TRL
UltraFlex	***150***	***9***
Flexible roll-out array	150	7
Deployable rigid array	80	9
Body-mounted array	N/A	9

Li-Ion Batteries

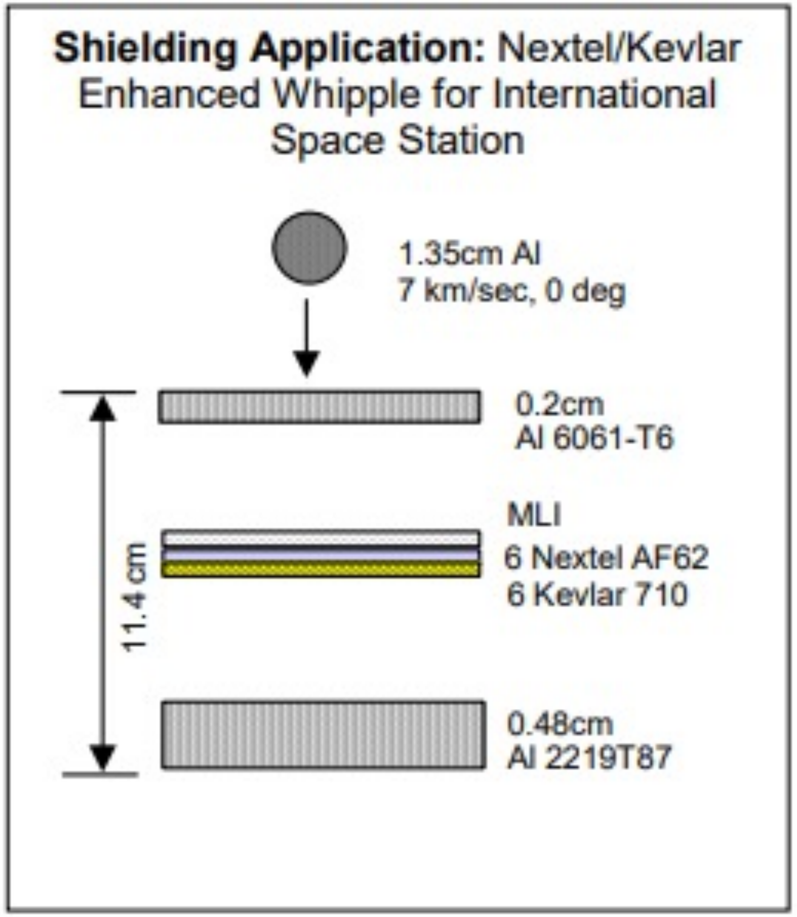
- 43 Ah Space Cell from EaglePicher Technologies (TRL 9)
  - High specific energy lowers overall system mass

Battery/Mission	Specific Energy (Wh/kg)
43 Ah Space Cell	***153***
Juno	110
Phoenix Lander	105
MSL Curiosity	104

✓ A reusable ascent/descent cabin/vehicle is based at the Gateway, where it is resupplied and refueled between lunar missions

Micrometeorite and Orbital Debris (MMOD)

- Stuffed Whipple shield (TRL 9)
  - Contains aluminum, MLI, Nextel, and Kevlar layers
  - Mounted to all exterior surfaces
  - Layers are separated to better disperse the impactor energy
    - Allows for lower areal densities while still maintaining adequate protection



Credit: NASA

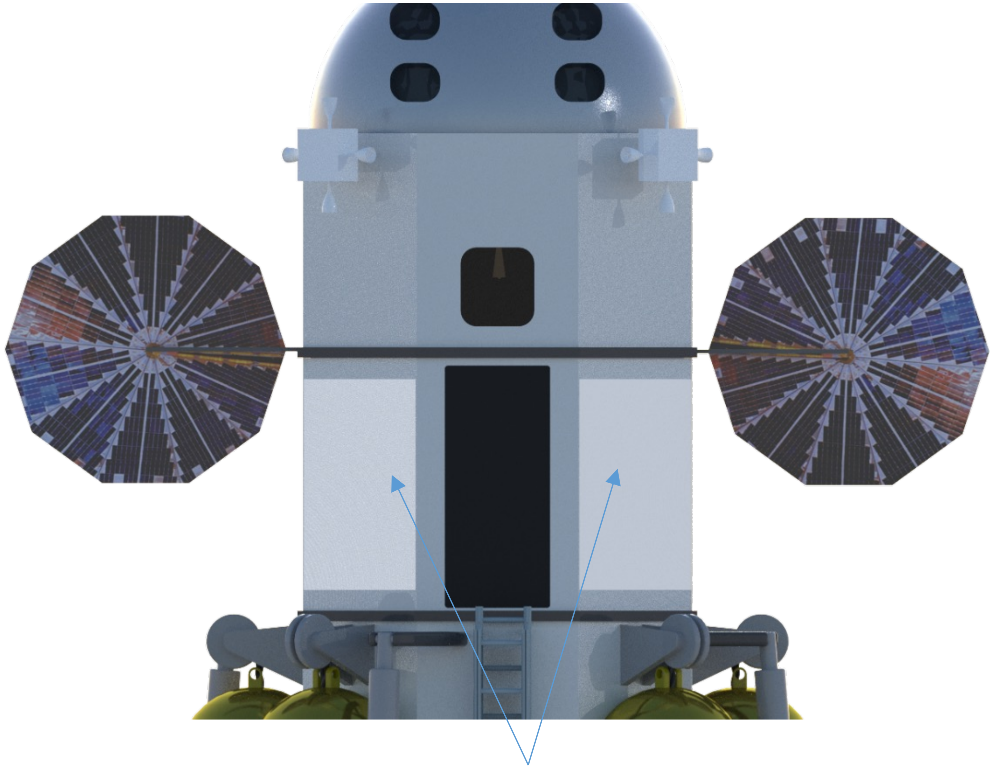
Radiation Shielding

	Carbon	**Polyethylene**
Z/A (Atomic Number over Atomic Weight)	0.5	***0.571***
Can be placed on the ship’s exterior?	***Yes***	No
X-Ray Attenuation Coefficient (at 10^{-2} MeV) (cm^2/g)	***2.373***	2.088

- Miralon from Nanocomp Technologies (TRL 9)
  - Made of carbon nanotubes
    - Carbon provides a lightweight alternative to polyethylene with nearly identical shielding properties
  - Used on the Juno spacecraft for protecting sensitive electronics
- Additional shielding sources:
  - Water
  - Epoxy in carbon fiber composite
  - Nextel/Kevlar in MMOD shielding
  - Aluminum in MMOD shielding

Thermal Control

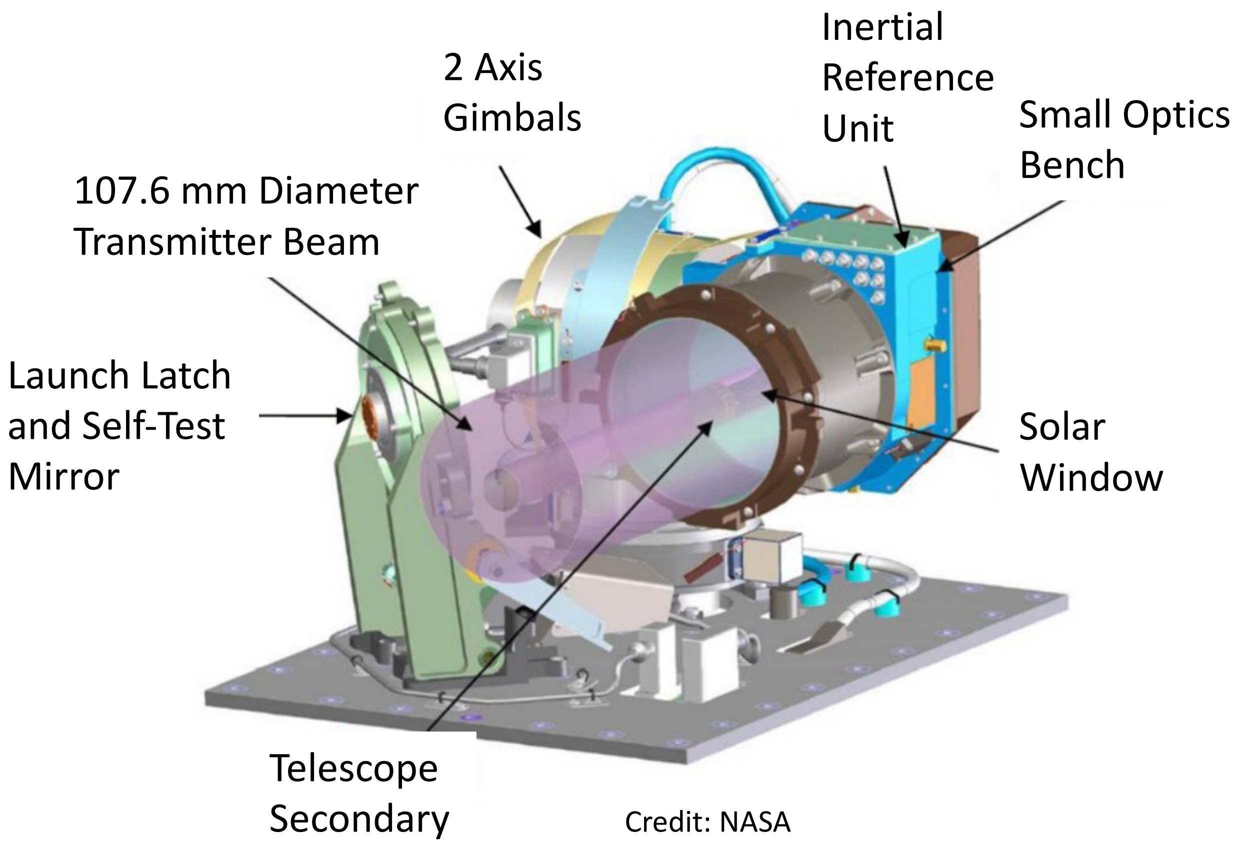
- Variable Emissivity Radiators from the Ashwin-Ushas Corporation (TRL 8)
  - Very lightweight (1.2kg/m^2)
  - Capable of handling the full range of heat loads ARTEMIS is expected to endure
  - Does not need mechanical components
  - Requires a 150W heater for when under low heat loads
- All exterior surfaces are covered in aluminized mylar
  - Reduces emissivity to 0.044



Variable Emissivity Radiators

Telemetry, Tracking, and Command

- Telemetry and Tracking
  - Laser Communication System for lander (TRL 9)
    - 622 Mbps downlink
  - S-band Communication array on orbiter (TRL 9)
    - Also serves as backup for lander communications
- Command and Data Handling
  - LEON4 from Cobham Gaisler (TRL 8)
    - Latest version of the LEON family of processors, which have been used on the ISS and various satellites

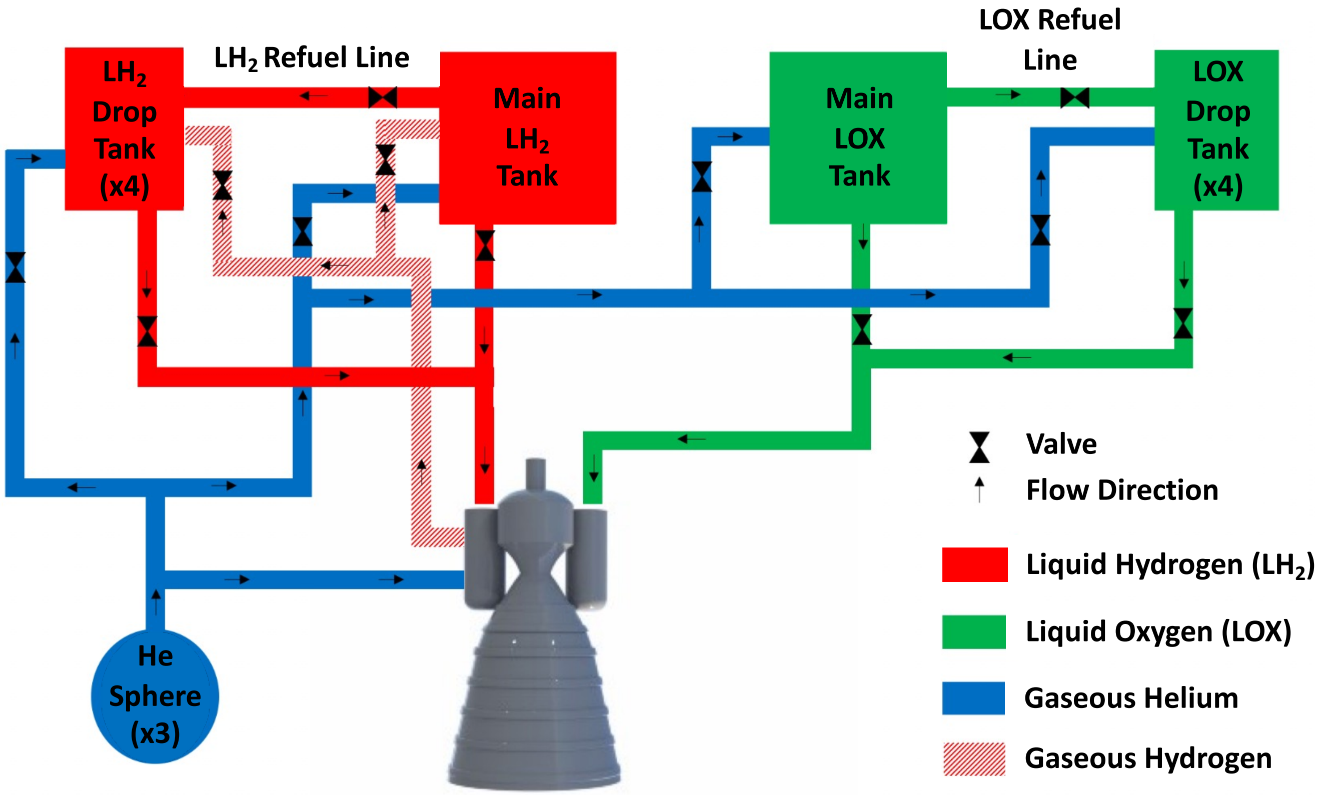


Credit: NASA

Propulsion

✓ Open for trade: Types of propellant and propulsion systems

- Two Aerojet Rocketdyne Common Extensible Cryogenic Engines (CECE) on lander and orbiter (TRL 6)
  - Developed as lunar engine for the Constellation program
  - Heritage from the RL10
  - LOX/LH_2 (high ISP of 445s)
  - Tested reliability of 99.95%
  - 50 restarts (to be improved)
  - Deep throttling to 5.9% power
  - Single engine abort capability
  - Propellant sizing accounts for 1% boil-off per day



Reaction Control Systems

Credit: Aerojet Rocketdyne

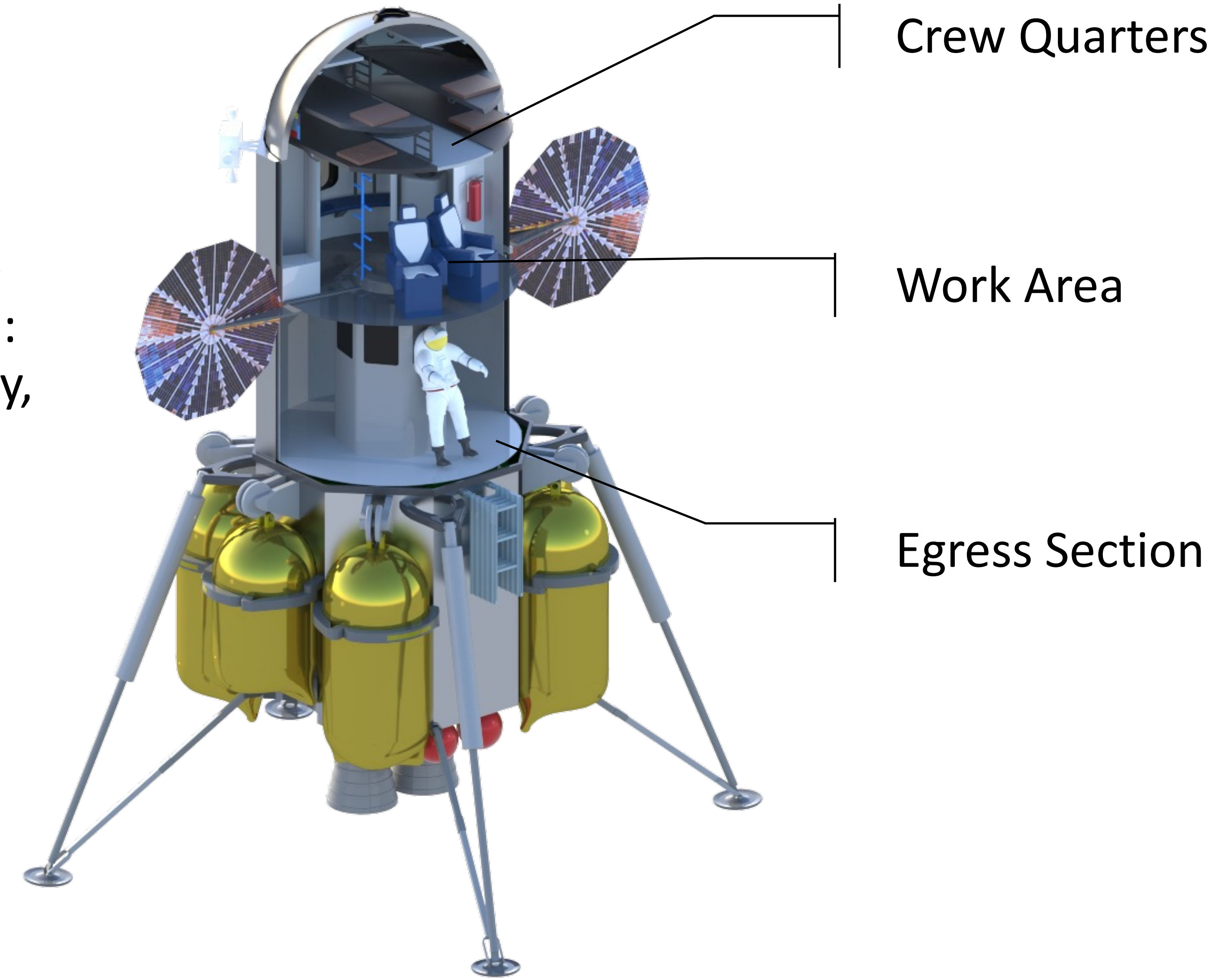
- Sixteen Aerojet Rocketdyne R-42DM thrusters on both lander and orbiter
- 415.2kg of hydrazine and nitrogen tetroxide total
- Provides attitude control during descent, ascent and maneuvers

ECLSS

Environmental Control and Life Support Systems

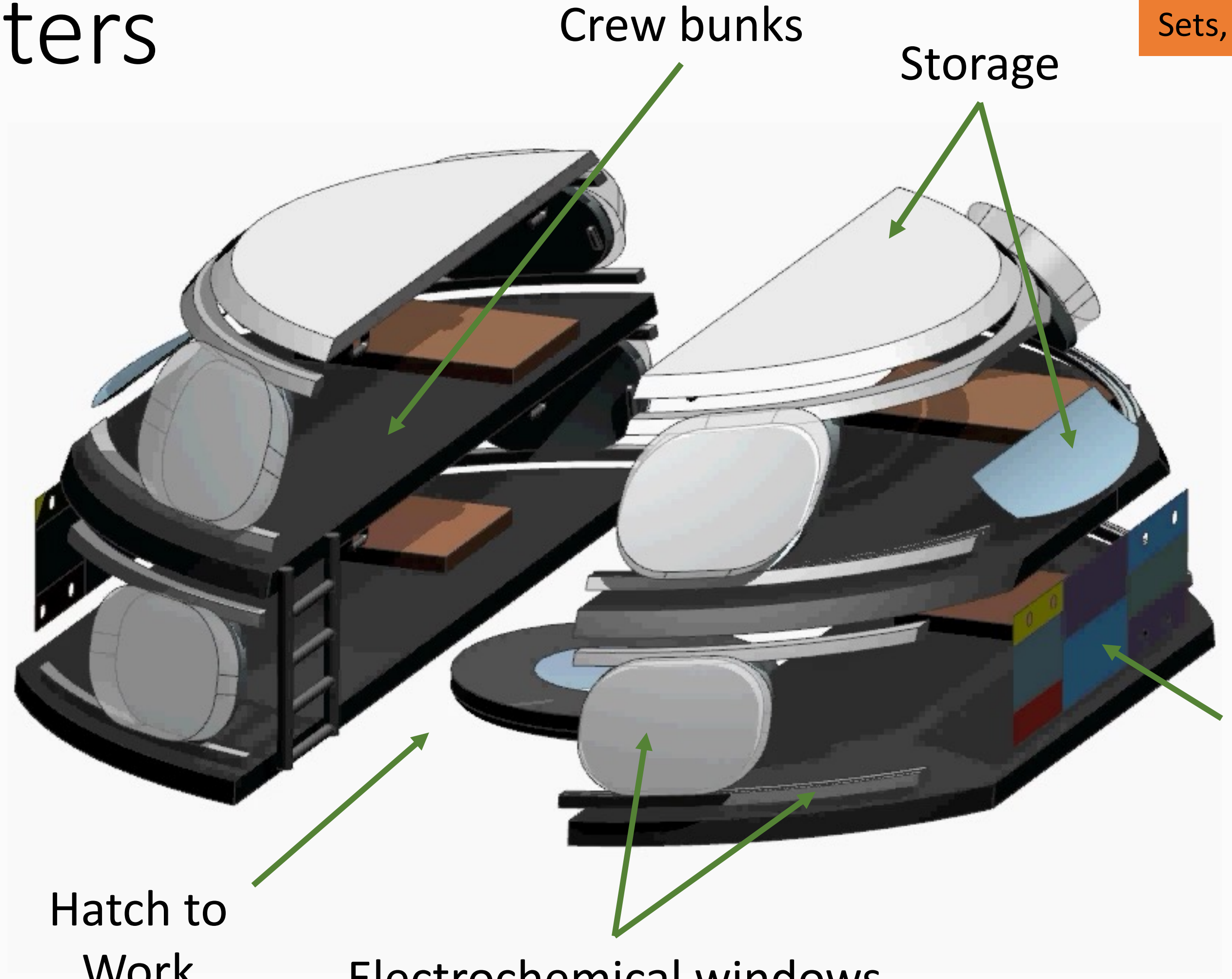
Overview

- Requirements:
  - NASA Space Flight Human-System Standard Volume 2: Human Factors, Habitability, and Environmental Health (**NASA-STD-3001**)
  - Human Integration Design Handbook (**HIDH**)



Crew Quarters

✓ STD-3001 Chp 4.1, 4.2, 7.9 — Physical Data Sets, Body Lengths, Sleep


Crew bunks

Storage

Clothing Storage, LED lighting, ventilation, and individual crew controls

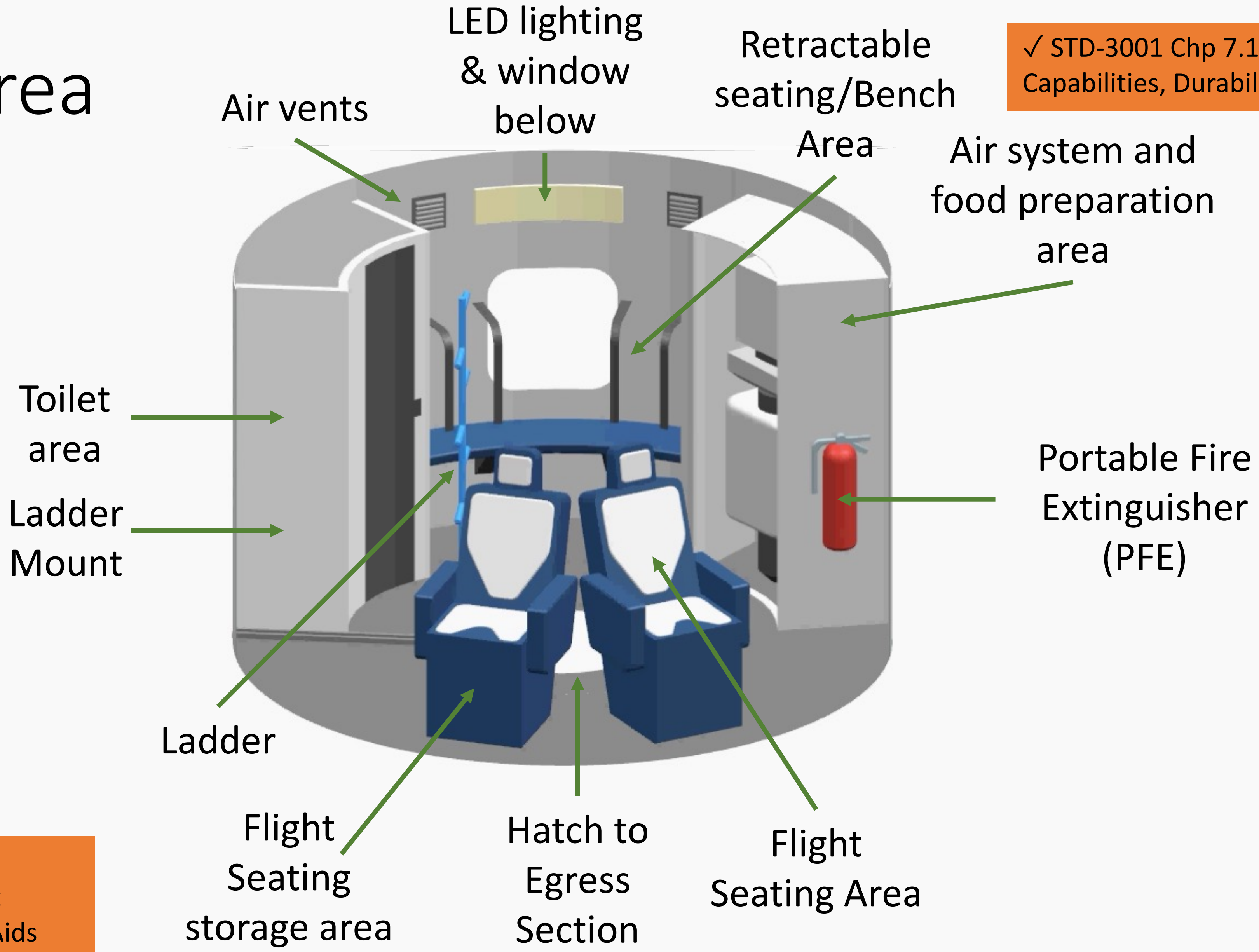
Hatch to Work Area

Electrochemical windows and sliding cover

✓ STD-3001 Chp 8.6,8.7,10.4 — Windows, Lighting, Controls

Work Area

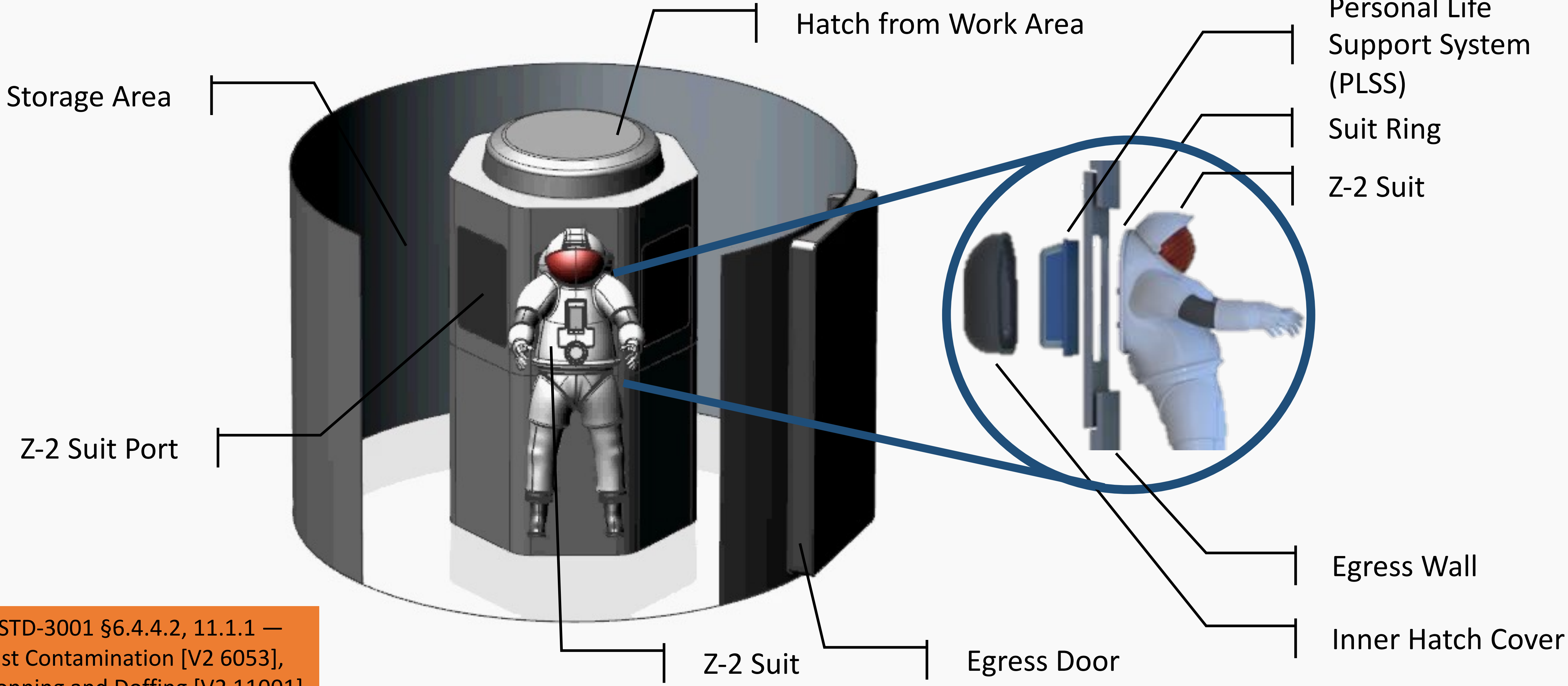
✓ STD-3001 Chp 7.12, 9.4 — Recreational Capabilities, Durability



✓ STD-3001 Chp 7.6,7.7,8.5 — Stowage, Inventory Management System, Restraints and Mobility Aids

Egress Section

✓ NASA-STD-3001 §8.3, 8.4 — Translation Paths, Hatches and Doorways



Hatch from Work Area

Storage Area

Personal Life Support System (PLSS)

Suit Ring

Z-2 Suit

Z-2 Suit Port

Egress Wall

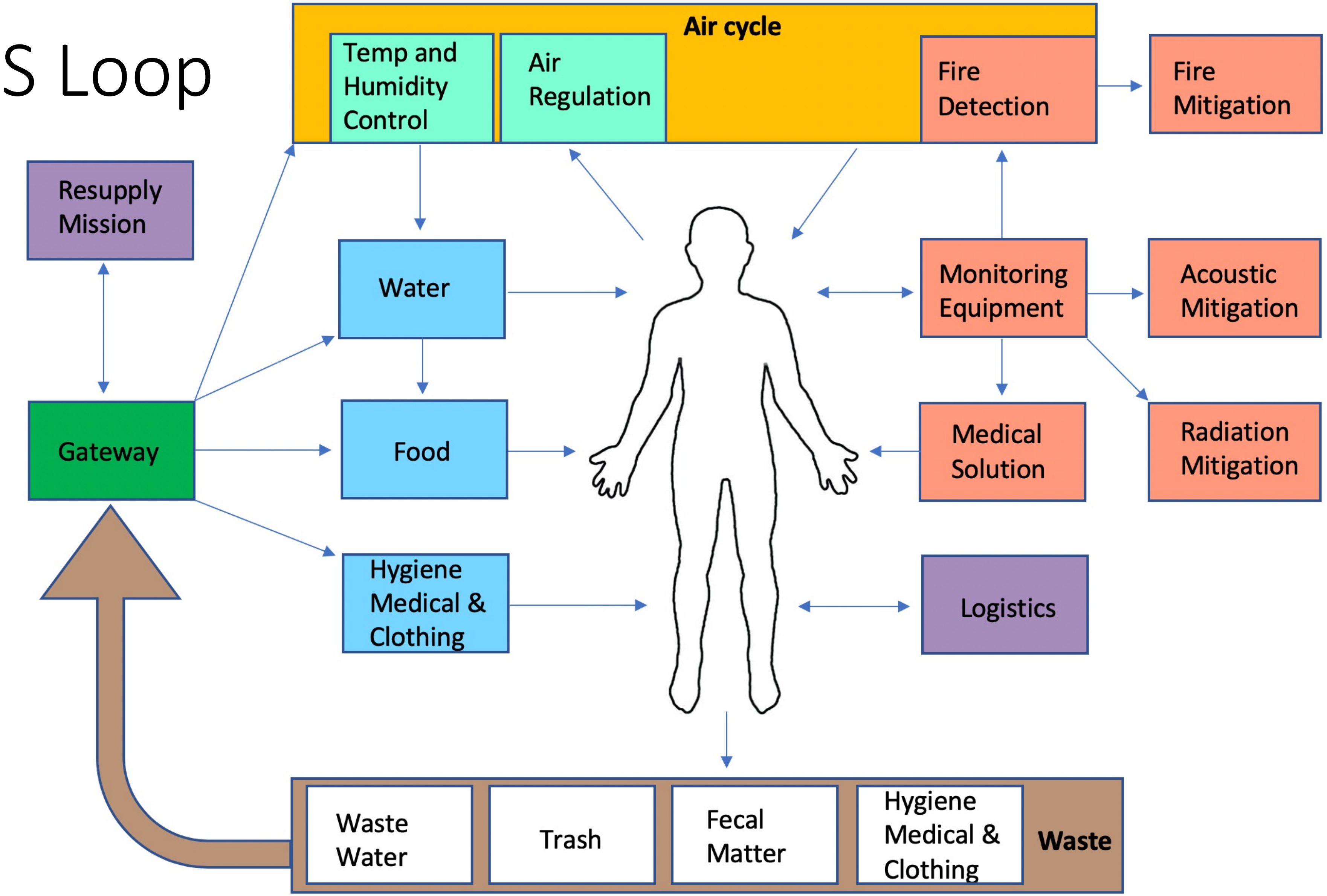
Inner Hatch Cover

Z-2 Suit

Egress Door

✓ NASA-STD-3001 §6.4.4.2, 11.1.1 — Lunar Dust Contamination [V2 6053], Suited Donning and Doffing [V2 11001]

ECLSS Loop


Air cycle
Temp and Humidity Control
Air Regulation
Fire Detection
Fire Mitigation
Resupply Mission
Water
Monitoring Equipment
Acoustic Mitigation
Gateway
Food
Medical Solution
Radiation Mitigation
Hygiene Medical & Clothing
Logistics
Waste Water
Trash
Fecal Matter
Hygiene Medical & Clothing
Waste

Internal Atmosphere

✓ NASA-STD-3001 §6.1,6.2 — Trend Analysis of Environmental Data, Internal Atmosphere

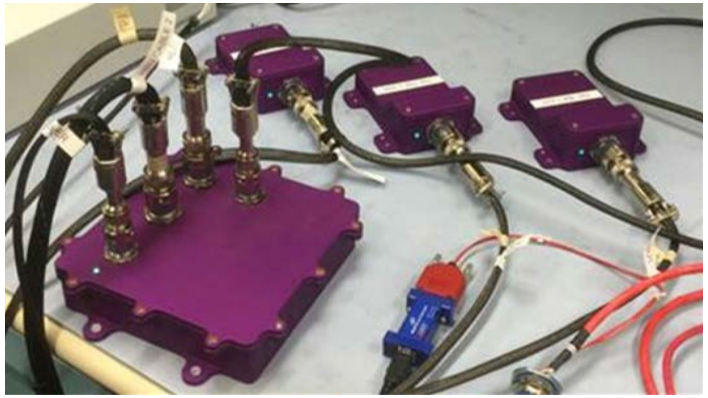
- Ventilation
  - Portable Fan Assembly (PFA)
- Filtration of Dust and Gas
  - Dust shields, charcoal beds, and catalyst canister
- Analysis
  - Mass constituent analyzer (MCA) and Differential Mobility Spectrometer (DMS)
- Temperature and Humidity Control
  - Common Cabin Air Assembly (CCAA)
- Carbon Dioxide Removal
  - Carbon dioxide And Moisture Removal Amine Swingbed (CAMRAS)

DMS (Credit: Draper)

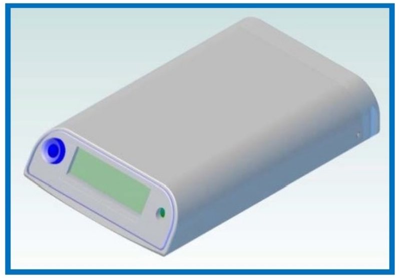
✓ NASA-STD-3001 §6.8 — Radiation

Crew Radiation Protection

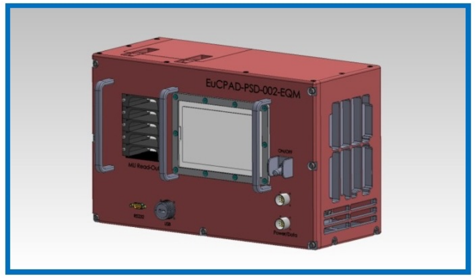
- Detection
  - Hybrid Electronic Radiation Assessor (HERA)
  - European Crew Personal Active Dosimeter (EuCPAD)
    - Mobile Unit (MU)
    - Personal Storage Device (PSD)
  - PAssive Dosimeter for Life science Experiments in Space (PADLES)
- Mitigation
  - AstroRad vests



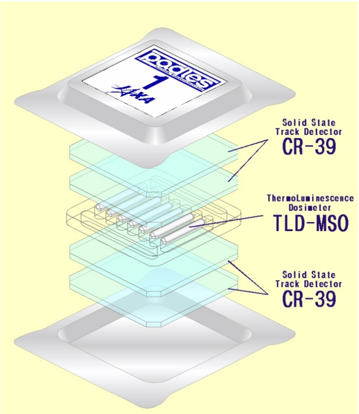
Hybrid Electronic Radiation Assessor (HERA)
(Credit: NASA)



Mobile Unit (Credit: ESA)



Personal Storage Device
(Credit: ESA)



PADLES dosimeter (Credit: JAXA)

AstroRad vest (Credit: StemRad)

Spacesuits

- Modified Advanced Crew Escape Suits (MACES)
  - Brought from Orion
  - Protection for atmospheric anomalies
- Z-2 Extravehicular Activity (EVA) Suits
  - Suit port integration for dust mitigation
- Portable Life Support System (PLSS) Developments
  - Rapid Cycle Amine (RCA) (TRL 6, 2015) removes CO_2

✓ NASA-STD-3001 §11.1,11.2 Suit Design and Operations, Suited Functions

MACES Suits in Orion (Credit: NASA)

Z-2 Suit (Credit: NASA)

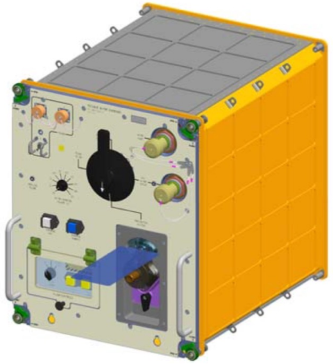
Consumables and Habitation

✓ NASA-STD-3001 §6.3, 6.4, 7.1, 7.2, 7.5 — Water, Contamination, Food and Nutrition, Personal Hygiene, Medical

- Water
  - Contained in Contingency Water Containers-Iodine (CWC-I)
  - Dispensed with Potable Water Dispenser (PWD)
- Food and Oxygen
  - Freeze dried and stored in Multi-Purpose Cargo Transfer Bag (MCTB)
  - High Pressure Vessels of O2 and N2
- Hygiene and Medical
  - Hygiene kits
  - Emergency Equipment
  - Fitness - Resistive Exercise Bands
- Fire Detection & Mitigation
  - Smoke Detector (in CCAA), Gas Analyzers, Photoelectric Smoke Alarms
  - Portable Breathing Apparatus (PBA)
  - Portable Fire Extinguisher (PFE)


Multi-Purpose Cargo Transfer Bag (MCTB)
(Credit: NASA)


CWC-I (Credit: NASA)

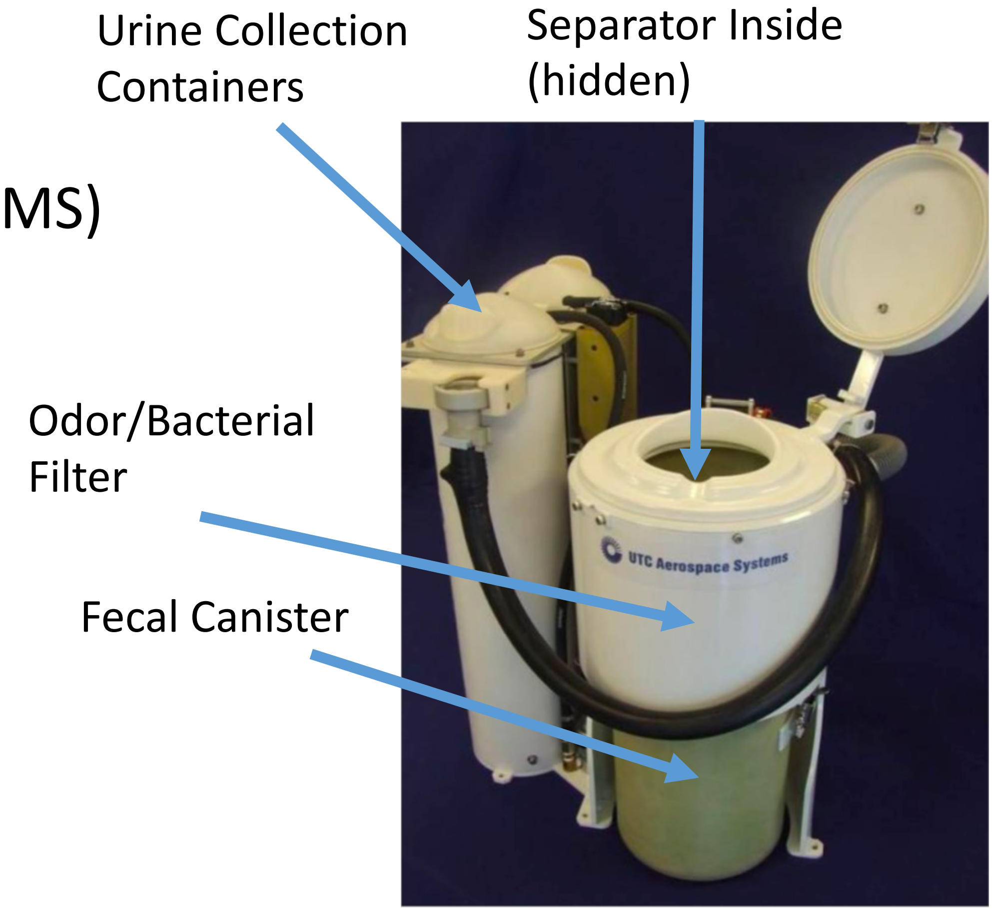

PWD (Credit: NASA)

✓ NASA-STD-3001 §6.2.7.4 Contamination Monitoring and Alerting [V2 6025]

Waste Management

- Human Waste
  - Universal Waste Management System (UWMS)
  - Minimum mass fecal canister
  - Return to Gateway for recycling

- Trash Management
  - Gather and Store
  - Return to Gateway for repurposing via the Heat Melt Compactor (HMC)



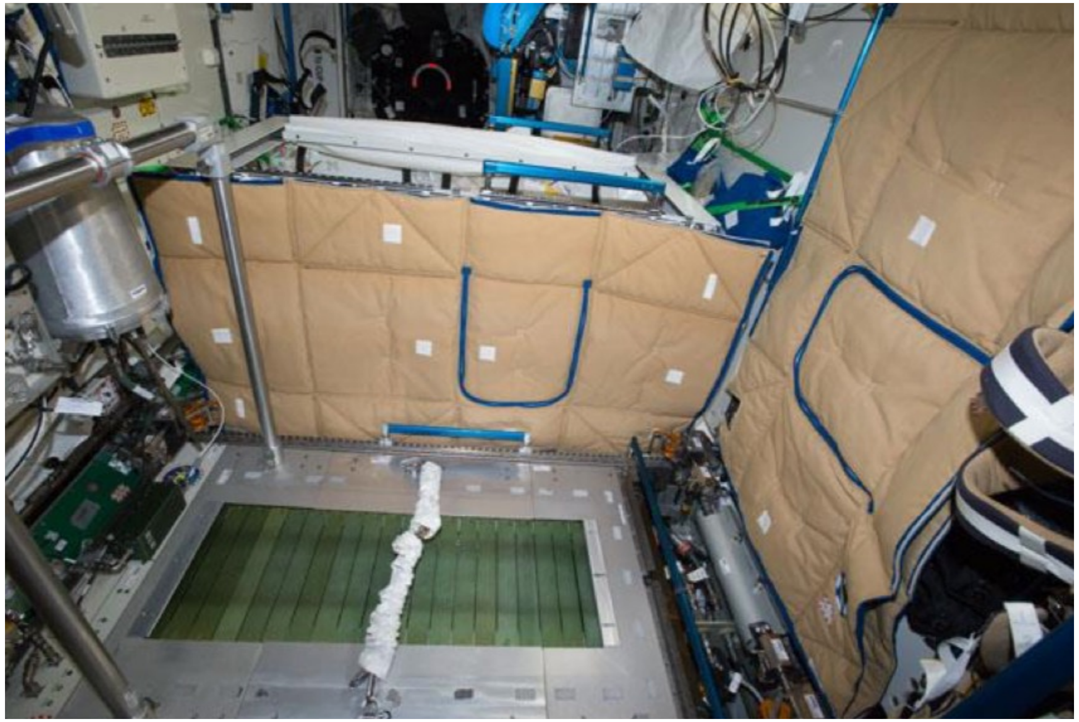
UWMS (Credit: NASA)

✓ NASA-STD-3001 §7.3,7.8 — Body Waste Management, Trash Management System

✓ NASA-STD-3001 §6.6 Acoustics

Acoustic Strategy

- Noise Paths Considered
  - Airborne
    - Inlet and outlet mufflers, Portable Fan Assembly
  - Structural
    - Vibration isolators, acoustically absorbent blankets, foam barriers
  - Enclosure
    - Flight Avionics, Crew Quarters



MCTBs used as acoustic shielding
(Credit: NASA)

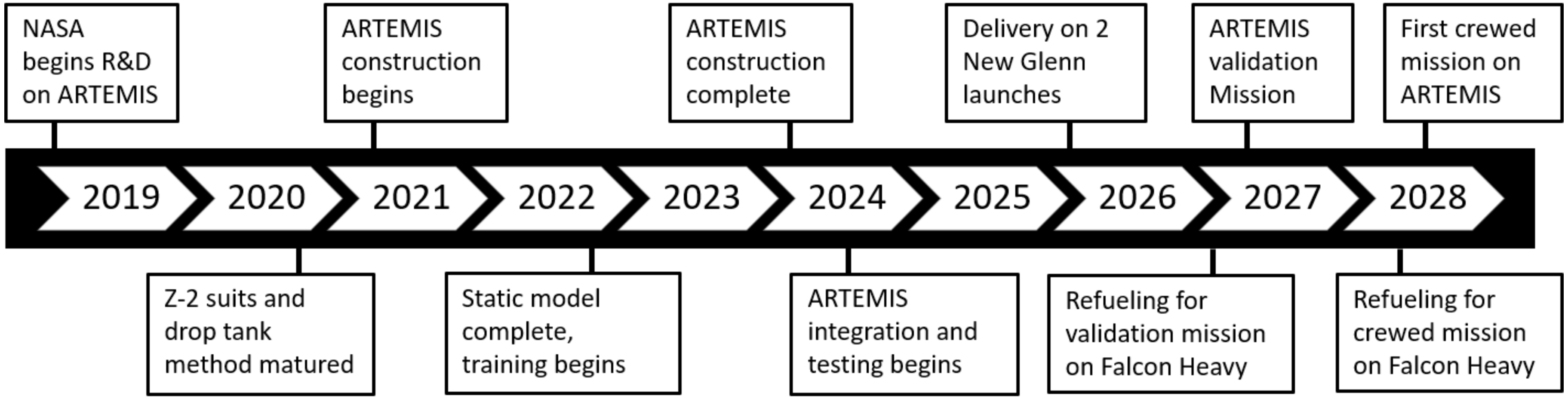
✓ HIDH §5.5 Auditory Perception

Design, Development, and Testing

✓ Technology readiness and cost to support a crewed lunar mission from the Gateway in 2028

Design and Development

- System-wide concept study complete
- Heritage and revolutionary Technology Readiness Levels (TRLs) matured by 2020
- Design requirements and specifications finalized by 2020
  - ARTEMIS flight articles
  - Crew training article



2019 2020 2021 2022 2023 2024 2025 2026 2027 2028

NASA begins R&D on ARTEMIS

Z-2 suits and drop tank method matured

ARTEMIS construction begins

Static model complete, training begins

ARTEMIS construction complete

ARTEMIS integration and testing begins

Delivery on 2 New Glenn launches

Refueling for validation mission on Falcon Heavy

ARTEMIS validation Mission

Refueling for crewed mission on Falcon Heavy

First crewed mission on ARTEMIS

Procurement, Manufacturing, and Testing

- Two phases of Invitations for Proposal (IFPs)
- Manufacturing completed at Michoud Assembly Facility
- Testing at Plum Brook Station
  - Environmental, Acoustic, and Vibration Testing
  - CECE testing to demonstrate restart capability

Credit: NASA

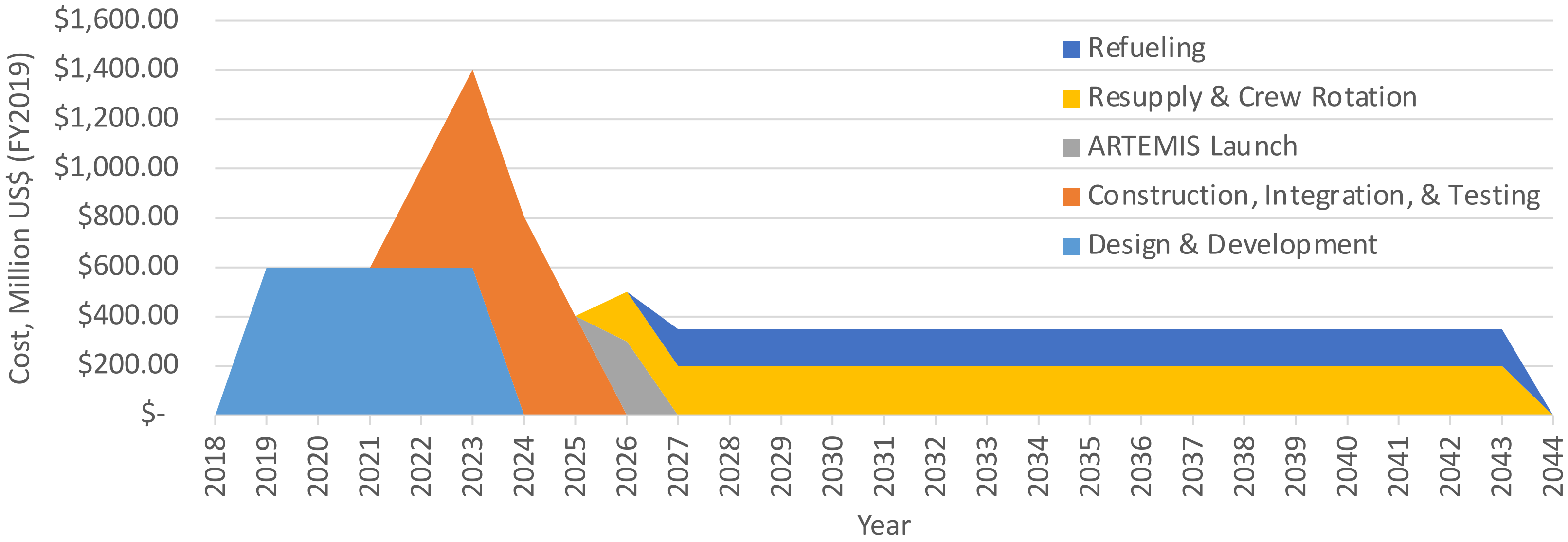
Credit: NASA

✓ Open for trade: System procurement mechanisms

Cost Breakdown

✓ Facilitates evolution from initial capability to a model that leverages commercial services
✓ Evolution path of NASA and commercial capabilities
✓ Technology readiness and cost to support a crewed lunar mission from the Gateway in 2028

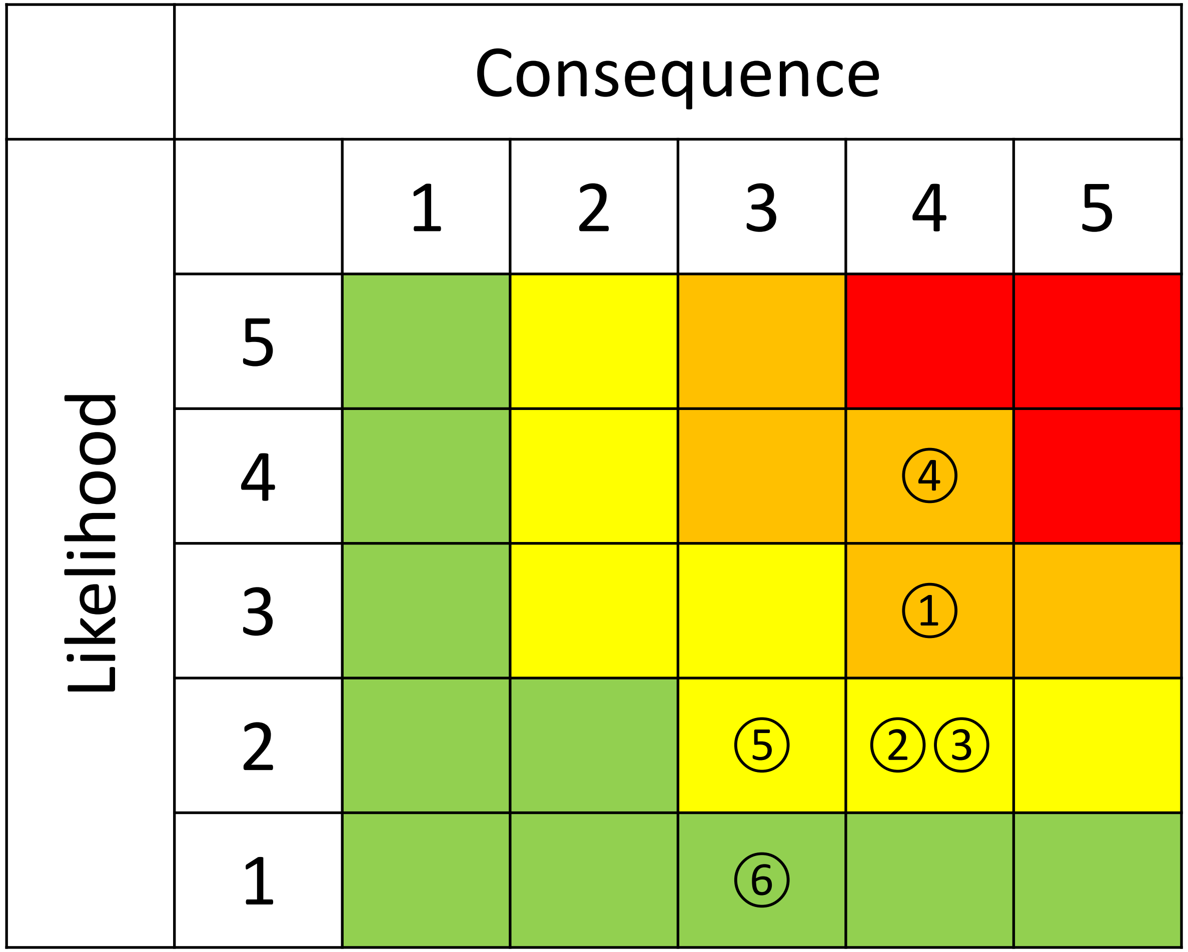
- ARTEMIS cost – US$ 8.25 billion
  - Design and Development – US$ 2.99 billion
  - Manufacturing and Testing – US$ 2.41 billion
  - Launch, Refueling, and Operations – US$ 2.85 billion
- 60% NASA, 20% International partners, and 20% Commercial partners



Risk and Hazard Assessment

Programmatic Risks

1. Drop tank TRL maturity
2. Z-2 suit TRL maturity
3. New Glenn 2026 readiness
4. Government agenda
5. Annual Funding
6. Public support



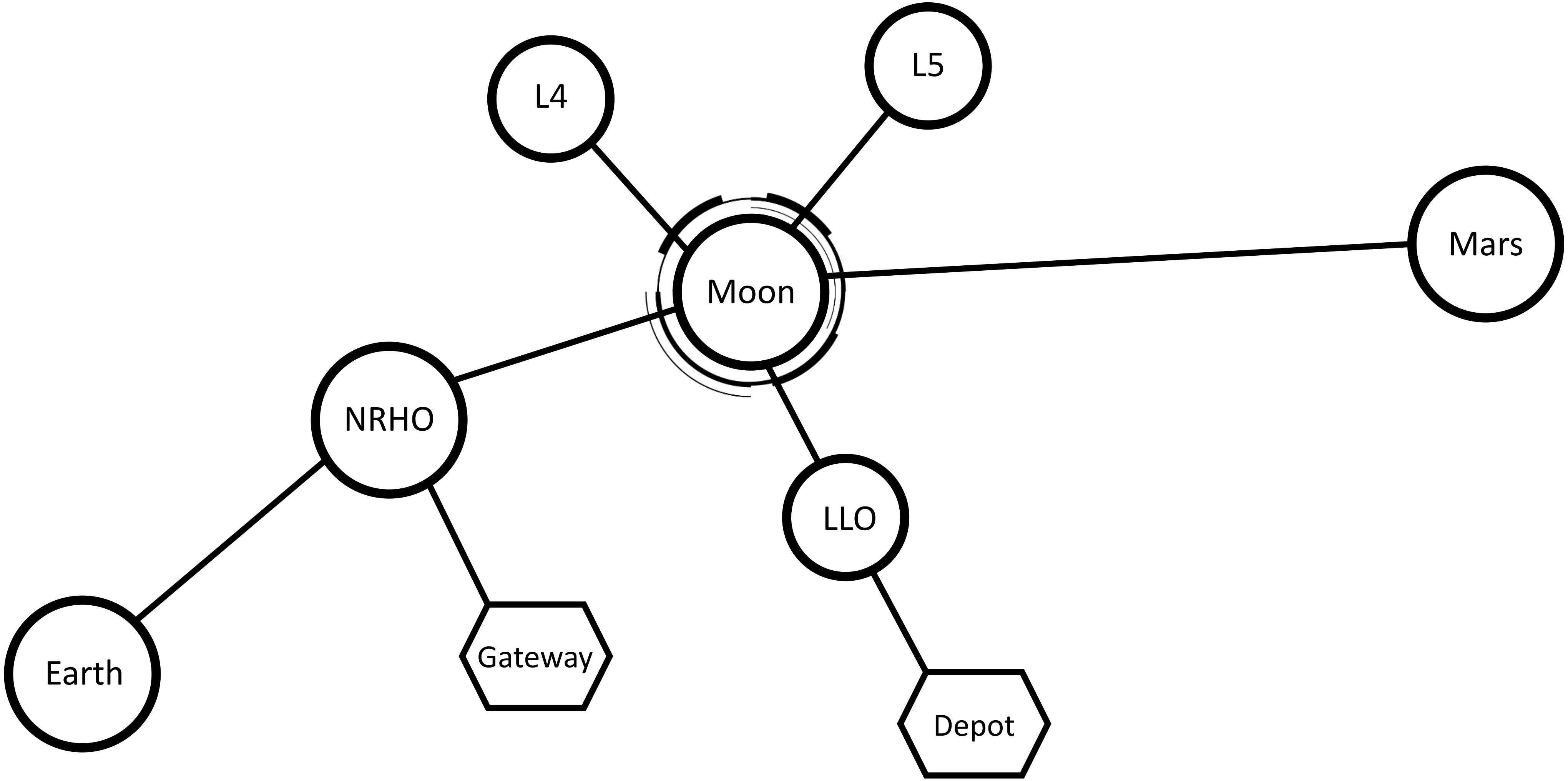
		Consequence				
		1	2	3	4	5
Likelihood	5	🟩	🟨	🟧	🟥	🟥
	4	🟩	🟨	🟧	🟧 ④	🟥
	3	🟩	🟨	🟨	🟧 ①	🟧
	2	🟩	🟩	🟨 ⑤	🟨 ②③	🟨
	1	🟩	🟩	🟩 ⑥	🟩	🟩

Hazards and Mitigation

- Missed Gateway window
  - Wait for next window (7 days); all consumables sized for 14-day duration
- Communications failure
  - Orbiter and Gateway serve as double-redundant relays to Earth
- Propulsion system failure
  - ARTEMIS can abort with one engine while maintaining thrust vector
- Fuel tank rupture
  - Abort to orbit; transfer fuel to undamaged tanks
- Power system failure
  - ARTEMIS can function with a single solar panel

Extended Capabilities

Extended Capabilities



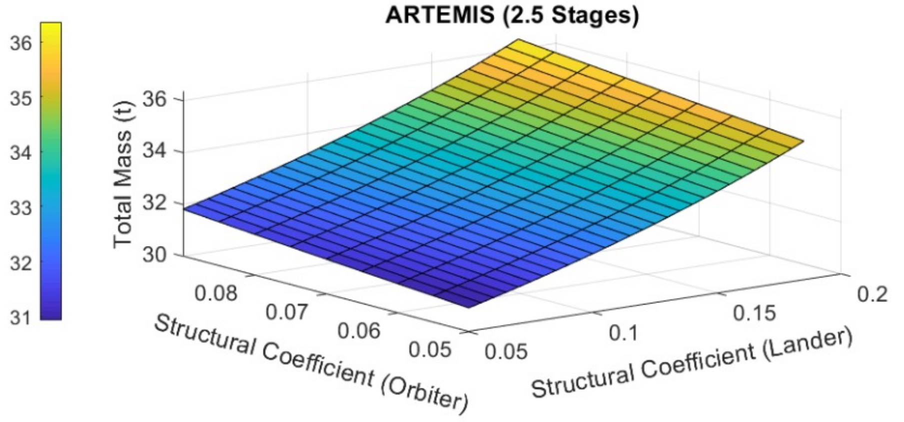
✓ Initial architecture and program model that is not “dead-ended” and facilitates evolution

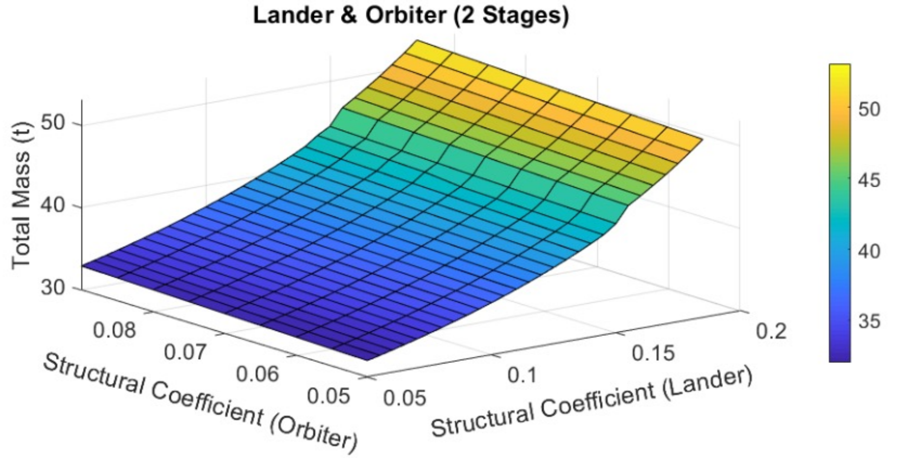
Thank You!

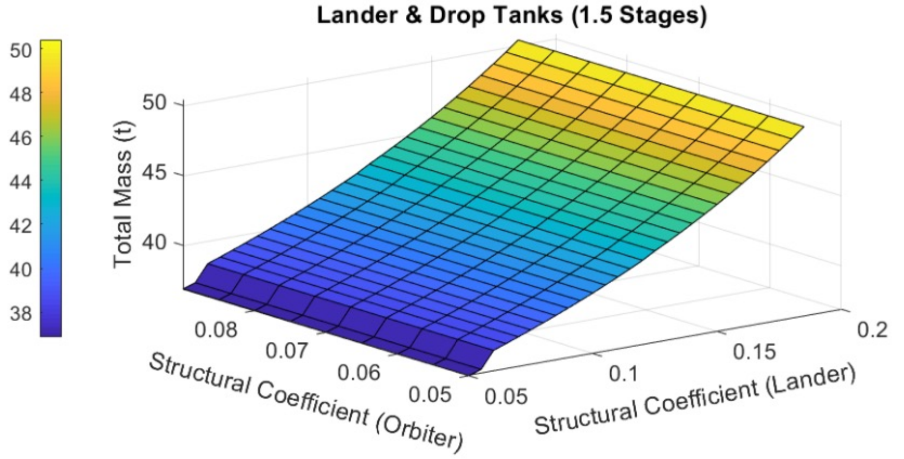
Questions

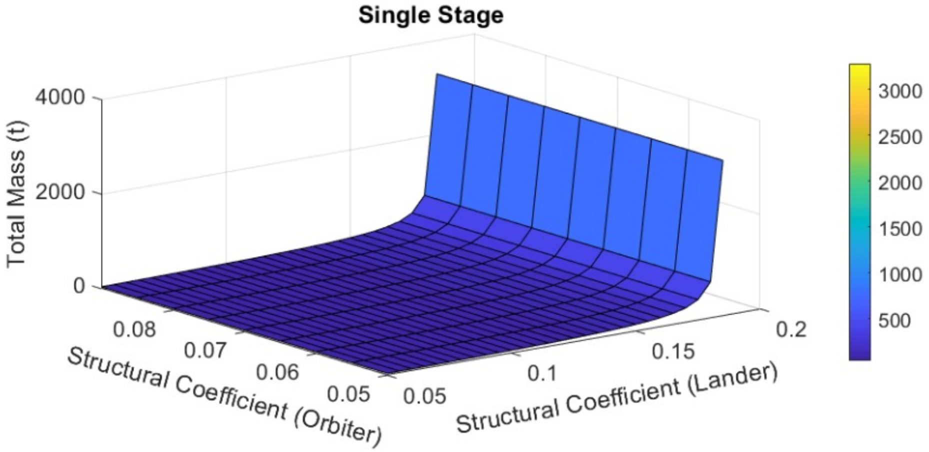
Supplemental Slides

Staging Method: Mass Trade Study

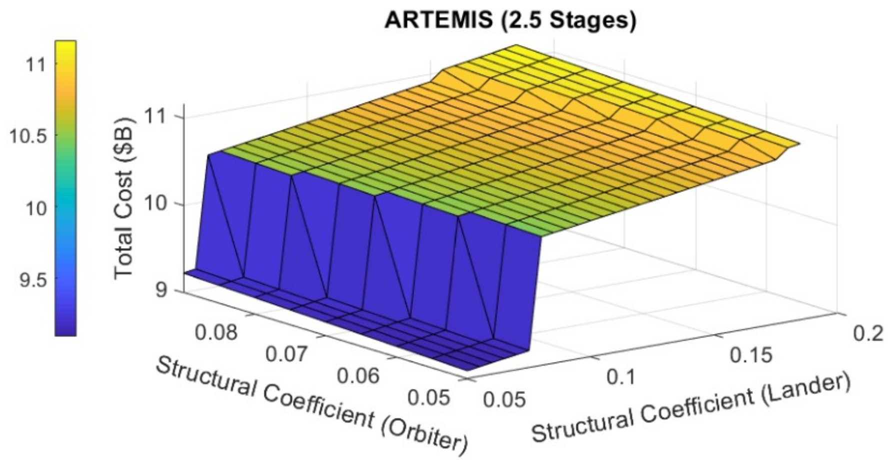

ARTEMIS (2.5 Stages)

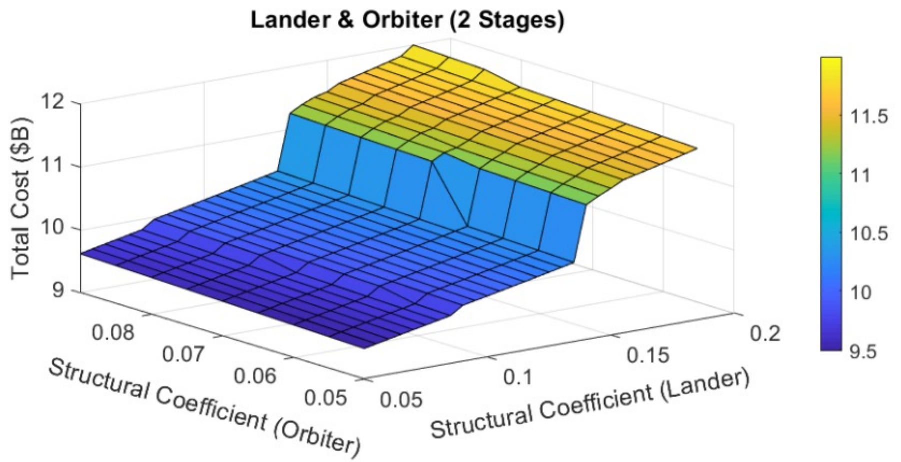

Lander & Orbiter (2 Stages)

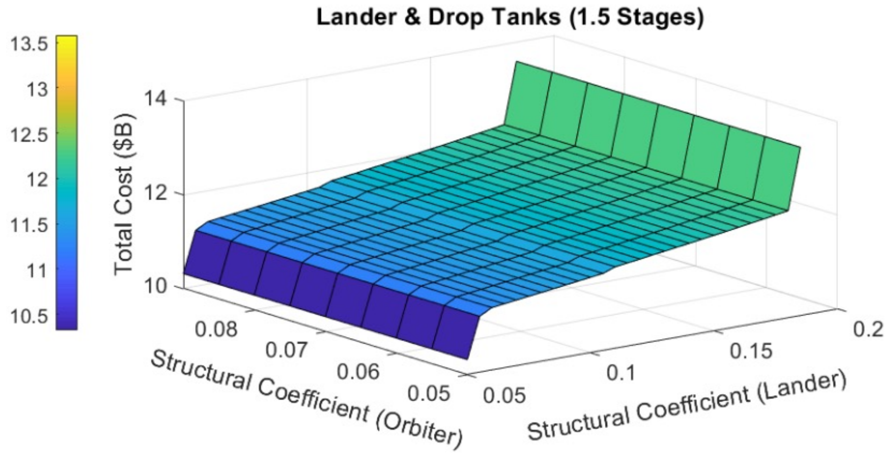

Lander & Drop Tanks (1.5 Stages)

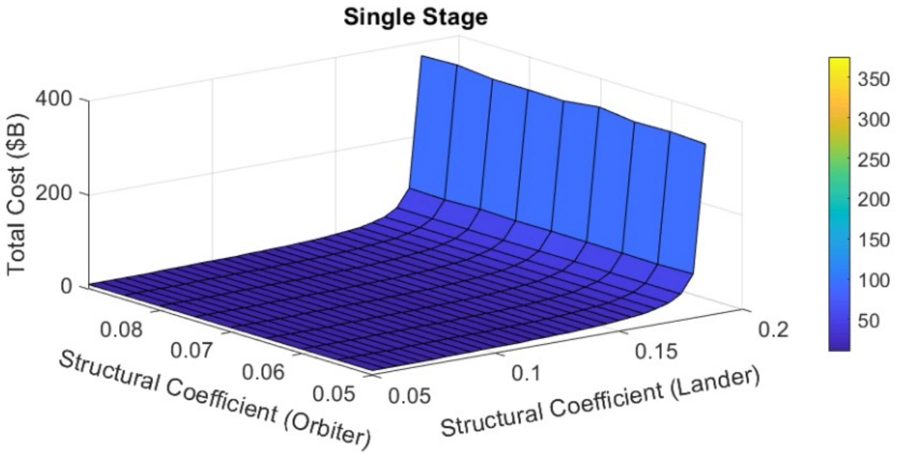

Single Stage

Staging Method: Cost Trade Study


ARTEMIS (2.5 Stages)


Lander & Orbiter (2 Stages)

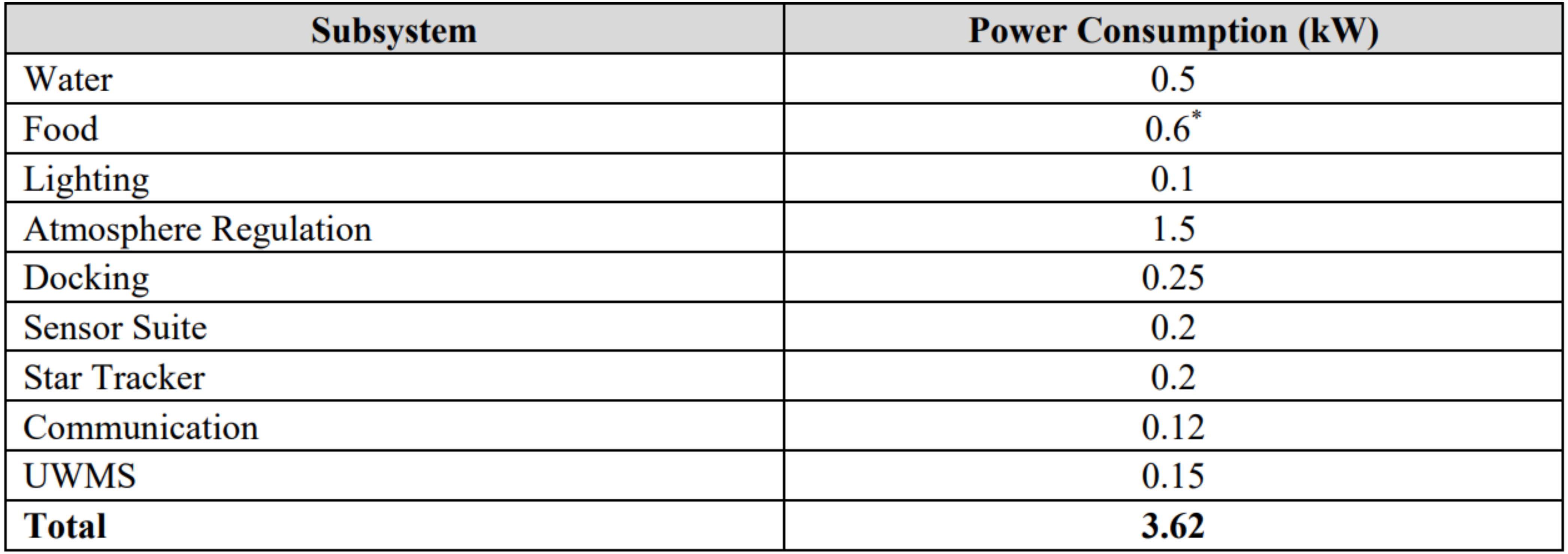

Lander & Drop Tanks (1.5 Stages)


Single Stage

Mass Budget

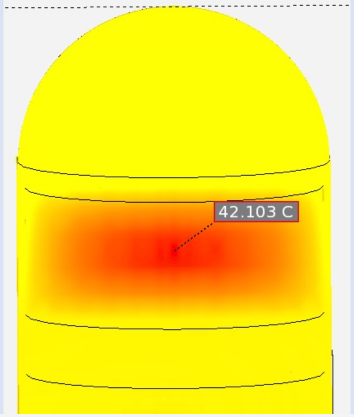
Vehicle Section	Vehicle Subsection	Subsystem	Mass (t)
Lander	*Habitable Section*	ECLSS	2.193
		ADCS	0.280
		GN&C	0.090
		C&DH	0.131
		Communications	0.030
		Power	0.171
		Thermal Control	0.010
		Structures	1.439
		MMOD/Radiation Shielding	0.155
		NDS Docking Port	0.324
		Subtotal	**4.823**
		Subtotal + 20% Margin	**5.787**
	Propulsion Section	2 Engines (CECE)	0.318
		Landing Legs	0.555
		MMOD/Radiation Shielding	0.110
		Remaining Structure	0.667
		Propellant (LOX/LH_2)	5.382
		Subtotal	**7.032**
Drop Tanks		Structure	0.455
		Propellant (LOX/LH_2)	9.228
		Subtotal	**9.683**
Orbiter		2 Engines (CECE)	0.318
		Power	0.009
		Communications	0.022
		MMOD/Radiation Shielding	0.202
		NDS Docking Port	0.324
		Remaining Structure	1.154
		Propellant (LOX/LH_2)	11.809
		Subtotal	**13.836**
Totals		**Dry Mass**	9.920
		Propellant Mass	26.419
		Wet Mass	36.338

Power Budget

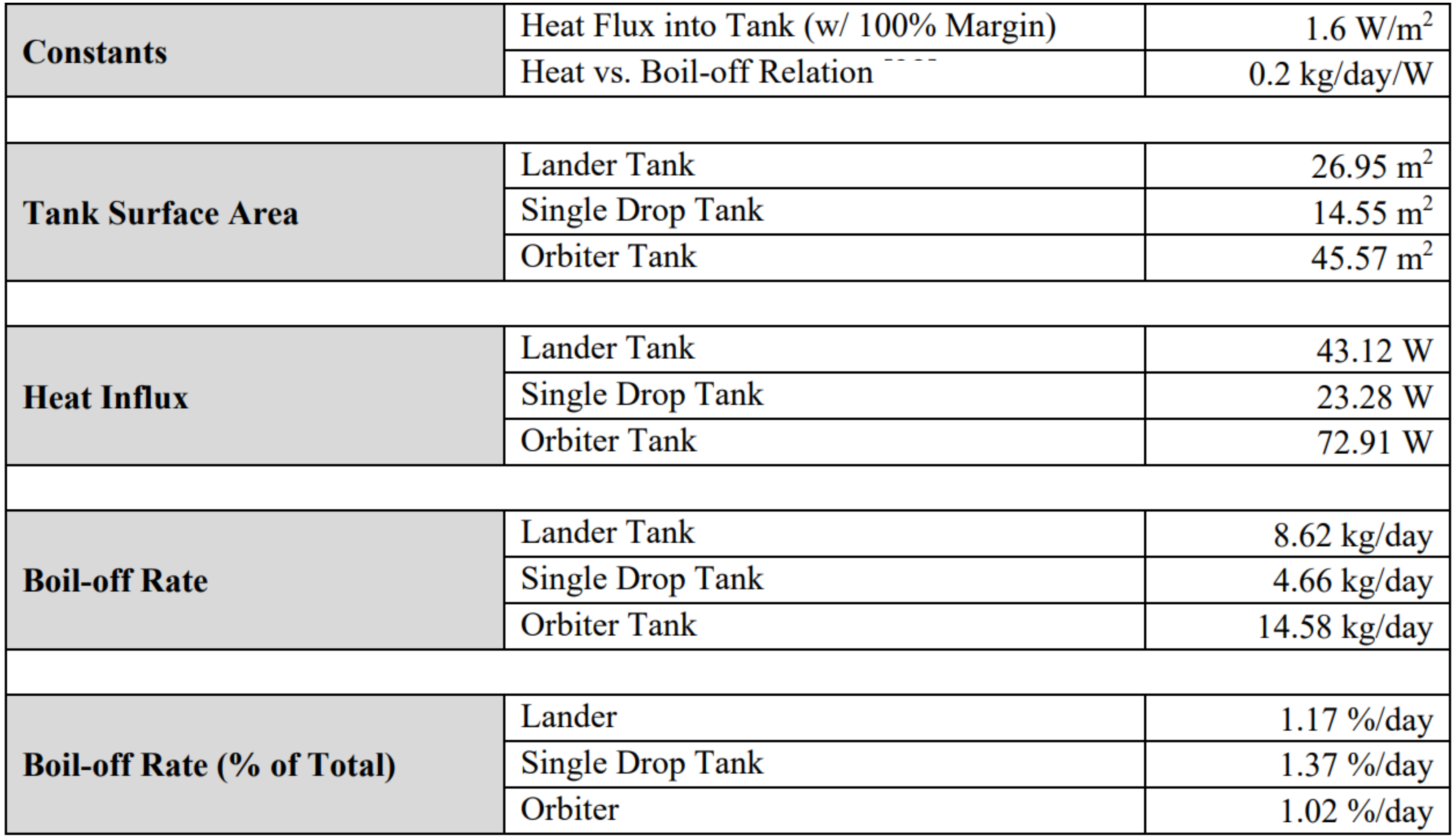


Subsystem	**Power Consumption (kW)**
Water	0.5
Food	0.6*
Lighting	0.1
Atmosphere Regulation	1.5
Docking	0.25
Sensor Suite	0.2
Star Tracker	0.2
Communication	0.12
UWMS	0.15
Total	**3.62**

Thermal Simulation

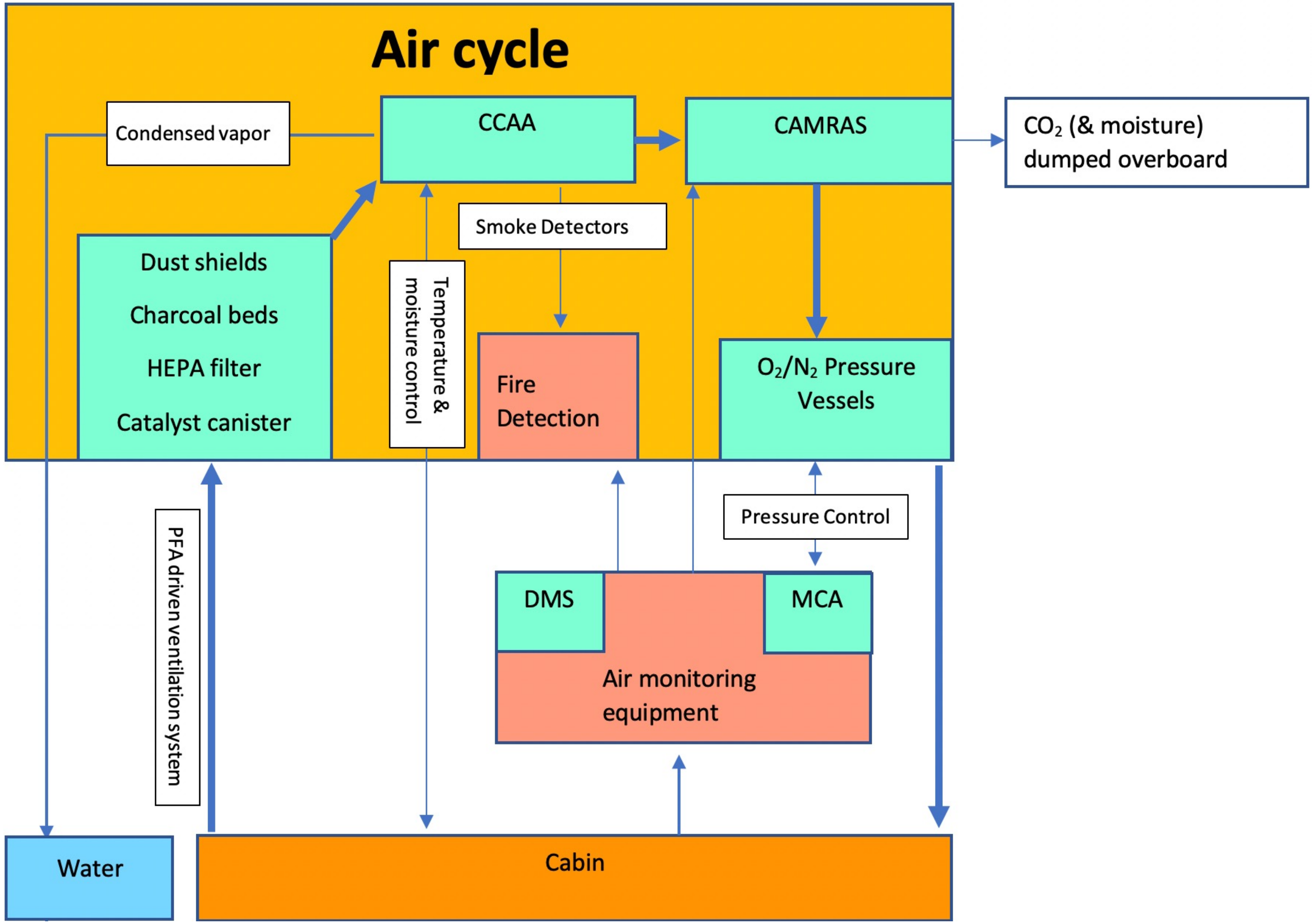
	Low Heat	High Heat
Low Emissivity		
High Emissivity		

Liquid Hydrogen Boil-off Calculations

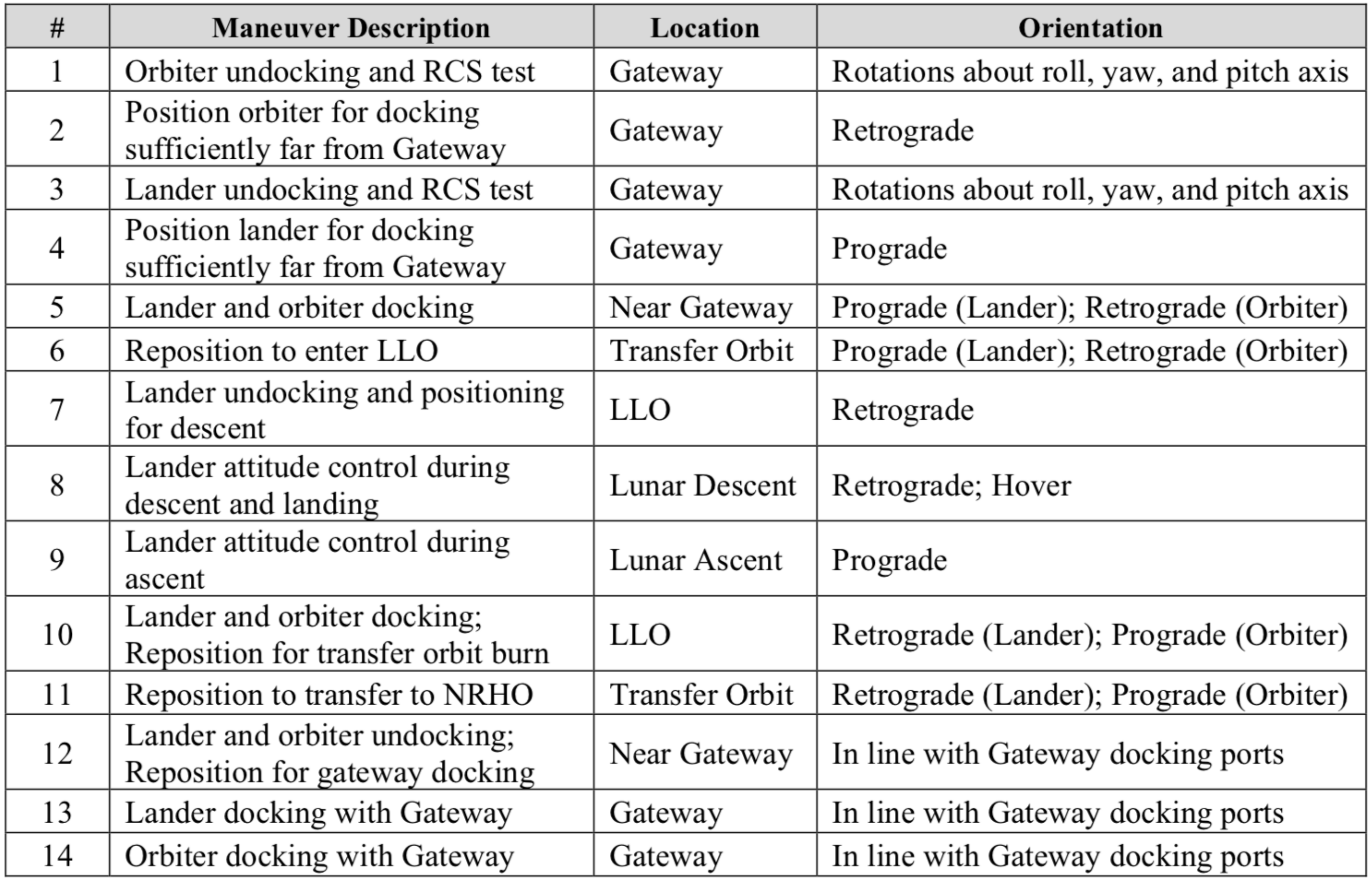


Constants	Heat Flux into Tank (w/ 100% Margin)	1.6 W/m^2
	Heat vs. Boil-off Relation	0.2 kg/day/W
Tank Surface Area	Lander Tank	26.95 m^2
	Single Drop Tank	14.55 m^2
	Orbiter Tank	45.57 m^2
Heat Influx	Lander Tank	43.12 W
	Single Drop Tank	23.28 W
	Orbiter Tank	72.91 W
Boil-off Rate	Lander Tank	8.62 kg/day
	Single Drop Tank	4.66 kg/day
	Orbiter Tank	14.58 kg/day
Boil-off Rate (% of Total)	Lander	1.17 %/day
	Single Drop Tank	1.37 %/day
	Orbiter	1.02 %/day

ECLSS Air System Breakdown



Reaction Control System Maneuvers

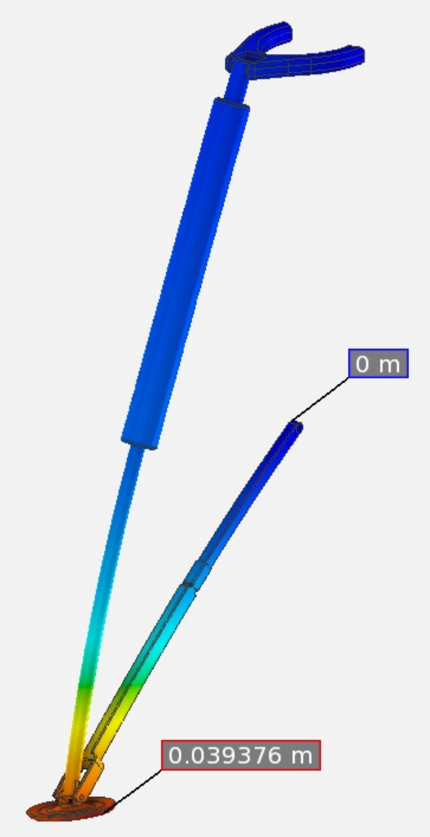


#	Maneuver Description	Location	Orientation
1	Orbiter undocking and RCS test	Gateway	Rotations about roll, yaw, and pitch axis
2	Position orbiter for docking sufficiently far from Gateway	Gateway	Retrograde
3	Lander undocking and RCS test	Gateway	Rotations about roll, yaw, and pitch axis
4	Position lander for docking sufficiently far from Gateway	Gateway	Prograde
5	Lander and orbiter docking	Near Gateway	Prograde (Lander); Retrograde (Orbiter)
6	Reposition to enter LLO	Transfer Orbit	Prograde (Lander); Retrograde (Orbiter)
7	Lander undocking and positioning for descent	LLO	Retrograde
8	Lander attitude control during descent and landing	Lunar Descent	Retrograde; Hover
9	Lander attitude control during ascent	Lunar Ascent	Prograde
10	Lander and orbiter docking; Reposition for transfer orbit burn	LLO	Retrograde (Lander); Prograde (Orbiter)
11	Reposition to transfer to NRHO	Transfer Orbit	Retrograde (Lander); Prograde (Orbiter)
12	Lander and orbiter undocking; Reposition for gateway docking	Near Gateway	In line with Gateway docking ports
13	Lander docking with Gateway	Gateway	In line with Gateway docking ports
14	Orbiter docking with Gateway	Gateway	In line with Gateway docking ports

Landing Leg Simulation

Fatigue Life (cycles)

Stress



Displacement