Design of Crewed Deimos Mission: Preliminary Design Review

EMAE 356: Aerospace Design

Team Alpha

April 24, 2025

Members:

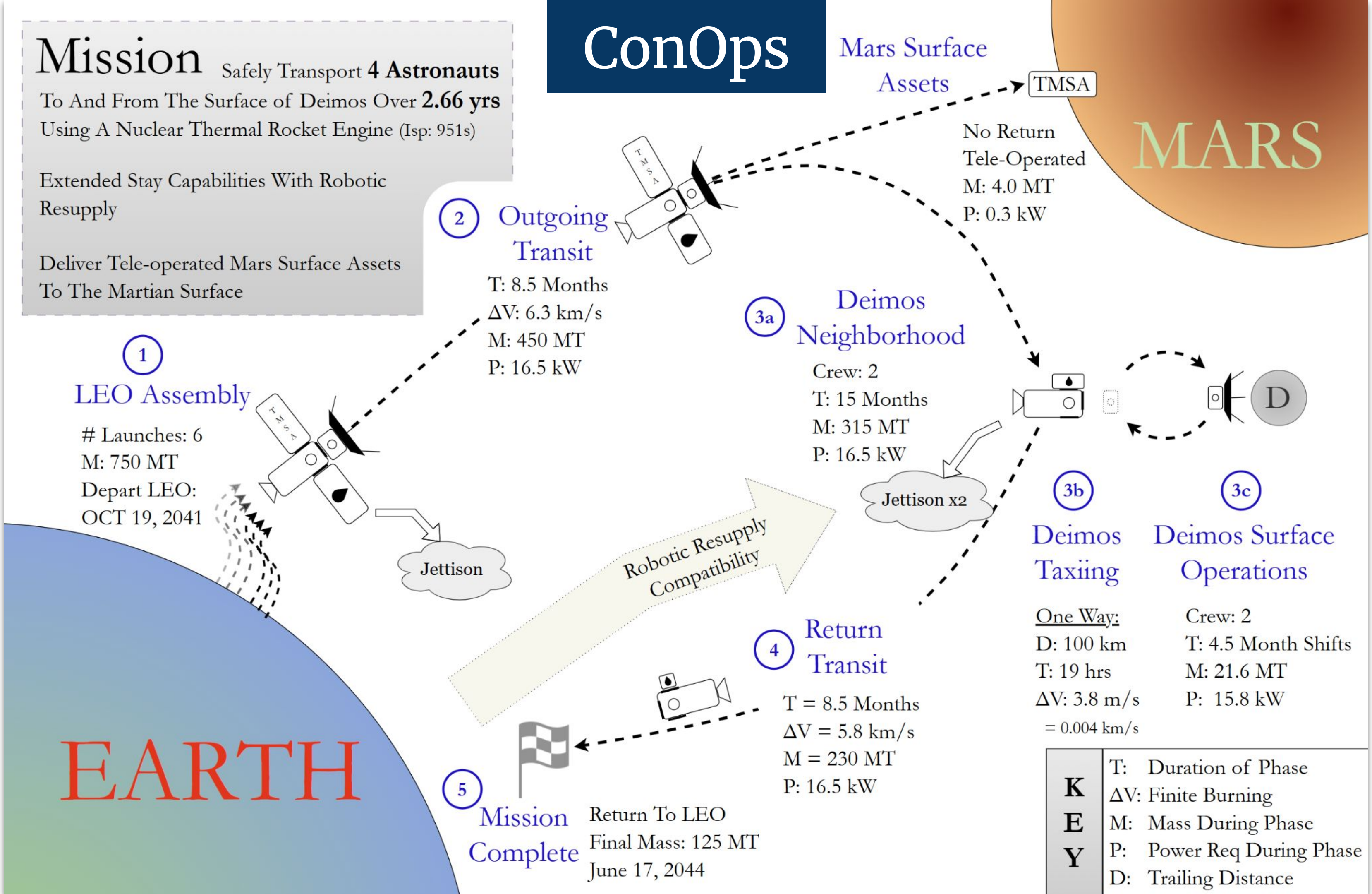
Ethan Cogdill, Paul Racanelli, Katelyn Lamm, Tyler Griffith, Jocelyn Schechter, Nathaniel Berntson, Owen Braun, Preston Yen, Abigail Burianek, Nathan Kralik, Joseph Schlager, Alex Schreiter, Alexander Dudowski, Joshua Berman

Important Requirements & Mission Overview

Mission Objectives/Constraints
Mission crew of 4, minimum
Deimos surface stay of 270 days Deliver tele-operating Mars surface assets
Resupply capability for extended stay (+454 days)
Use of 150mT, 12m diameter SLS and Orion capsule
Complete mission within 20 year, 2025-2045 window

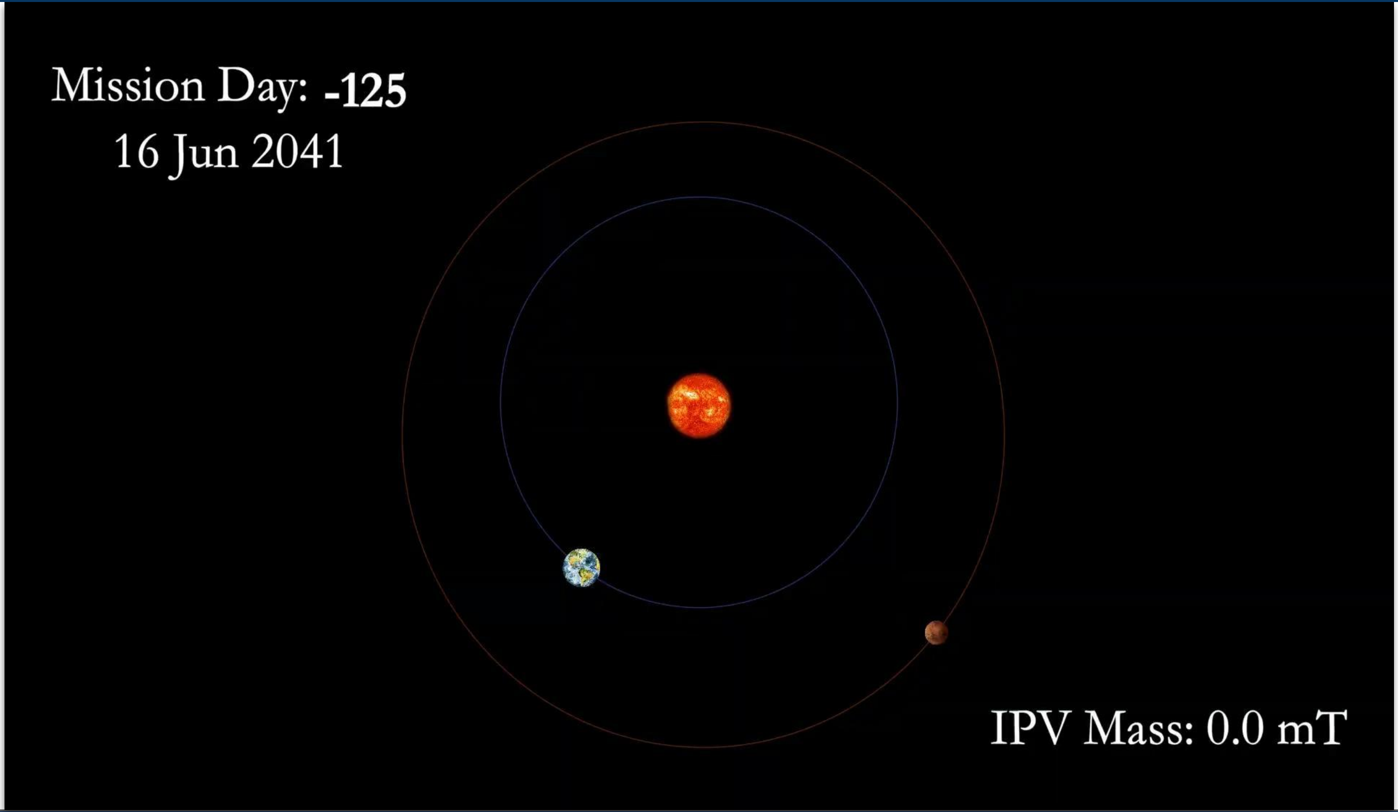
Driving Requirements
12.1 km/s of ΔV
Mission length: **2.66 years** (972 Days)
Max **750mT** departure mass
6 SLS Launches
Depart LEO on **Oct 19, 2041**

ConOps



Mission
Safely Transport 4 Astronauts
To And From The Surface of Deimos Over 2.66 yrs
Using A Nuclear Thermal Rocket Engine (Isp: 951s)
Extended Stay Capabilities With Robotic Resupply
Deliver Tele-operated Mars Surface Assets To The Martian Surface
1
LEO Assembly
Launches: 6
M: 750 MT
Depart LEO:
OCT 19, 2041
TMSA
Jettison
2
Outgoing Transit
T: 8.5 Months
ΔV: 6.3 km/s
M: 450 MT
P: 16.5 kW
TMSA
Mars Surface Assets
TMSA
No Return
Tele-Operated
M: 4.0 MT
P: 0.3 kW
MARS
3a
Deimos Neighborhood
Crew: 2
T: 15 Months
M: 315 MT
P: 16.5 kW
Jettison x2
D
3b
Deimos Taxiing
One Way:
D: 100 km
T: 19 hrs
ΔV: 3.8 m/s
= 0.004 km/s
3c
Deimos Surface Operations
Crew: 2
T: 4.5 Month Shifts
M: 21.6 MT
P: 15.8 kW
Robotic Resupply Compatibility
4
Return Transit
T = 8.5 Months
ΔV = 5.8 km/s
M = 230 MT
P: 16.5 kW
5
Mission Complete
Return To LEO
Final Mass: 125 MT
June 17, 2044
EARTH
KEY
T: Duration of Phase
ΔV: Finite Burning
M: Mass During Phase
P: Power Req During Phase
D: Trailing Distance

Mission Animation



Mission Animation (or manimation) Made with Manimgl

Top Level FBD

1. Crew Habitation	2. Life Support	3. Power	4. Environmental Control	5. Structural	6. Propulsion	7. Mars Assets
1.1 DEV and IPV Hab Spaces	2.1 Breathable Air	3.1 IPV Bimodal	4.1 Radiation Shielding	5.1 Hab Primary Structures	6.1 Nuclear Thermal	7.1 Aeroshell
	2.2 Food	3.2 DEV Reactor	4.2 MMOD Shielding	5.2 Propellant Tanks	6.2 IPV OMS	7.2 Surface Assets
	2.3 Water	3.3 Backup Power		5.3 Truss Structures	6.3 DEV RCS	7.3 Science Equipment
				5.4 Payload Adapters	6.4 DEV Main Thrusters	

Ethan Cogdill
Systems Engineer

Joshua Berman
Propulsion (NTP) TL

Tyler Griffith
Propulsion (NTP)

Jocelyn Schechter
Propulsion (DEV)

Paul Racanelli
Propulsion (DEV) & Deimos Ops

Alexander Dudowski
Propulsion (IPV OMS)

Nathaniel Berntson
Heat Rejection, CAD

Preston Yen
Structures (Truss)

Alex Schreiter
MLI & Heat Rejection

Ethan Cogdill
Structures (Tanks)

Nathan Kralik
Mass, Fluid Systems

Owen Braun
Power TL, Mars Assets

Joseph Schlager
Power, Mars Assets

Katelyn Lamm
Budget, Assembly

Abigail Burianek
Human Factors, IPV CAD

PDR Work Breakdown Structure

Structures	**Power**	**Heat Rejection**	**Life Support**	**Propulsion** OMS, NTP, DEV	**Science & Ops**	**Mars Assets**
FoS and Standards	Power Requirements	Radiator Analysis	Oxygen Requirement	Cycle Design	Deimos Science	TMSA Vehicle Decision
Isogrid Analysis	DEV Reactor Size	Heat Exchanger Analysis	Food Requirement	Isp & Geometry Decisions	Deimos Landing Ops	EDL Analysis
COPV Analysis	Bimodal Sizing	NaK Cooling Loops	Water Requirement	Propellant Type	Mars Science	Rover Design
Truss Sizing	Turbomachinery Analysis	H_2O / NH_3 Cooling Loops	Recycling Analysis	Turbomachinery Analysis	Teleoperation Plan	Stake Instrumentation
Vibrations	Redundant Power	MLI Analysis	System Power Reqs	Ullage		
MMOD Shield				Plumbing		
Assembly Plan						

Budget & Timeline

Schedule: Structures

Pressure ...	Design Standards Research & Mat'l Options	Nate	Preston	3/18/2025	3/23/2025
Pressure ...	Design Standards Research & Mat'l Options	Alex	Ethan	3/18/2025	3/23/2025
Pressure ...	Analysis Write-Up	Nate	Preston	3/18/2025	3/25/2025
Pressure ...	Analysis Write-Up	Alex	Ethan	3/18/2025	3/25/2025
Truss	Design Process Research (Talk to Ali)	Preston	Nate	3/18/2025	3/23/2025
Truss	Initial Analysis Framework Write-Up	Preston	Nate	3/20/2025	3/23/2025
Pressure ...	Micrometeoroid Analysis Progress Slide	Abby	***Ethan***	3/20/2025	3/30/2025
Pressure ...	Updated Boil Off Model	Alex	Ethan	3/18/2025	4/1/2025
Pressure ...	Isogrid Selection for Dev and Hab	Ethan		3/23/2025	3/27/2025
Truss	Design Goals/Drivers, Allowable Loads, FoS	Preston	Nate	3/23/2025	4/1/2025
Pressure ...	SLS Launch Loading	Ethan	Preston	3/25/2025	3/30/2025
Pressure ...	Composite and Hab End Caps	Ethan		3/27/2025	4/3/2025
Pressure ...	Micrometeoroid Shielding Mass/Construction	Ethan	Nathan	3/30/2025	4/5/2025
Pressure ...	Vibrations for Structures: Natural Freqs	Ethan	Preston	3/30/2025	4/14/2025
Pressure ...	Composite Tank Compressive Loading	Nathan	Ethan	4/3/2025	4/7/2025
Pressure ...	Propellant Tanks: Link to mass budget	Ethan	Nathan	4/1/2025	4/6/2025
Pressure ...	Vibration Analysis Tanks and Pressure Vessels	Ethan		4/8/2025	4/13/2025
Pressure ...	water / o2 storage	AJ		4/8/2025	4/13/2025
Pressure ...	Isogrid Mars Asset	Owen	Ethan	4/8/2025	4/10/2025
Truss	Thrust Structure	Ethan	Preston	4/17/2025	4/20/2025
Truss	Saddle Truss	Preston		4/12/2025	4/20/2025
Pressure...	Plumbing	Nathan	Josh	4/15/2025	4/21/2025
Pressure...	Composite Tank Intermediate Liner	Ethan		4/15/2025	4/19/2025

Schedule: Propulsion

Engine D...	Nuclear Engine Performance Analysis Write-Up	Tyler	Josh	3/16/2025	3/20/2025
Engine D...	Nuclear Engine Notional Diagram	Tyler	Josh	3/16/2025	3/20/2025
Engine D...	Nuclear Engine Design Process Description	Tyler	Josh	3/20/2025	3/23/2025
Engine D...	Orbital Maneuvering System Analysis	AJ	Ethan	3/18/2025	4/8/2025
Trajectory	Lambert Method MATLAB Code for Transfer	Paul		3/16/2025	3/27/2025
Engine D...	Engine cycle, states	Josh	Tyler	3/23/2025	3/27/2025
Engine D...	Engine nozzle	Josh	Tyler	3/23/2025	3/27/2025
Trajectory	Transfer Trajectory Course Corrections dV Margin	Jocelyn	Paul	3/23/2025	3/30/2025
Engine D...	Orbital Maneuvering System Detail Design	AJ	Abby	3/25/2025	3/30/2025
Engine D...	DeV Engine Cycle Analysis	Jocelyn		3/25/2025	4/7/2025
Engine D...	Nuclear Reactor Design	Tyler	Josh	3/27/2025	4/6/2025
Engine D...	RCS Design: P&ID and Design Decisions	Jocelyn	Paul	3/30/2025	4/3/2025
Engine D...	NTP Engine Nozzle Sizing Analysis	Josh	Tyler	3/27/2025	3/30/2025
Engine D...	NTP Engine Nozzle Cooling	Josh		3/30/2025	4/1/2025
Trajectory	Finite Burn MATLAB Losses and Burn Times	Paul	Ethan	4/8/2025	4/13/2025
Engine D...	Finish Nozzle	Josh	Tyler	3/30/2025	4/8/2025
Engine D...	Cool Down Period	Tyler	Josh	4/1/2025	4/8/2025
Engine D...	Ullage + Piping	Nathan	Josh	4/3/2025	4/8/2025
Engine D...	P&ID	Josh	Tyler	4/1/2025	4/8/2025
Engine D...	Turbomachinery	Josh	Tyler	4/1/2025	4/8/2025
Trajectory	Mars Assets Cruise Stage Maneuvers	Nathan	Owen	4/8/2025	4/10/2025
Trajectory	DeV RCS and Maneuvering	Jocelyn		4/8/2025	4/10/2025
Trajectory	Finite Burn MATLAB Visuals	Ethan		4/20/2025	4/22/2025
Engine D...	NTP Mass Fix	Josh	Tyler	4/17/2025	4/19/2025

Schedule: Power / Heat Rejection

Power	DeV Nuclear Reactor Analysis Framework	Joseph	Owen	3/18/2025	3/23/2025
Power	Spacecraft Radiator Design Research	Katelyn		3/18/2025	3/23/2025
Power	Radiator Design: Materials	Nate		3/23/2025	3/30/2025
Power	Brayton Cycle Analysis: Mass Flow	Owen		3/23/2025	3/28/2025
Power	Bimodal Power: Cycle Analysis	Owen	Nathan	3/27/2025	4/15/2025
Power	DeV and IPV Heat Transfer	Nate	Alex	3/30/2025	4/6/2025
Power	DeV Reactor P&ID	Owen	Joseph	3/30/2025	4/4/2025
Power	Bimodal P&ID	Owen	Joseph	3/30/2025	4/4/2025
Power	Pressure drop across tie tubes	Owen		4/8/2025	4/10/2025
Power	Turbomachinery for Bimodal and DeV	Owen		4/8/2025	4/13/2025
Power	Fix Bimodal Radiator Design	Nate		4/8/2025	4/13/2025
Power	*DeV and IPV Heat Rejection***	Alex		4/8/2025	4/13/2025
Power	Heat Rejection Heat Exchangers	Alex		4/15/2025	4/17/2025
Power	Radiator Analysis & Materials	Nate		4/8/2025	4/20/2025
Power	DEV & Hab Loop Pressure Losses	Ethan		4/15/2025	4/20/2025
Power	Combine Analyses	Alex	Nate	4/20/2025	4/21/2025
Power	MLI for Habs	Alex		4/21/2025	4/21/2025

Schedule: CAD

Models	Updated DeV 3 View	Jocelyn		3/20/2025	3/23/2025
Models	Updated IPV 3 View	Nate		3/20/2025	3/23/2025
Models	Mars Asset Refined Concept	Joe	Owen	3/25/2025	4/1/2025
Models	Updated DeV 3 View	Jocelyn		3/25/2025	4/1/2025
Models	Updated IPV 3 View	Nate		3/25/2025	3/30/2025
Models	**Center of Mass**	Nathan		4/1/2025	4/7/2025
Models	CAD: DeV	Jocelyn		4/1/2025	4/6/2025
Models	Updated IPV 3 View	Nate		4/1/2025	4/6/2025
Models	CAD: IPV Hab	Abby		4/8/2025	4/13/2025
Models	CAD: Propellant Tanks	Nathan	Ethan	4/8/2025	4/13/2025
Models	CAD: Trusses and Payload Adapters	Preston		4/8/2025	4/13/2025
Models	CAD: Docking and Assembly Operations	Katelyn		4/8/2025	4/13
Models	CAD: Thrust Structures	Preston		4/8/2025	4/13
Models	CAD: Secondary Engine CAD	AJ		4/8/2025	4/13
Models	CAD: Nuclear Engine CAD	Josh	Tyler	4/8/2025	4/13
Models	Detailed Assembly Vehicle	Katelyn		4/7/2025	4/13/2025
Models	Full Assembly CAD Draft	Nate	everyone	4/7/2025	4/13/2025
Models	Mars Asset Assembly CAD	Joe		4/15/2025	4/16/2025
Models	DEV CAD	Jocelyn		4/15/2025	4/21/2025
Models	Launch Packaging in CAD	AJ	Katelyn	4/15/2025	4/17/2025
Models	Assembly CAD Improvement	Nate		4/15/2025	4/19/2025
Models	Mars Ops Diagrams	Joe		4/20/2025	4/22/2025
Models	Deimos Ops Diagrams	Paul		4/21/2025	4/22/2025
Models	Tank Docking Mechanism	Katelyn	AJ	4/21/2025	4/22/2025
Models	Assembly CAD Done	Nate		4/21/2025	4/22/2025

Trade Studies

Color Key:

(Yellow)	**Warnings:** Things to know before using a sheet as well as important values that have yet to be added
(Orange)	**Imported Values:** Values that are imported from other sheets, can only be changd through those sheets
(Lavender)	**Useful Tables:** Tables used to help make decisons and mae sure values make sense but are not part of the calculations i.e. just for help the numbers you see make sense
Text	**Inputs:** Values you are alble to easily alter in a sheet allowing for the sheet to return proper values
Text	**Important Outputs:** Important or useful output for the sheet that the sheet is able to easily varied based on Inputs
Text	**Constants:** Values that should only be changed by or with knowledge from the sheet creator

Earth Departure	
μ_Earth	3.99E+05
R_LEO	6,780
V_circ	7.667
V_∞	2.948
a	4.59E+04
e	1.148
b	2.58E+04
ψ	29.40
V_Hyp,P	11.24
ΔV_D	**3.986**
ΔV_D_simul	3.819
C3	8.688

Mars Capture	
μ_Mars	4.28E+04
V_∞	1.35
R_MPO	23,458
V_circ	2.658
a	6,062
e	4.870
b	2.89E+04
ψ	78.15
V_Hyp,P	3.27
ΔV_C	**1.922**
ΔV_C_simul	2.130

Inputs	
Number of	5
Isp	951
Mass Loss	0

Launches to LEO	
#	Mass Achievable
1	150,000
2	300,000
3	450,000
4	600,000
5	750,000
6	900,000

Isp Requirements	
M_0 1 -> 2	**750,000**
Isp	951
M_i / M_f	1.50605
M_D	497,992
M_i / M_f	1.25658
M_C	396,308
M_Jettisoned	0
M_0 2 -> 1	396,308
M_i / M_f	1.25658
M_D	315,386
M_i / M_f	1.53333
M_C (Final Mass)	**205,687**
LEO Assembled Dry Mass	**236,154**

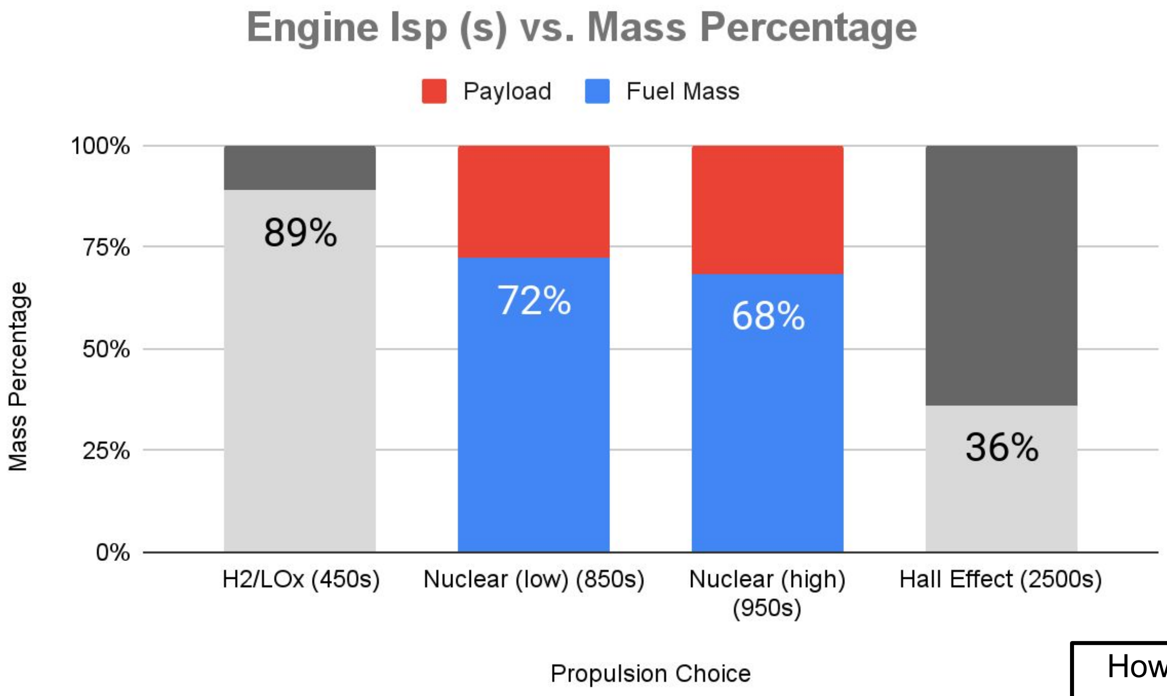
ΔV Requirements	
ΔV E -> M	5.91
ΔV M -> E	5.91
ΔV_tot	11.82
ΔV_tot w/	**12.0654**

Fuel Masses	
Departure	**256,281**
Mars Cap	**96,485**
Mars Dep	**69,802**
Earth Cap	**91,278**
Total Fuel	**513,846**

Timing		
Period	(Days)	(Yrs)
T1	365	1.00
T2	687	1.88
S	780	2.14
α / π	0.42	-
t_w	**454**	**1.24**
t_tot	**972**	**2.66**

CASE WESTERN RESERVE UNIVERSITY
Case School of Engineering

Trade Studies



$$T = 2\pi\sqrt{\frac{a^3}{\mu}}$$

$$\frac{\Delta V}{V_{eff}} = \ln\left(\frac{m_0}{m_f}\right)$$

$$\Delta V_a = V_a\left[\left(\frac{2a_2}{a_2+a_1}\right)^{\frac{1}{2}} - 1\right]$$

$$\Delta V_b = V_b\left[1 - \left(\frac{2a_1}{a_2+a_1}\right)^{\frac{1}{2}}\right]$$

$$V_{hyp} = \left(\frac{e+1}{e-1}\right)^{\frac{1}{2}}\sqrt{\frac{\mu}{a}}$$

Howard Curtis, “Fundamentals of Orbital Mech. for Eng. Students”, 2005.

TRL Assessment

Technology	TRL	Current State
Nuclear Thermal Propulsion	6/7	Terrestrial systems have been fired but higher quality ZrC-NbC solutions need to be created for T_0 ~ 3150 K. (Borowski et al., Nuclear Thermal Propulsion: A Proven Growth Technology for Human NEO / Mars Exploration Missions, 2012)
Bimodal Power	6	Brayton cycles with Xenon-Helium have been tested in space like environments (Experimental Results From a 2kW Brayton Power Conversion Unit, Hervol, 2003)
Fission Microreactors (DEV)	6/7	Experimentation with closed loop XeHe brayton cycles took place in the early 2000's in a space-like environment and fission reactors were actually flown in the past Hervol, D., Mason, L., & Birchenough, A. (2003). *Experimental results from a 2kW Brayton power conversion unit* (NASA/TM-2003-211999). NASA Glenn Research Center. https://ntrs.nasa.gov/citations/20030016687 Johnson, G. A., and L. S. Mason. Initial Test Results of a Dual Closed-Brayton-Cycle Power Conversion System. NASA/TM-2008-215080, NASA Glenn Research Center, 2008.
Composite LH_2 Tanks	5/6	Boeing/NASA manufactured 5.5m tank with 10m tank loading (Boeing/NASA, "Design, Manufacture and Test of Cryotank Components", 2017)

TECHNICAL RISK LIST (1 - LOW) (3-MODERATE) (5- HIGH)

ID	Risk	Type	Risk Description	L	C	Mitigation
4	In-Space Assembly	Technical	In Space Assembly Technical Challenges	2	4	Mitigate
1	Boil Off Management	Technical	Development of boil off prevention technologies to meet max allowable limits falls	2	2	Mitigate
8	Mass Budget Overrun	Technical	Total mass breakdown over 750mT allocation (past expected dry mass margin)	2	3	Watch
7	SLS Launch Number	Technical	Cannot package all modules into 5 launches (due to mass or geometry)	2	2	Mitigate
2	NTP Engine Isp	Technical	Nuclear Thermal Propulsion does not meet specified 950s Isp.	2	2	Mitigate
10	OMS Mass Overrun	Technical	OMS Secondary Propulsion overruns mass allocation	3	2	Watch
5	Micrometeroid Shielding	Technical	Shielding unable to meet impact energy requirements while meeting mass allocation	1	2	Mitigate
3	Radiation Protection Mass	Technical	Radiation Shielding unable to meet mass allocation	1	2	Watch
11	Radiator / Heat Rej System Mass	Technical	Radiator and heat rejection system mass higher than previously thought	3	3	Watch
12	Lined Composite Tank	Technical	Thermal expansion, manufacturability concerns	3	3	Mitigate

RISK

LIKELIHOOD \ CONSEQUENCE	1	2	3	4	5
5					
4					
3			8, 11, 12		
2		2, 10, 7	1	4	
1		3, 5			

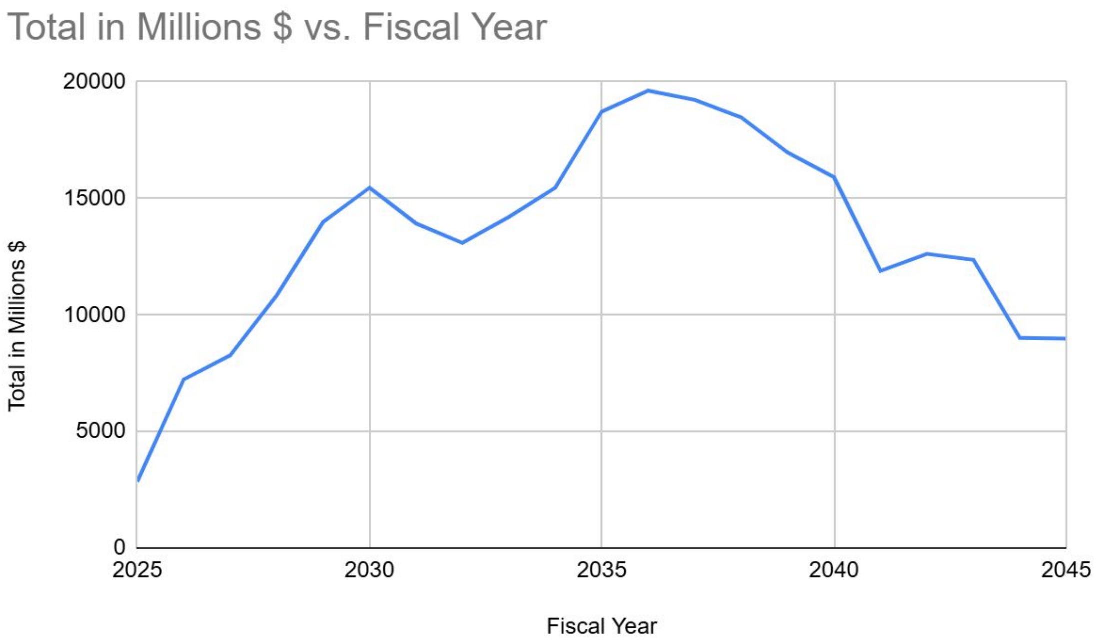
Budget

Line Item Name	DDT&E [M]	Production [M]	Total [M]
Mission to Deimos	**$ 274,287.5**	**$ 4,829.3**	**$ 279,116.8**
Flight System/Spacecraft	**$ 67,271.9**	**$ 4,829.3**	**$ 72,101.2**
Crewed Vehicle	$ 48,690.9	$ 4,536.9	**$ 53,227.8**
IPV Hab	$ 1,315.2	$ 325.6	**$ 1,640.8**
DEV	$ 7,000.0	$ 900.0	**$ 7,900.0**
Assembly Vehicle	$ 2,400.0	-	**$ 2,400.0**
TMSA	$ 5,000.0	-	**$ 5,000.0**
Structures	$ 202.9	$ 45.3	**$ 248.2**
Tanks	$ 352.6	$ 71.8	**$ 424.4**
Propulsion			
NTP Engines	$ 20,893.5	$ 397.4	**$ 21,290.9**
RCS	$ 5,961.1	$ 1,561.6	**$ 7,522.7**
Avionics			
GNC & CCDH	$ 1,052.0	$ 595.4	**$ 1,647.4**
Power	$ 449.3	$ 28.1	**$ 477.4**
Life Support	$ 3,905.7	$ 600.5	**$ 4,506.2**
Integration, Assembly, Checkout	$ 337.8	$ 292.4	**$ 630.2**
System Test Operations	$ 11,577.8	-	**$ 11,577.8**
Ground Segment	$ 6,665.4	-	**$ 6,665.4**

Line Item Name	Total [M]
Launch Vehicles	**$ 12,000.0**
6 SLS	**$ 12,000.0**
Operations	**$ 78,798.0**
Program Development Studies	**$ 1,098.0**
Mission Support	**$ 14,700.0**
Mission Operations	**$ 63,000.0**
Total Indirect Cost	**$ 116,217.6**
Tracking and Data Acquisition	**$ 24,000.0**
Construction of Facilities	**$ 17,217.6**
Research and Program Management	**$ 75,000.0**

Total: $279 billion

Budgets by Year



2025-2028 →
Pre-Phase A: Concept Studies

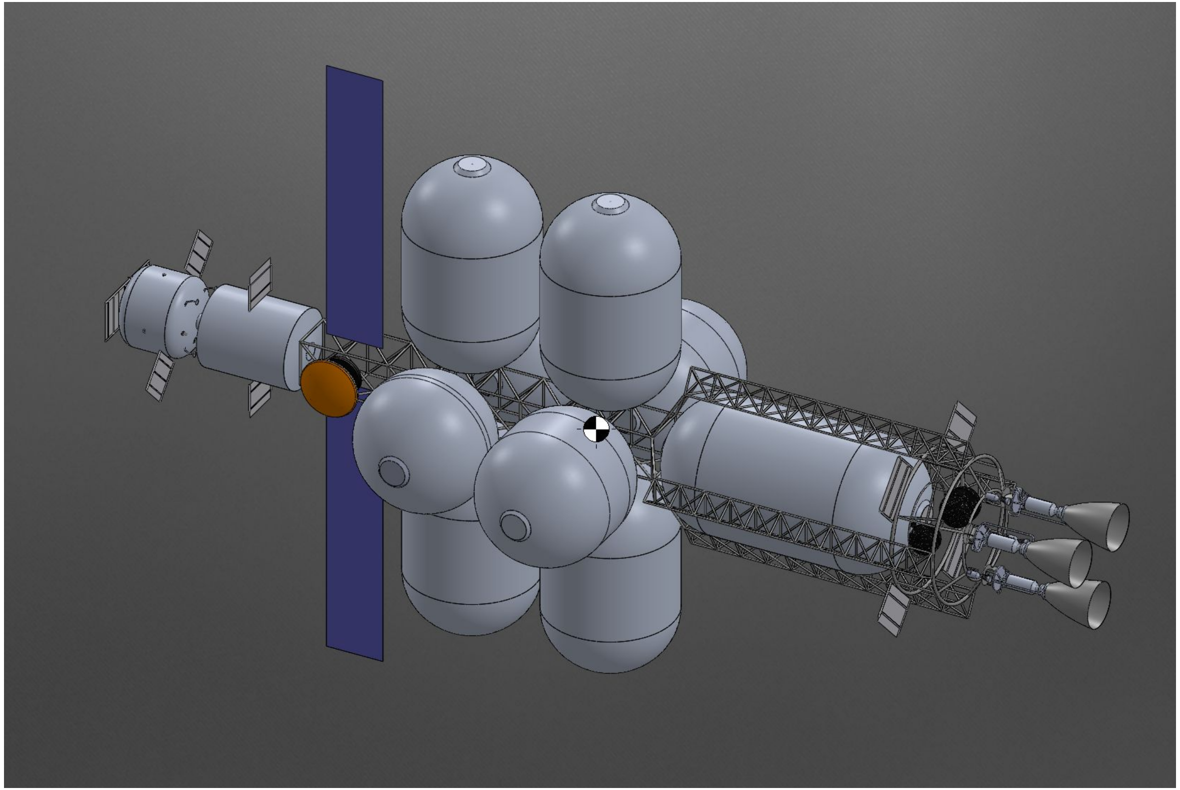
2028-2031 →
Phase A: Concept & Technology Development

2031-2035 →
Phase B: Preliminary Design & Technology Completion

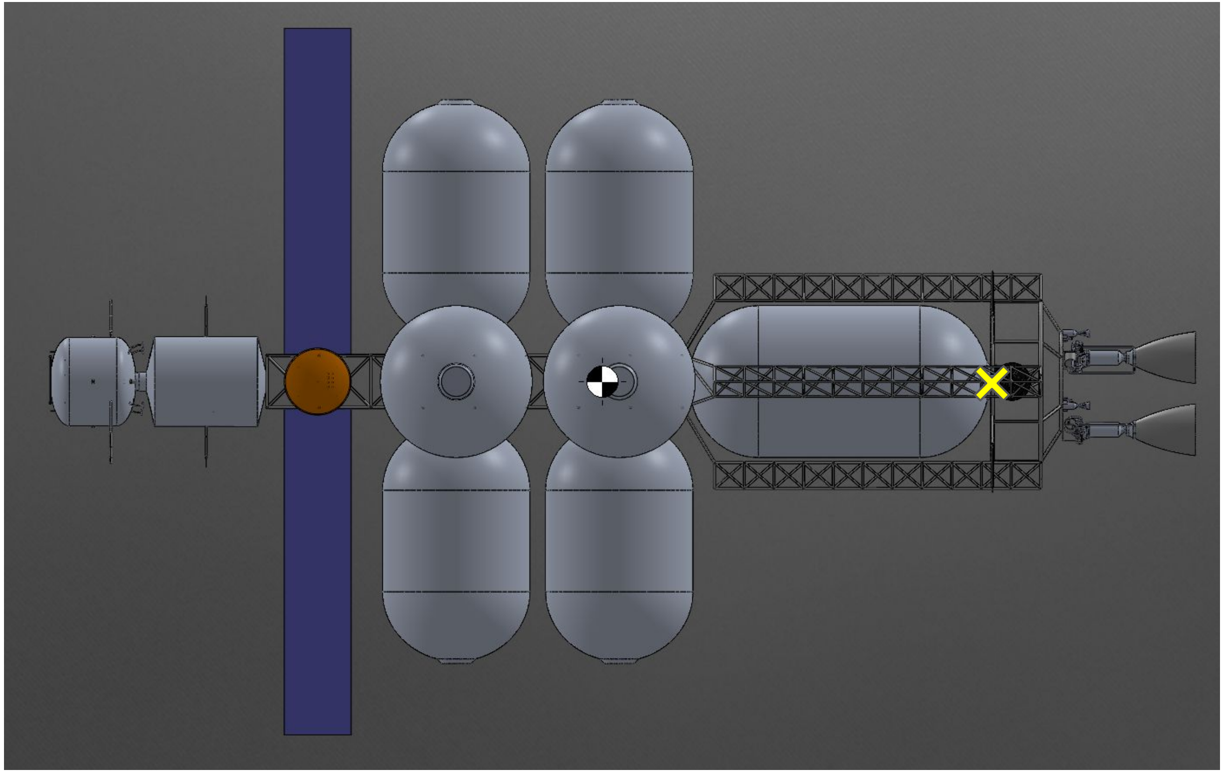
2035-2040 →
Phase C: Final Design & Fabrication

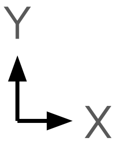
2040-2045 →
Phase D: System Assembly, Integration, and Test, Launch

IPV Assembly CAD



IPV Assembly CAD Center of Mass Location





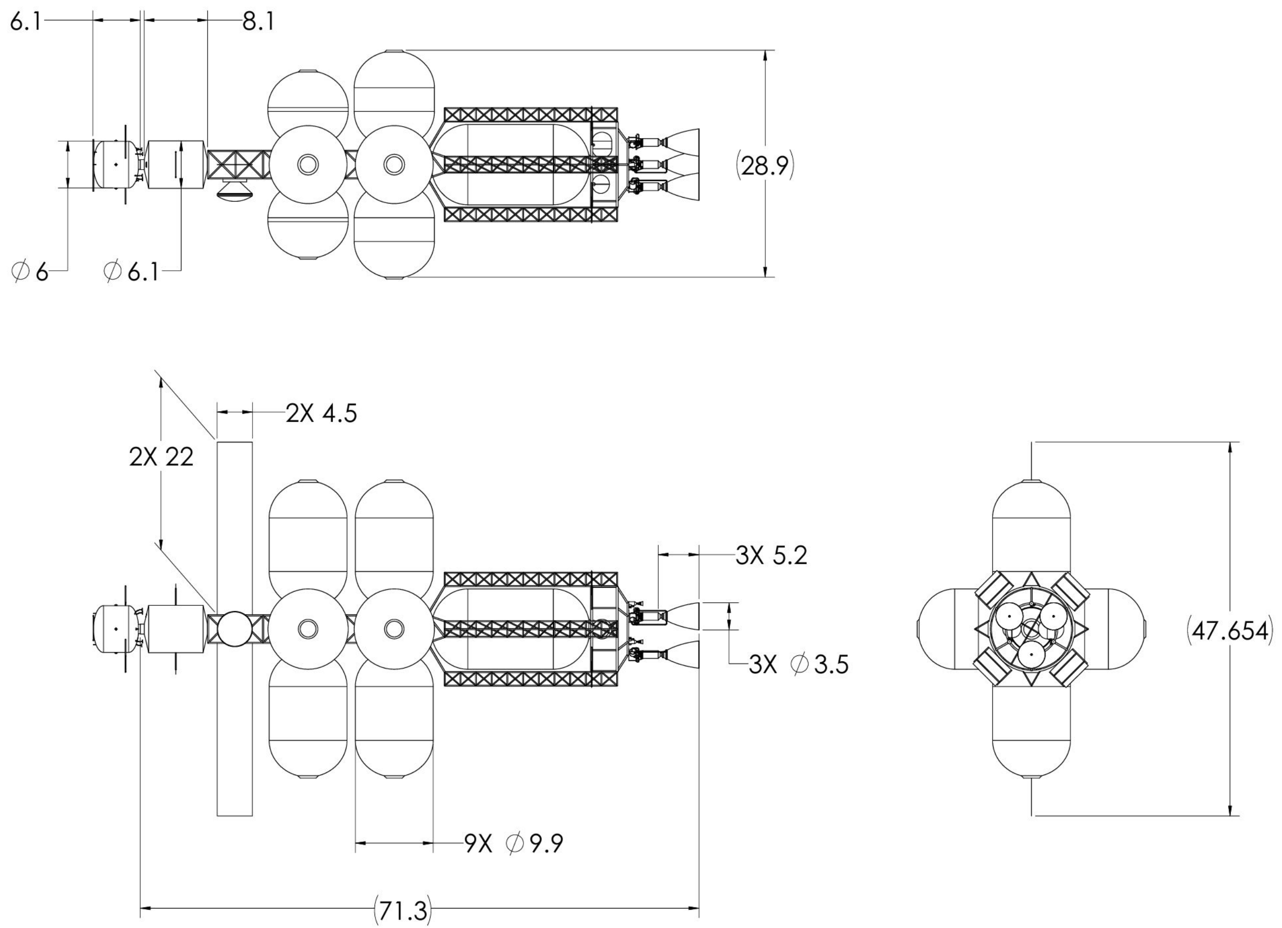
CoM Coordinates:

X = -25.779

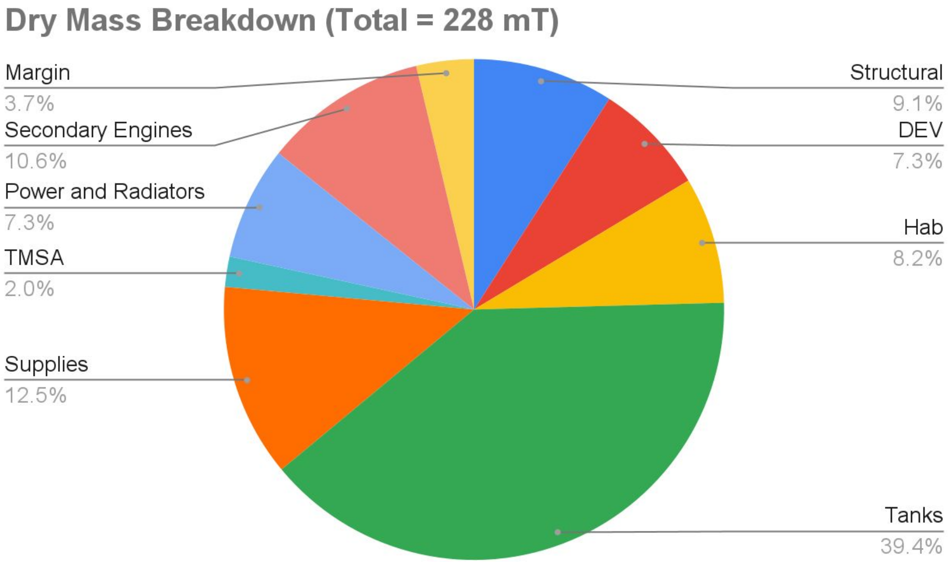
Y = -0.008

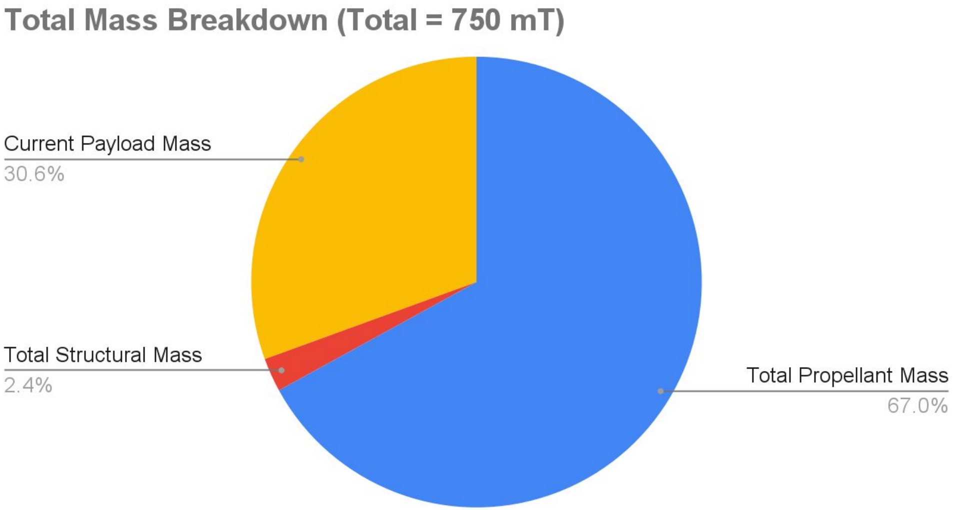
Z = -0.010

3-View of Entire Assembly



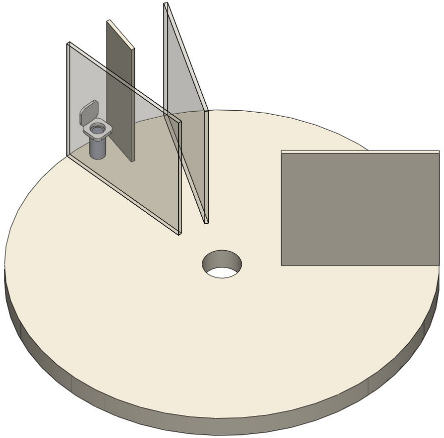
Mass Budget

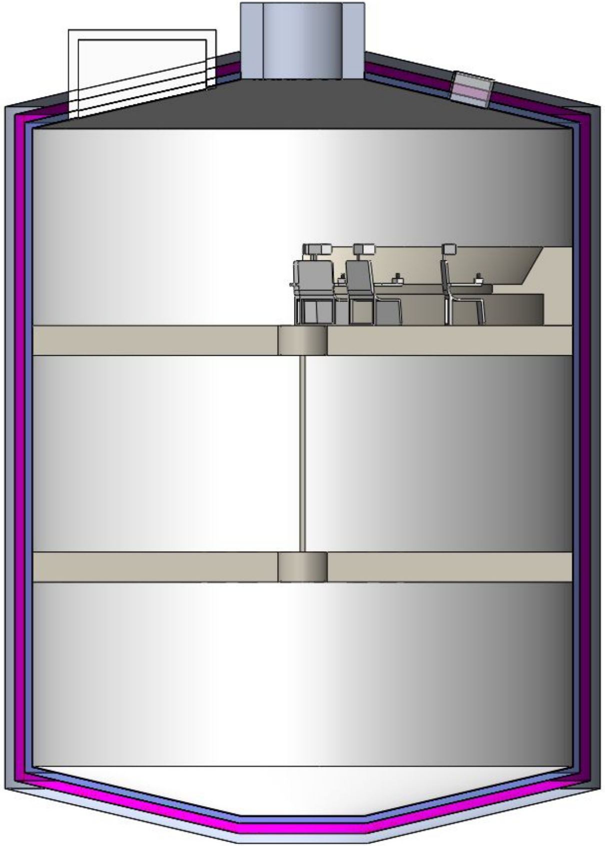

Dry Mass Breakdown (Total = 228 mT)
Margin
3.7%
Secondary Engines
10.6%
Power and Radiators
7.3%
TMSA
2.0%
Supplies
12.5%
Structural
9.1%
DEV
7.3%
Hab
8.2%
Tanks
39.4%

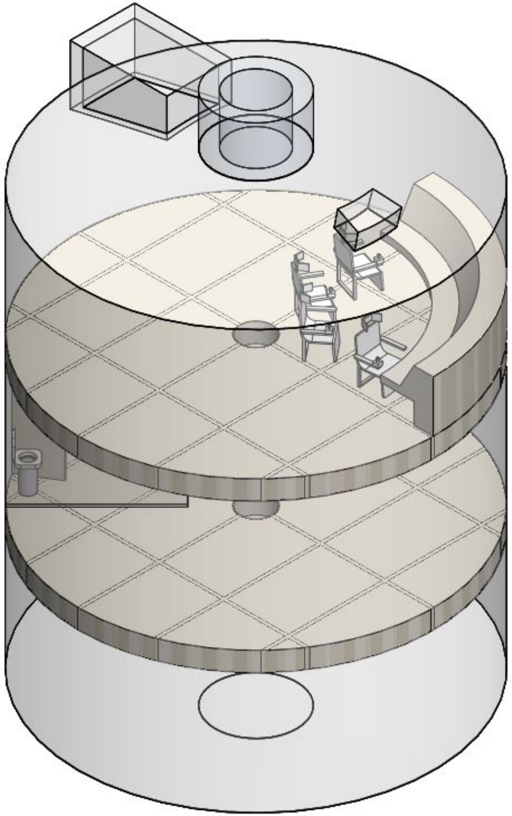

Total Mass Breakdown (Total = 750 mT)
Current Payload Mass
30.6%
Total Structural Mass
2.4%
Total Propellant Mass
67.0%

IPV Hab CAD

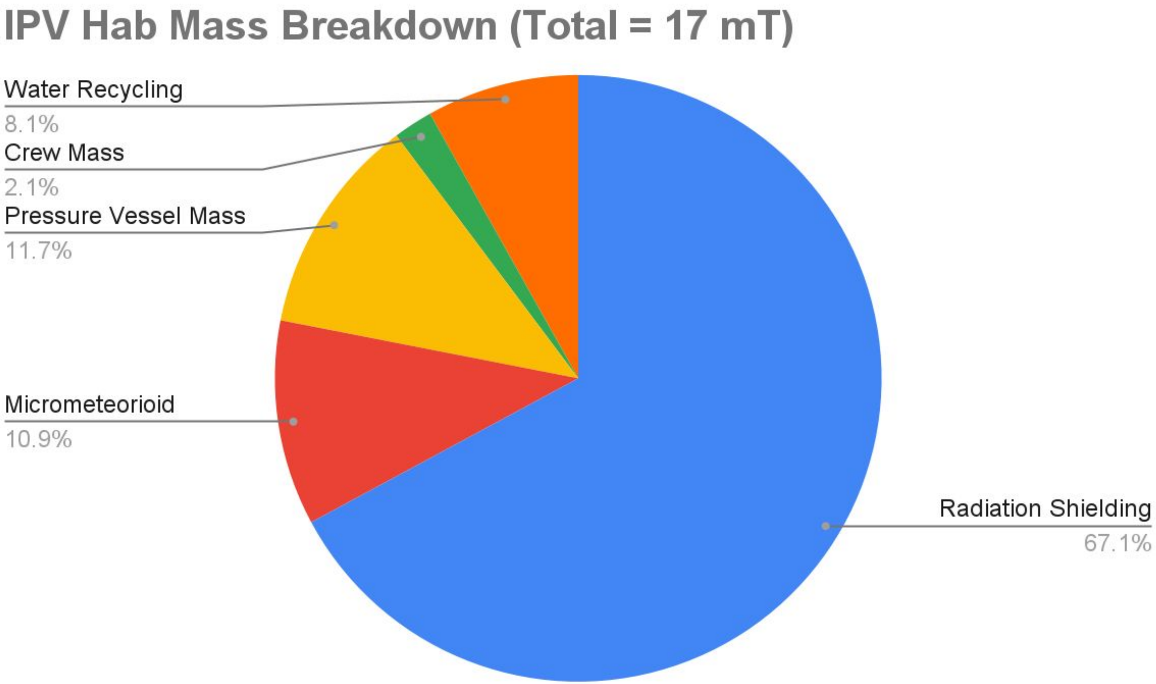
Diameter	6.05 m
Length	8.5 m





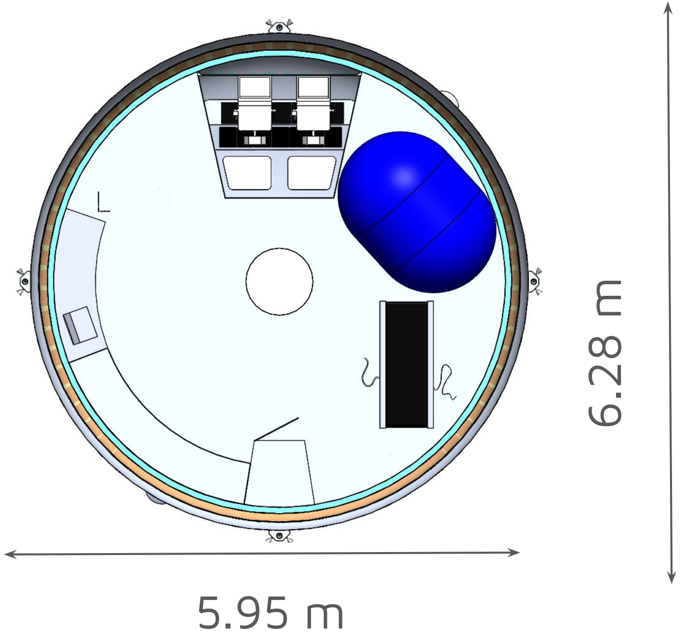


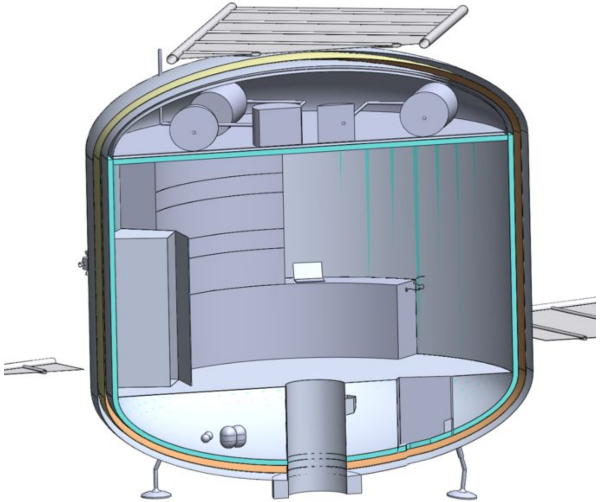
IPV Hab Mass Budget

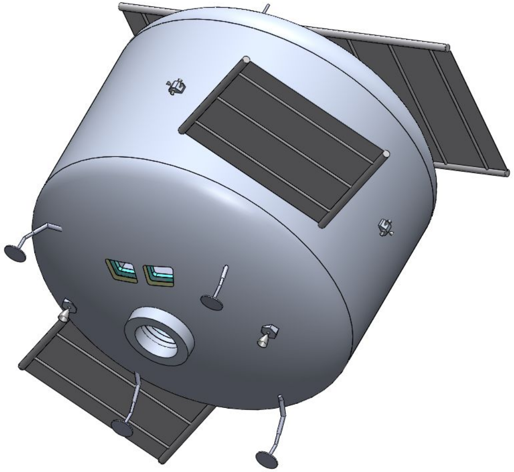


Component	Mass (mT)
Rad. Shielding	11.5
Micrometeoroid Shielding	1.9
Pressure Vessel	2
Water Recycling	1.4
Crew	0.36
Total	**17**

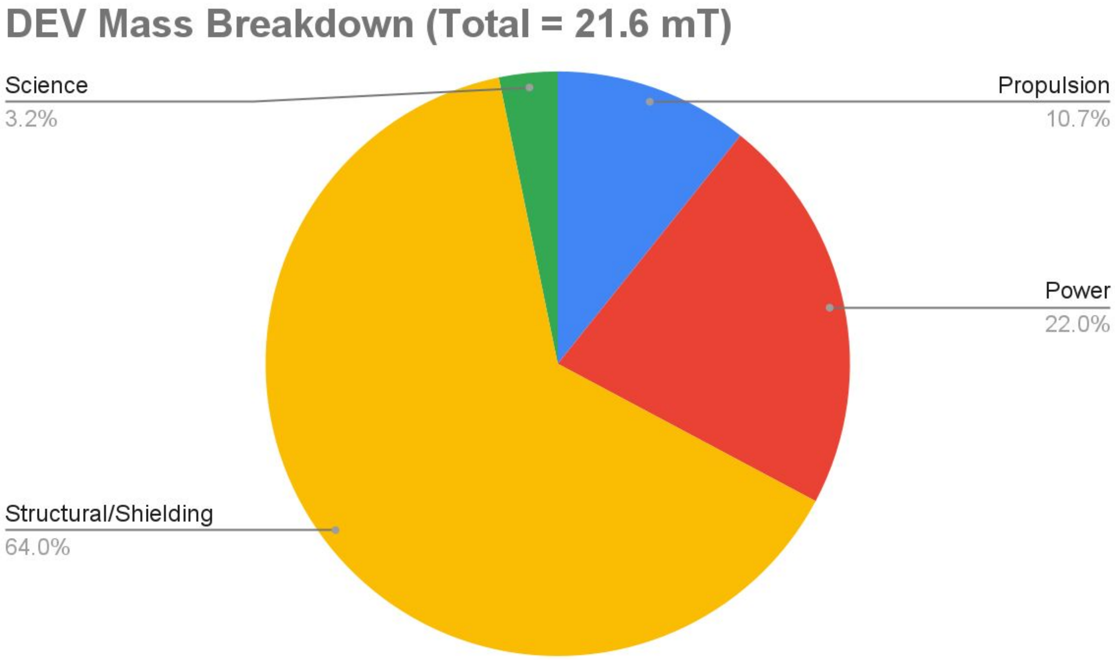
DEV CAD







DEV Mass Budgets



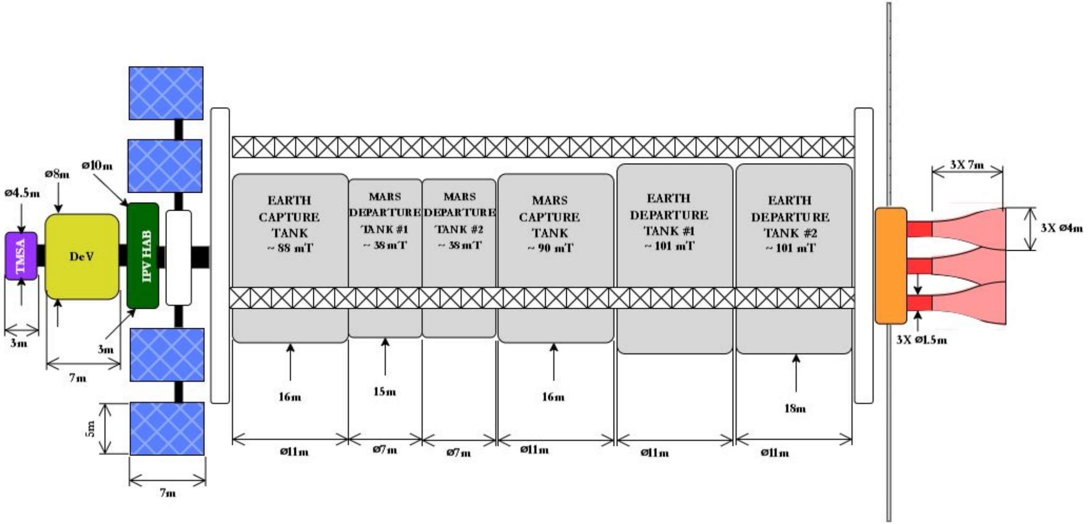
Component	Mass (mT)
Structural/Shielding	13.9
Power	3.4
Propulsion	1.7
Science	0.5
Total	21.6

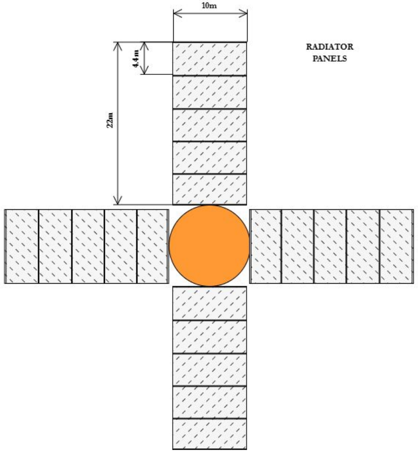
Alternative Concepts

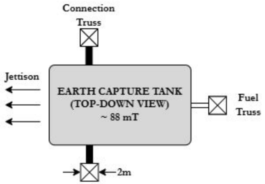
- Vending Machine Design
- Inline Tanks

Not Selected:

- Too much Truss Mass





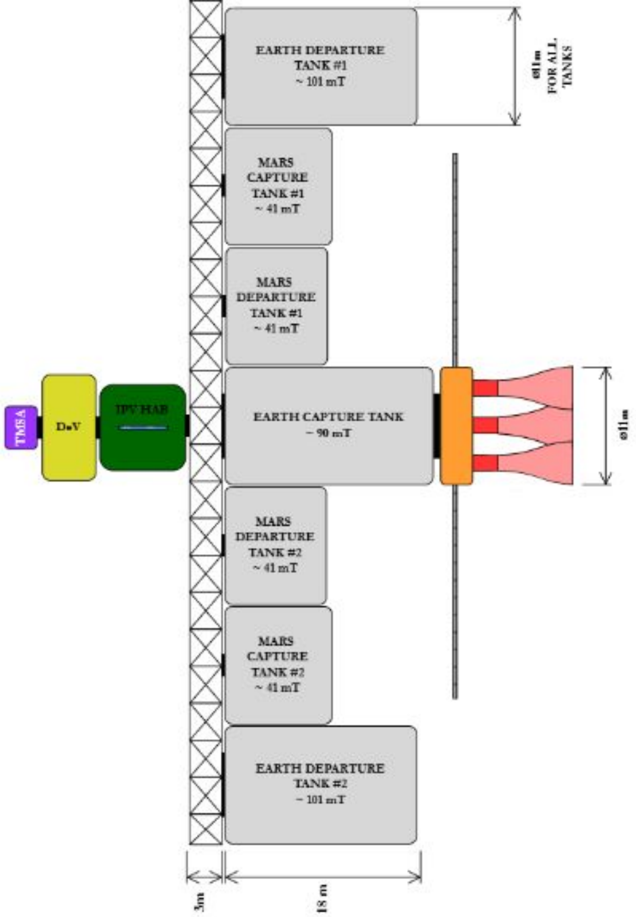


Alternative Concepts

- Albatross Design
- Adjacent Tanks

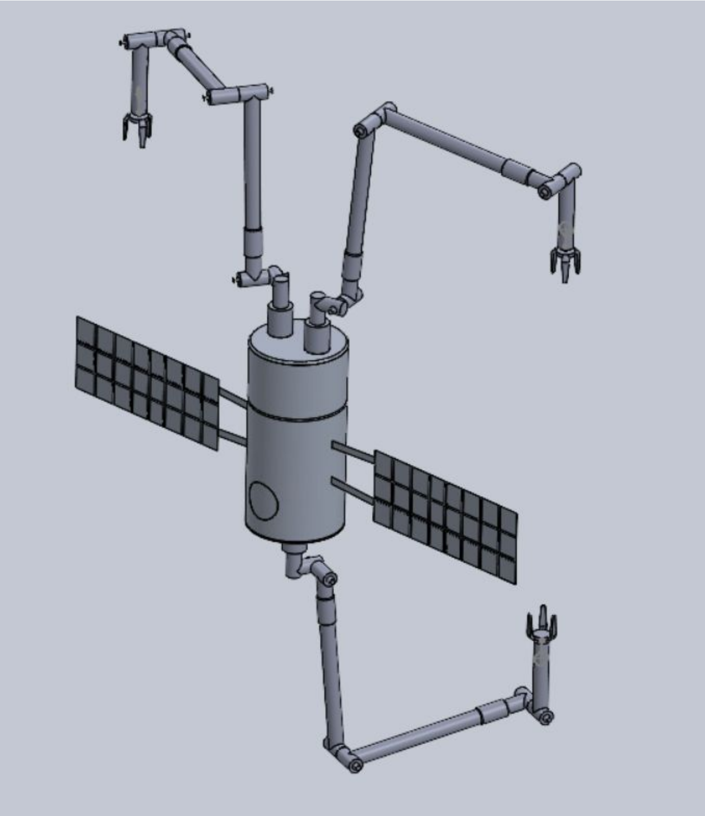
Not selected:

- IPV Hab is in radiation zone
- Engines are thrusting into EC Tank



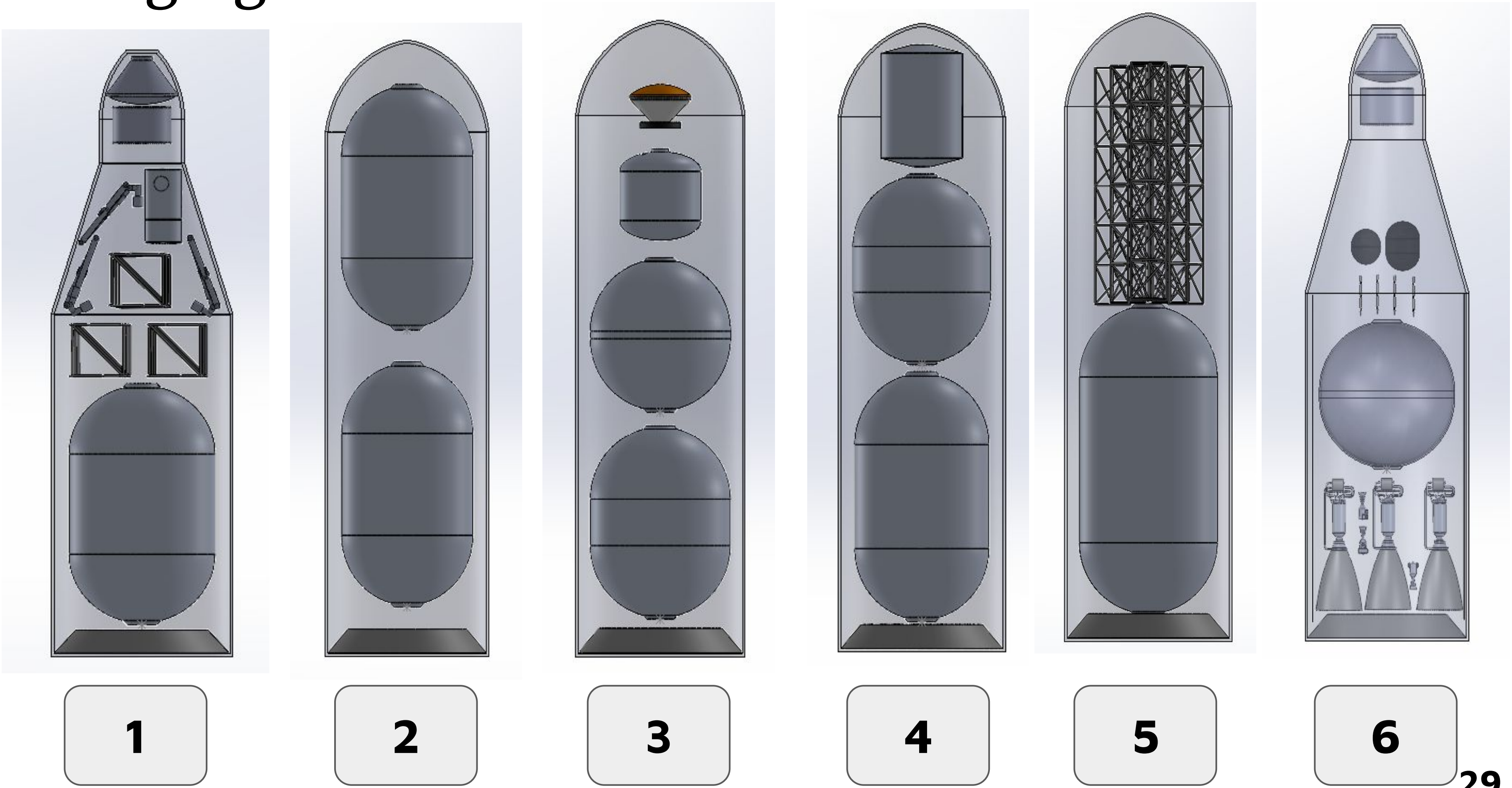
Assembly Vehicle CAD

A2 Specs	
Diameter (m)	2.5
Height (m)	5
Arm Length (m)	10
Material	Aluminum 7075
Total Mass (mT)	1.8
Propellant Mass (mT)	0.178
Propellant	MMH & N_2O_4



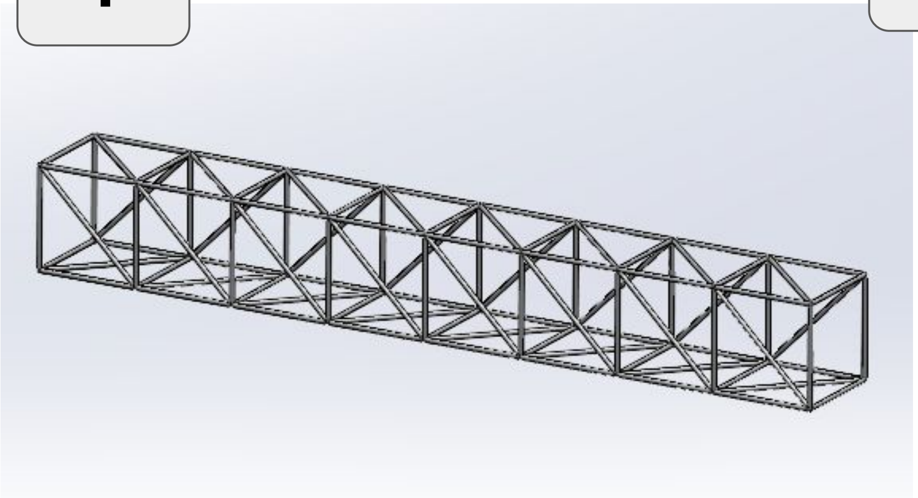
Packaging

Fairing Diameter / Length: 12m / 41m

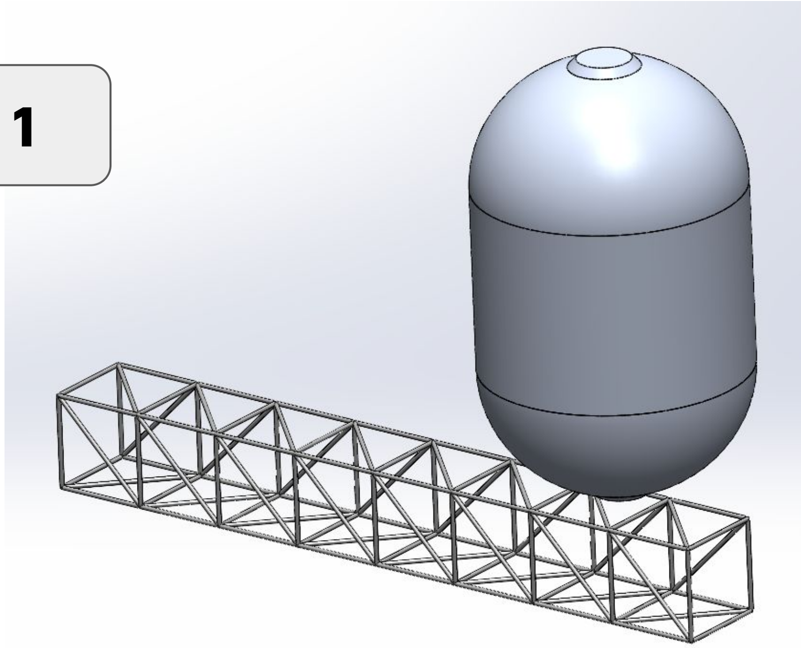


Assembly Steps

1



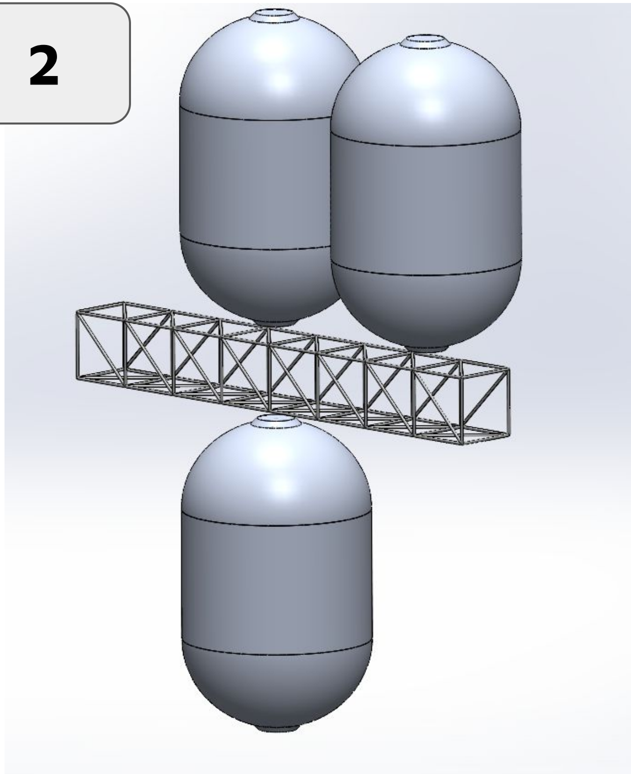
1



[Truss Assembly Details]

Assembly Steps

2



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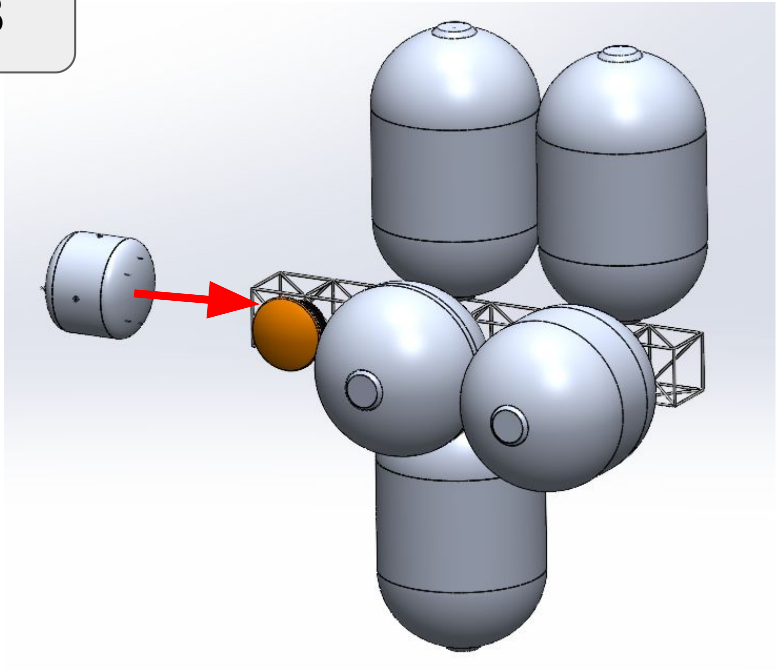
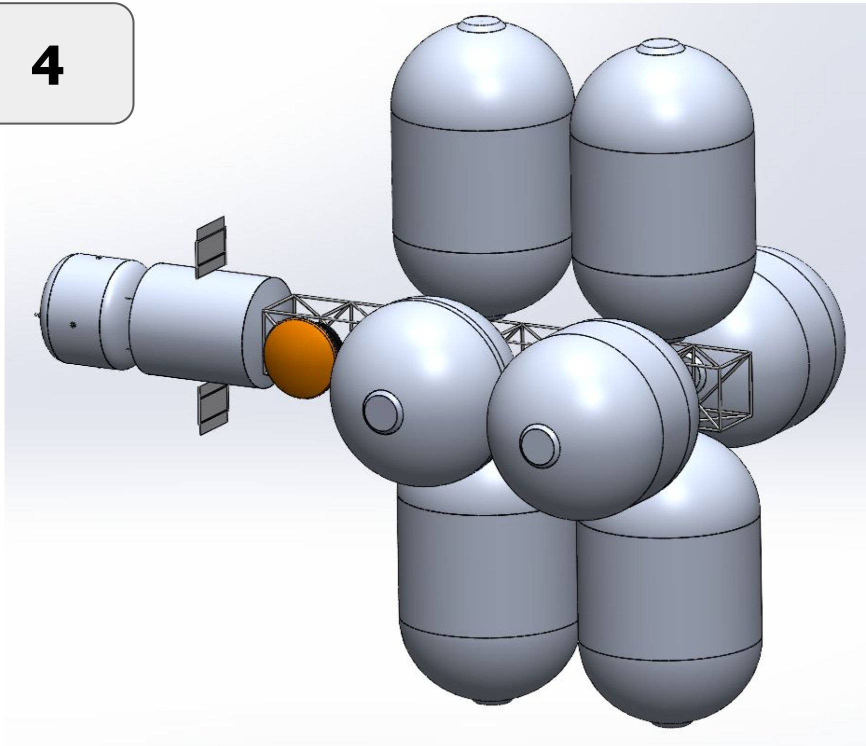


Assembly Steps

4



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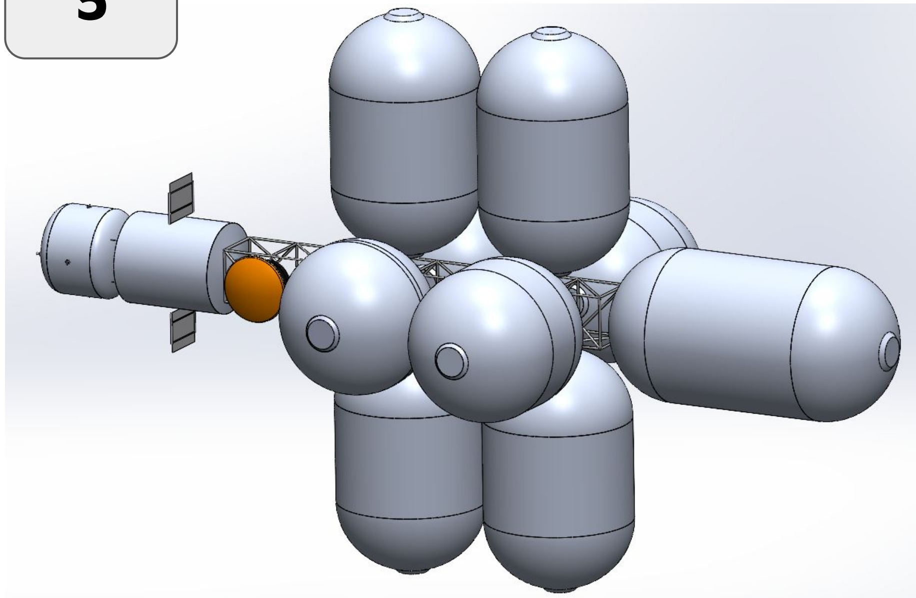
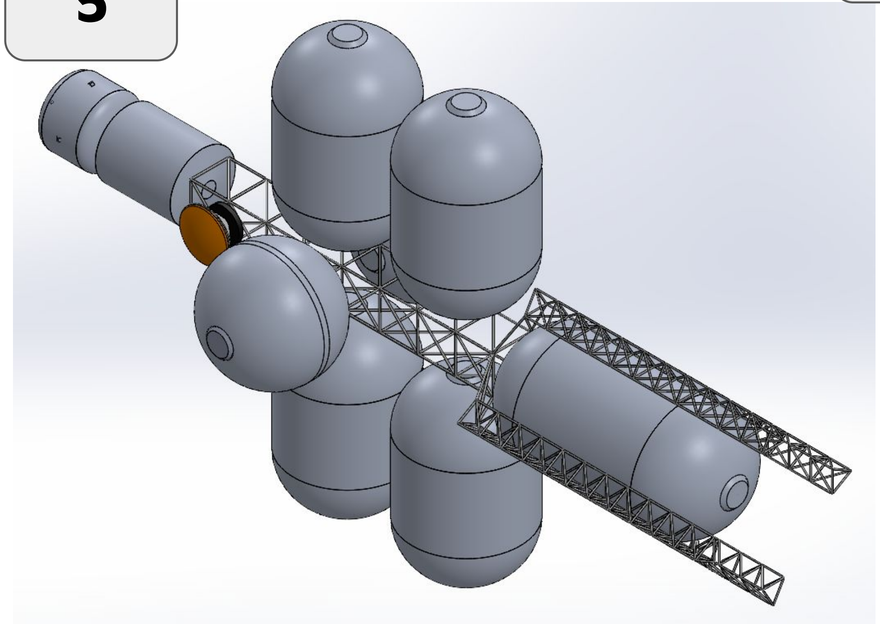


Assembly Steps

5



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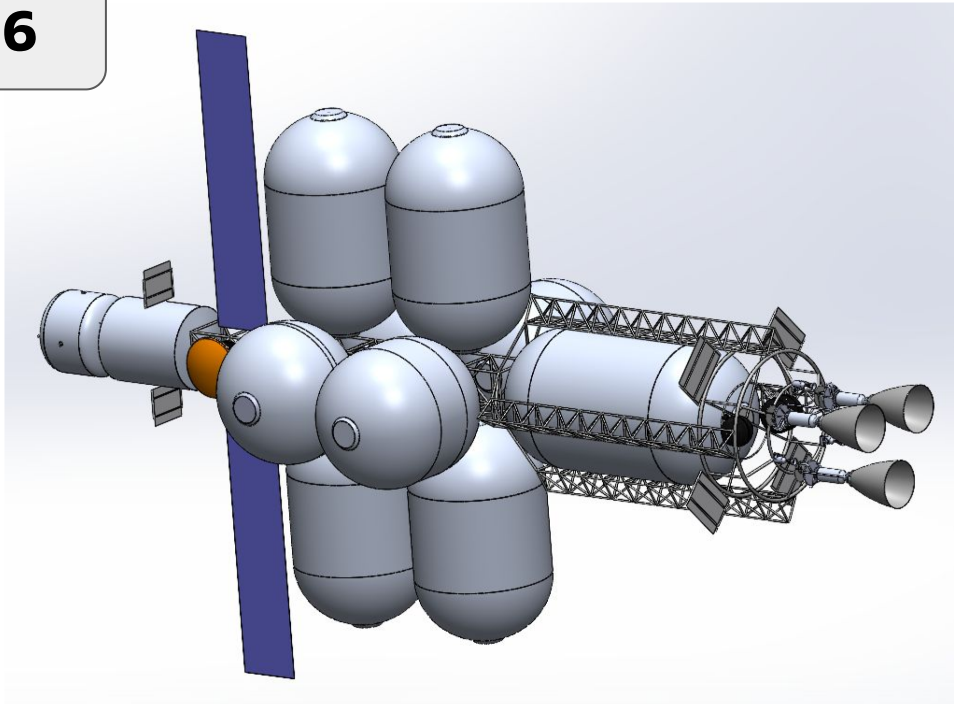
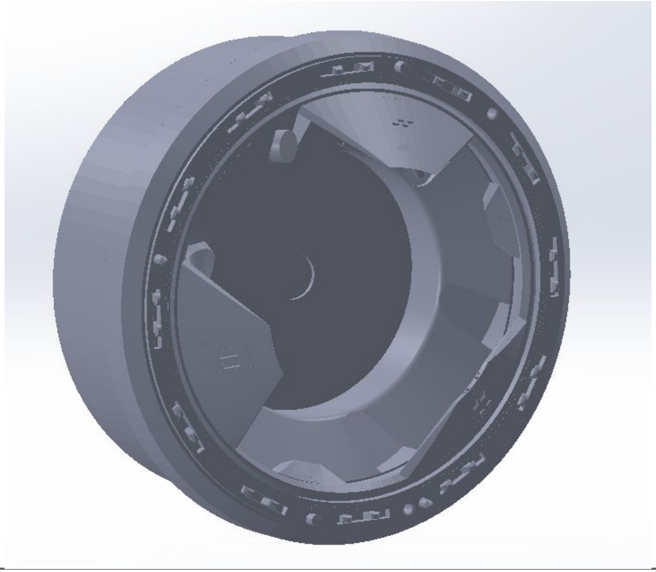
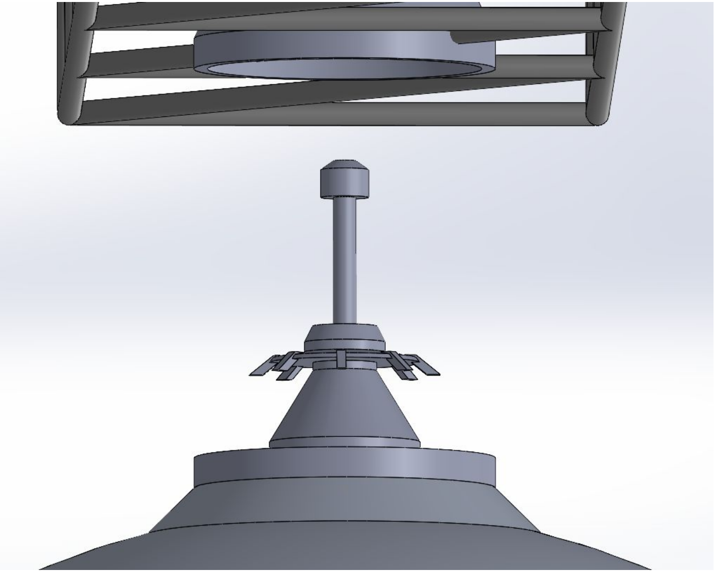


Docking Mechanisms

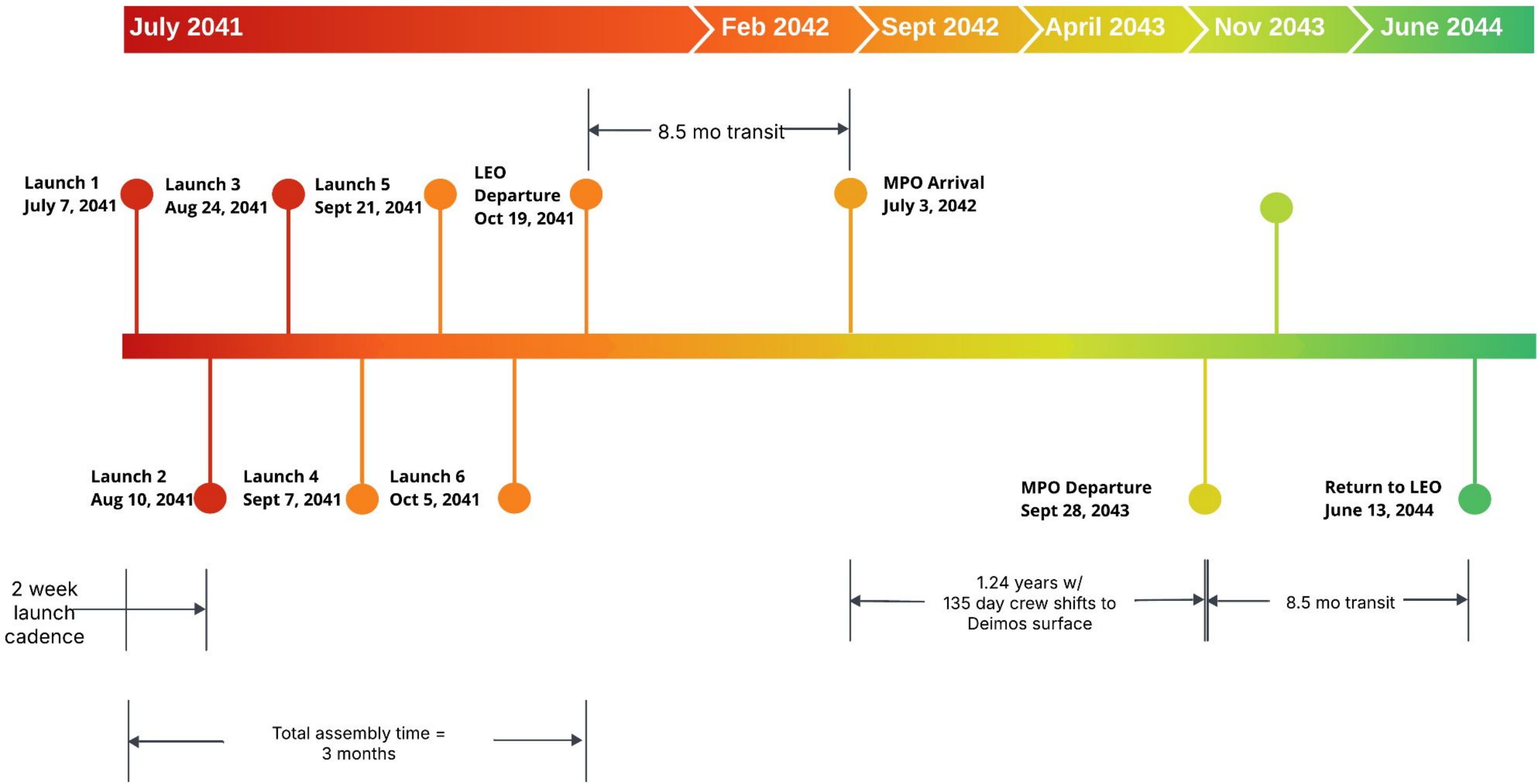
Pressurized Connections
IDSS Docking System for DEV, Hab
1.2m Tunnel Diameter



Unpressurized Connections
Probe and Drogue with LH_2 Crossfeed
2m Drogue Diameter



Launch and Assembly Timeline



Mission Profile

Earth Departure:

- Impulsive ΔV: 3.819 km/s
- Finite ΔV losses: 0.390 km/s (10.2% inc.)
- **ΔV: 4.209 km/s**

Mars Departure:

- Impulsive ΔV: **2.13 km/s**

Mars Capture:

- Impulsive ΔV: **2.13 km/s**

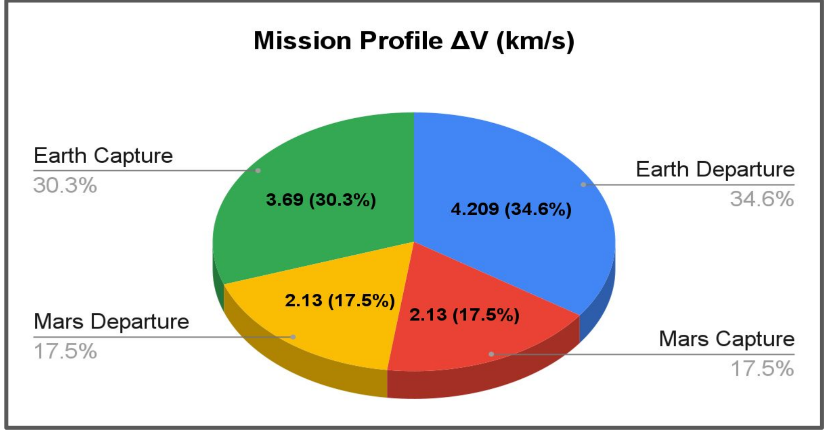
Earth Capture:

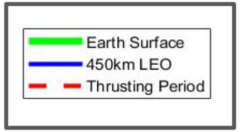
- Impulsive ΔV: 3.61 km/s
- Finite ΔV losses: 0.080 km/s (2.2% inc.)
- **ΔV: 3.69 km/s**

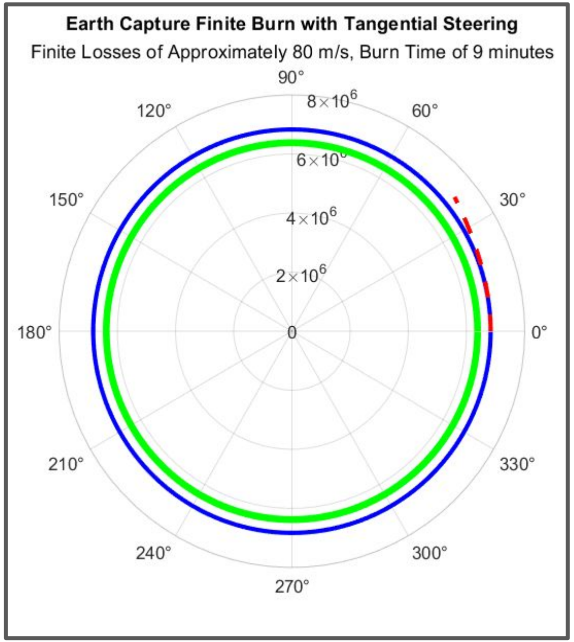
Total ΔV: 12.16km/s

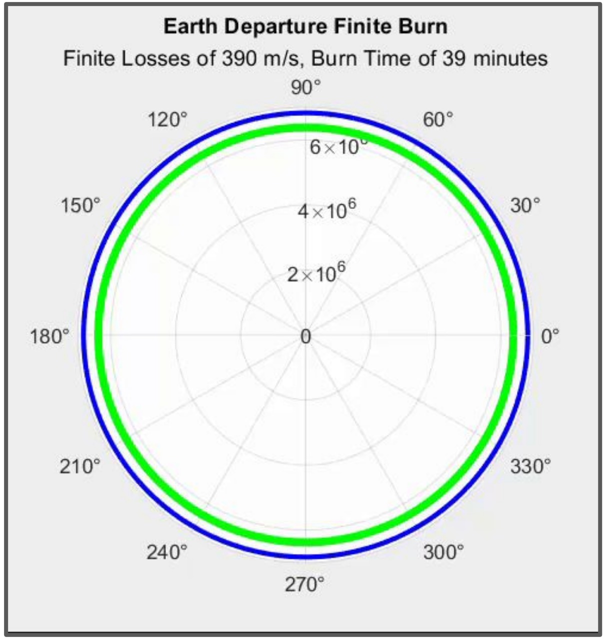
Finite-Thrust Escape From and Capture Into Circular and Elliptic Orbits, Edward A. Willis, Jr., Lewis Research Center, 1966

Finite Burn Analysis Appendix Slide



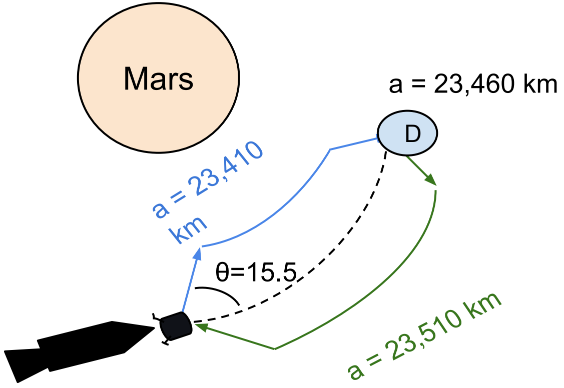






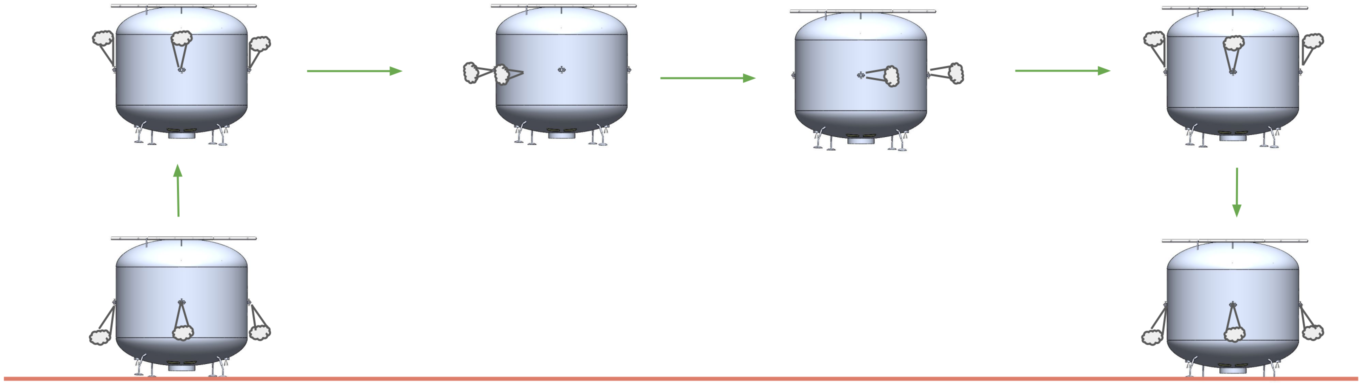
Deimos Ops Maneuvers

Maneuver	Time	ΔV	Distance
IPV to Deimos	19.26 hrs	3.79 m/s	100km
Deimos to IPV	19.32 hrs	3.78 m/s	100km



Deimos Surface Maneuvering

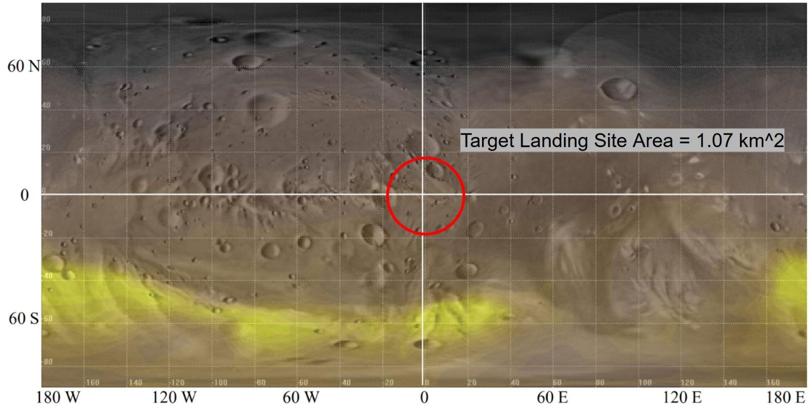
Total Burn Time	Total ΔV
140 sec	1.4 m/s



Landing Zone and Target Sites

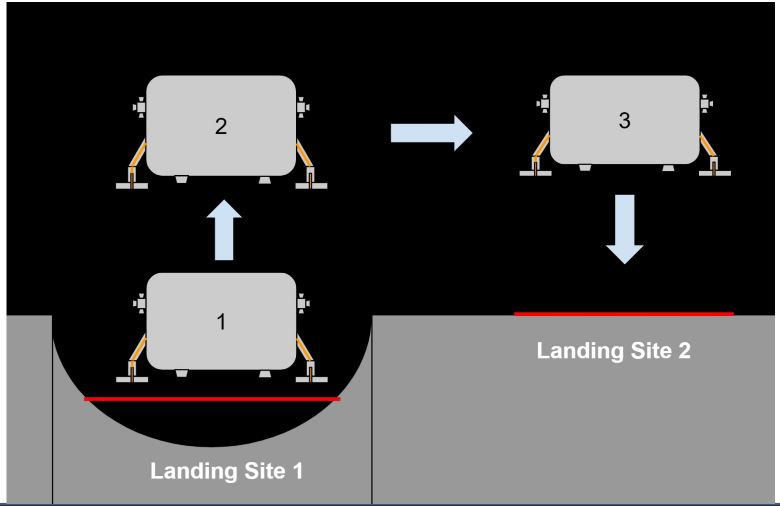
Landing Zone:

- Landing Zone: 0-20°N,E,S,W
- Optimal line of sight to Mars
- Low solar radiation
- Multiple craters for maximum science operation data collection



Target Sites:

- 10 target sites per 135 day trip
- Maneuvers site to site done by RCS propulsion
- 5% propellant mass margin for maneuvers over 20m

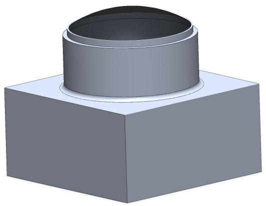


Joshua B. Hopkins, "Comparison of Deimos and Phobos as Destinations for Human Exploration and Identification of Preferred Landing Sites", Lockheed Martin Space Systems, 2011

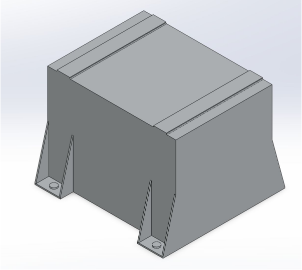
Deimos Science Operations

Goal: Determine whether Deimos originated from Mars or was captured as an asteroid

Science Device:	Purpose:
Ground Penetrating Radar (GPR) (1)	Determine the depth of the Regolith layer
LiDAR (1)	Determine surface composition & age of craters
FTIR Spectroscopy Probe (1 per leg)	Complete spectral analysis on Deimos Regolith samples

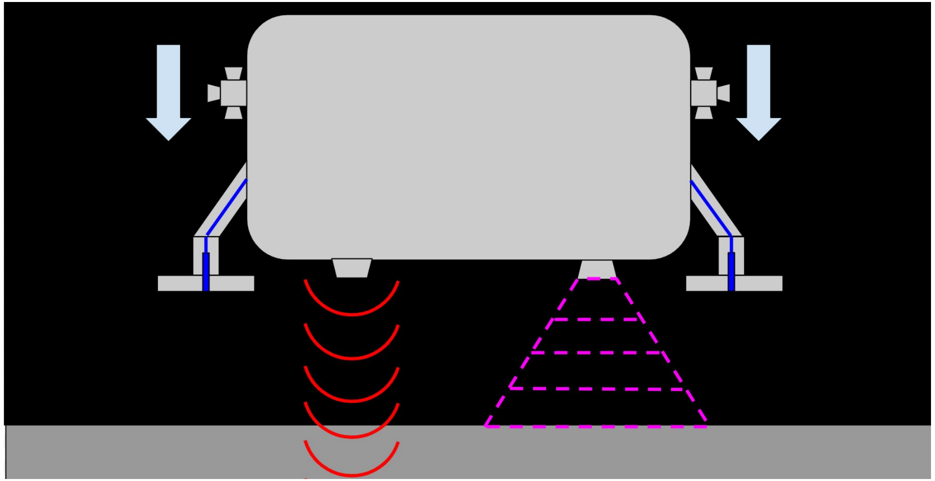


LiDAR:
20x20x15 cm
14 kg



GPR:
20x19x8 cm
9.6 kg

FTIR Probe:
3x3x15cm
0.24 kg



Life Support Consumables

-	DEV	TOTAL/IPV	Redundancy	Rate	Rate (Mission Scale)
Oxygen	360 kg	6920 kg	100%	.89 kg/day/CM	0.11 mT/Month
Nitrogen	75 kg	1770 kg	50%	80/20 (N/O)	0.43 mT/Month
Water	2640 kg	9230 kg	100%	4.03 kg/day/CM	0.48 mT/Month
Food	345 kg	6220 kg	100%	.80 kg/day/CM	0.10 mT/Month
Water Rec. Sys.	-	1390 kg	75% recycling	-	**Total Mass Consumption Rate**
Habitable Vol.	73 m^3	164 m^3	-	-	**1.11 mT/Month**

Astronaut Mass Balance for Long Duration Missions, Michael K. Ewert, NASA Johnson Space Center, 2019

Resupply Option

Oxygen	
kg/person/day	0.89
Redundancy	2
Extra for 454 day wait (mT)	3.23

Food	
kg/day	3.20
Redundancy	1.4
Extra for 454 day wait time (mT)	2.03

Water	
kg/person/day	4.03
Redundancy	2
Extra for 454 day wait time (mT)	14.64

LH_2		
	Mars Depart Tanks	Earth Capture Tank
Trip to Mars boil off (mT)	0.88	2.94
454 day wait boil off (mT)	1.51	4.9
Extra needed (mT)	2.39	7.9

Total Resupply mass: 28.91mT

5. Structures

5.1 Habitable Structures

- 5.1.1 DEV Primary Structure
- 5.1.2 IPV Hab Primary Structure

5.2 Propellant Tanks

- 5.2.1 IPV LH_2 Tanks
- 5.2.2 DEV Tanks
- 5.2.3 OMS MMH N_2O_4 Tanks
- 5.2.4 Ullage Tanks

5.3 Trusses

- 5.3.1 Main Truss
- 5.3.2 Truss Connection
- 5.3.3 Thrust Structure

5.4 Radiation Shielding

- 5.4.1 DEV Shielding
- 5.4.2 IPV Hab Shielding

5.5 Insulation

- 5.5.1 Propellant Tanks
- 5.5.2 Habitats
- 5.5.3 Radiators

5.6 MMOD Shield

- 5.6.1 Habitats
- 5.6.2 Propellant Tanks

NASA-STD-5001B, 2014 (General Factors of Safety)
ANSI/AIAA S-080 (COPVs)
ANSI/AIAA S-081 (PVs)

Isogrid Structures: Habitable Volumes

Loading	
Pressure (MPa)	0.2
Thrust LF	- 4.1g
Lateral LF	3.0g
FoS	1.5
Material	Al 2219-T62

	IPV Hab (42mT)*	DEV (21mT)
$N_{cr\ allow}$ (kN/m)	309.85	187.88
Failure Load (N_{cr} min) (kN/m)	310.53	211.03
P_{allow} (MPa)	0.22	0.19
Cylinder Mass (kg)	900	340
Total Mass (kg)	1840	2605

Computing the Loads per Unit Length:

Axial Loading:

$$N_a = \frac{F_a * FS}{2\pi R}$$

Bending Loading:

$$N_b = \frac{M * FS}{\pi R^2}$$

Combined Loading Condition:

$$N_a + N_b = N_{cr}$$

General Instability

$$N_{cr(1)} = c_0 E \frac{t^2}{R} \beta$$

Skin Buckling:

$$N_{cr(2)} = c_1 E t (1+\alpha) \frac{t^2}{h^2}$$

Rib Crippling:

$$N_{cr(3)} = c_2 E t (1+\alpha) \frac{b^2}{d^2}$$

Burst Pressure:

$$p_{burst} = \frac{F_{tu} t (1+\alpha)}{R}$$

Computing Failure Loads:

$$NL_{cr(n)} = 2\pi N_{cr(n)} R$$

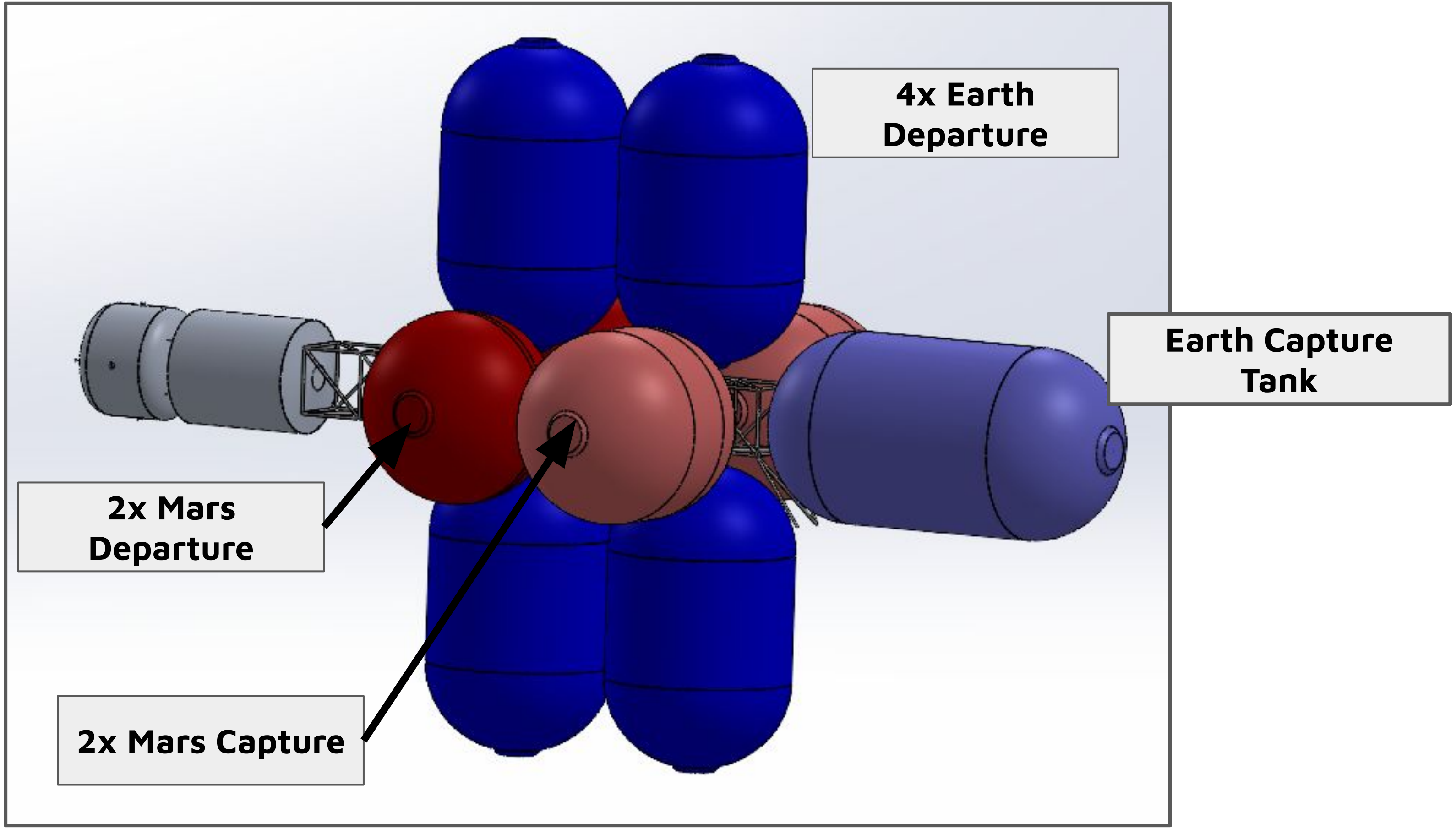
Meyer R.R, Harwood O.P, et al., 1973, *Isogrid Design Handbook, NASA*

NASA ESD, 2018, *SLS Mission Planner's Guide*

ASME, 2017, *Pressure Vessel Code Section VIII 1-4*

[Isogrid Dimensions Appendix]

Propellant Tank CAD Diagram



Structures: Composite Tanks

N_ϕ: Axial Loading

N_θ: Hoop Loading

α: Helical Winding Angle (degrees)

X_t: Ultimate Tensile Strength (MPa)

P: Internal Pressure (MPa)

$t_{\alpha f}$: Thickness Req for Helical Wind (mm)

t_{90f}: Thickness Req for Circumferential Wind (mm)

$V.F.$: Assumed Volume Factor of Composite (0.7)

$$N_\theta = PR \tag{7}$$

$$N_\phi = PR/2 \tag{8}$$

$$\sigma_{allow} = X_t/F.S. \tag{9}$$

$$t_{\alpha f} = \frac{N_\phi}{\sigma_{allow}\cos^2(\alpha)} \tag{10}$$

$$t_{90f} = \frac{N_\theta - N_\phi \tan^2(\alpha)}{\sigma_{allow}} \tag{11}$$

$$t = \frac{t_{\alpha f} + t_{90f}}{V.F.} \tag{12}$$

Tew, B. W., 1995. "Preliminary Design of Tubular Composite Structures Using Netting Theory and Composite Degradation Factors." ASME. J. Pressure Vessel Technol. November 1995

LH_2

Al 2219-T87 Liner

Intermediate Layer

CyCom IM7-977-3

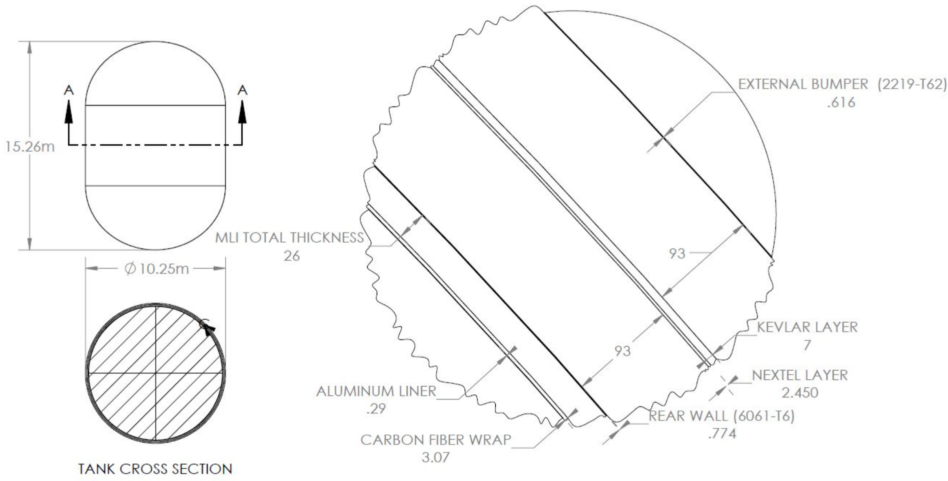
Parameters	Values
FoS	1.5
Axial LF	-4.1g
Lateral LF	3.0g
CF	Cycom 5250-4
Vol % Full	95%

*thermal expansion analysis appendix slide

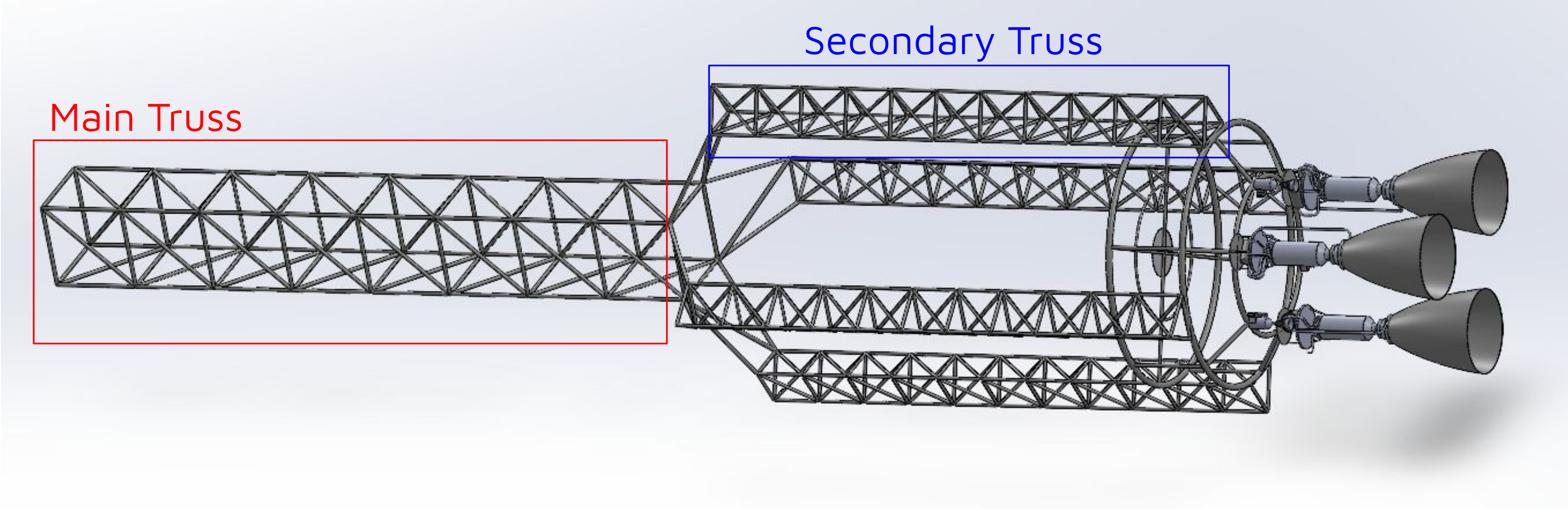
Parameter	Earth Departure Tanks
Radius (m)	4.90
Length (m)	15.60
CF Thickness (mm)	2.97
Aluminum Liner Thickness (mm)	0.33
CF End Cap Thickness (mm)	0.86
Structure Mass/Tank (kg)	**2850**

Structure: Tank Mass Breakdown

Layer (mT)	Earth Depart (x4)	Mars Capture (x2)	Mars Depart (x2)	Earth Capture (x1)
LH_2	64.25	47.90	34.40	90.05
Primary Structure	2.90	2.38	1.88	3.92
MLI	0.50	0.43	0.34	0.71
MMOD	6.01	4.56	3.19	7.72
Total Mass	73.8	55.3	40.21	101.91



Truss Subassembly Components

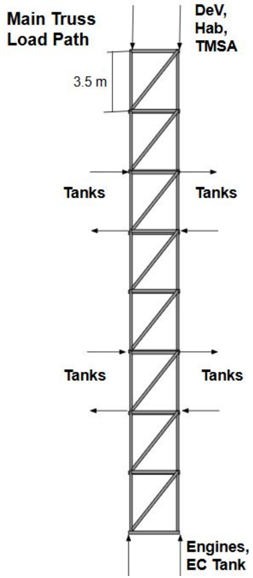


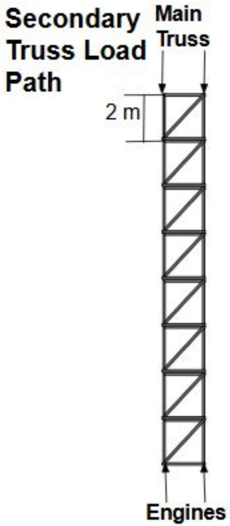
Structure: Main and Secondary Trusses

Loading	
Axial	- 4.1g
Lateral	3.0g
FOS	1.5

IM7/5555	
Failure Stress (MPa)	1330
Allowable Stress (MPa)	886.67

Parameter	Main	Secondary
Diagonal Member Diameter (m)	0.15	0.115
Side Member Diameter (m)	0.154	0.118
Diagonal Member Length (m)	4.95	2.83
Side Member Length (m)	3.5	2
Thickness (m)	0.023	0.019
Maximum Stress (MPa)	507.8	860.5
Total Mass (mT)	5.97	9.83





$$I_{member} = \frac{FL^2}{\pi^2 E}$$

$$I_{member} = \frac{\pi}{4}\left(r_o^4 - r_i^4\right)$$

$$r_i = r_o - t$$

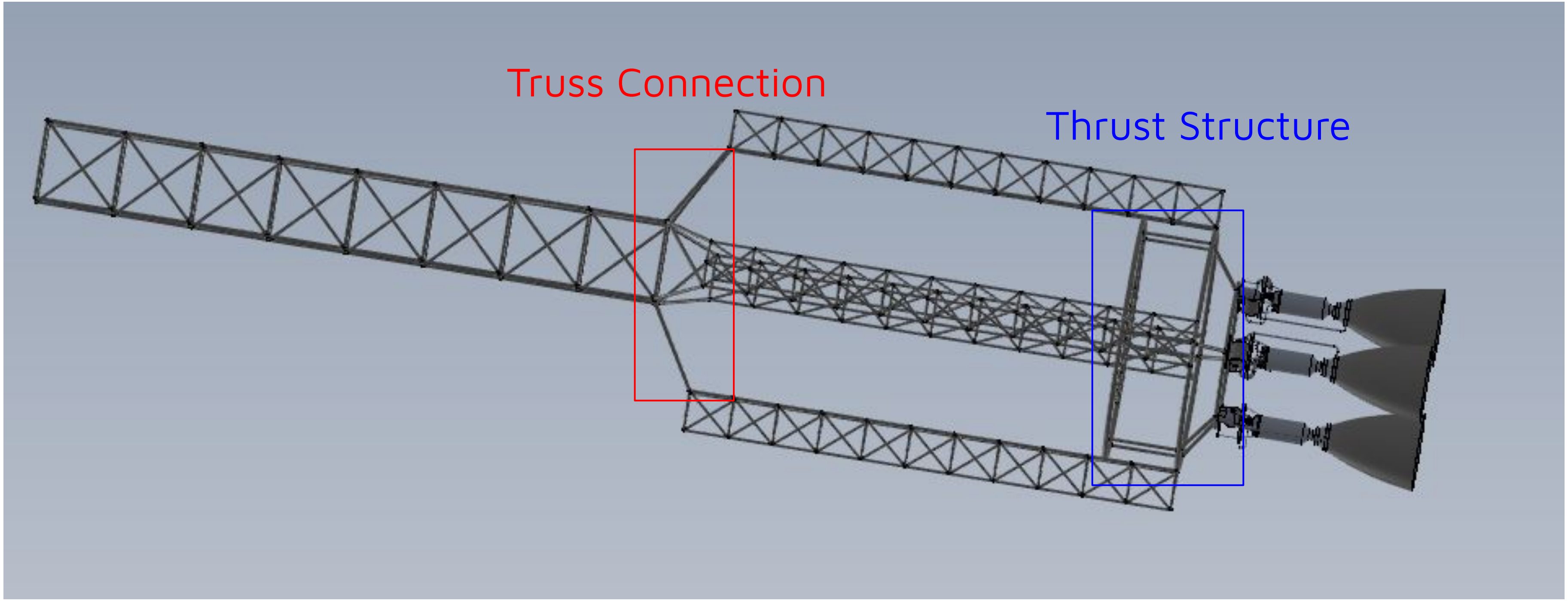
$$A_{member} = \pi\left(r_o^2 - r_i^2\right)$$

$$\sigma_{max,\,axial} = F / A_{member}$$

$$\sigma_{allowable} = \sigma_{failure} / FOS$$

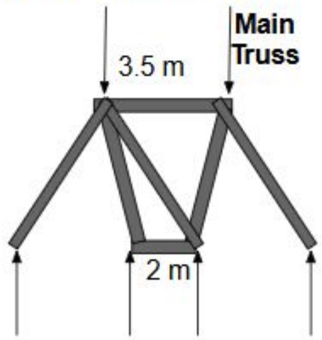
Jacob J Wijker, “Spacecraft Structures”, 2008

Truss Subassembly Components



Structure: Truss Connections

Loading	
Axial	- 4.1g
Lateral	3.0g
FOS	1.5



	Middle Members from Main to Secondary	External Members from Main to Secondary
Number of Members	4	8
Length (m)	5.062	4.316
Outer Diameter (m)	0.1750	0.1547
Thickness (m)	0.0175	0.0155
Max Stress (MPa)	129	151.8
Total Mass (mT)	0.64	

IM7/5555	
Failure Stress (MPa)	1330
Allowable Stress (MPa)	886.67

$$I_{member} = \frac{FL^2}{\pi^2 E}$$

$$I_{member} = \frac{\pi}{4}(r_o^{\ 4} - r_i^{\ 4})$$

$$r_i = r_o - t$$

$$A_{member} = \pi(r_o^{\ 2} - r_i^{\ 2})$$

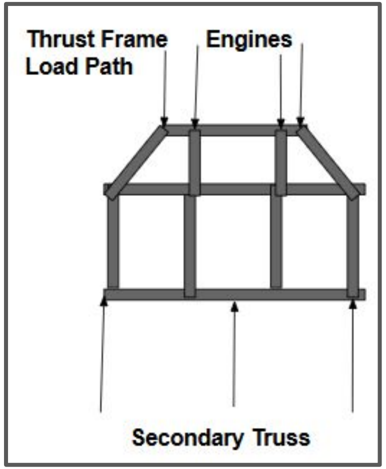
$$\sigma_{max,\,axial} = F\ /A_{member}$$

$$\sigma_{allowable} = \sigma_{failure}/FOS$$

Jacob J Wijker, “Spacecraft Structures”, 2008

Structure: Engine Thrust Frame

Loading	
Axial	- 4.1g
Lateral	3.0g
FOS	1.5



$$I_{member} = \frac{FL^2}{\pi^2 E}$$

$$I_{member} = \frac{\pi}{4}(r_o^{\ 4} - r_i^{\ 4})$$

$$r_i = r_o - t$$

$$A_{member} = \pi(r_o^{\ 2} - r_i^{\ 2})$$

$$\sigma_{max,\,axial} = F / A_{member}$$

$$\sigma_{max,\,lateral} = 2\sigma_{max,\,axial}$$

$$\sigma_{allowable} = \sigma_{failure} / FOS$$

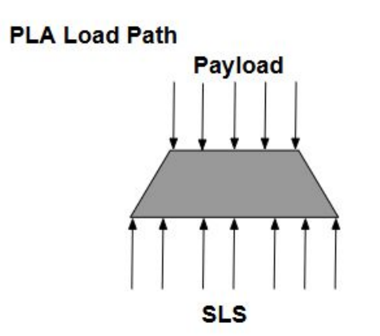
IM7/5555	
Failure Stress (MPa)	1330
Allowable Stress (MPa)	886.67

	Ring Frame		Engine Connections	
	Horizontal Ring	Vertical Members	Diagonal Members	Horizontal Ring
Number of Members	2	6	6	1
Length (m)	34.56	3	2.31	19.79
Outer Diameter (m)	0.25	0.152	0.186	0.2
Max Stress (MPa)	600	184.9	149	527
Thickness	0.025	0.015	0.019	0.04
Ring Diameter (m)	11			6.5
Total Mass (mT)	2.18			

Jacob J Wijker, "Spacecraft Structures", 2008

Structure: Payload Adapter

Loading	
Axial	-4.1g
Lateral	3.0g
Max Load Stress (MPa)	33.2
FOS	1.5



$$F_{cr} = \gamma \frac{2\pi E t^2 (\cos(\alpha))^2}{\sqrt{3(1-\nu^2)}}$$

$$\sigma_{cr} = \gamma \frac{E}{\sqrt{3(1-\nu^2)}} \frac{t}{r}$$

$$\gamma = \frac{0.83}{\sqrt{1+0.01\frac{\rho_o}{t}}} \text{ for } \frac{\rho_o}{t} \leq 212$$

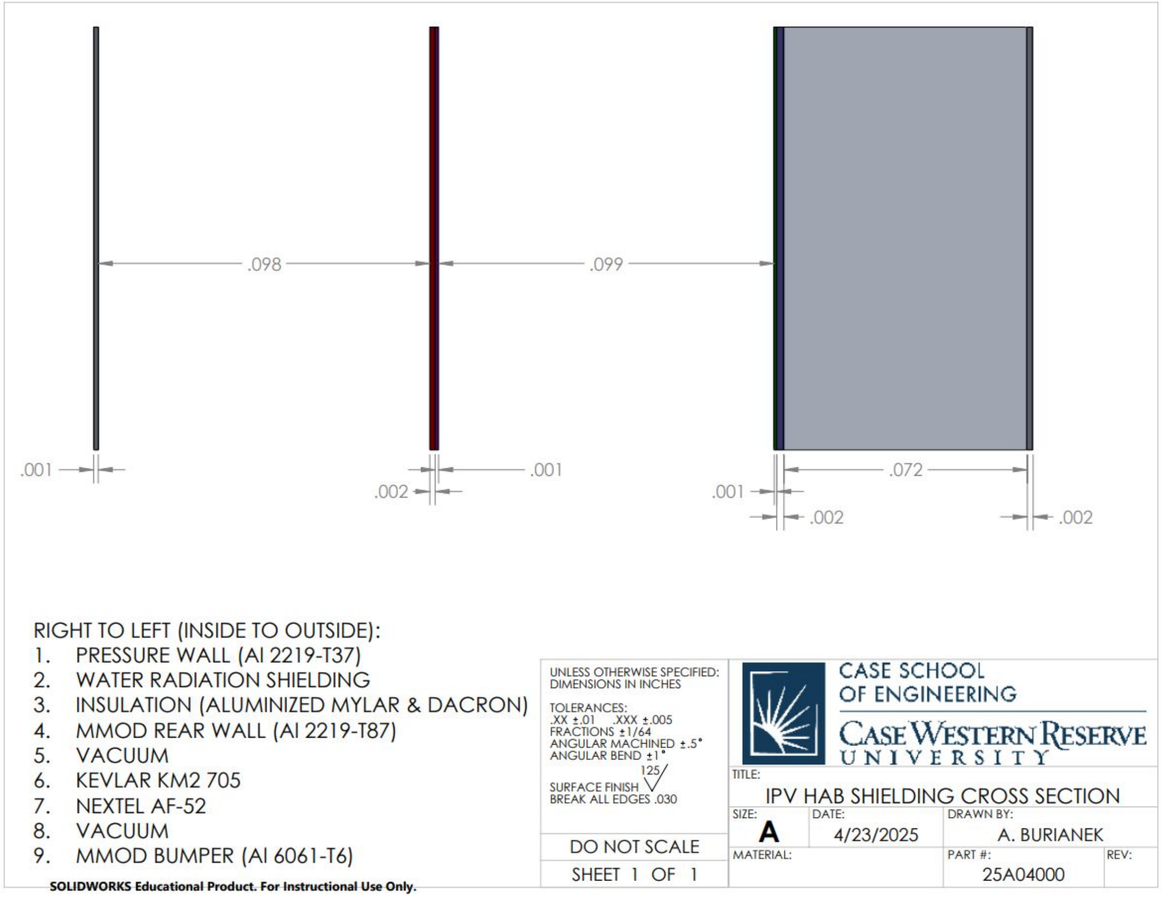
$$\rho_o = \frac{R_o}{\cos(\alpha)}$$

T800S	
Failure Stress (MPa)	3000
Poisson's Ratio	0.35

Parameter	Value
Number of Adapters	6
alpha (°)	61.35
Height (m)	1.52
Base Diameter (m)	12
Top Diameter (m)	8
Thickness (mm)	10
Max Critical Stress (MPa)	129
Mass per Adapter (mT)	0.94

Jacob J Wijker, "Spacecraft Structures", 2008

MMOD Shield



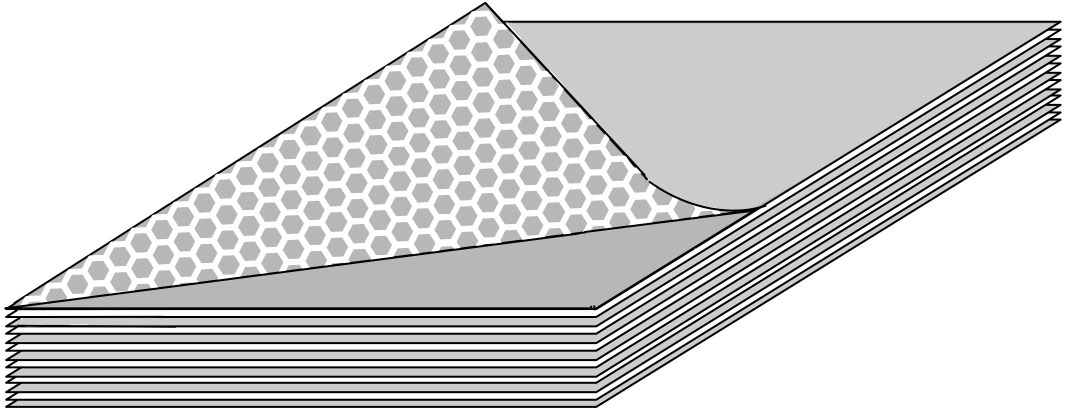
Triple Stuffed Whipple Shield

Maximum Allowable MMOD	
Diameter	1 cm
Mass	1.31g
Impact Velocity	10.5 km/s Normal to shield

Christiansen, Dr., E. L, et al., 2009, *Handbook for Designing MMOD Protection, NASA JSC*

MLI and Boil Off

q: Heat flux $(\frac{W}{m^2})$
T_H: Hot side Temperature (K)
T_C: Cold Side Temperature (K)
N_S: # of Layers
$\bar{N}$: Layer Density $(\frac{\#}{cm})$
SA: Total Surface Area (m^2)
H_V: Specific Vaporization Enthalpy $(\frac{kJ}{kg})$
M: LH2 Mass (kg)



$$q = \frac{[3.07*10^{-11}(T_h^2 - T_C^2) - 2.13*10^{-14}(T_H^3 - T_C^3)] * \bar{N}^{3.91}}{N_S + 1} + \frac{2.49*10^{-11}}{N_S}(T_H^{4.67} - T_C^{4.67})$$

$$BOR(\%perDay) = \frac{q * SA * 8640}{H_V * M}$$

$$t = \frac{N_S}{\bar{N}}$$

	Material	Specification
Reflector Layer	Double Aluminized Mylar	MDACSTM0691, Type II, Class 1, GradeA
Separator	Dacron Netting	Rockwell MB0135-042, MDAC--STM0605-03

C. W. Keller, “Thermal Performance of Multilayer Insulations”, 1974.
M. M. Finckenor, “Multilayer Insulation Material Guidelines”, 1999.
Ryan Honour, “Thermal Optimization and Assessment of a Long Duration Cryogenic Propellant Depot”, 2012.

MLI and Boil Off

	Earth Departure	Mars Capture	Mars Departure	Earth Capture	Hab	DEV
Layer Count	224	224	224	224	10	5
MLI Thickness (cm)	4.71	4.71	4.71	4.71	0.21	0.11
Maximum BOR	0.009%	0.006%	0.005%	0.013%	N/A	N/A
MLI Mass (mT)	2.00	0.86	0.68	0.71	0.27	0.15
Boil Off Mass (mT)	3.63	1.09	2.41	8.7	N/A	N/A
Total Mass (mT)	5.63	1.95	3.09	9.41	0.27	0.15

C. W. Keller, “Thermal Performance of Multilayer Insulations”, 1974.
M. M. Finckenor, “Multilayer Insulation Material Guidelines”, 1999.
Ryan Honour, “Thermal Optimization and Assessment of a Long Duration Cryogenic Propellant Depot”, 2012.

Radiation Shielding

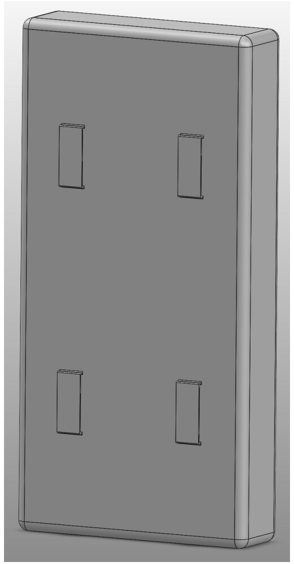
- Chosen solution: Water Walls
  - Low wall thickness & mass efficient
- Implementation Method: Polyethylene Bags
  - Modular & packaging efficient
  - Form a flexible and complete radiation shield

DEV:

Surface Area (m^2)	Material	Thickness (cm)	Total Mass (mT)
109.0	Aluminum	17.8	19.4
mSV/Day	LH_2	256.0	0.3
1.3	Water	7.2	7.8

IPV Hab:

Surface Area (m^2)	Material	Thickness (cm)	Total Mass (mT)
159.8	Aluminum	17.8	28.4
mSV/Day	LH_2	256.0	0.4
1.3	Water	7.2	11.5

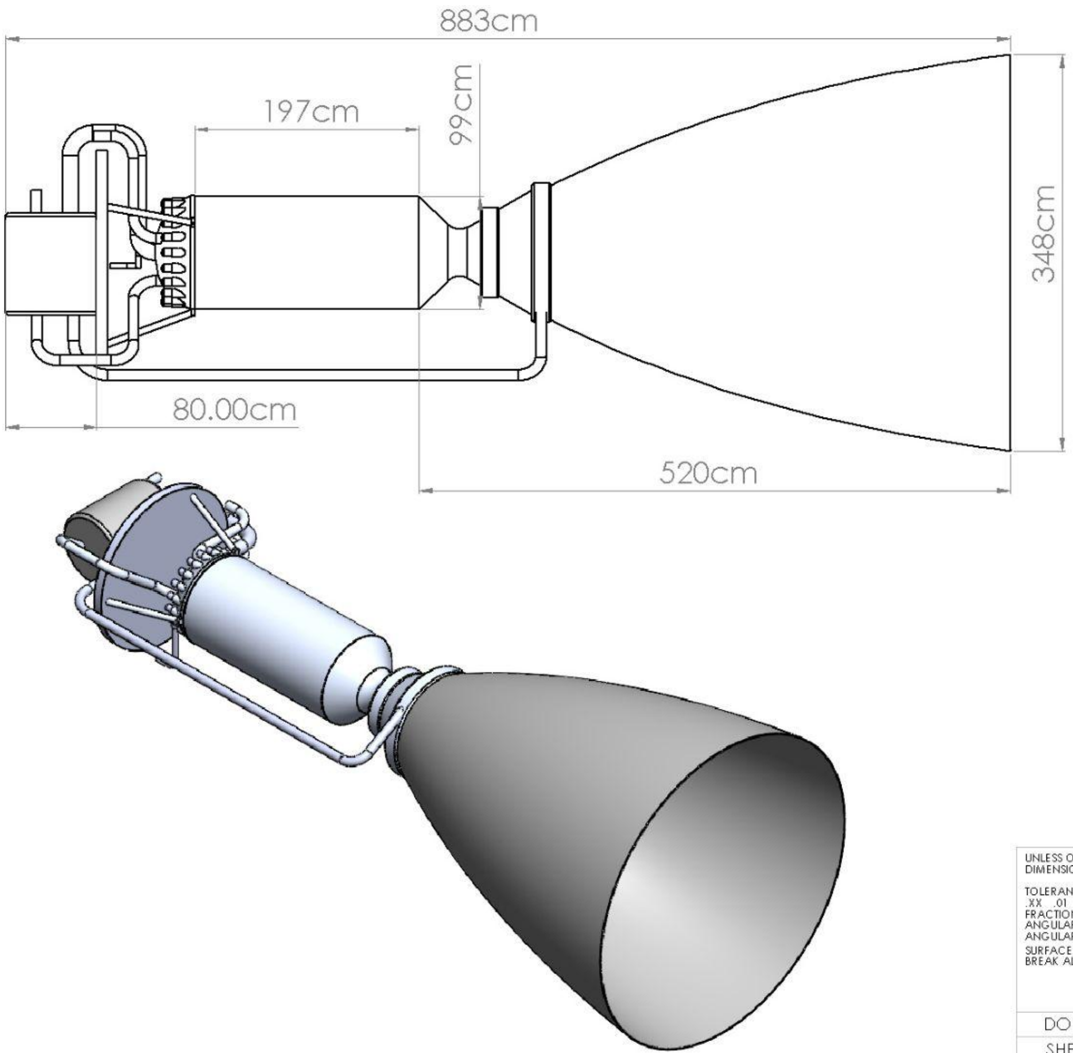


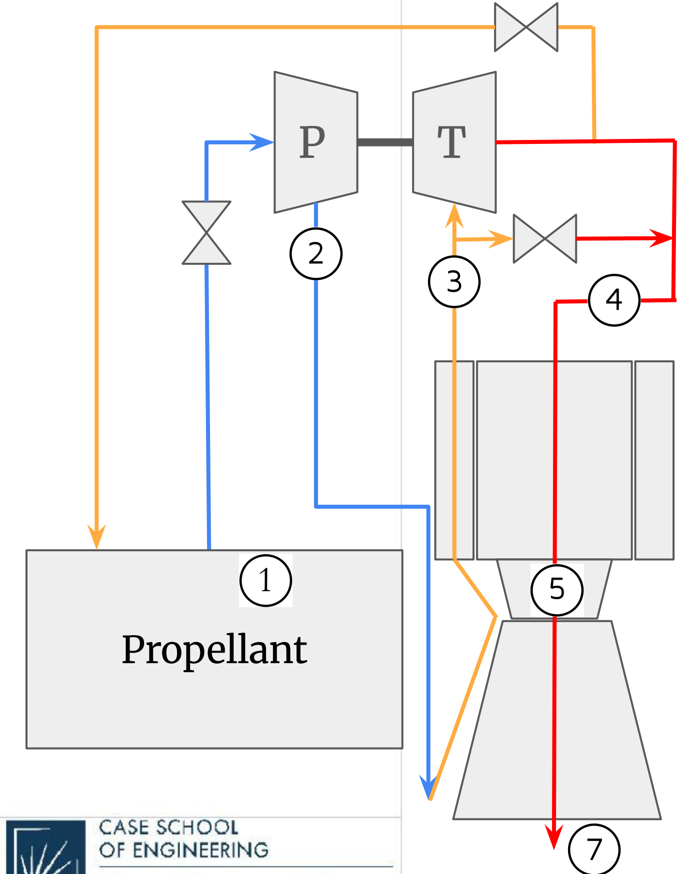
Dimensions:
25cmx**50cm**x**7.2cm**

M. Rais-Rohan, "On Structural Design of a Mobile Lunar Habitat With Multi-Layered Environmental Shielding", NASA Marshall Flight Center, 2005
Michael T. Flynn, "Water Walls Architecture: Massively Redundant and Highly Reliable Life Support for Long Duration Exploration Missions", NASA Ames Research Center, 2018

6. Propulsion

6.1 Nuclear Thermal	**6.2 IPV OMS**	**6.3 DEV RCS**	**6.4 DEV Main Thrusters**
6.1.1 Structure and Geometry	6.2.1 Structure	6.3.1 Structure	6.4.1 Structure
6.1.2 Turbomachinery	6.2.2 Performance	6.3.2 Performance	6.4.2 Performance
6.1.3 Performance	6.2.3 Fuel Mass	6.3.3 Mass	6.4.3 Mass
6.1.4 Reactor Design			
6.1.5 Cooldown			





UNLESS OTHERWISE SPECIFIED:
DIMENSIONS IN INCHES

TOLERANCES:
.XX .01 .XXX .005
FRACTIONS 1/64
ANGULAR MACHINED .5
ANGULAR BEND 1
SURFACE FINISH
BREAK ALL EDGES .030

DO NOT SCALE

SHEET 1 OF 1

CASE SCHOOL OF ENGINEERING
CASE WESTERN RESERVE UNIVERSITY

TITLE: NTP Assembly

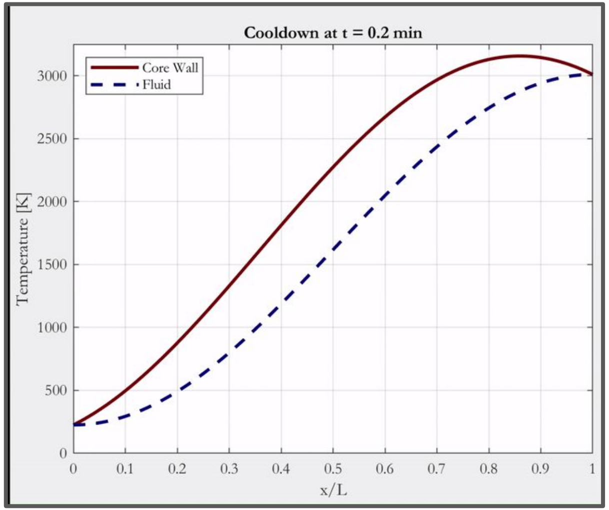
SIZE: B | DATE: 4/23/2025 | DRAWN BY: JMB548

MATERIAL: N/A | PART #: PART NO. | REV: A

NTP: Engine Mass and Cooldown

Reactor Parameters				
L	D_h	#Hex Elements	f	T_{in}
2.0 m	3.0 mm	300	0.00125	350 K

Cooldown	
Time	13 min
Mass	0.39 mT
$\dot{m}$	0.5 kg/s



Mass	
Item	Mass (mT)
Nozzle	0.9
Reactor	4.6
Turbomachinery	0.75
Radiation Shielding	0.8
Mounts	0.2
Total	**7.25**

(Borowski et al., Small Fast Spectrum Reactor Designs Suitable for Direct Nuclear Thermal Propulsion, 2012)
(Gomez et al., Shielding Development for Nuclear Thermal Propulsion, 2013)

NTP: Thrusting Performance Summary

Turbomachinery				
	P ratio	ΔT (K)	Efficiency	Power (MW)
Pump	49.5	41	32%	18.2
Turbine	0.107	-50	80%	18.4

Performance Fully Defined by:

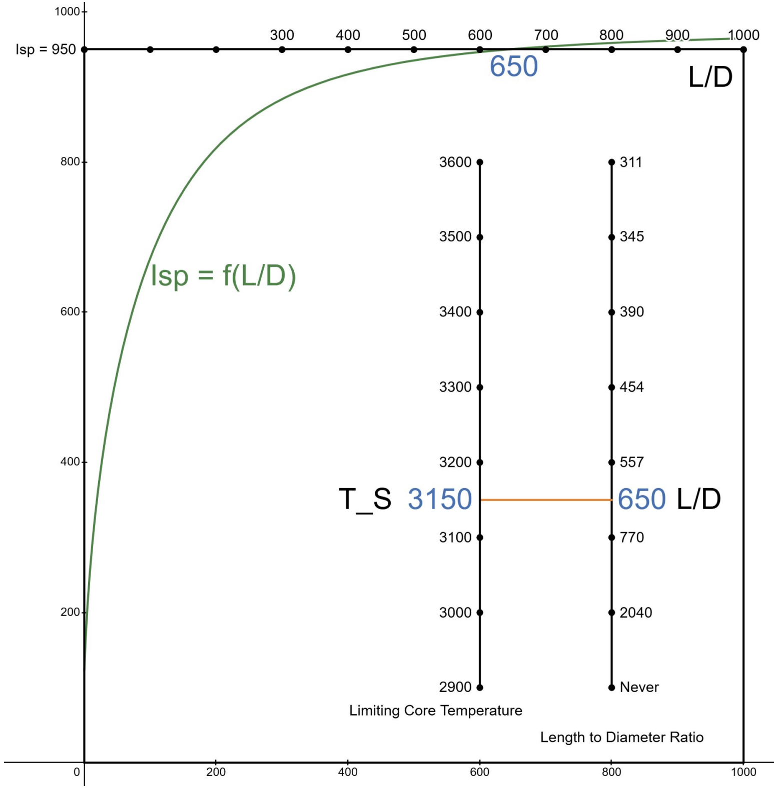
Reactor Temp, Nozzle Ratio, Mass Flow Rate

$$I_{sp} = \sqrt{\frac{2\gamma}{\gamma-1}\frac{\bar{R}}{M_w}T_0\left(1-\frac{P_e}{P_0}\right)^{\frac{\gamma-1}{\gamma}}} + \underbrace{\frac{P_e A_e}{\dot{m}\, g_0}}_{\text{small}}$$

Rocket Performance Summary						
T_0	P_0	A_e/A_{th}	P_e	Isp	ṁ	Thrust
3150 K	1.2 MPa	300 ⟹	64 Pa	**951 s**	38 kg/s	**354 kN**

Big ⟹ small

Given our Nozzle: Reactor $L/D_h \Longrightarrow T_0 \Longrightarrow I_{sp}$



NTP: Ullage, & Piping

Parameter	Value
Draining Flow Rate (kg/s)	38
LH2 Storage Temperature (K)	20
Tank Pressure (MPa)	.225
Ullage H2 Temperature (K)	350
Ullage H2 Pressure (MPa)	1.2
Ullage Mass Flow Rate (kg/s)	.096
Total Ullage Mass (mT)	1.29
Draining Pipe Diameter (cm)	9.3
Ullage Pipe Diameter (cm)	1.4
Draining Pipe Thickness (mm)	1.2
Ullage Pipe Thickness (mm)	0.91
Total Piping Mass (kg)	32.7

$$\dot{m} = \rho UA = \rho U(\pi/4)d^2 = \rho Q$$

$$P_1 + (\tfrac{1}{2})\rho U^2 = \text{const.}$$

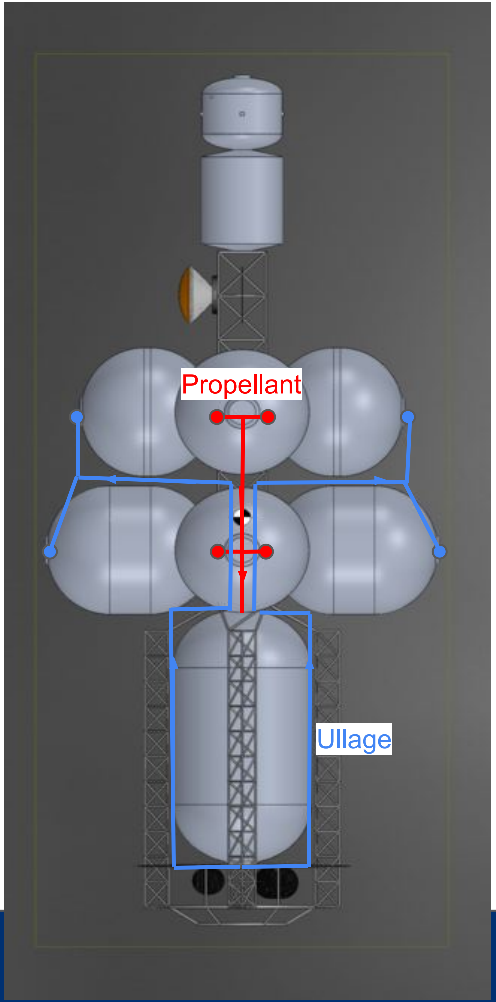
$$t = \frac{PD}{2(SEW + PY)}$$

Chosen Piping Material:
Al 6061-T6

Thicknesses multiplied by a factor of **5** from values calculated by B31.3

Michael Moran, “Fundamentals of Engineering Thermodynamics”, 2018.

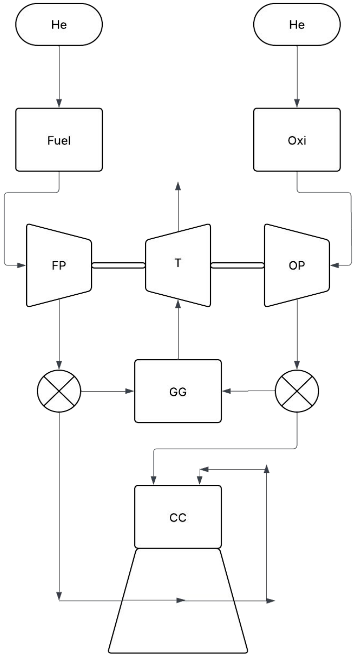
ASME B31.3 Process Piping, 2020.

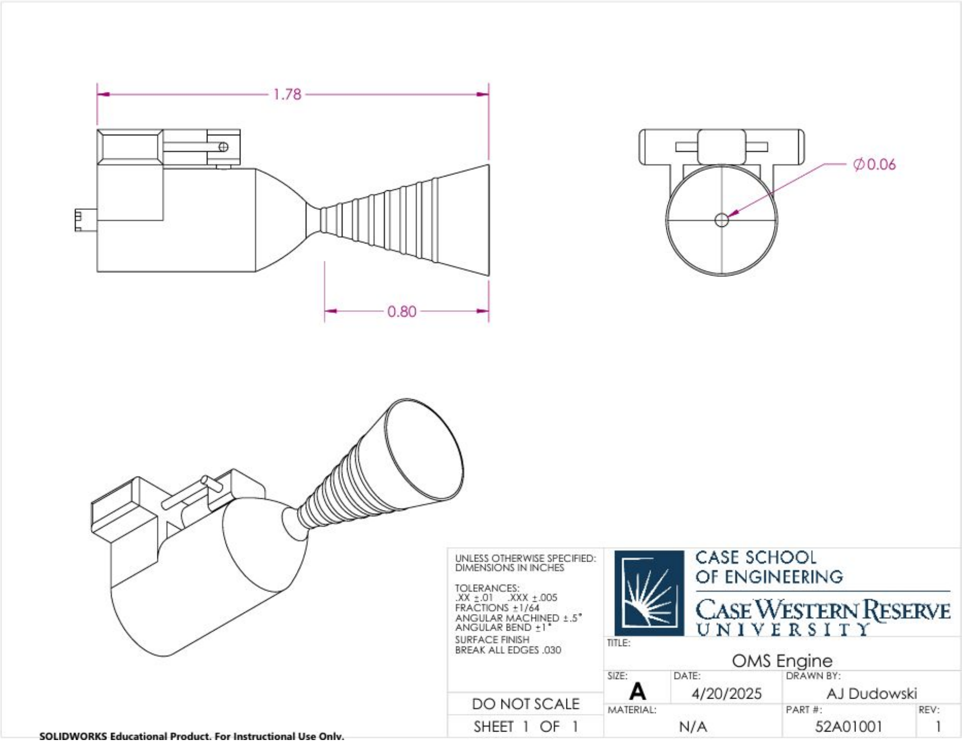


CASE WESTERN RESERVE UNIVERSITY
Case School of Engineering

OMS

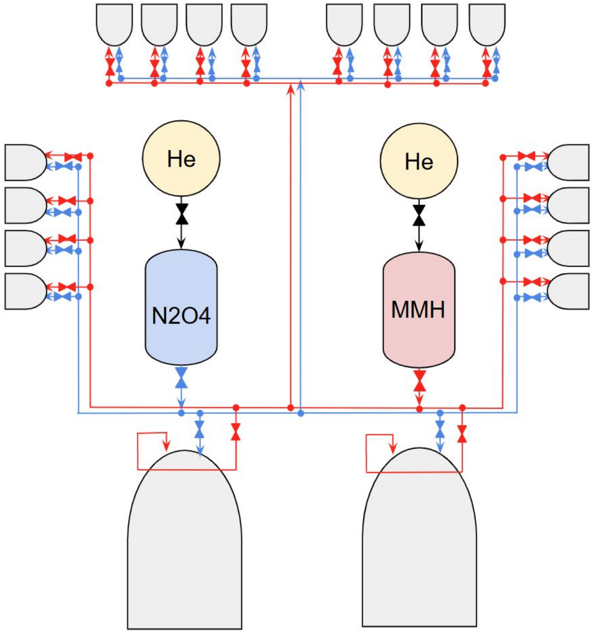
Fuel	MMH	-
Oxidizer	N_2O_4	-
Isp	340	s
Corrected Isp	**339.5**	s
Thrust	**35000**	N
ΔV	**150**	m/s
O/F	1.4	-
Combustion Pres.	6890	kPa
Combustion Temp.	2995	K
Exit Mach	**5.6**	-
Total Mass	**21.5**	mT





MODERN ENGINEERING FOR DESIGN OF LIQUID-PROPELLANT ROCKET ENGINES, Dieter K. Huzel and David H. Huang, 1992
Cryo-Rocket. "5.1 LTMCC Geometry." Cryo-Rocket, n.d., https://www.cryo-rocket.com/flow-model/5.1-ltmcc-geometry/. Accessed Mar. 2025.
MIT 16.512, Rocket Propulsion, Professor Manuel Martinez-Sanchez, Accessed Apr. 2025

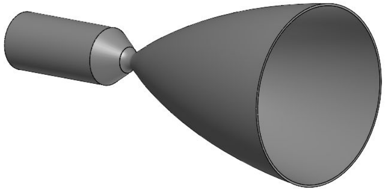
DEV Engines Overview

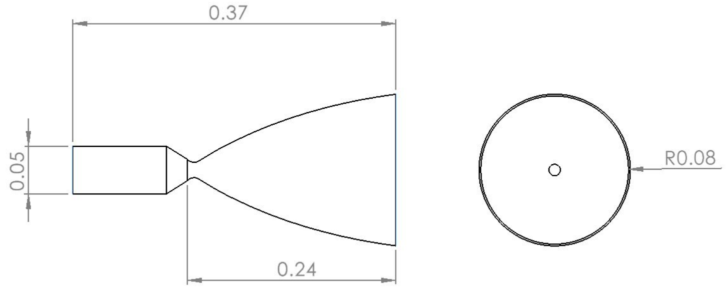


Tank Volumes		
MMH	0.00713	m^3
N_2O_4	0.00740	m^3
He (MMH)	0.00085	m^3
He (N_2O_4)	0.00088	m^3
Tank Pressure		
MMH and N_2O_4	2.5	Mpa
He	30	Mpa
Propulsion Mass		
MMH	188.91	kg
N_2O_4	302.26	kg
He (MMH)	0.038	kg
He (N_2O_4)	0.039	kg
Tanks	174.21	kg
Piping + misc.	79	kg

Huzel, D. K., and Huang, D. H., 1992, *Design of Liquid Propellant Rocket Engines*, 2nd ed., American Institute of Aeronautics and Astronautics, Washington, DC.

DEV Main Engines





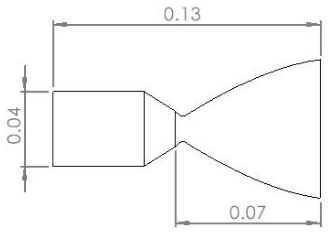
Main Engine Analysis		
Thrust	500	N
Isp	304.1	s
# of thrusters	16	
ε (Ae/A*)	100	
Me	5.70	
T07 (CEA)	3027.03	K
P07	1000	kPa
Pe	0.80	kPa
Thrust coefficient	2.01	
A*	0.00025	m^2
Ae	0.025	m^2
ṁ	0.17	kg/s

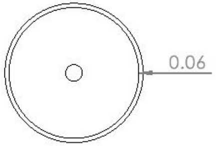
Mass		
Nozzle (x2)	2.64	kg
Combustion chamber (x2)	0.72	kg
Total Mass	6.72	kg

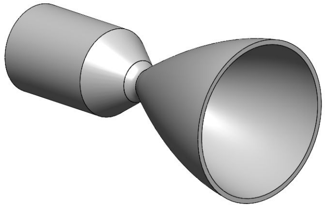
Materials	
Nozzle	Platinum-Aluminum Alloy
Combustion chamber	Platinum-Aluminum Alloy
Tanks	Cycom IM7/977-3

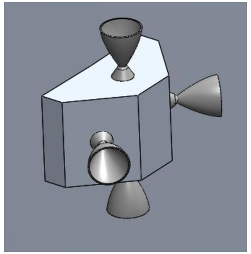
Regenerative Cooling		
Gas Static Temp	3027.03	K
Coolant Temp	298.15	K
Wall Thickness	0.002	m
Total Heat Flux	1736.04	kW/m^2
Wall Temp. Gas Side	409.37	K
Wall Temp. Coolant Side	373.45	K

DEV RCS









RCS Analysis		
Thrust	200	N
Isp	298	s
# of thrusters	16	
ε (Ae/A*)	60	
Me	4.16	
T07	3081.28	K
P07	2000	kPa
Pe	9.30	kPa
Thrust coefficient	1.70	
A*	0.00006	m^2
Ae	0.001	
ṁ	0.068	kg/s

Mass		
Nozzle (x16)	0.30	kg
Combustion chamber (x16)	0.22	kg
Total Mass (w/o prop.)	8.32	kg

Materials	
Nozzle	Platinum-Aluminum Alloy
Combustion chamber	Platinum-Aluminum Alloy
Tank	Cycom IM7/977-3

Regenerative Cooling		
Gas Static Temp	3081.28	K
Coolant Temp	298.15	K
Wall Thickness	0.002	m
Total Heat Flux	2009.08	kW/m^2
Wall Temp. Gas Side	412.29	K
Wall Temp. Coolant Side	375.42	K

6. Power

6.1 Power Draw	6.2 Solar Panels	6.3 Fuel Cells	6.4 DEV Reactors	6.5 Bimodal
6.1.1 IPV Hab Peak	6.2.1 Power Generation	6.3.1 Power Generation	6.4.1 Core	6.5.1 Core
6.1.2 IPV Hab Nominal	6.2.2 Area	6.3.2 Fuel	6.4.2 Turbine	6.5.2 Turbine
6.1.3 DEV Peak			6.4.3 Recuperator	6.5.3 Recuperator
6.1.4 DEV Nominal			6.4.4 Radiators	6.5.4 Radiators
			6.4.5 Compressor	6.5.5 Compressor

Bimodal Switchover – Battery Power

Battery Trade Study (ISS Batteries)			
Inputs			
Power Needed (kWe)	**Amount of Cycles**	**Hours of Operation**	**Depth of Discharge (%)**
25.1	<100	1	70%
Outputs			
Number of Batteries		**Weight (mT)**	
9		1.53	

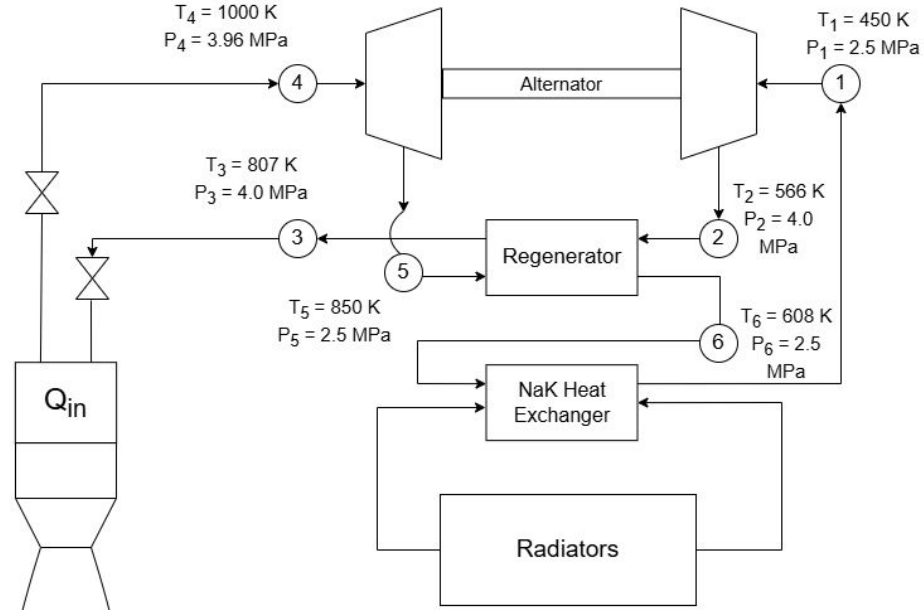
Table 3.1.2.2-1
DOD Limits for Cyclic Operations

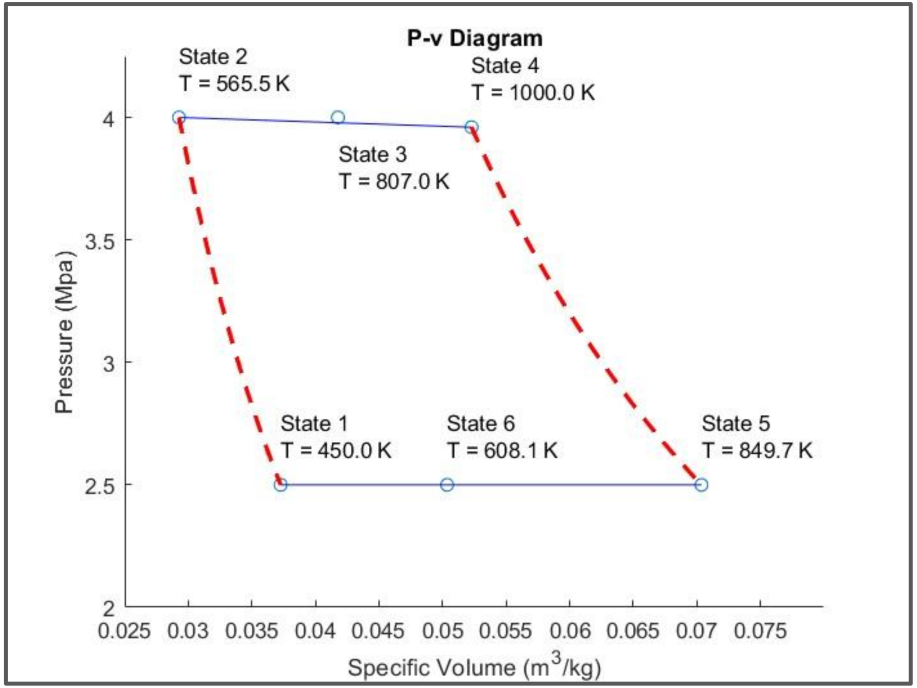
Number of cycles	Allowable DOD
<100	<70%
100 < # cycles < 5,000	<60%
5,000 < # cycles < 30,000	<40%
> 30,000	<20%

ARC-STD-8070.1

ISS Batteries	
Weight (kg)	170
Storage (kWh)	4

NTP: Bimodal Operation

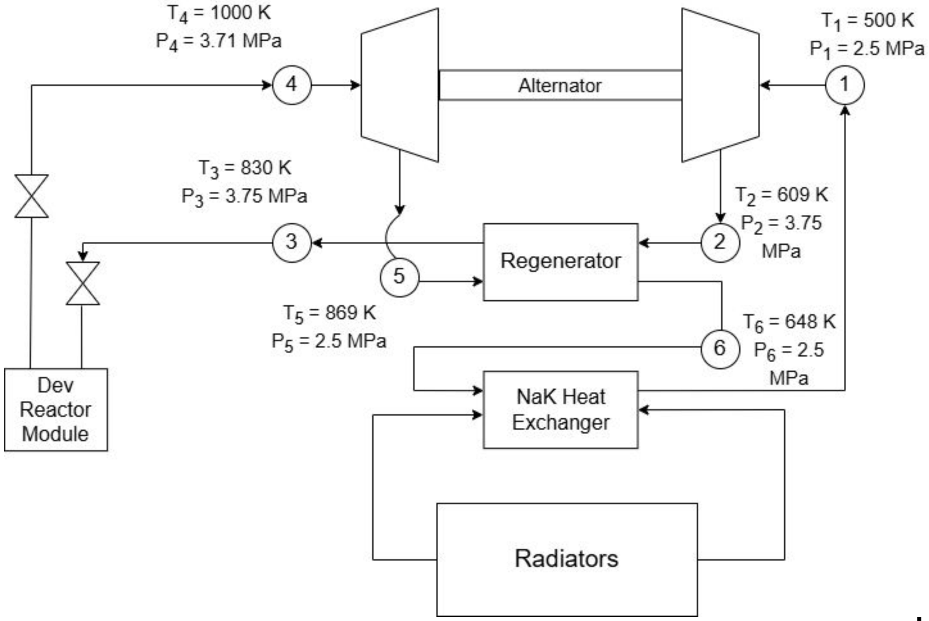


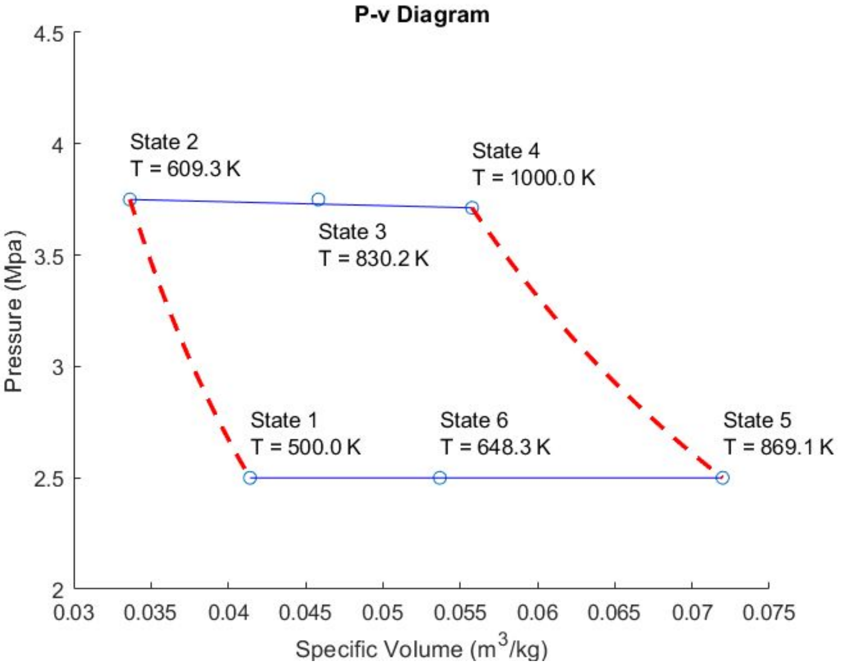


X_{Xe}	X_{He}	ṁ (kg/s)
0.29	0.71	1.4

W_{net}(kWe)	Q_{in}(kWt)	Q_{out} (kWt)	$\eta_{thermal}$ (%)
25.4	140.7	115.3	18.1

DEV Power Cycle (2x)



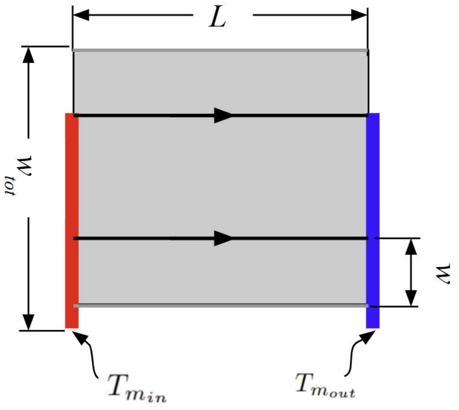


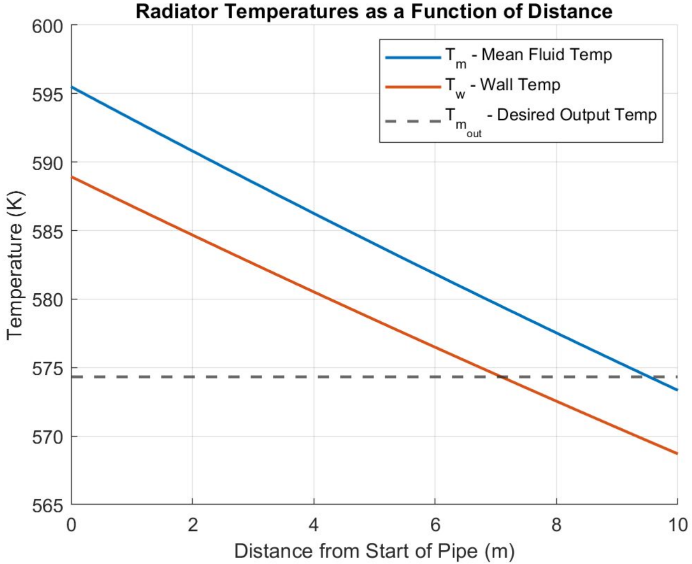
X_{Xe}	X_{He}	$\dot{m}$ (kg/s)
0.29	0.71	1.0

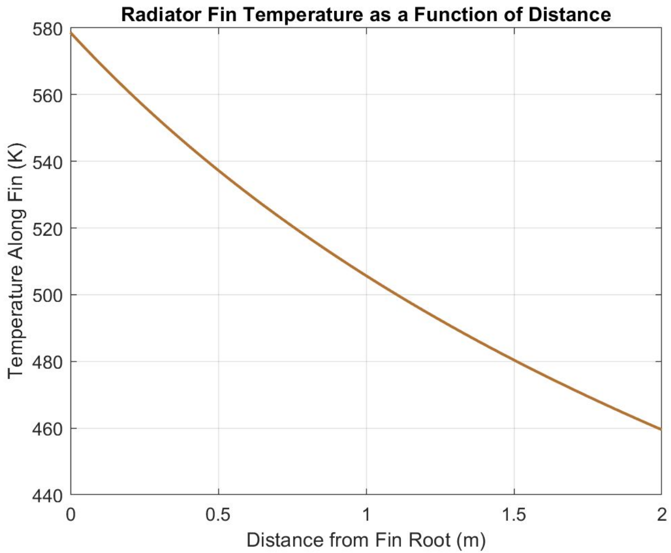
W_{net}(kWe)	Q_{in}(kWt)	Q_{out} (kWt)	$\eta_{thermal}$ (%)
11.3	88.5	77.2	12.7

Heat Rejection Radiators

Results Shown are for Bimodal Radiator:







$$\dot{Q}_{conv} = \Delta x\, \pi\, D_i\, h\, (T_m - T_w) \qquad \dot{Q}_{rad} = \Delta x\, \pi\, D_o\, \epsilon\, \sigma\, (T_w^4 - T_s^4)$$

$$\dot{Q}_{conv} = \dot{Q}_{rad} \qquad \dot{Q}_{cond} = \dot{Q}_{rad} \qquad h = \frac{k}{D_i}(5 + 0.025\ \mathrm{Pe}^{0.8})$$

$$\dot{Q}_{cond} = k\, L\, t\, \frac{(T_x - T_{x+1})}{\Delta y} \qquad T_{out} = \frac{-\dot{Q}}{\dot{m}\, c_p} + T_{in}$$

Heat Rejection Radiators Continued

Radiator Name	Working Fluid	$T_{m,in}$ (K)	$T_{m,out}$ (K)	$T_{fin,tip}$ (K)	Total Area, m^2
Bimodal Radiator	NaK	595.5	574.3	525	6.8
DEV Power Radiator	NaK	647.3	618	600	7.4
IPV Hab Radiator	Ammonia	283.2	282.8	281	7.9
DEV Hab Radiator	Ammonia	283.9	282.8	282	18.1

Foust, O.J., "Sodium-Nak Engineering Handbook," *Division of Reactor Development and Technology United States Atomic Energy Commission*, Volume I, 1972

Bergman, Theodore L., et. al., *Fundamentals of Heat and Mass Transfer*, 7th Edition, 2011

Daryabeigi, Kamran, et. al., "Heat Transfer In High-Temperature Multilayer Insulation," *NASA*

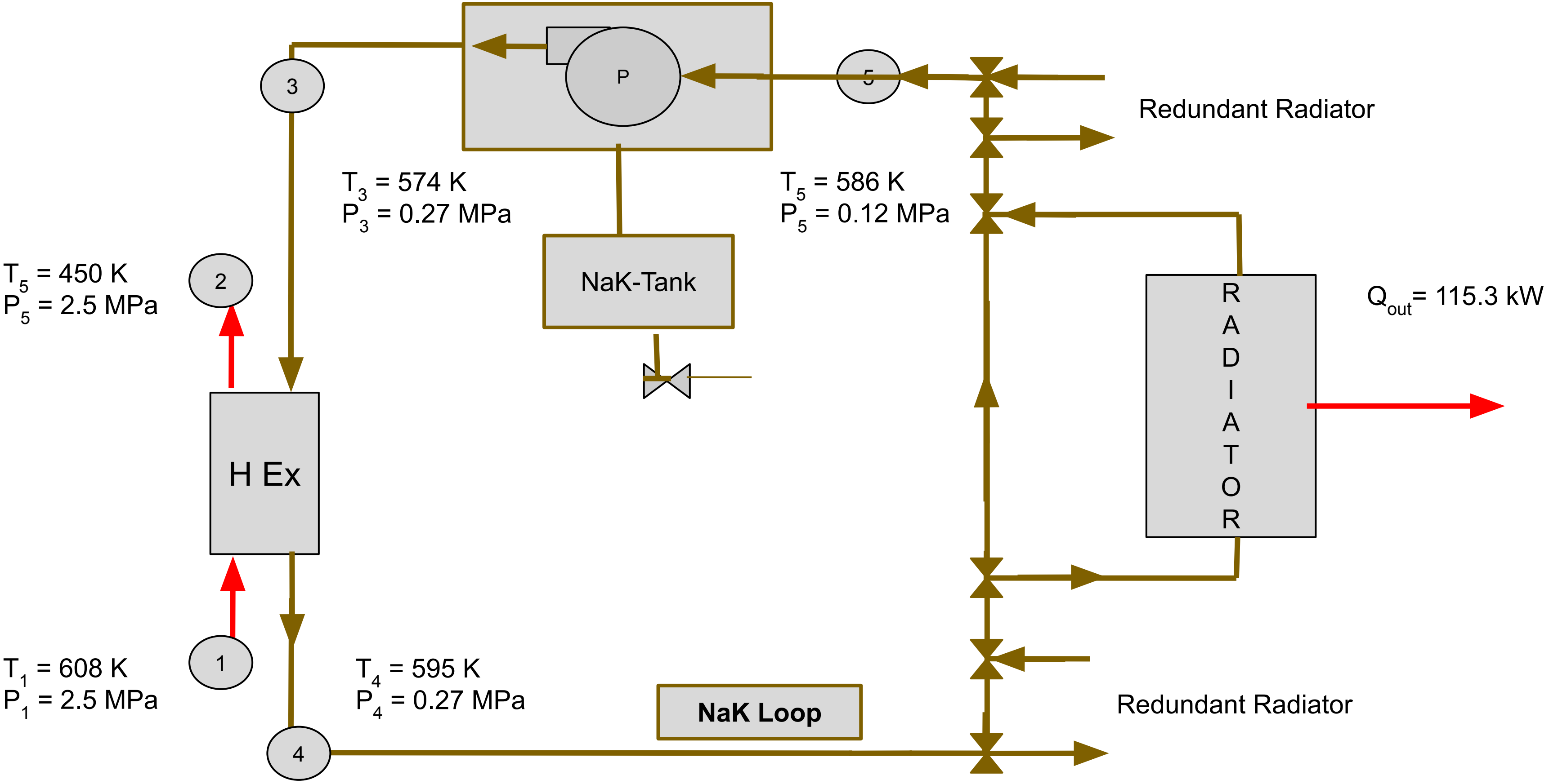
"A Coating That Cools and Cuts Costs," *NASA*, 2004, https://spinoff.nasa.gov/Spinoff2004/ip_7.html

Fin Material:
Aluminum
(k = 237W/m-K)

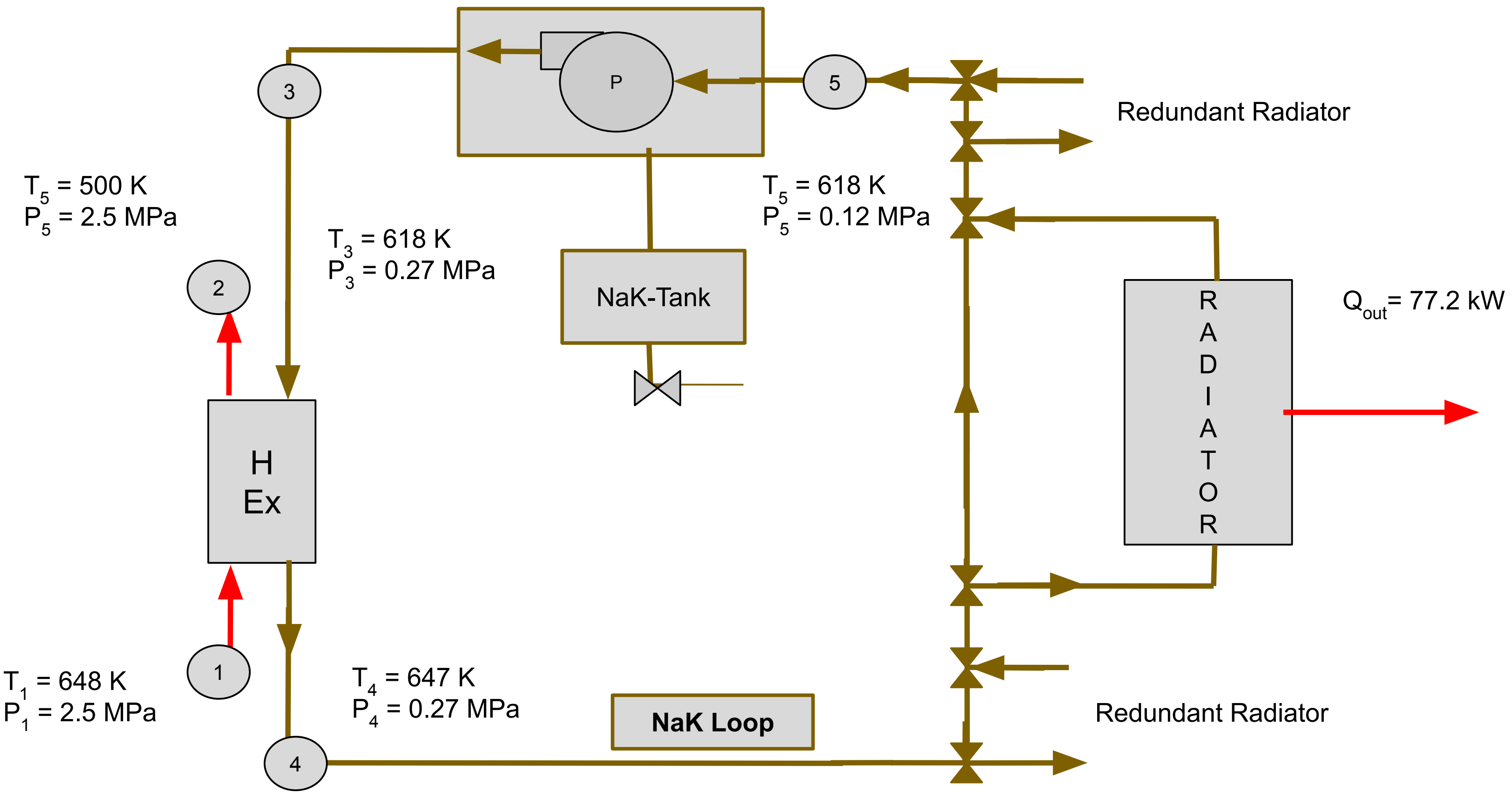
Insulation:
MLI with Ceramic Foil & Fibrous Insulation

Coating:
PCCM (Emisshield)
(ε = 0.9)

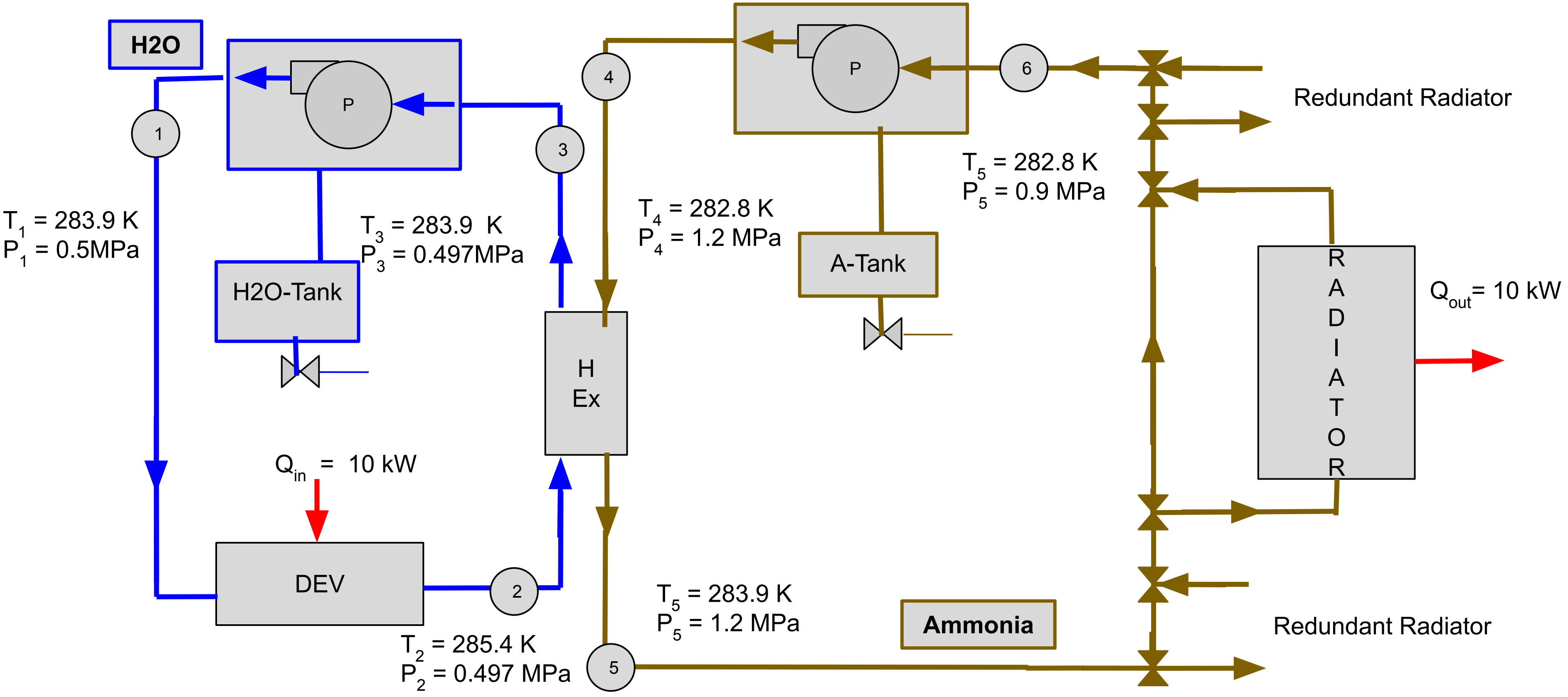
Bimodal Heat Rejection P&ID



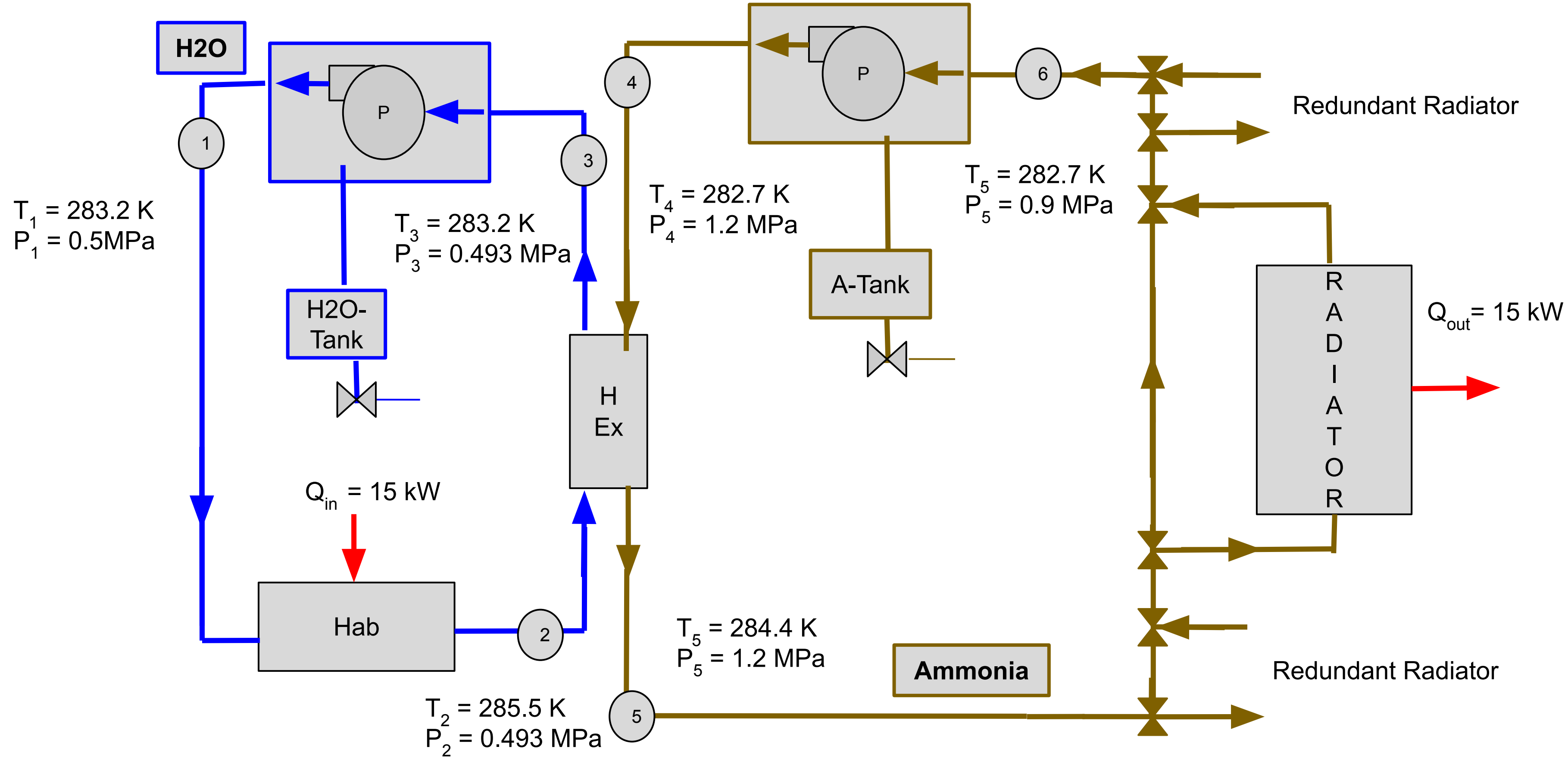
DEV Heat Rejection P&ID



DEV Heat Rejection System P&ID



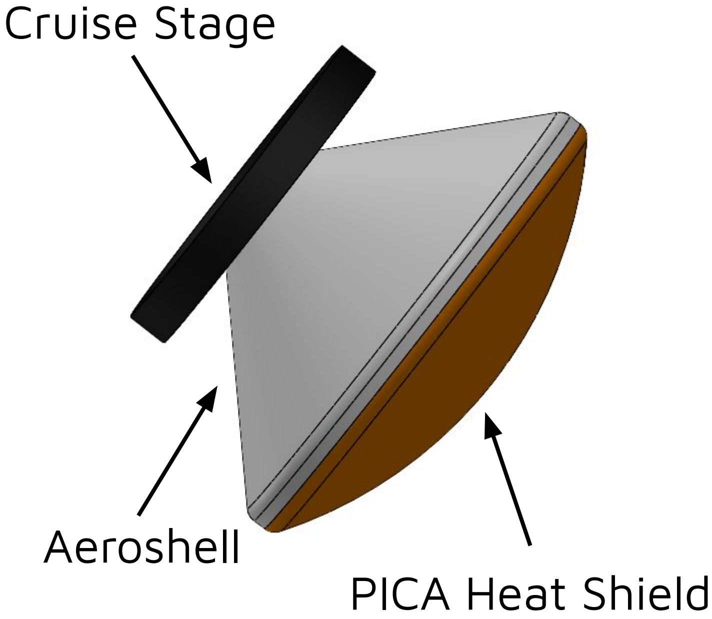
IPV Hab Heat Rejection System P&ID



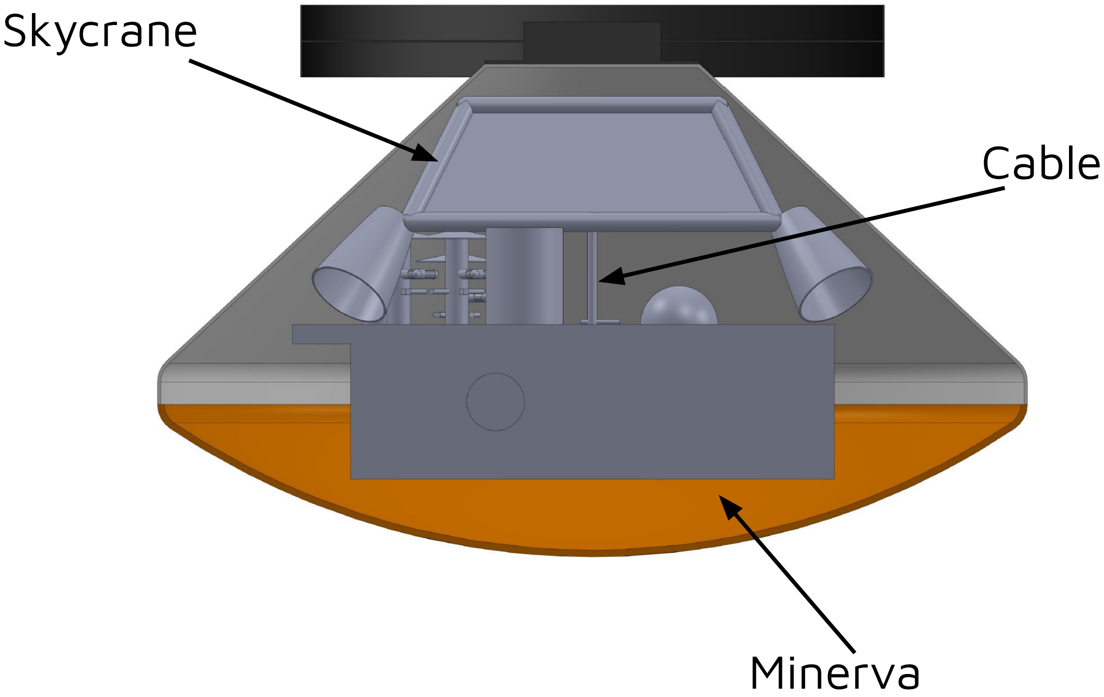
7. Mars Assets

7.1 Detachment	7.2 Ballistic Entry	7.3 Capsule	7.4 Skycrane	7.5 Rover	7.6 Landing
7.1.1 Orbit	7.2.1 Capsule	7.3.1 Mass	7.4.1 Mass	7.5.1 Mass	7.6.1 Architecture
	7.2.2 Atmosphere	7.3.2 Internal Volume	7.4.2 Dimensions	7.5.2 Stowed Dimensions	7.6.2 Operations
		7.3.3 Heat Shield		7.5.3 Power	7.6.3 Landing Site
				7.5.4 Science Instruments	

Mars Assets

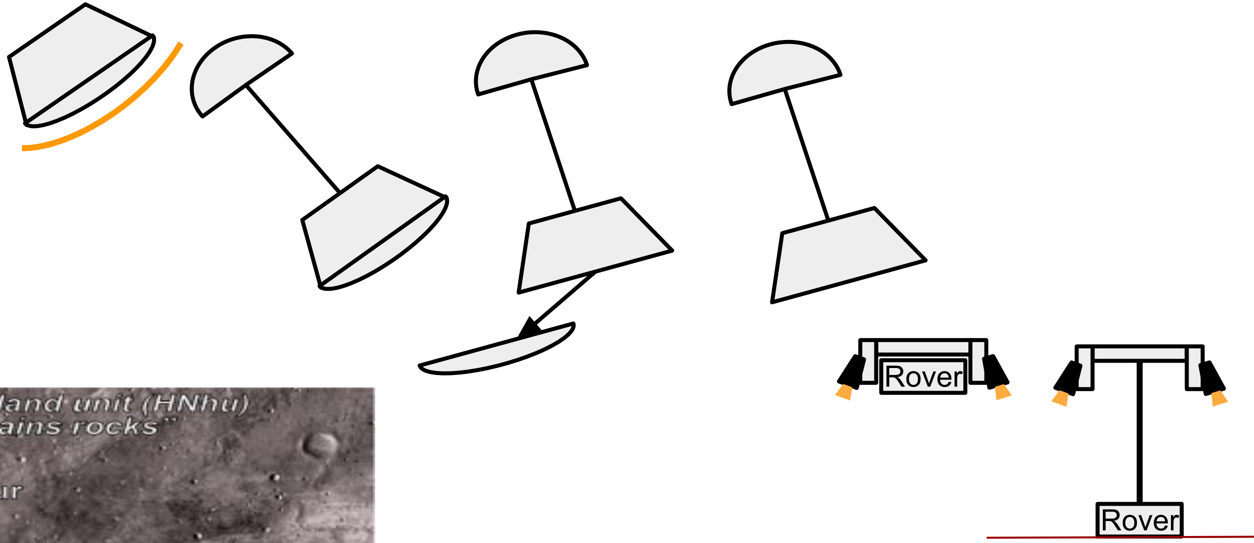


Cruise Stage
Aeroshell
PICA Heat Shield



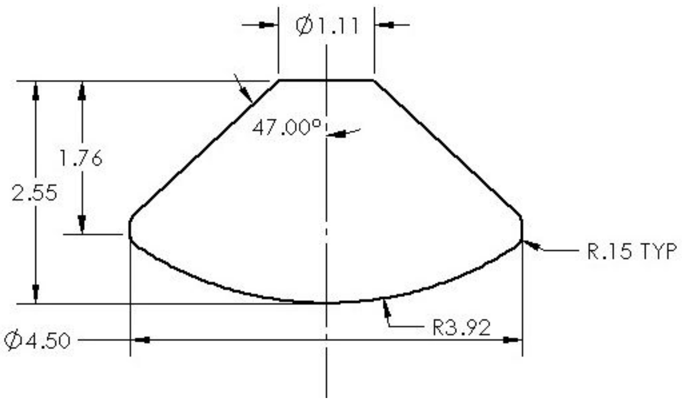
Skycrane
Cable
Minerva

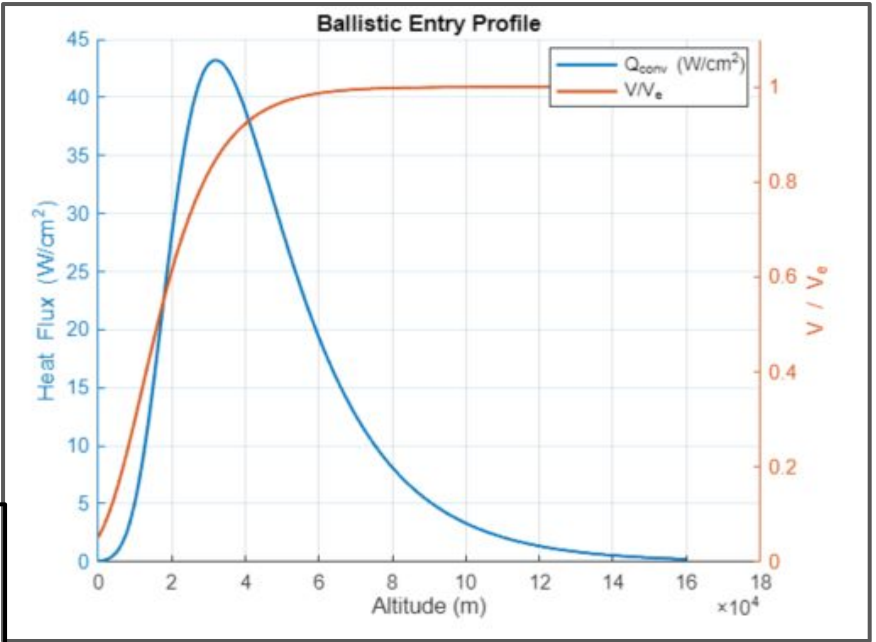
Mars Assets EDL



Minerva	
Rover Mass (kg)	700
Rover Dimensions	3 m x 2.8 m x 2.2 m
Cruise + Entry Mass (kg)	4000 kg
Peak Power Usage (kWe)	0.9
Landing Technique	Skycrane
Power Generation	Solar Panels

Ballistic Entry





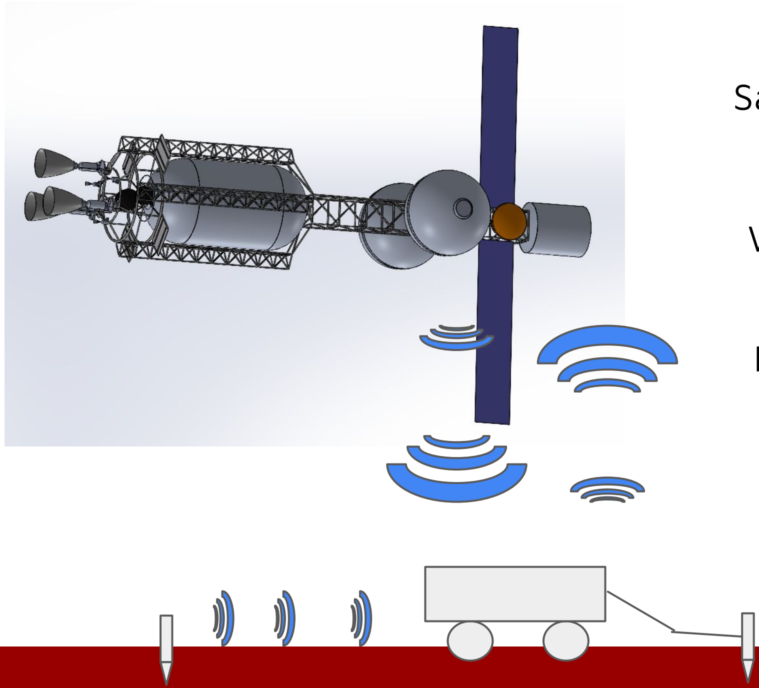
Sutton and Graves, A General Stagnation-Point Convective-Heating Equation For Arbitrary Gas Mixtures, 1971

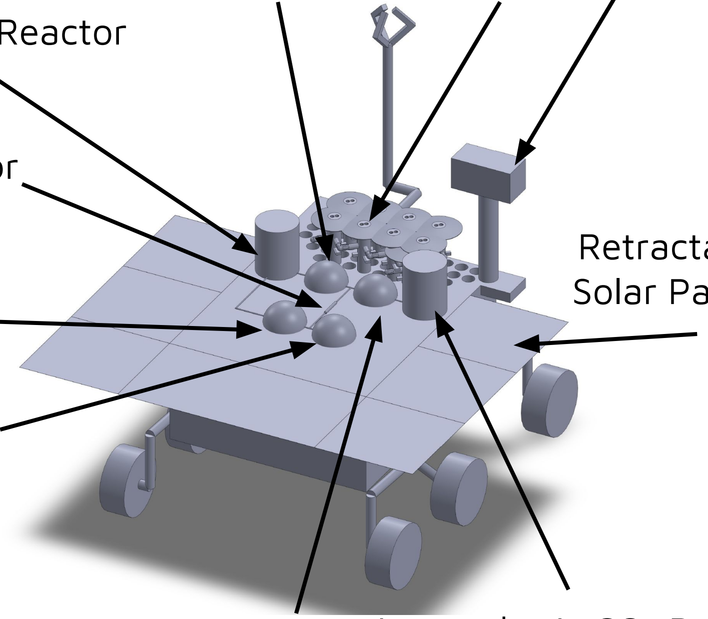
Zoby and Sullivan, "Effects of Corner Radius on Stagnation Point Velocity Gradients on Blunt Axisymmetric Bodies", 1966

Anderson, Putnam and et. al, Strategies for Landing Large Ballistic Coefficient Vehicles on Mars, Georgia Tech, 2016

3.5 cm of Heat Shield Needed

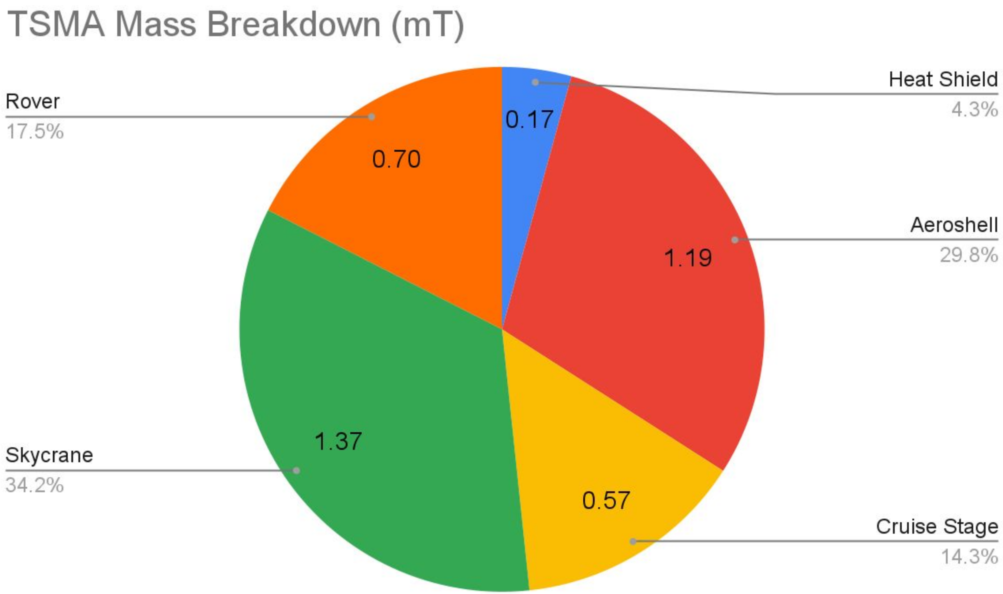
Mars Assets Operations





Not To Scale

Mars Assets



Total Mass: 4.0 mT

Requirements vs. Capability: 1

Requirement	Design Performance	Compliance	Changed? (Cause)
Shall support crew of 4, minimum	Crew of 4	Yes	No
Shall utilize 6 SLS launches, maximum	6 SLS launches	Yes	Yes
Shall have NTP Isp of 950s	951s	Yes	No
LEO depart mass of 750 mT maximum	744 mT	Yes	No
NTP shall have total thrust of 1002 kN of thrust.	1005 kN	Yes	No

Requirements vs. Capability: 2

Requirement	Design Performance	Compliance	Changed?
MMOD shield shall survive impact of 10 km/s	10.5 km/s	Yes	No
Radiation shielding shall allow a maximum of 1.3 mSv/day from galactic cosmic rays	1.3 mSv/day	Yes	No
Structures shall have FoS of 1.5 minimum	FoS of 1.5	Yes	No
IPV Hab shall require peak power 25.1kWe, nominal 16.5kWe	25.4 kWe	Yes	No
DEV shall require peak power 20.1kWe, nominal 15.8kWe.	22.6 kWe	Yes	No

Requirements vs. Capability: 3

Requirement	Design Performance	Compliance	Changed?
Crew of 2 to Deimos each expedition	Crew of 2	Yes	No
270 days at Deimos total	2 trips of 135 days	Yes	Yes
Hab shall maintain minimum 0.89 kg/day/CM of oxygen	6920 kg (100 % redundant)	Yes	No
Hab shall maintain minimum 6.47kg/day/CM of water	9230 kg (100 % redundant and 75% recycling)	Yes	No
Hab shall maintain minimum 0.80kg/day/CM of food solids	6220 kg (100 % redundant)	Yes	No

Questions?

Section Links:

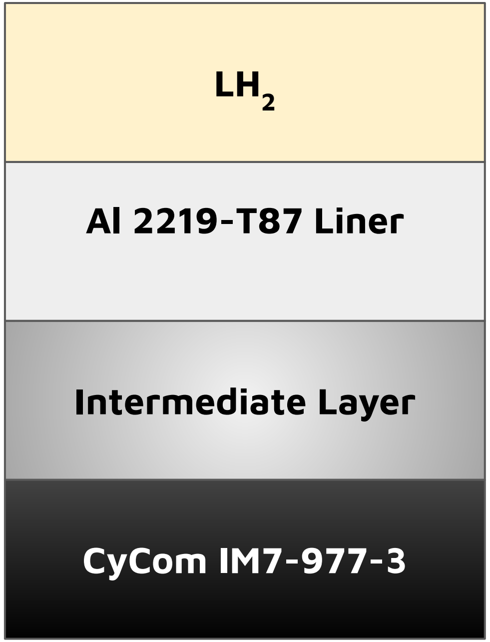
Appendices

Structural Appendix: Isogrid Parameters

```
INPUTS: IPV Hab
Chosen Skin Thickness (t): 2mm
Chosen Rib Thickness (b): 1.5mm
Chosen Rib Depth (d): 19.1mm
Number Cells: 150
N cr allow (Loading): 1769.2751lbf/in
RESULTS:
General Instability: 1773.1975lbf/in
Skin Buckling: 2839.3647lbf/in
Rib Crippling: 3562.3567lbf/in
Allowable Pressure: 32.4323psi
t_star: 13.2001mm
Equivalent Weight Thickness: 2.7405mm
```

```
INPUTS: DeV
Chosen Skin Thickness (t): 1.7mm
Chosen Rib Thickness (b): 1.5mm
Chosen Rib Depth (d): 18.6mm
Number Cells: 125
N cr allow (Loading): 1072.7933lbf/in
RESULTS:
General Instability: 1417.9535lbf/in
Skin Buckling: 1205.6304lbf/in
Rib Crippling: 3177.204lbf/in
Allowable Pressure: 27.4391psi
t_star: 12.4764mm
Equivalent Weight Thickness: 2.3011mm
```

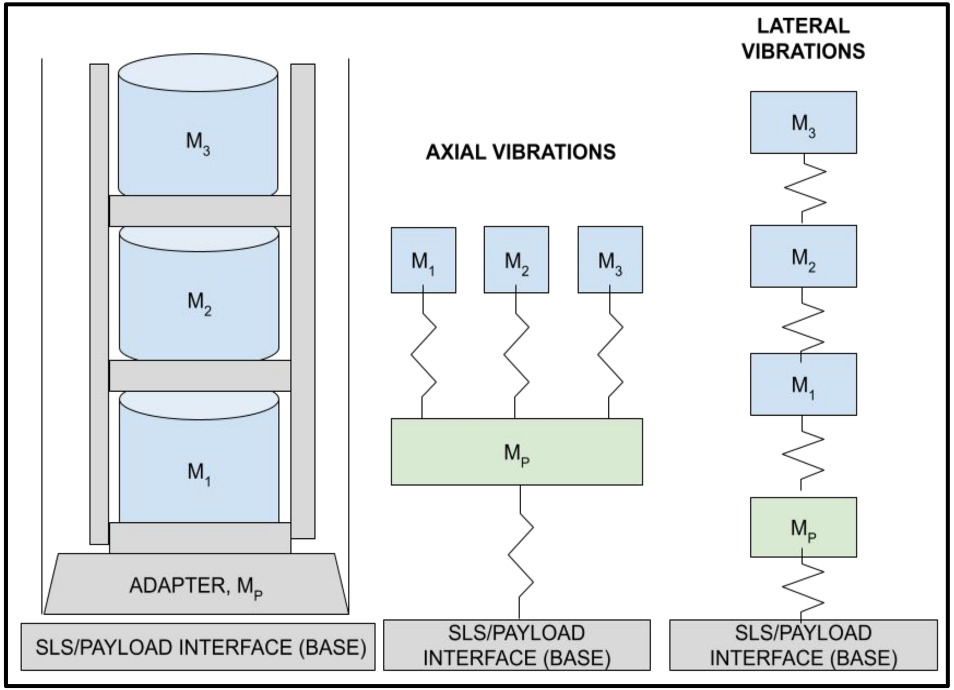
Structural Appendix: Prop Tank Thermal Expansion



Thermal Expansion		
Earth Capture Tank Parameter (Largest Tank)	**Ambient Temperature (298K)**	**Cryogenic Temperature (20K)**
2219 Liner Radius (m)	4.900	4.870
CF Radius (m)	4.900	4.901
TE Gap (m)	n/a	0.031
Possible Solution	Discontinuous Reinforced Metallic Composite Liner	

NASA, Cryogenic Materials Data Handbook, July 1970
back to main slides

Structural Appendix: Vibrations



Mass Matrix (same for both Axial and Lateral Vibrations):

$$[m] = \begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & m_3 & 0 \\ 0 & 0 & 0 & m_4 \end{bmatrix}$$

5.1 Axial Vibrations

Axial Stiffness Matrix:

$$[k_{Axial}] = \begin{bmatrix} k_p + k_1 + k_2 + k_3 & -k_1 & -k_2 & -k_3 \\ -k_1 & k_1 & 0 & 0 \\ -k_2 & 0 & k_2 & 0 \\ -k_3 & 0 & 0 & k_3 \end{bmatrix}$$

5.2 Lateral Vibrations

Lateral Stiffness Matrix:

$$[k_{Lateral}] = \begin{bmatrix} k_p + k_1 & -k_1 & 0 & 0 \\ -k_1 & k_1 + k_2 & -k_2 & 0 \\ 0 & -k_2 & k_2 + k_3 & -k_3 \\ 0 & 0 & -k_3 & k_3 \end{bmatrix}$$

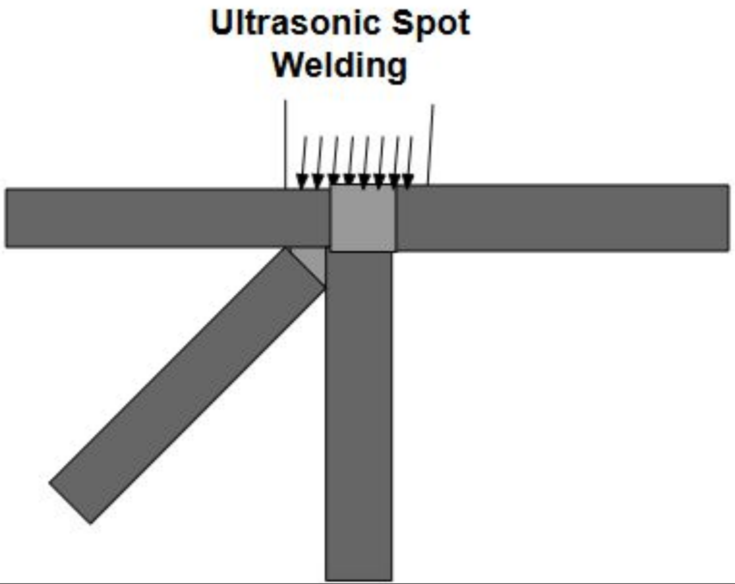
$$k_{axial} = \frac{EA}{L}$$

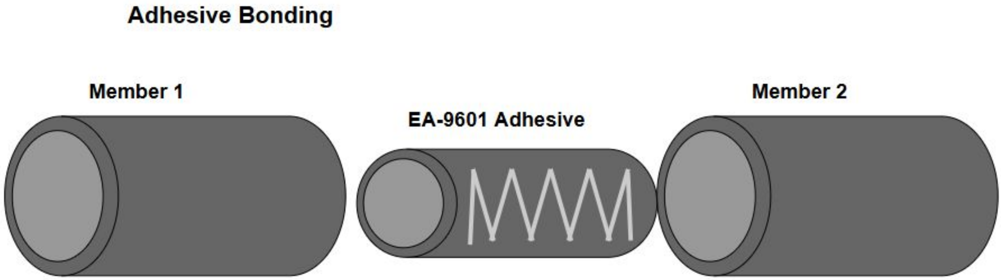
$$k_{lateral} = \frac{48EI}{L^3}$$

Launch No.	Min Lat (Hz)	Axial Nat. Freq. (Hz)	Min Axial (Hz)	Lat NF	Min Lat (Hz)
1	*8*	**25.74**	*15*	**37.2**	*8*
2	*8*	**25.23**	*15*	**35.6**	*8*
3	*8*	**25.56**	*15*	**32.5**	*8*
4	*8*	**31.3**	*15*	**54.3**	*8*
5	*8*	**20.3**	*15*	**33.7**	*8*
6	*8*	**30.6**	*15*	**54.0**	*8*

Dr. Majid Rashidi
SLS Mission Planner's Guide, NASA, *2018*

Structural Appendix: Ultrasonic Spot Welding and Adhesive Bonding





Peng Li, “Design and Mechanical Characterisation of a Large Truss Structure for Continuous Manufacturing in Space”, 2022
Frank E. Hancock, “Adhesives and the ATS Satellite”, 1972
[Link to Assembly]

Trajectory Appendix: Finite Burn

- Orbital equations of motion **numerically integrated** using MATLAB script during thrusting period
- Stop when C3 is desired value
- Mars Capture/Departure burns **impulsive** due to high orbit period.

$$r' = v \sin \alpha$$

$$v' = a \cos u - \frac{\sin \alpha}{r^2}$$

$$\alpha' = \frac{a \sin u}{v} + \left(v^2 - \frac{1}{r}\right) \frac{\cos \alpha}{rv}$$

$$\theta' = \frac{v}{r} \cos \alpha$$

back to main slides

OMS Appendix #'s

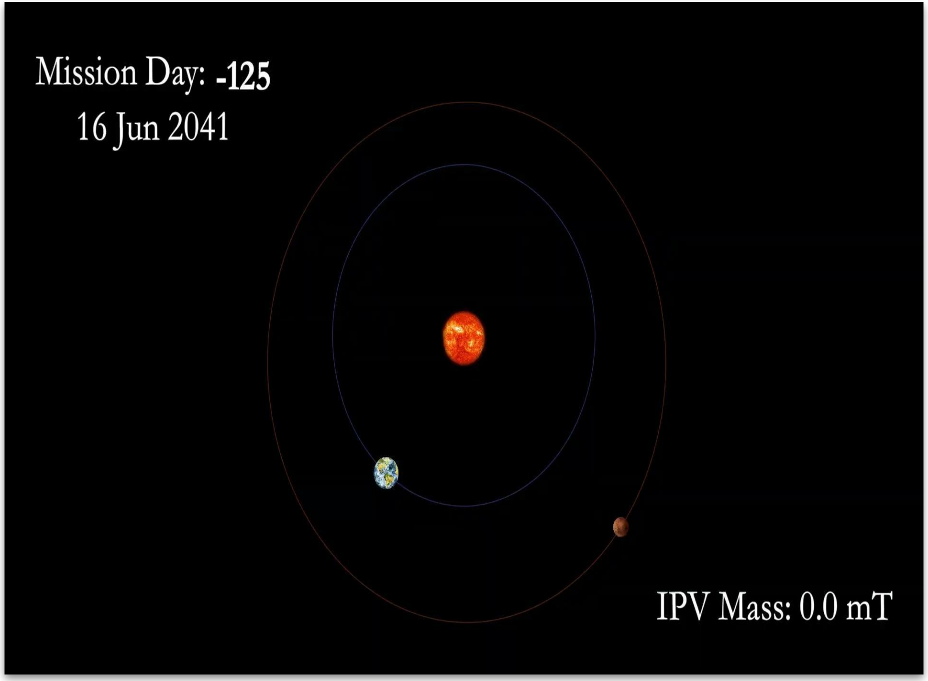
Isp	**340.000**	s	Injector Pressure Drop	0.2	20%	**Regenerative Cooling**		
Corrected Isp	**339.5468**	s	**Fuel Pump**	-	-	Total Heat Flux	1894191	W/m^2
Thrust	**35000.000**	N	Corrected Exit Pres.	8268.000	kPa	Wall Temp. Gas Side	459.11	K
Delta-V	**150.000**	m/s	ṁ	4.301	kg/s	Wall Temp. Coolant Side	371.00	K
O/F	1.440	-	**Oxi Pump**	-	-			
Combustion Pres.	6890.000	kPa	Corrected Exit Pres.	8268.000	kPa	Helium Tank(s) Volume	0.0413	m^3
Combustion Temp.	2995.000	K	ṁ	6.193	kg/s	Propellant Tank(s) Volume	17.397	m^3
Nozzle Area Ratio	55.000	-	Total Shaft Power	74.067	kW	Mass of Propellant	18221	kg
Chamber Diameter	0.449	m	**Gas Generator**	-	-	Mass of Ullage Helium	9.3401	kg
Throat Diameter	0.060	m	ṁin	0.0485	kg/s	Mass of Engine	650	kg
ṁtot	10.493	kg/s	O/F	0.25	-	Number of Engines	3	-
Nozzle Angle	15.000	degrees	Chamber Temp	1343.0000	K			
Nozzle Length	0.800	m						
Exit Mach	5.593	-	**Relative Isp Loss**	**-0.4532**	s	Total Mass	**20171**	kg

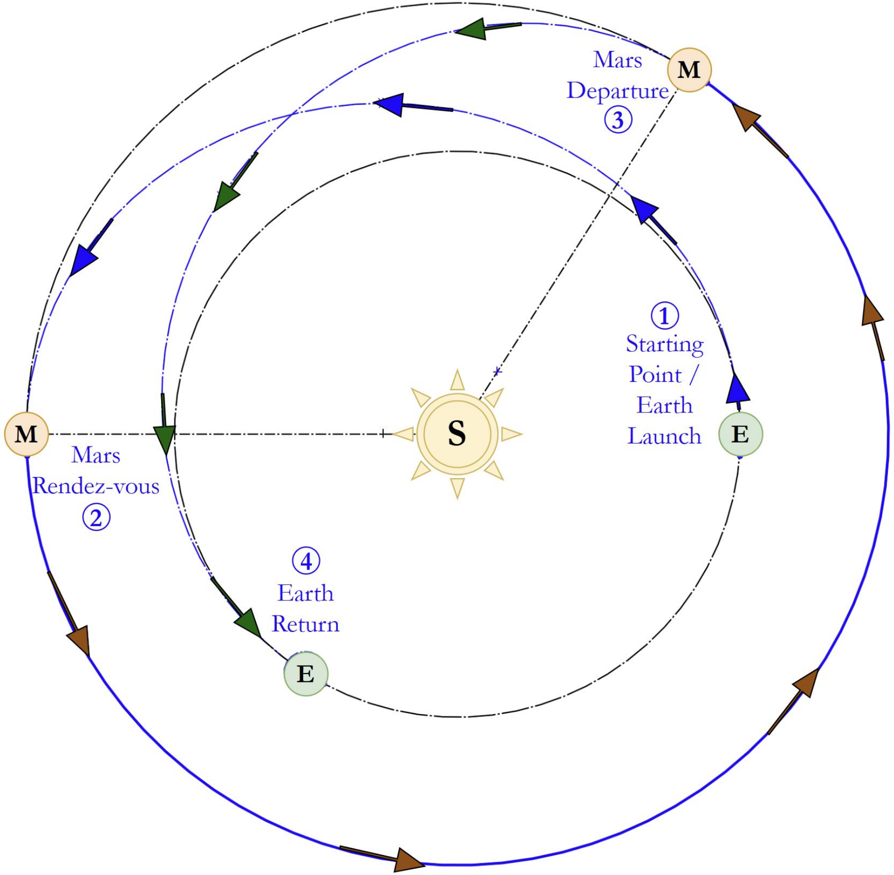
Human Systems Integration

HSI Domain	Implementation
Human Factors Engineering	• Human/machine function allocation: craft assembly steps by robot or crew
Maintainability & Supportability	• MMOD shielding • Resupply capability
Habitability & Environment	• Non-mission areas • Windows • Temperature & pressure regulation
Safety	• Shielding • Cooling fluid

NASA Human Systems Integration Handbook NASA/SP-2021001-952

Mission Animation

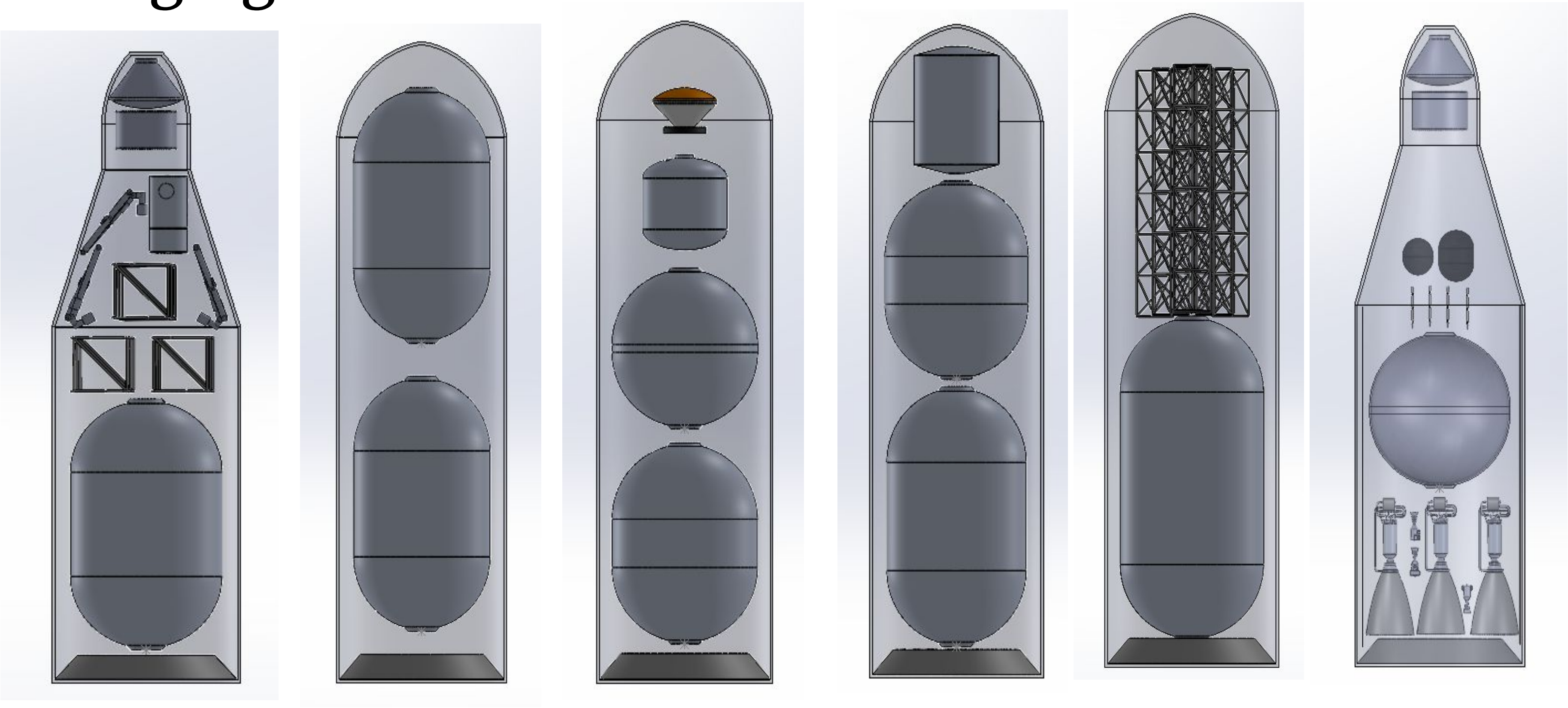




Mission Animation (or manimation) Made with Manimgl

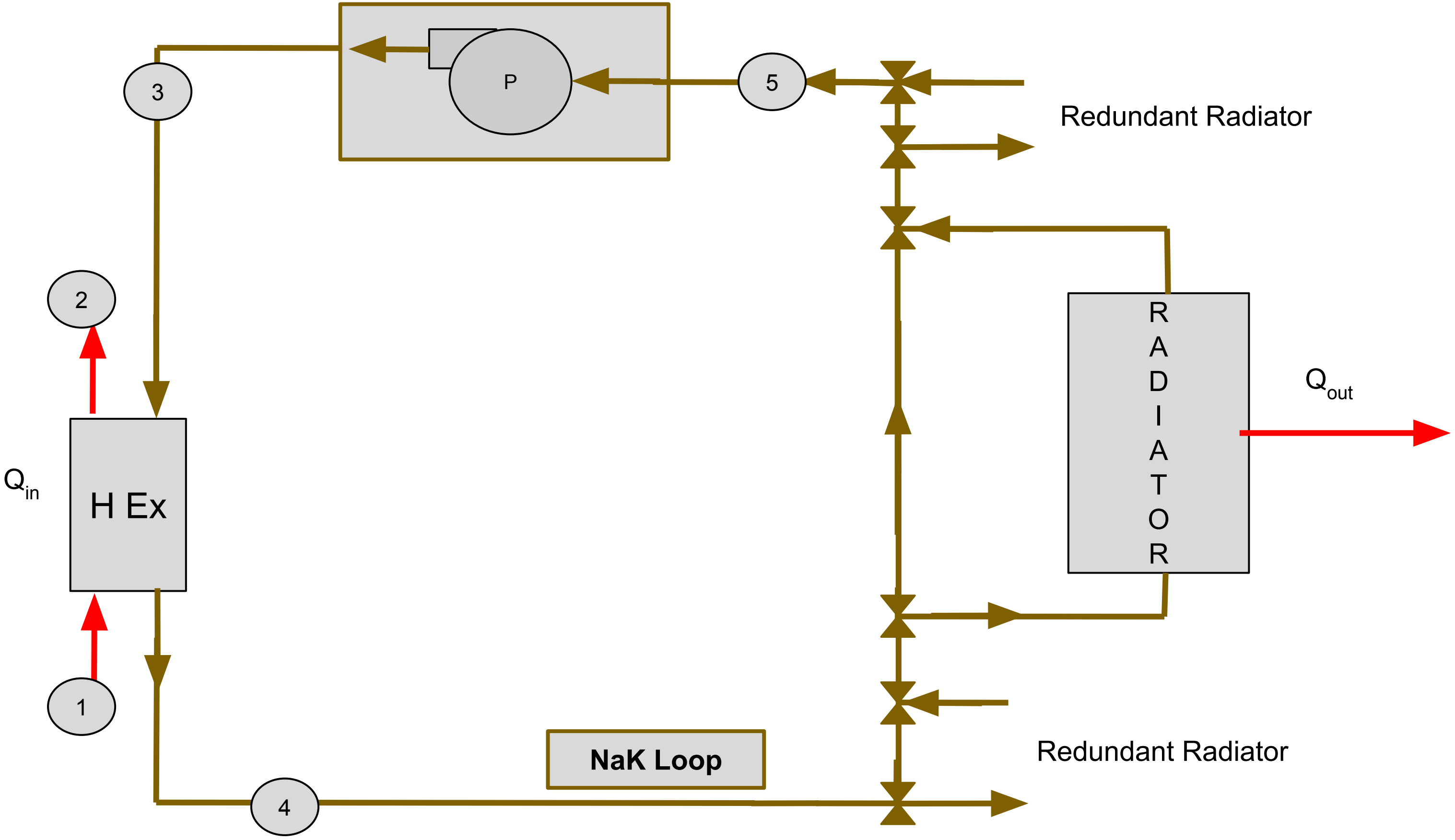
Packaging

Mass Breakdown



~ 120	~ 130	~148	~130	~135	~142

Bimodal Heat Rejection P&ID



DEV Heat Rejection System P&ID