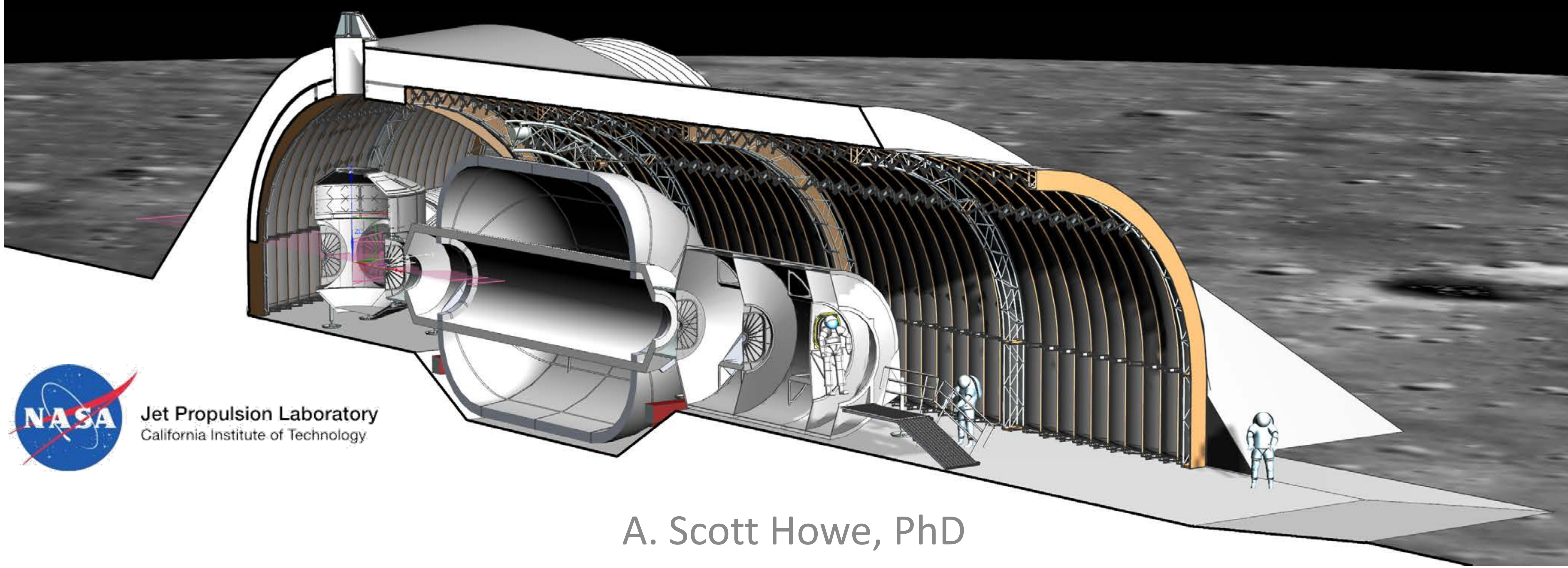
SPACE ARCHITECTURE & CONSTRUCTION



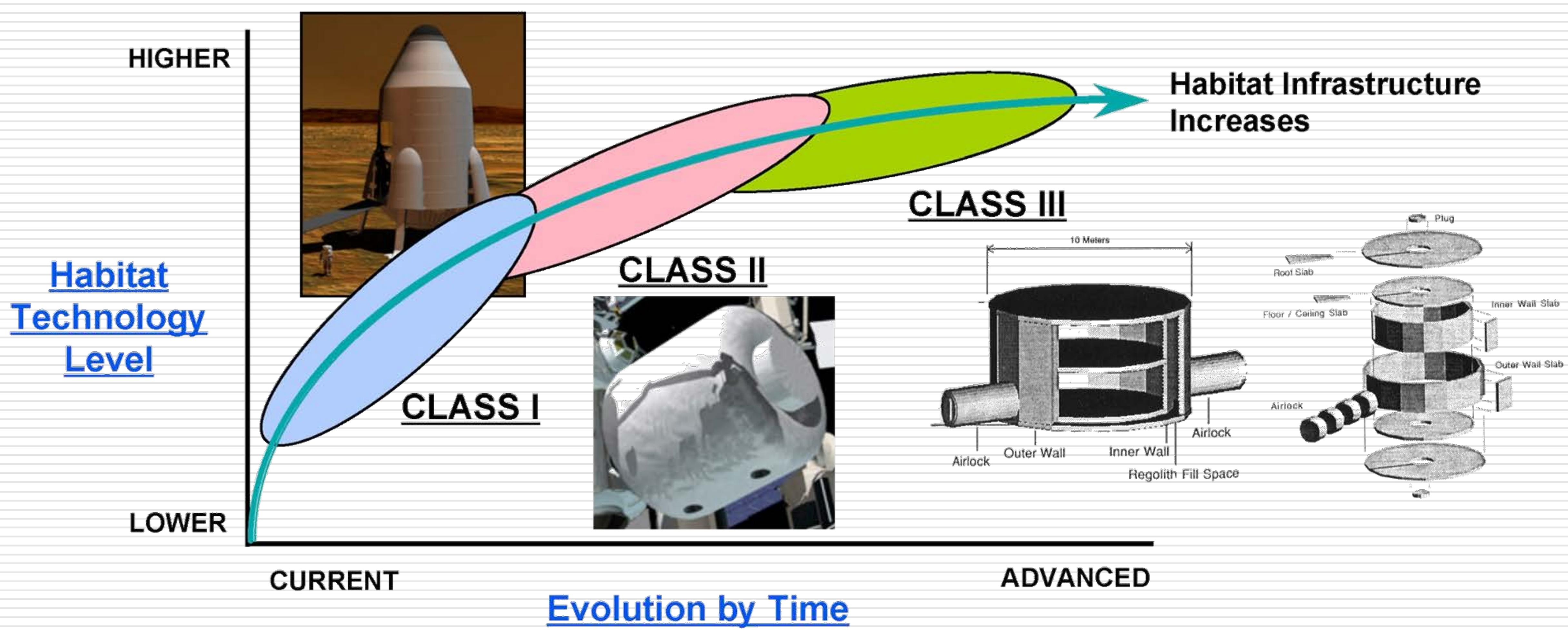
A. Scott Howe, PhD

NASA Jet Propulsion Laboratory, California Institute of Technology

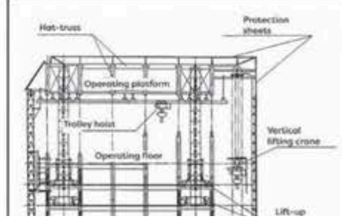
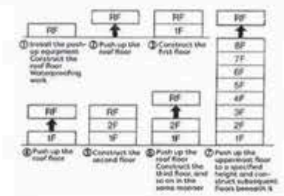
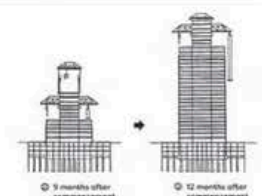
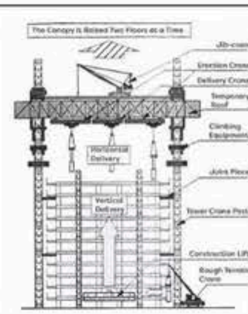
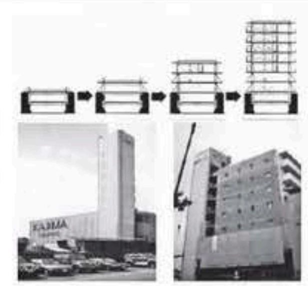
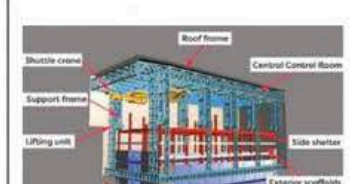
22 August 2020

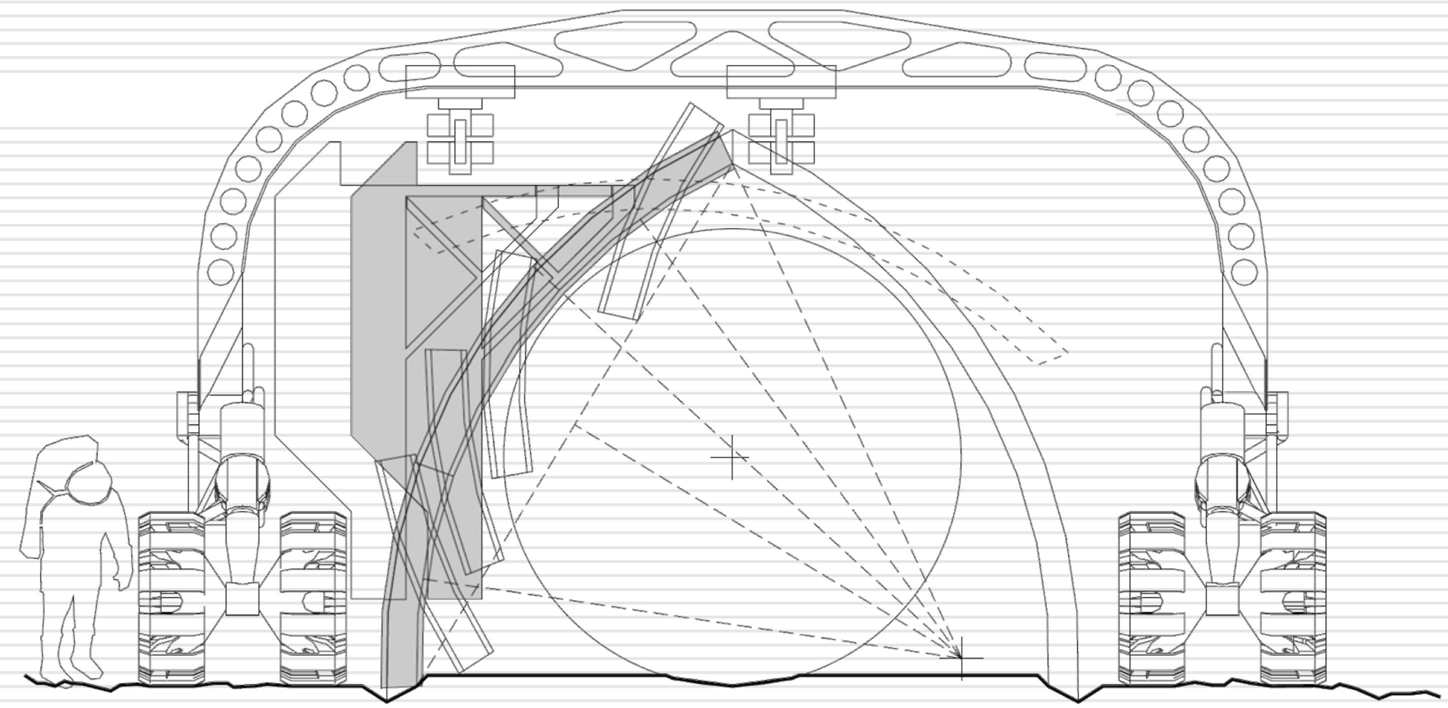
Phased Approach to Space Construction

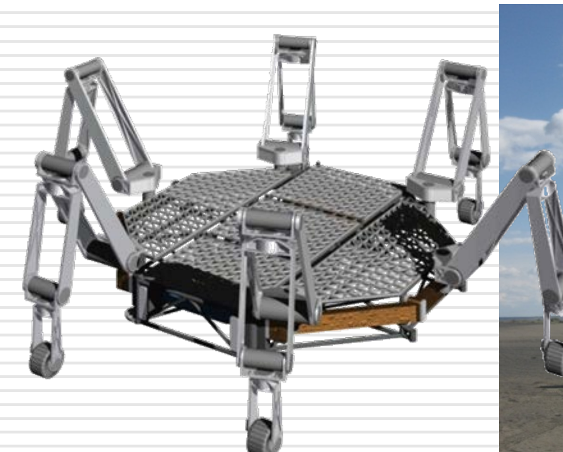
- CLASS I:
  - Preintegrated, Hard Shell Module
- CLASS II:
  - Prefabricated, Surface Assembled
- CLASS III:
  - ISRU Derived Structure w/ Integrated Earth components



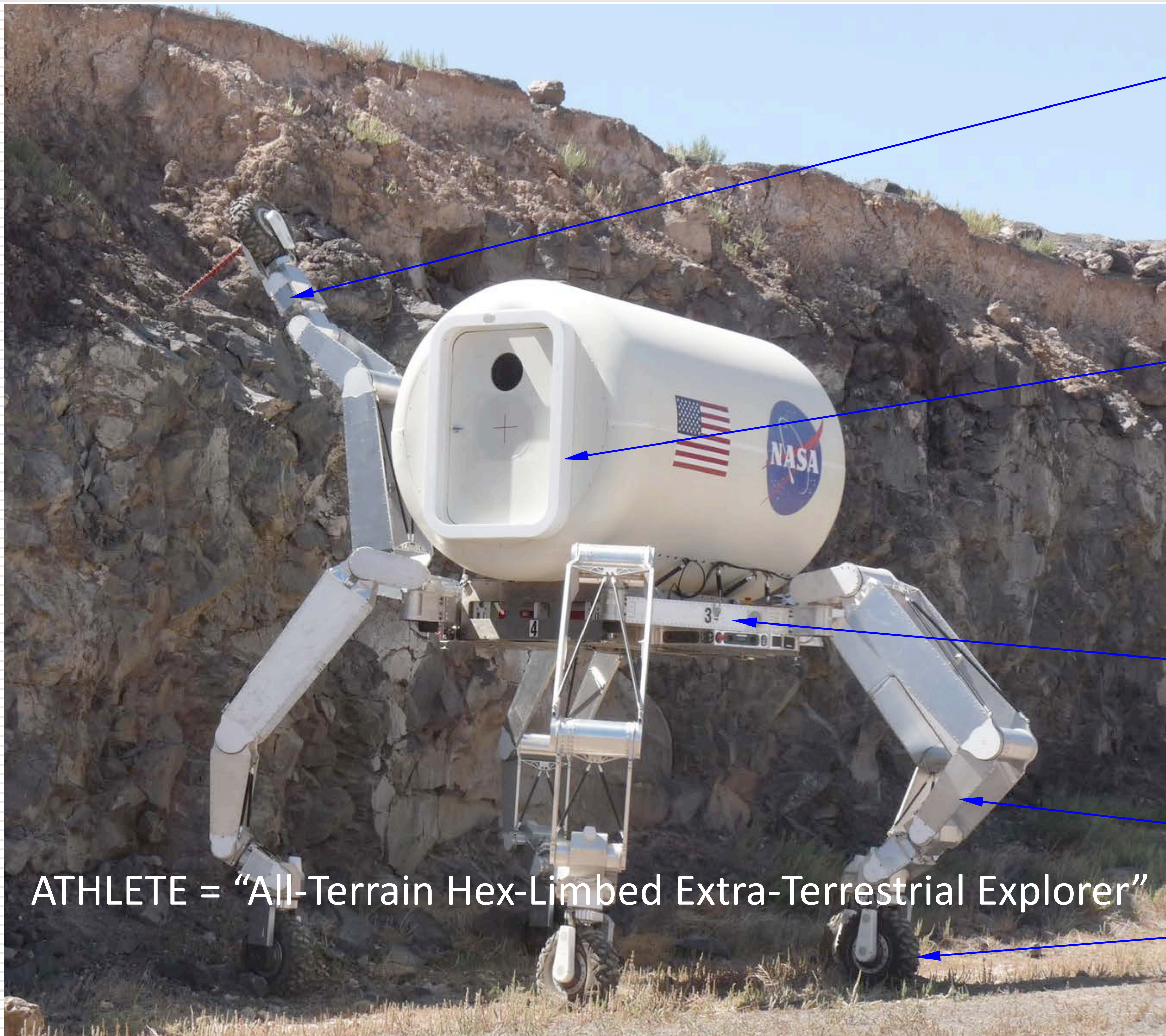
Robotic Construction Precedents

Year	Product Name	Company	Climbing Mechanism	Example
1990	The SMART System (the Shimizu Manufacturing System by Advanced Robotics Technology)	Shimizu	A hat-truss is supported by four jacking towers, operated by hydraulic jacks. The hat-truss is jacked up to working height for the construction of the first storey and repeat [18].	
1990	Roof Push-up	Takenaka	Push-up floor or roof floor (RF) is first constructed. Push up RF, construct the 1st floor, then push up the roof floor, construct the 2nd floor and repeat [19].	
1990	ABCS (Automated Building Construction System)	Obayashi	Super Construction Factory (SCF), a working space on a pre-assembled roof, supported on building under construction [20]. See Figure 1.25.	
1992	T-Up System (Totally Mechanised Construction System)	Taisei and Mitsubishi	With the building core as the support, the production platform is elevated with hydraulic jacks to the desired floor along guide columns [21].	
1995	The Big Canopy	Obayashi	With four external tower masts and a gigantic canopy at the top. Gantry cranes are fixed to the underside of the canopy operated by remote control. The canopy is jacked up two storeys per lift. See Figure 1.26.	
1996	AMURAD (Automatic Uprising Construction by Advanced Technique)	Kajima	Building top floor down, starting from roof and top floor and working down until the ground floor. Lower floor levels as the construction factory, build the roof floor first, push up using hydraulic hacks by one level, allowing work to begin for the next floor, push up and repeat [22].	
1997	FACES (The Future Automated Construction Efficient System)	Penta-Ocean	A steel frame unit as a canopy housing a computer control centre, crane robots and automated equipment, all attached to the ceiling of the structure. The frame is lifted along the pillars of the building to the next floor level and repeat [23].	





ATHLETE Robotic Constructor



ATHLETE limb grasping a tool -- drilling into a rock cliff -- tools can be lifted well above main body

Payload on modular pallet (showing a mockup habitat with 60" high door)

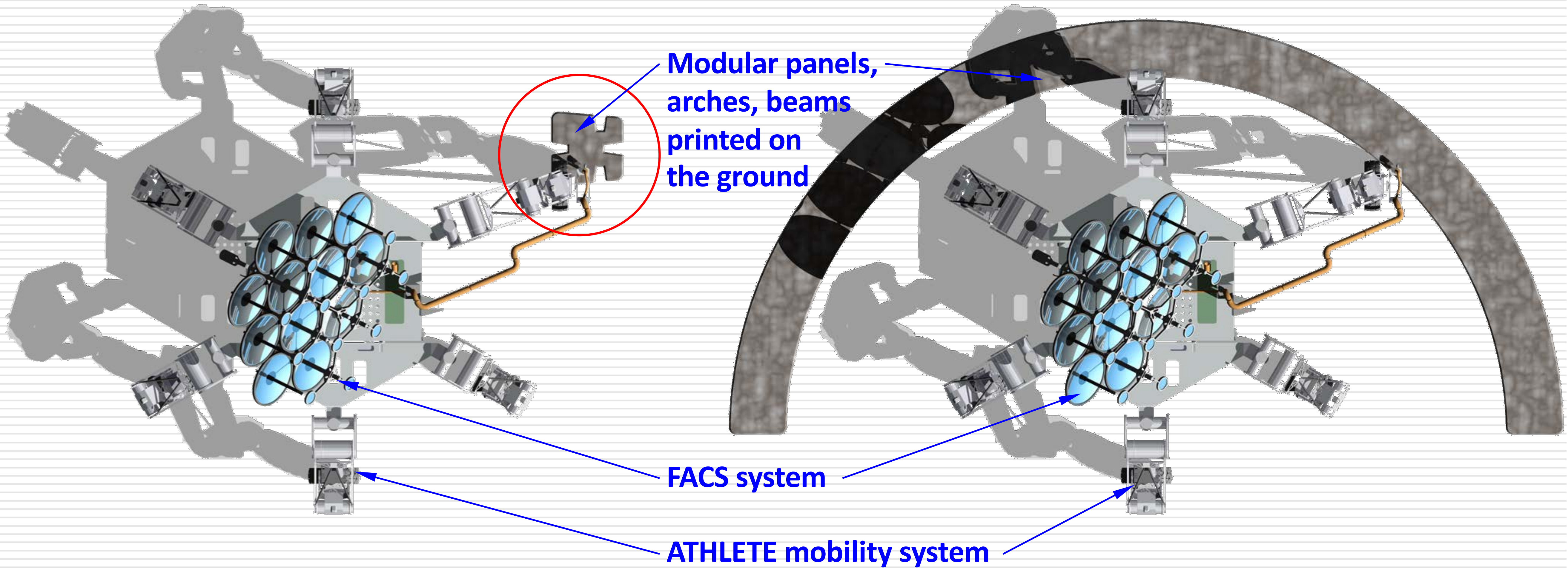
Tri-ATHLETE vehicle with three limbs x2 = six limbs total

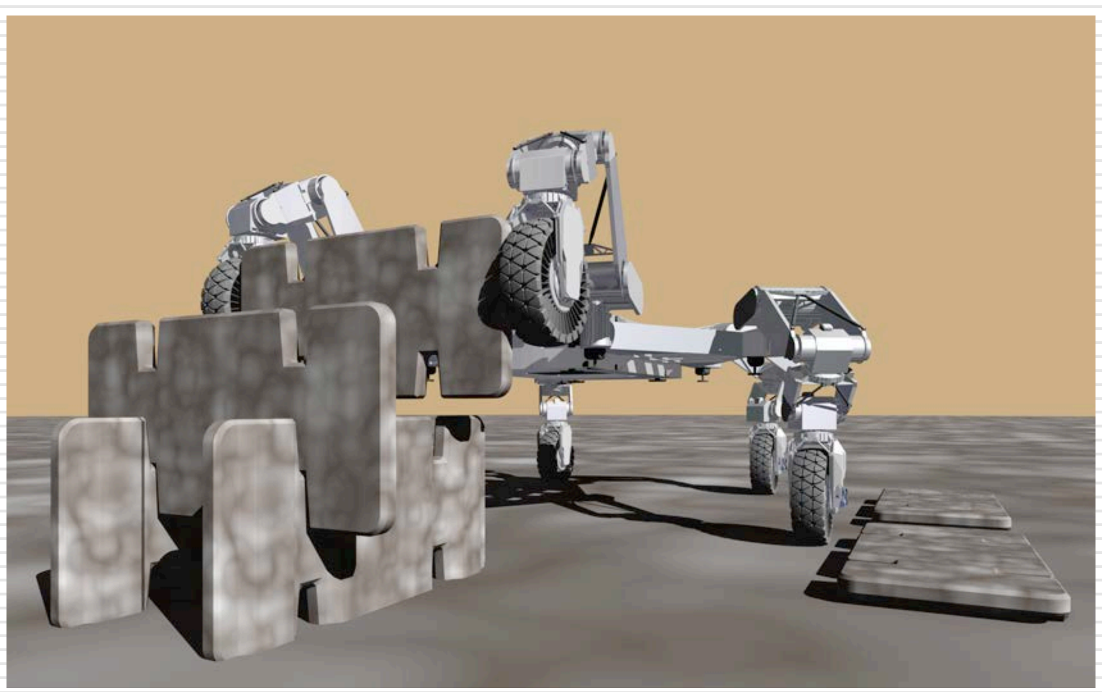
Limbs

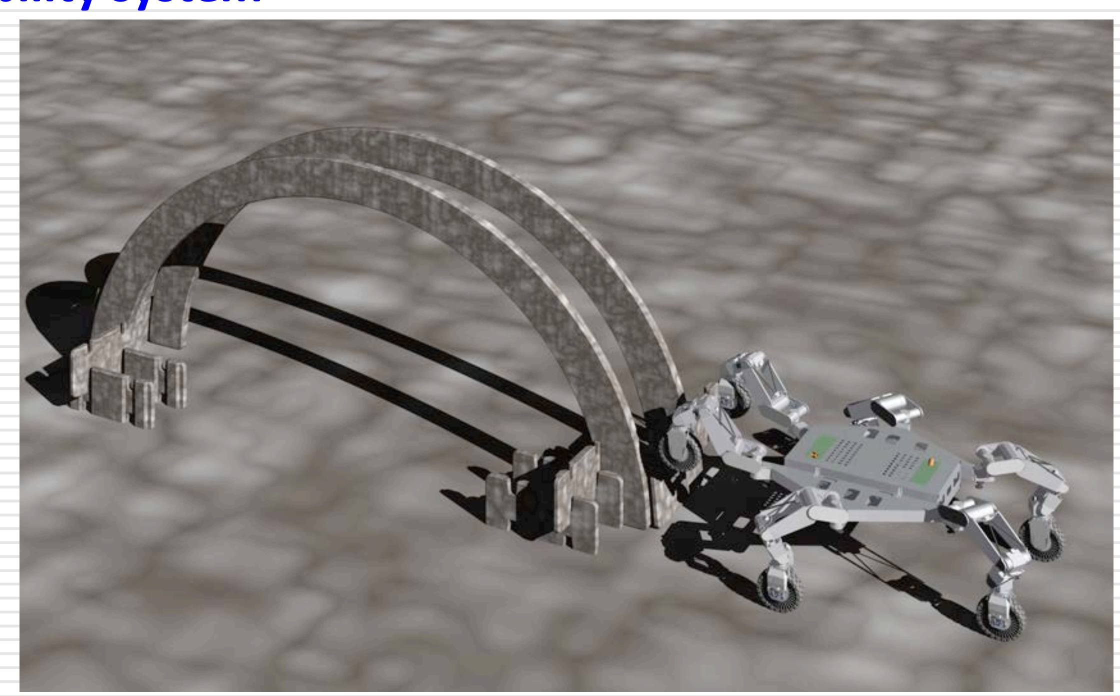
Wheels on limbs for mobility

Robotic Assembly of Outpost

Additive Construction: Large-scale 3D Print

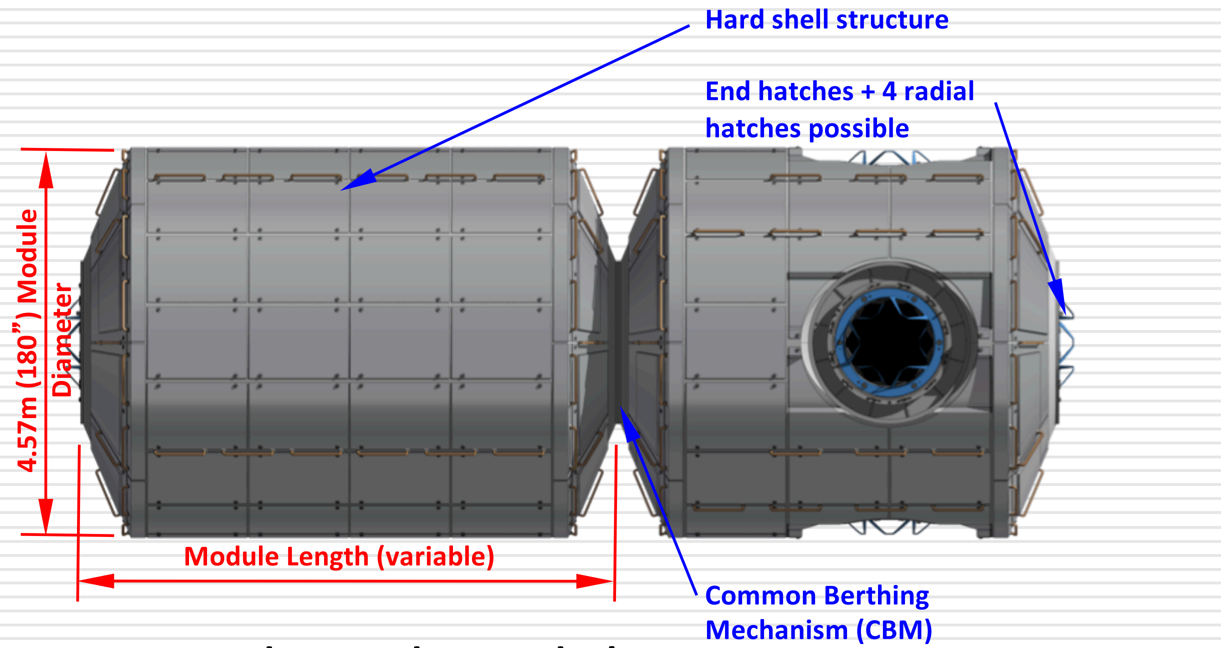




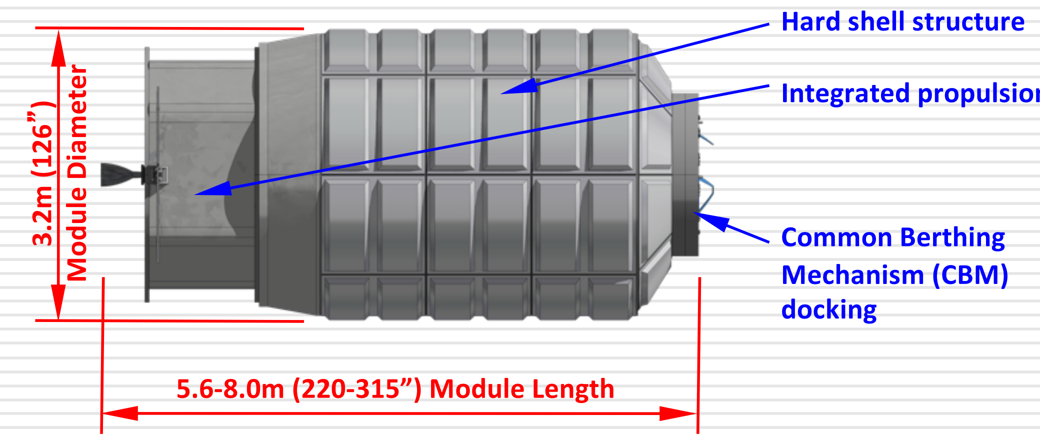


Additive Construction: Large-scale 3D Print

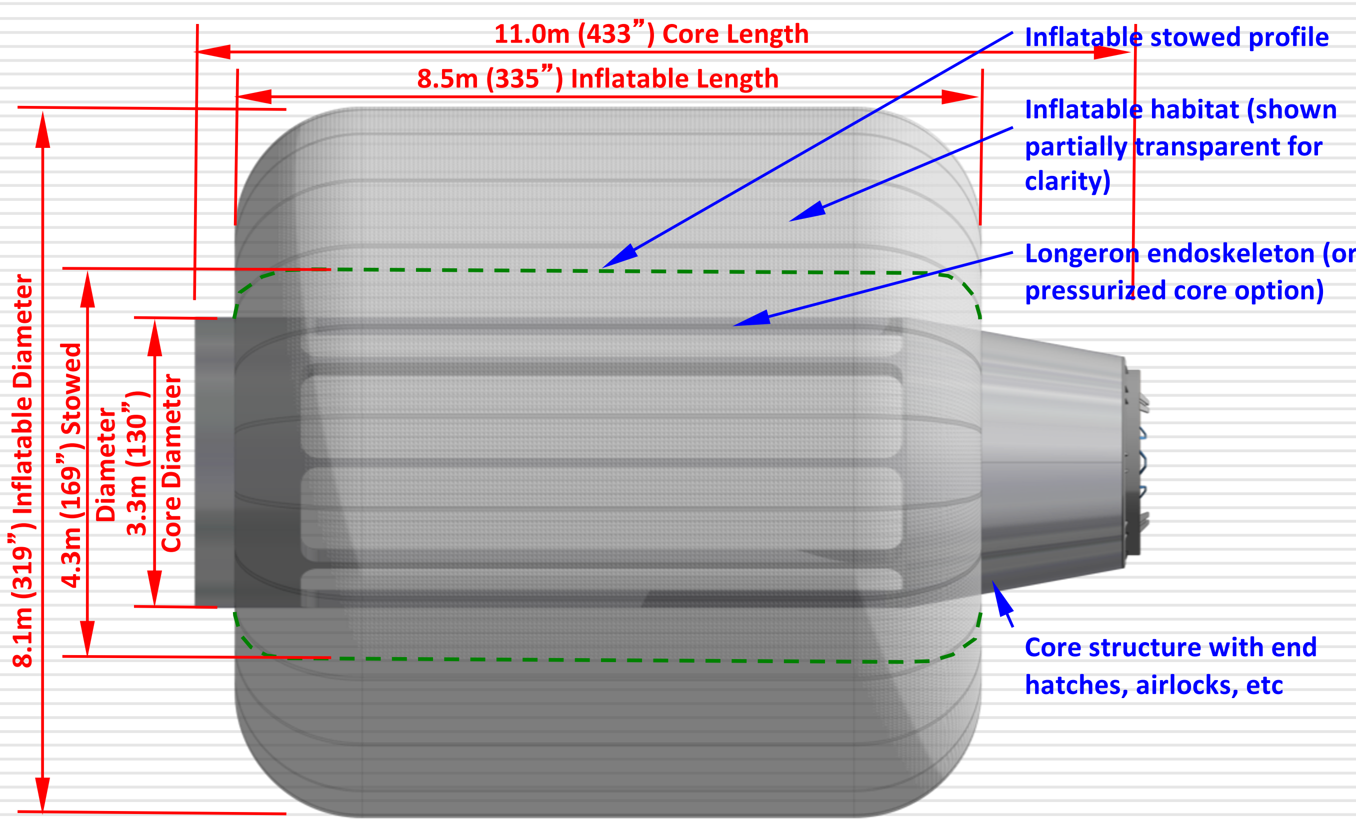
Typical Habitat Structure Types (1 of 3)



ISS Derived Hard Module

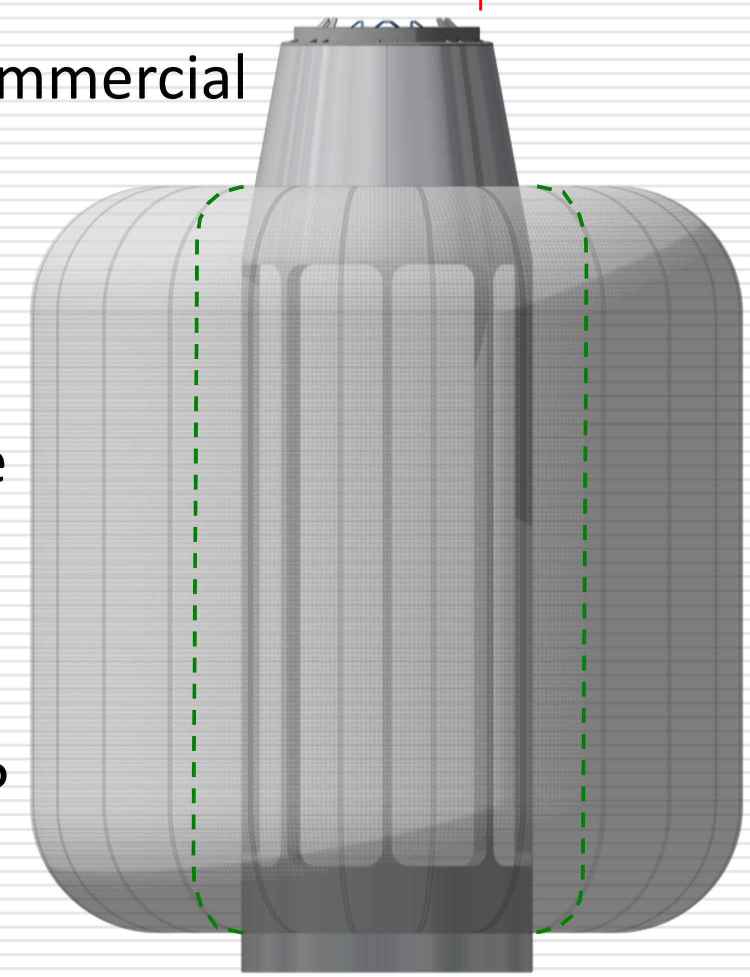


Commercial



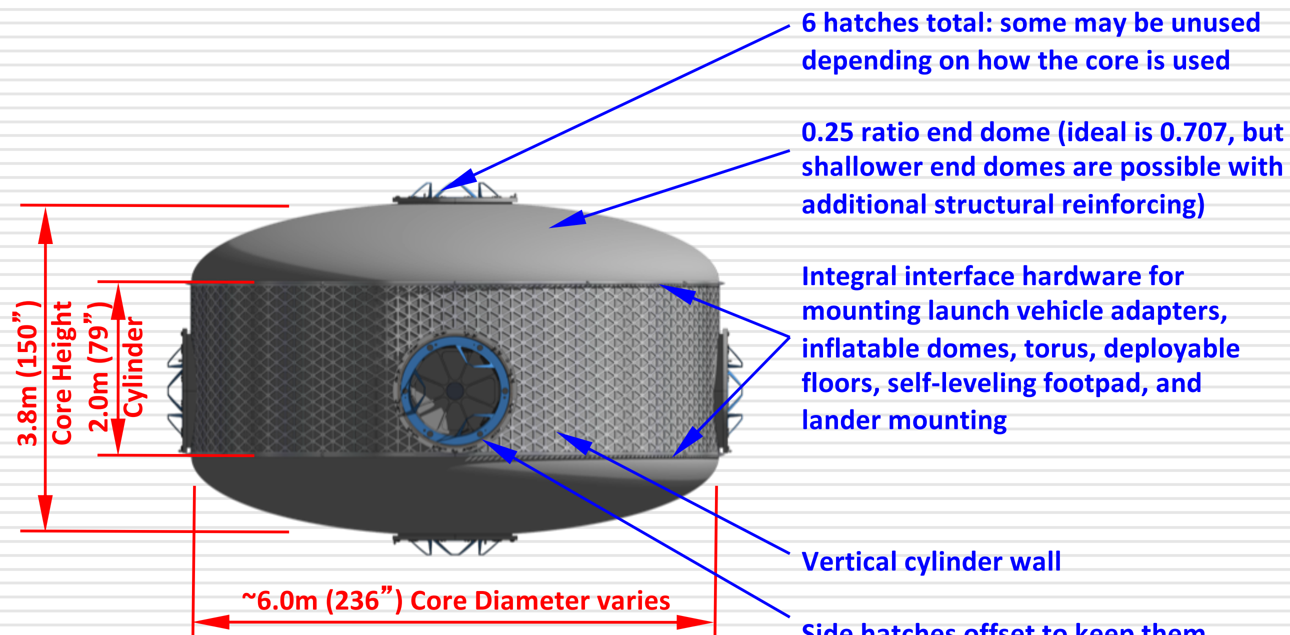
TransHab / Bigelow Hybrid Inflatable

Note: these are the common habitat types proposed in NASA NextSTEP

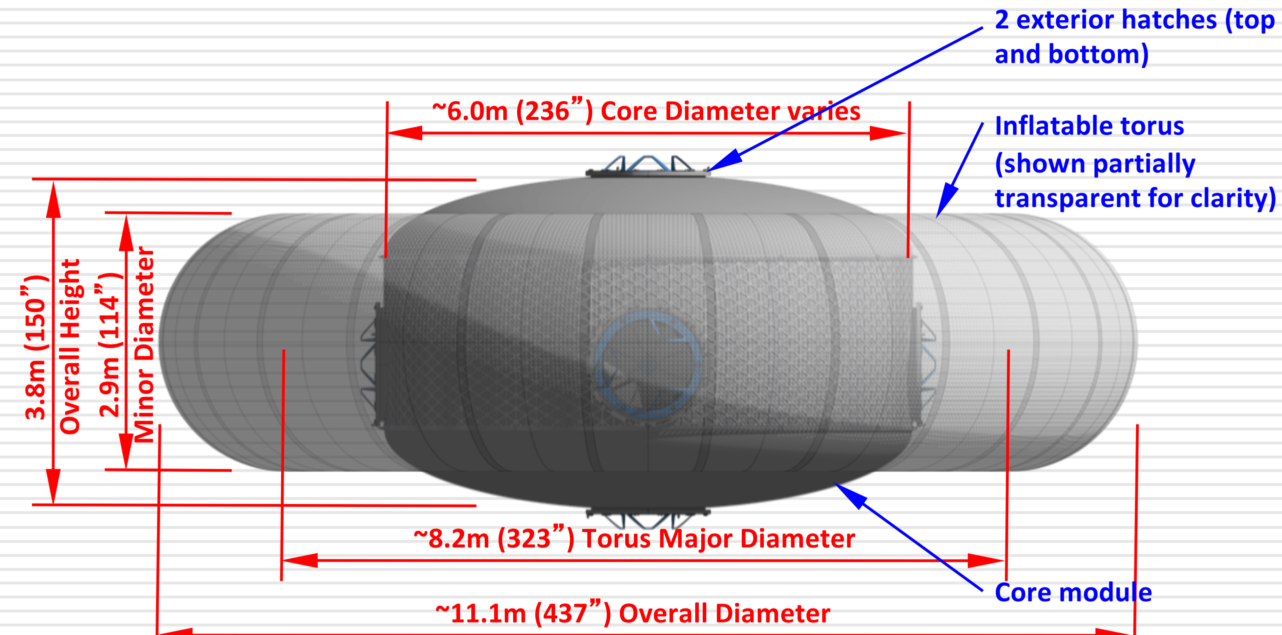


Hybrid Inflatable Vertical

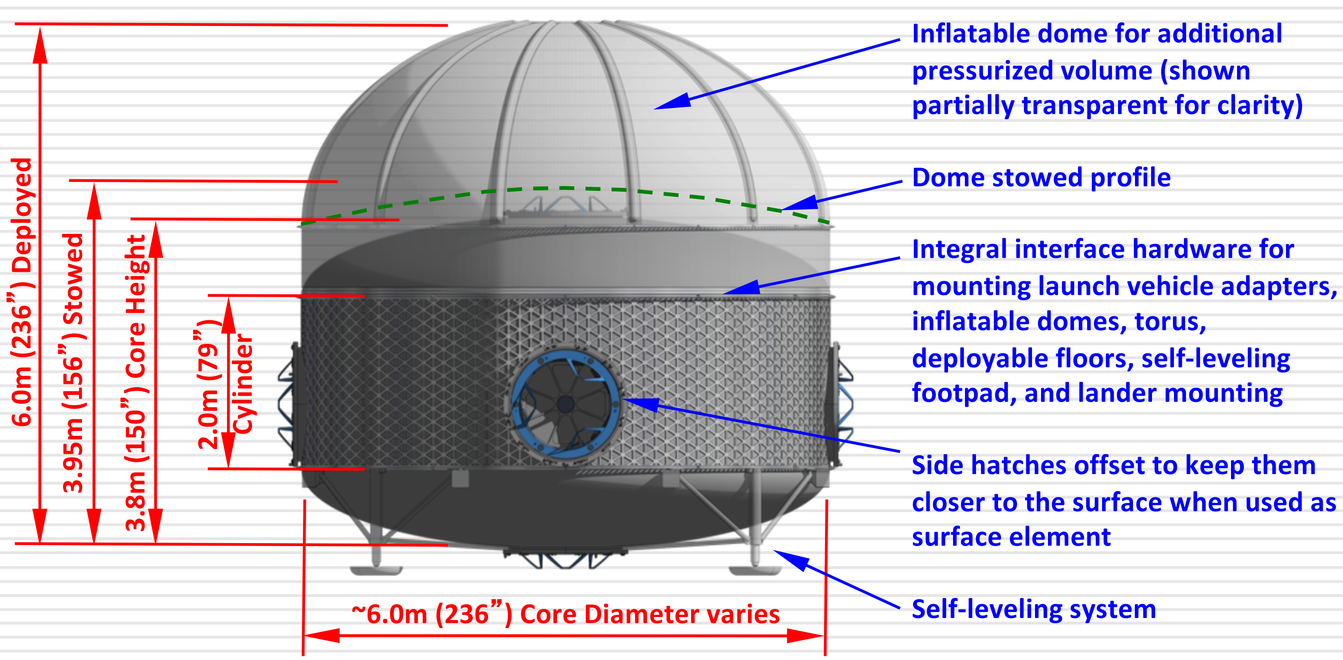
Typical Habitat Structure Types (2 of 3)



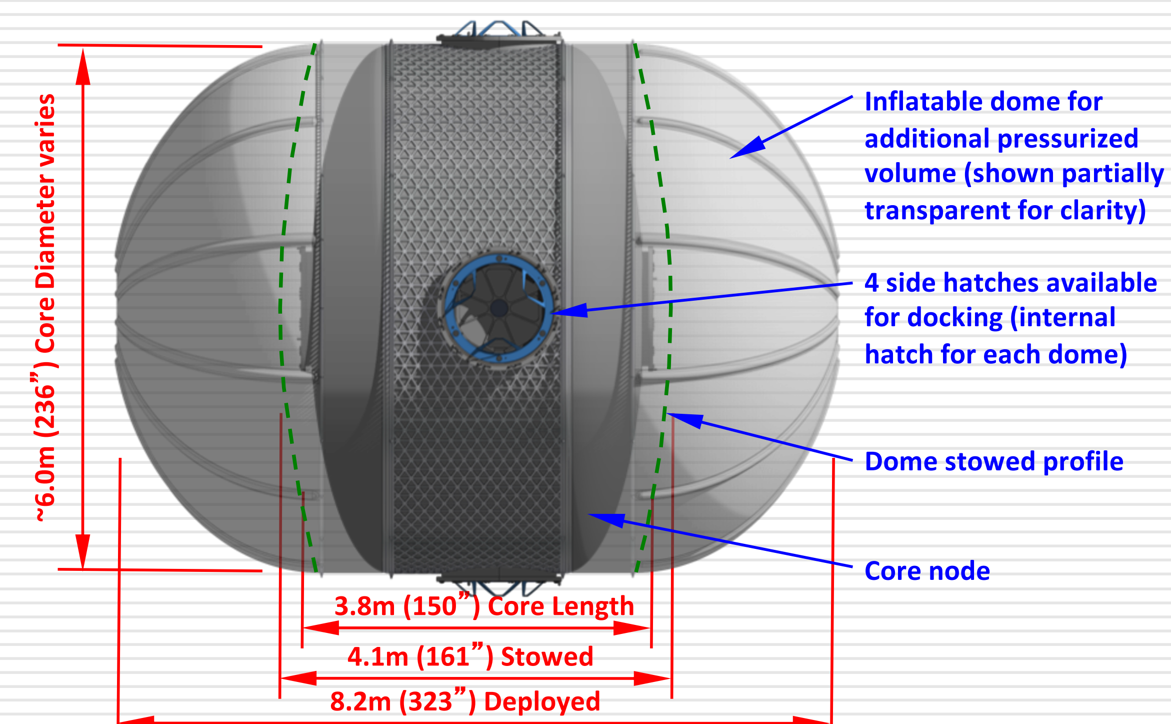
Vertical Core Module



Vertical Surface Sortie (Inflatable Torus)

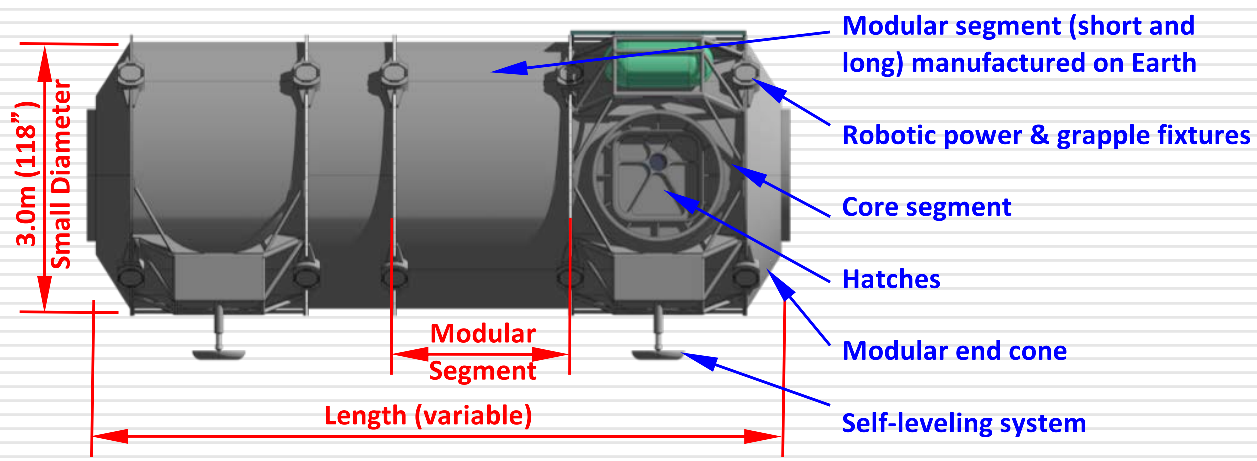


Vertical Surface Outpost (Inflatable Dome)

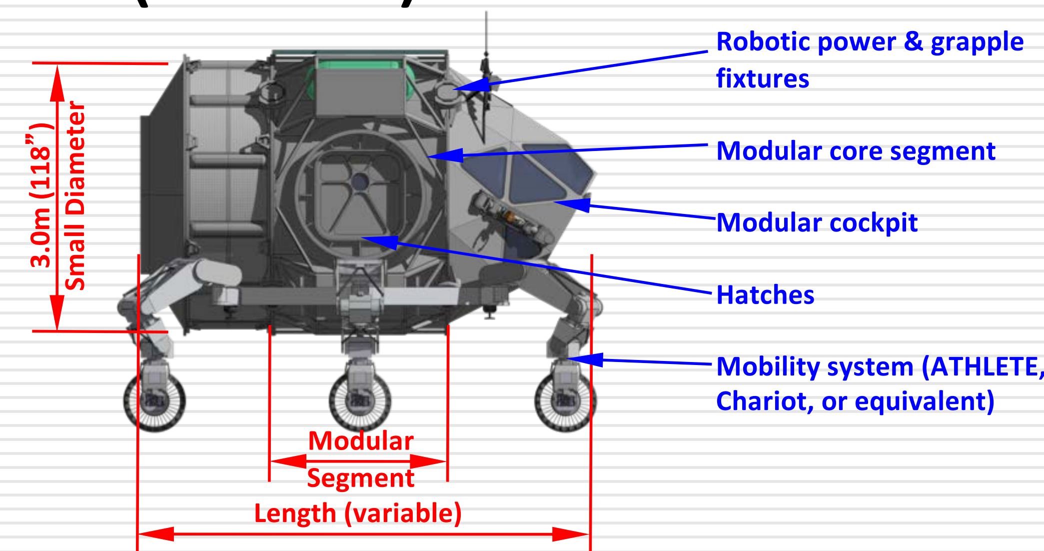


Vertical Transit (Inflatable Dome)

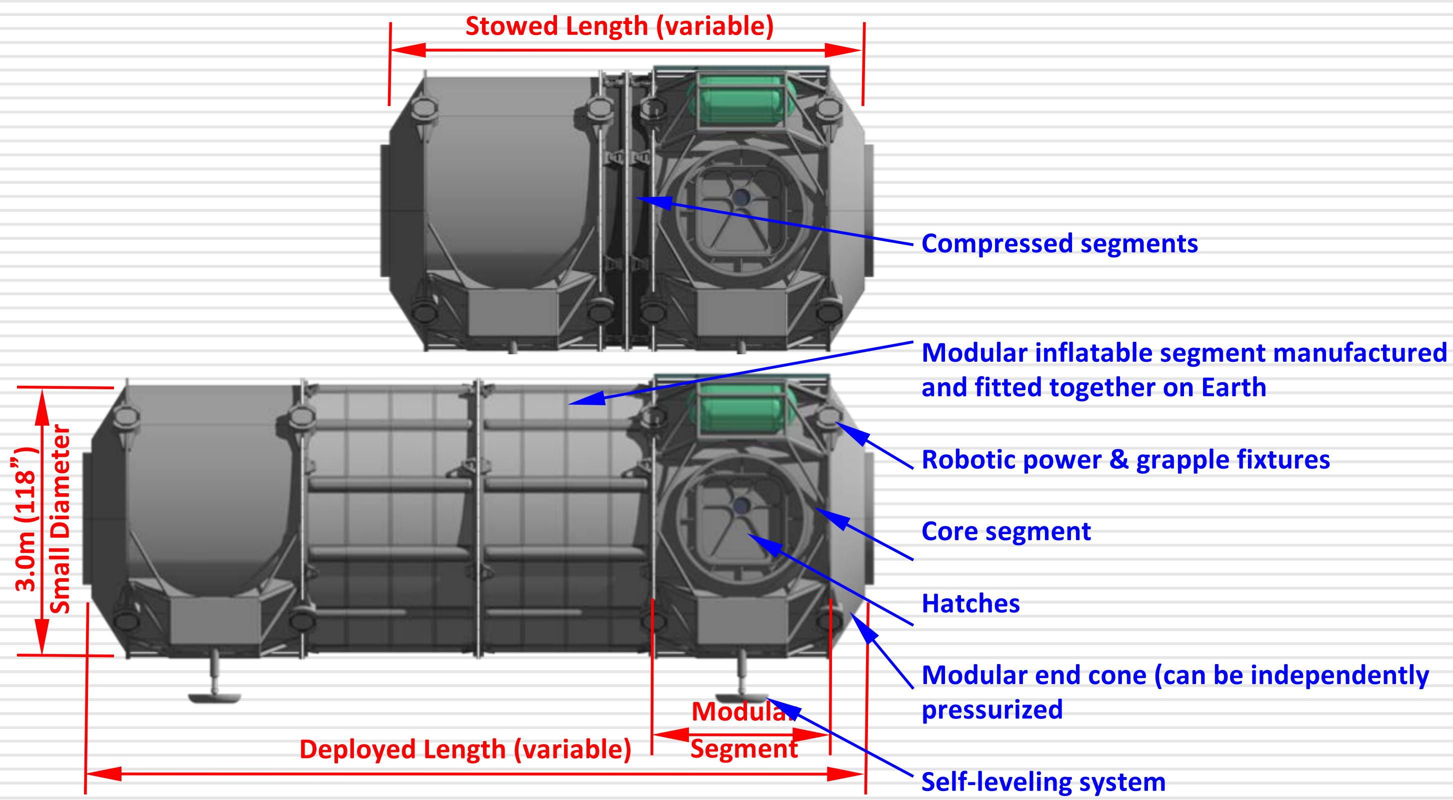
Typical Habitat Structure Types (3 of 3)



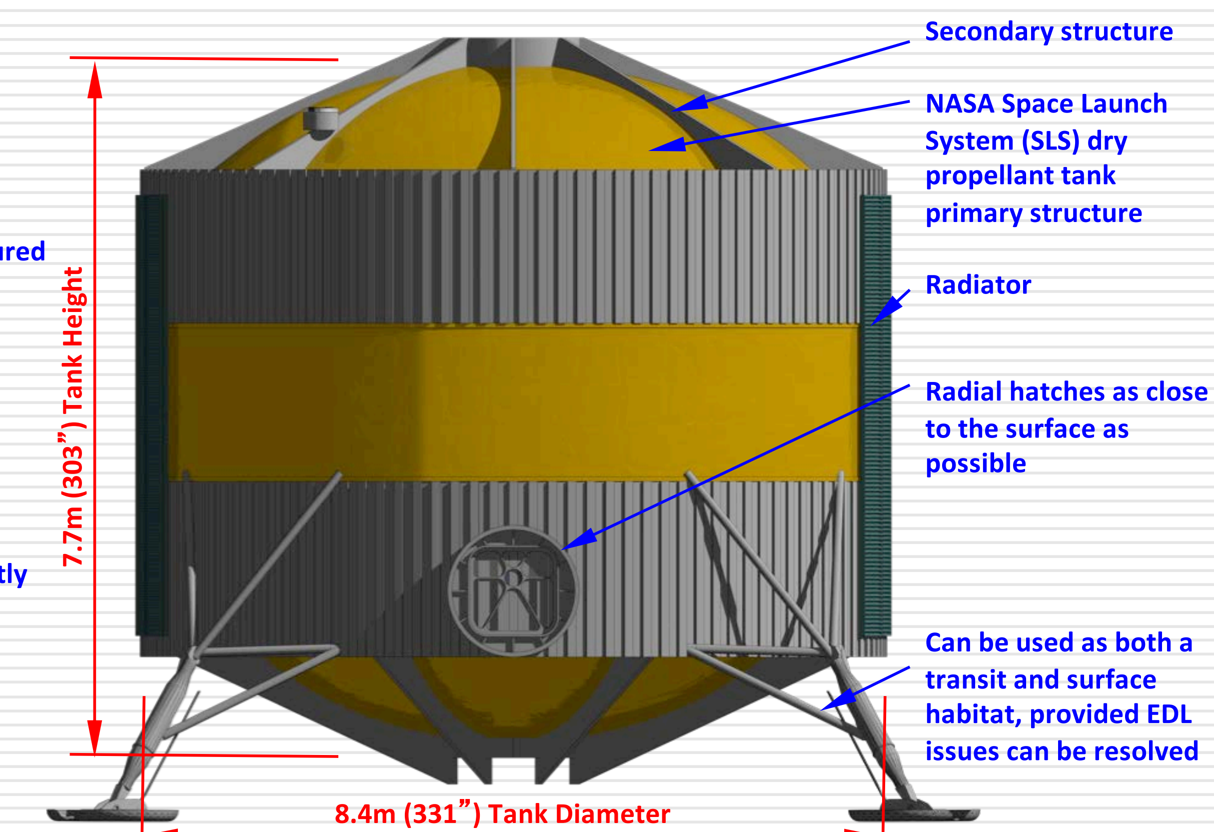
Small Cabin Habitat



Small Cabin Rover



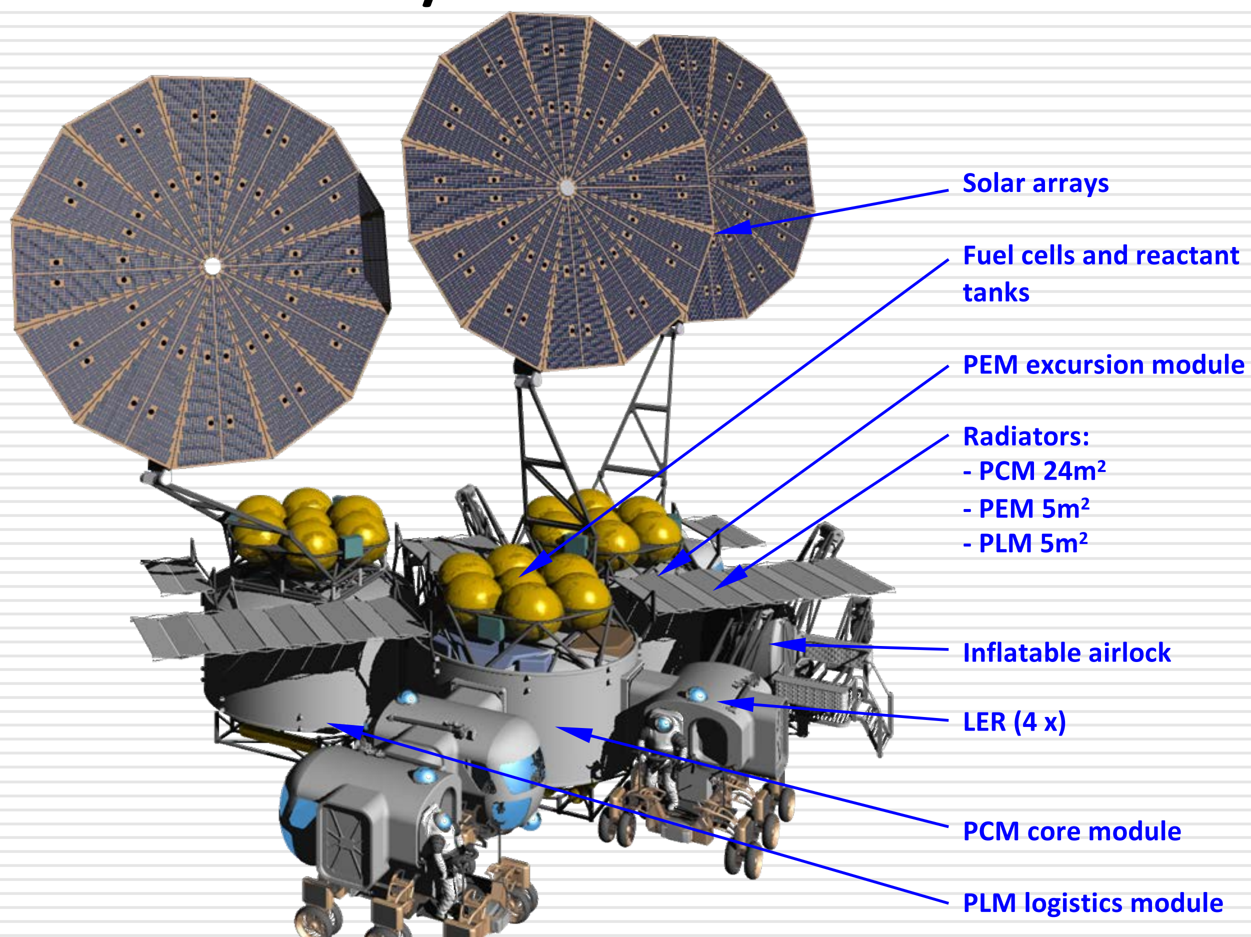
Small Cabin Midex (inflatable expansion)

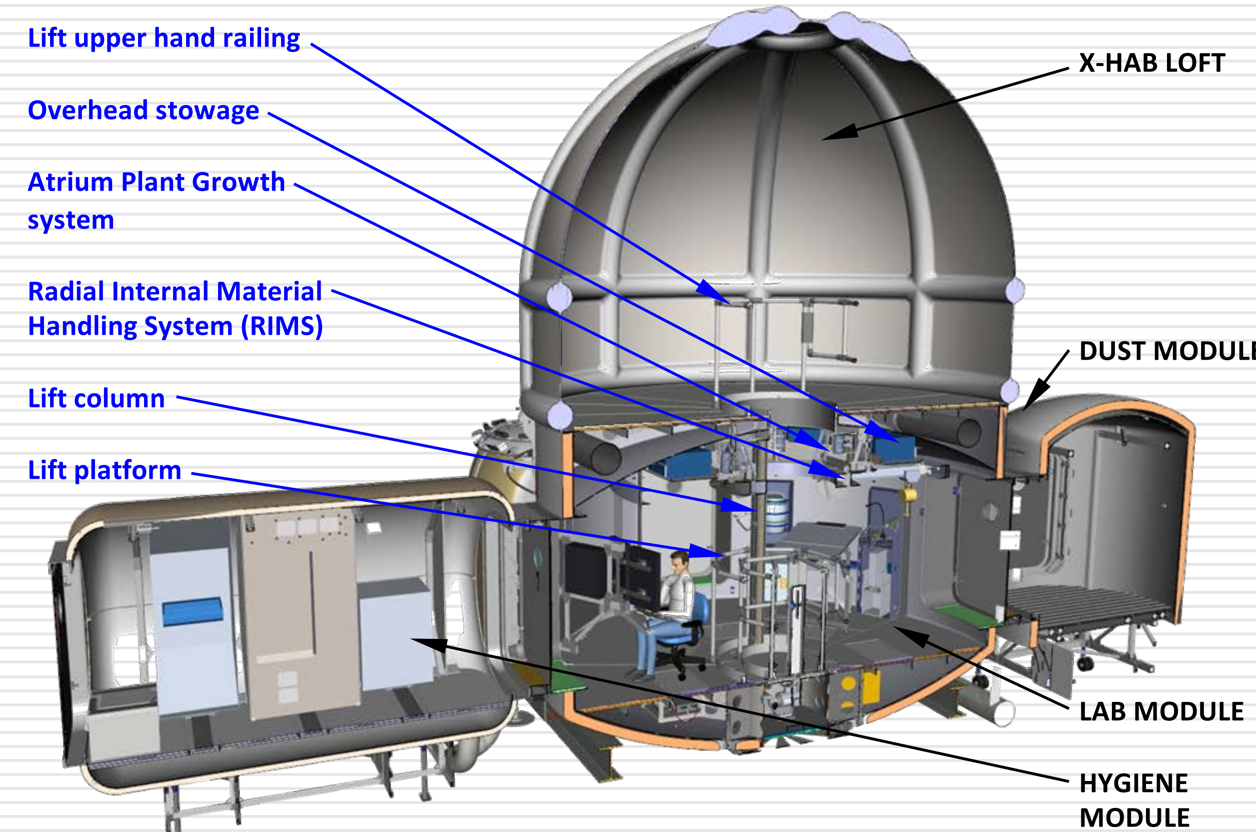


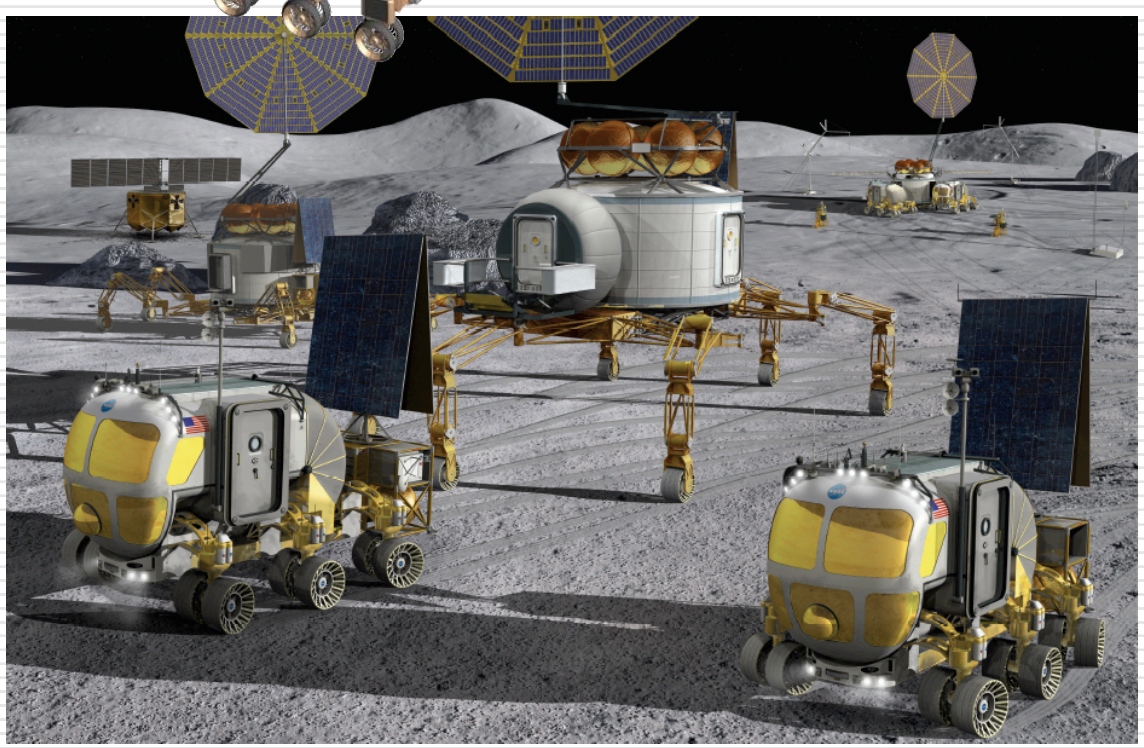
SLS Dry Prop Tank Derived "Skylab2"

Lunar / Mars Habitat Demonstration Unit

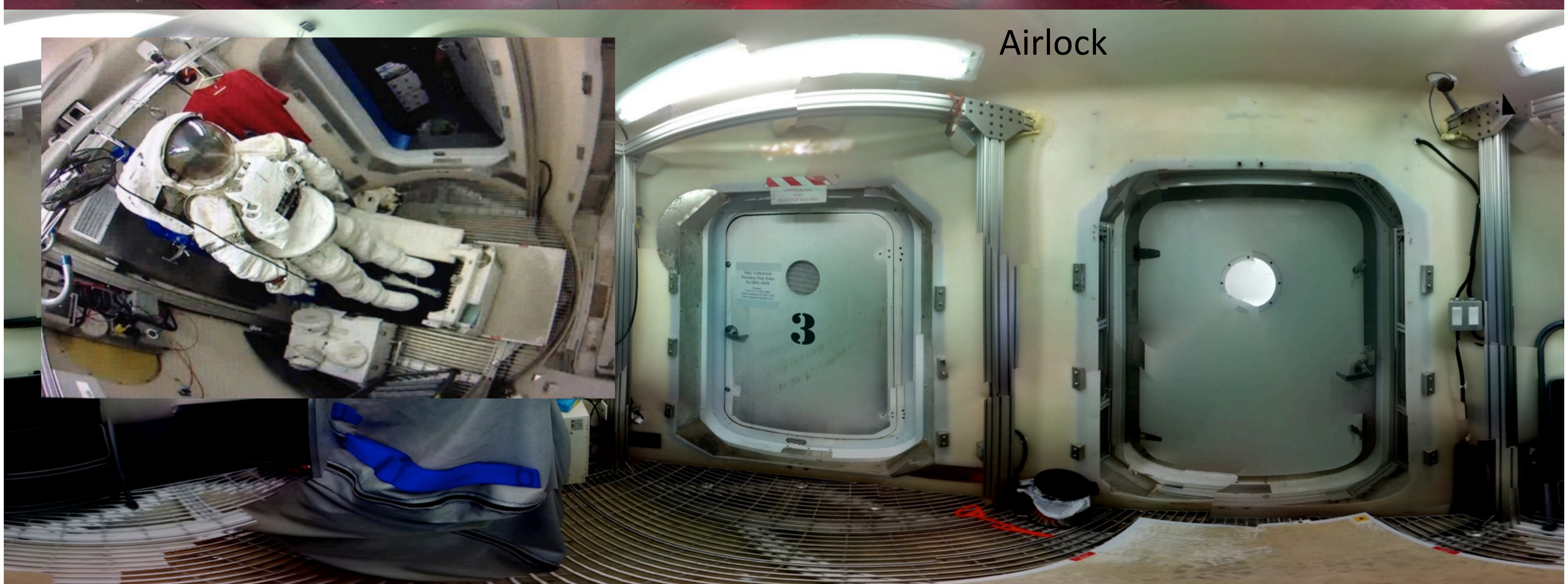
Lunar / Mars Habitat Demonstration Unit








HDU Lab deck


Airlock


X-Hab Inflatable Loft

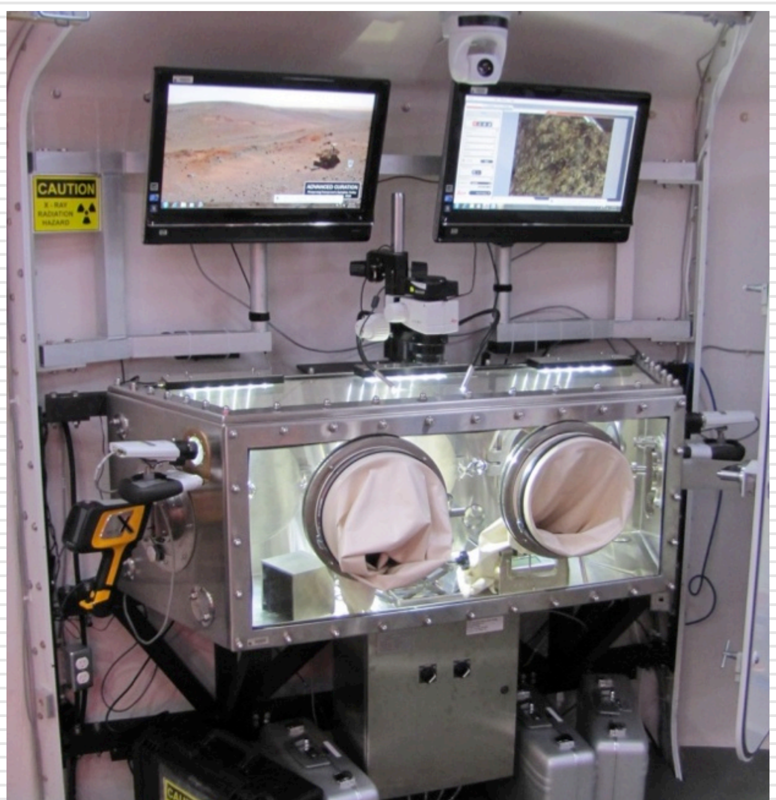
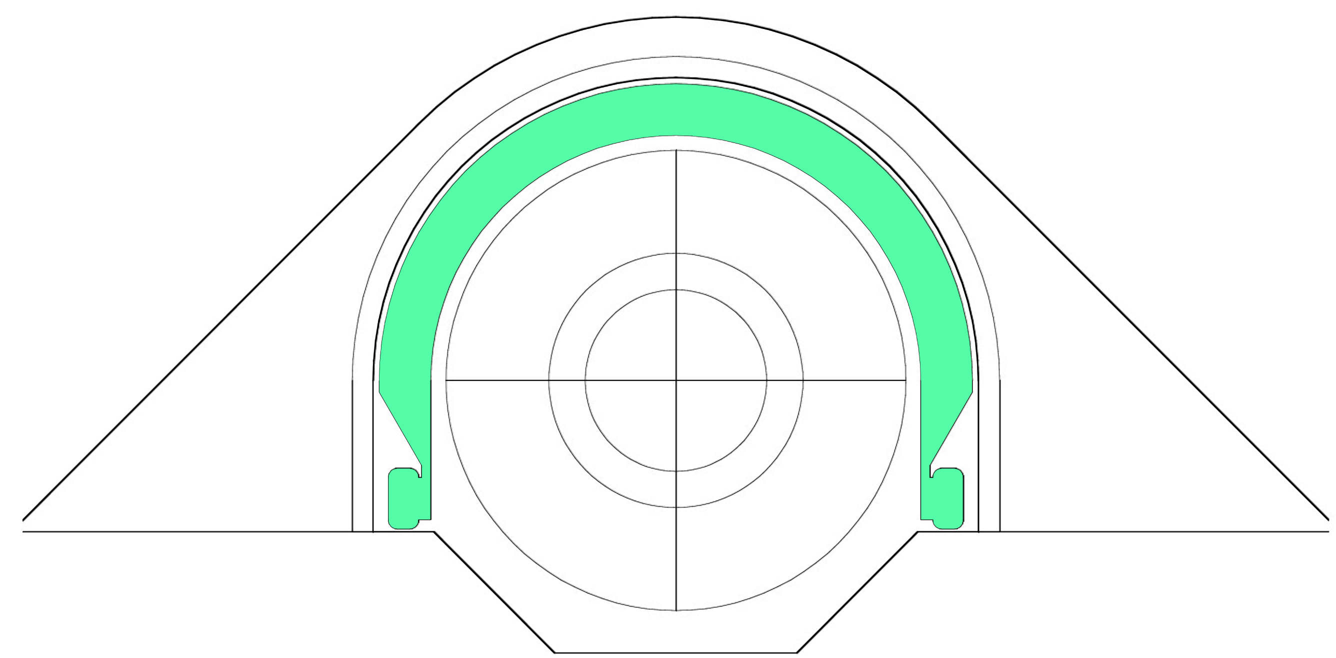


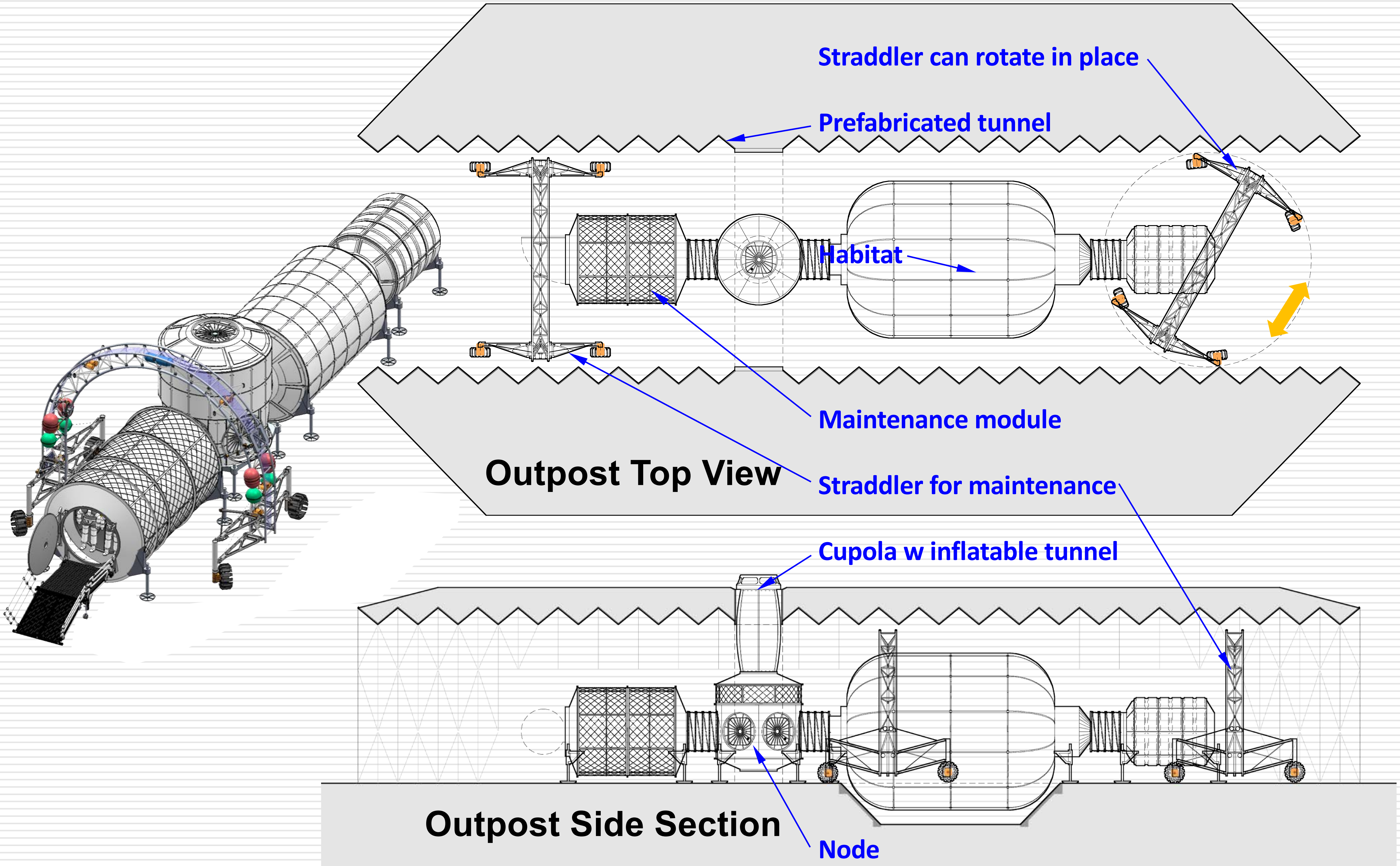

Photo: James W. Young

Planetary Autonomous Construction

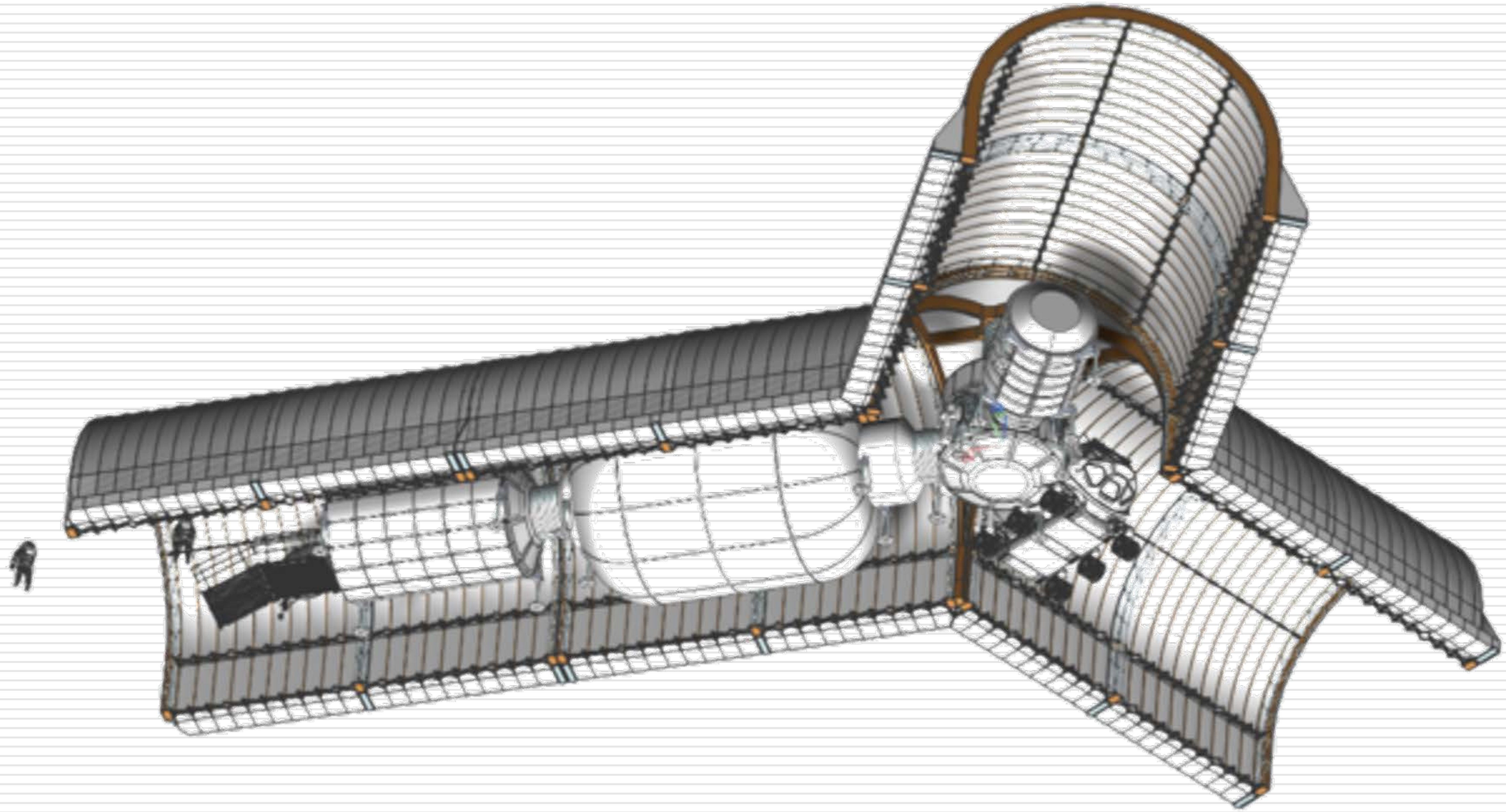
- Outpost will need to be constructed independent of whether crew are present or not
- Using robotic delivery and set-up, an autonomous construction system can build the outpost and make it ready for human occupancy
- Robotic systems and maintenance will allow for continuous operations
- Crew will not be burdened by construction, housekeeping, and maintenance but will be employed where humans do best
- All systems need to be designed in parallel, according to common geometries and interface principles
- Design "Parti" is a diagram that defines abstract relationships to make sure each system works together seamlessly



Robotic Lunar Surface Operations (RLSO) Lunar Outpost

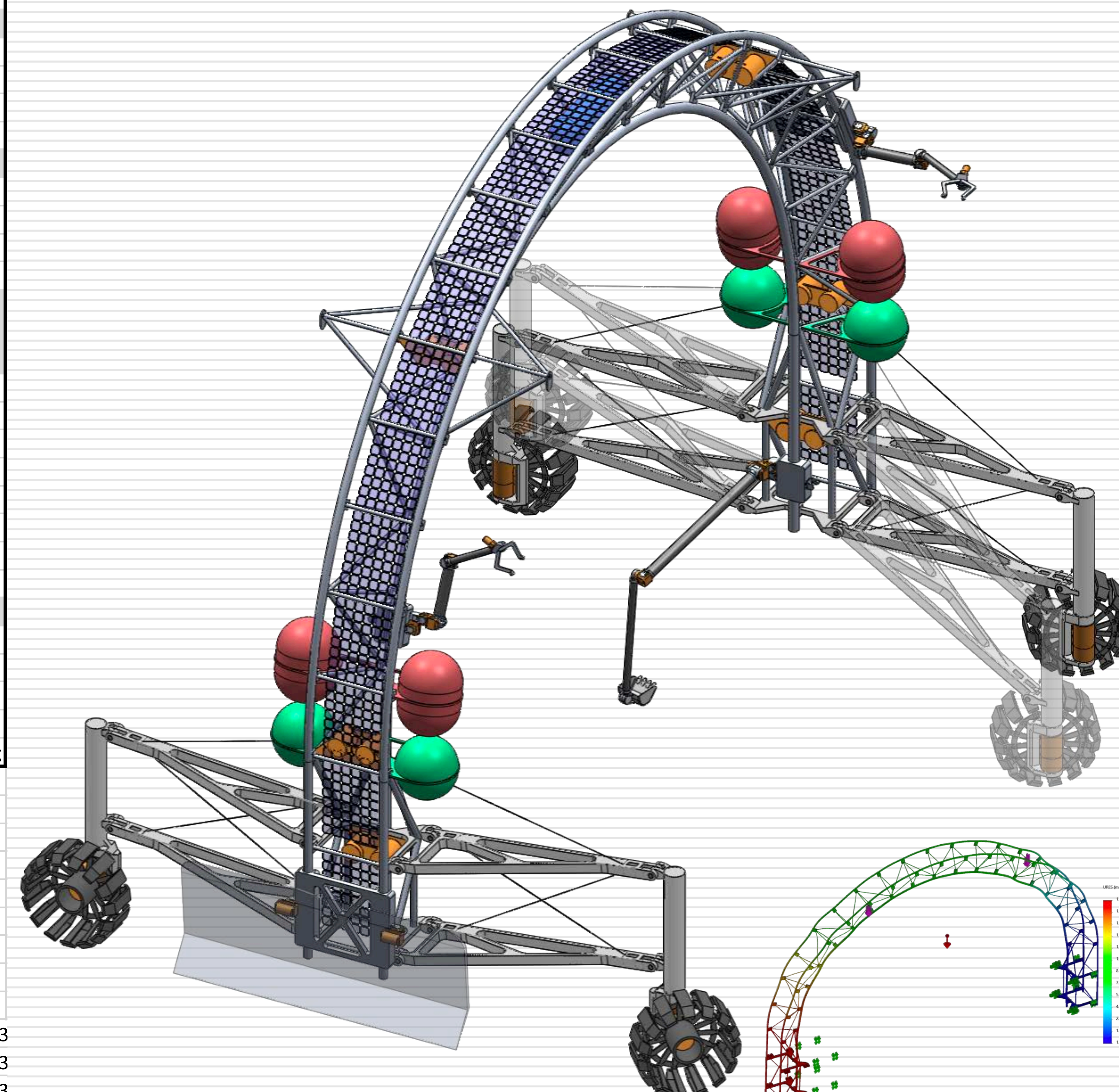


RLSO Lunar Outpost + Shield Tunnel



Gantry Straddler

Robotic Gantry MEL								
Element		Percentage		Unit Mass		Units	Total Mass	
Structure		32	%				1,670	kg
Truss				631	kg	1	631	kg
Fourbar Linkage				51	kg	8	408	kg
Wheelmount Post				65	kg	4	258	kg
Wheel				93	kg	4	372	kg
Mechanisms		39	%				2,012	kg
Main Winch				85	kg	8	677	kg
Wheel Actuator				50	kg	4	201	kg
Steering Actuator				84	kg	4	334	kg
Robotic Arm				200	kg	4	800	kg
Thermal Protection		9	%				468	kg
Avionics & Control		10	%				520	kg
Power System		10	%				530	kg
Solar Array		1	%	2	kg	22	53	kg
Batteries		2	%	104	kg	1	104	kg
Water Tank				11	kg	1	11	kg
LH2 Tank				12	kg	4	50	kg
LO2 Tank				8	kg	4	31	kg
Fuel Cell				18	kg	1	18	kg
Electrolysis System				159	kg	1	159	kg
Power Avionics		2	%	104	kg	1	104	kg
Vehicle Dry Mass		100	%				5,200	kg
Growth Margin		25	% V Mass				6,500	kg
Volatiles Storage							114	kg
LH2 3000psi				13	kg			
LO2 3000psi				102	kg			
Vehicle Wet Mass (w/ growth margin)							**6,615**	**kg**
1	kg water =	0.1112	kg hydrogen +			0.8888	kg oxygen	
	Water needed			114	kg			
	tank calculations:			density =		1600	kg/m3	
Water tank	0.11	m3 vol=		0.05715		r each =	0.2389512	m
LH2 tank	0.71	m3 vol=		0.355		r each =	0.43925149	m
LO2 tank	0.36	m3 vol=		0.1785		r each =	0.34928763	m
area each =	0.71751053	tank wall =		0.005	m	vol =	0.00358755	m3
area each =	2.42457911	tank wall =		0.005	m	vol =	0.0121229	m3
area each =	1.53312043	tank wall =		0.005	m	vol =	0.0076656	m3

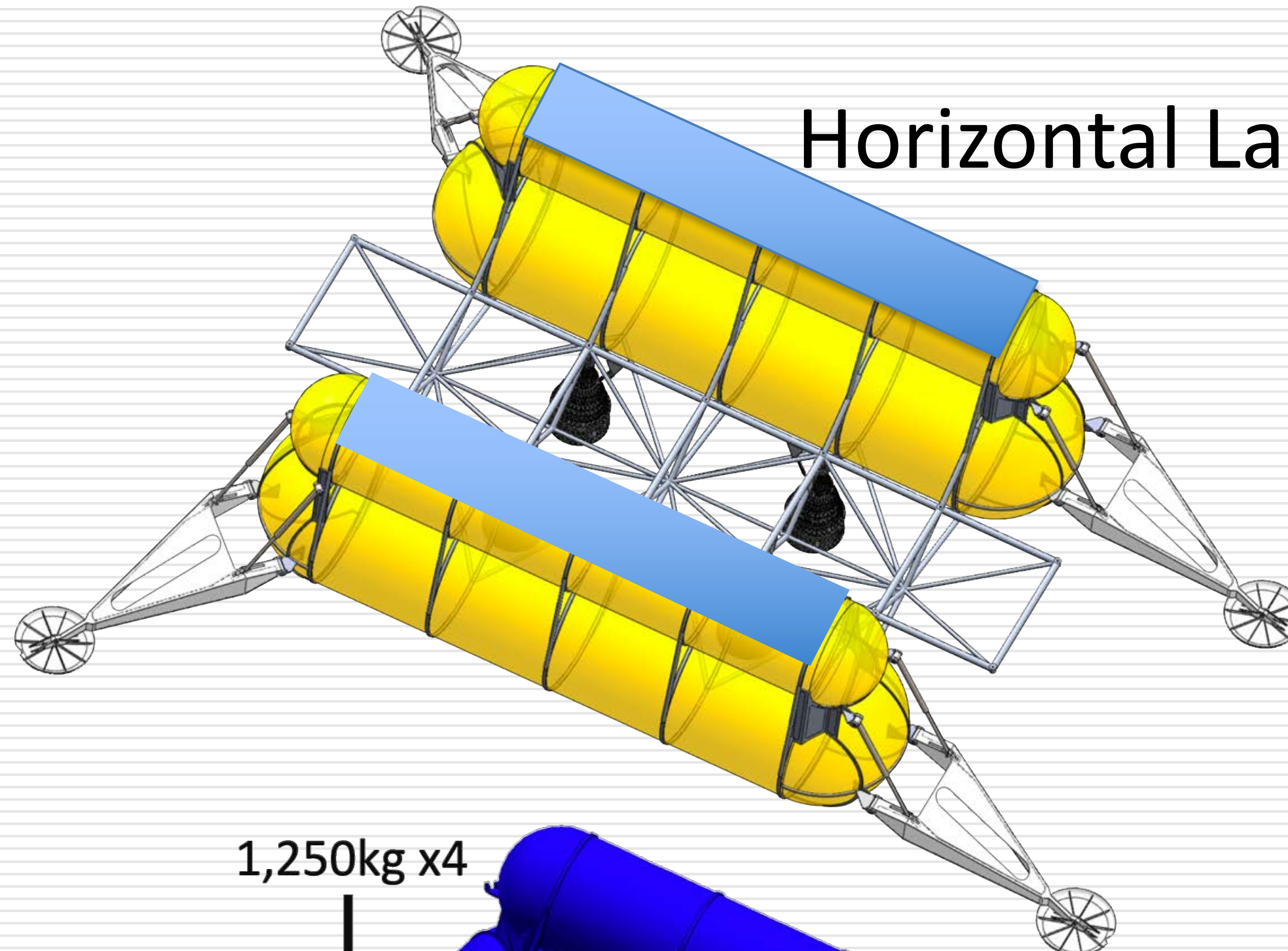


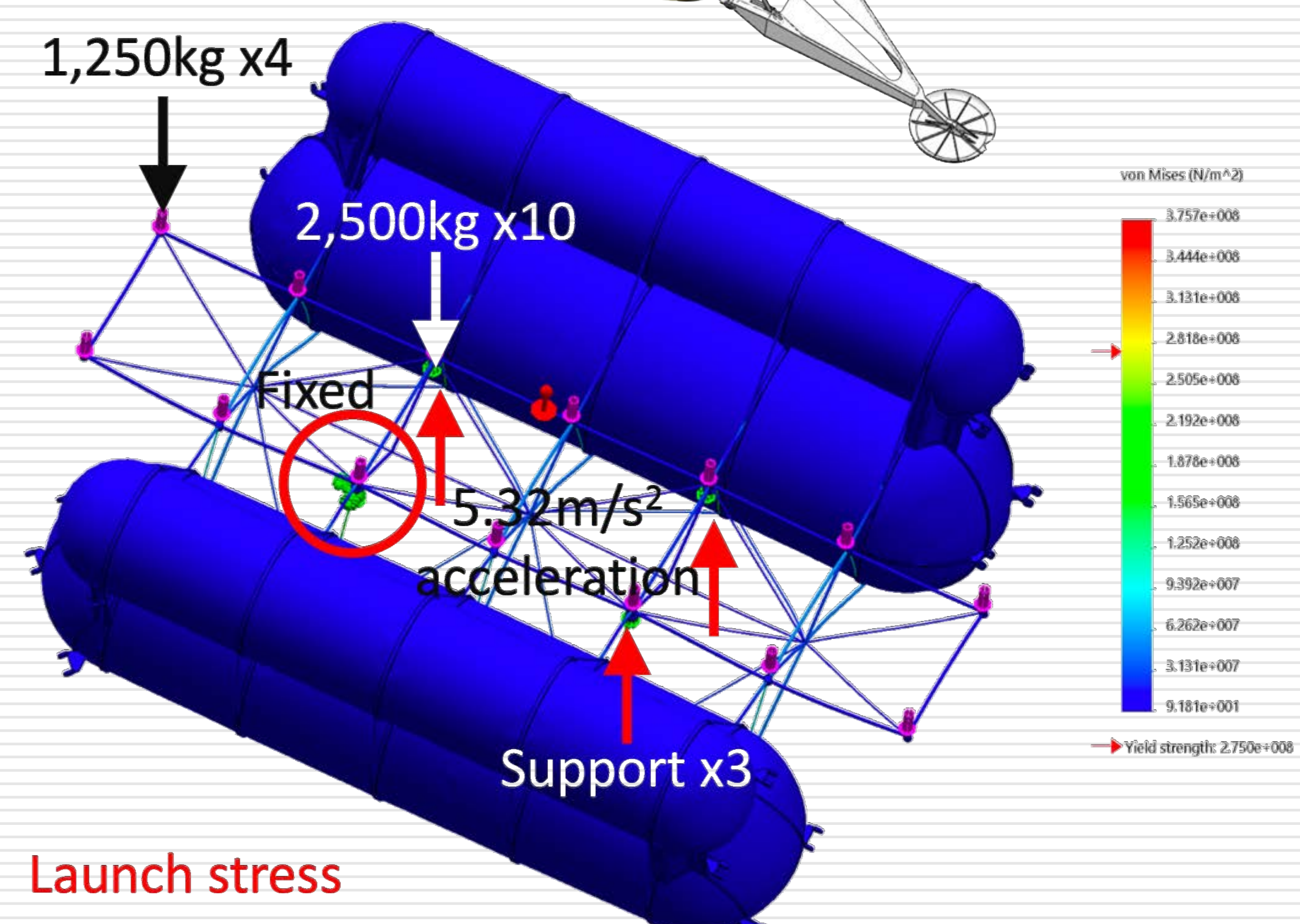
Vehicle Calculator		H	H = LOX/LH2, C = LOX/CH4, N = N2O4/MMH				
Delta-V		Exhaust-V		thrust must exceed		Isp (earth)	
3,016	m/s	4,462	m/s	757,172	N	455	s
% Structure		Wet Mass		Dry Mass		Vehicle Mass	
12	%	77,184	kg	39,725	kg	9,725	kg
Payload						mass fraction	
30,000	kg					0.509	
Propellant		Oxidant LOX	6:1	Fuel LH2		% prop	
37,922	kg	32,504	kg	5,417	kg	49.13	%
		28.488	m3	76.301	m3		

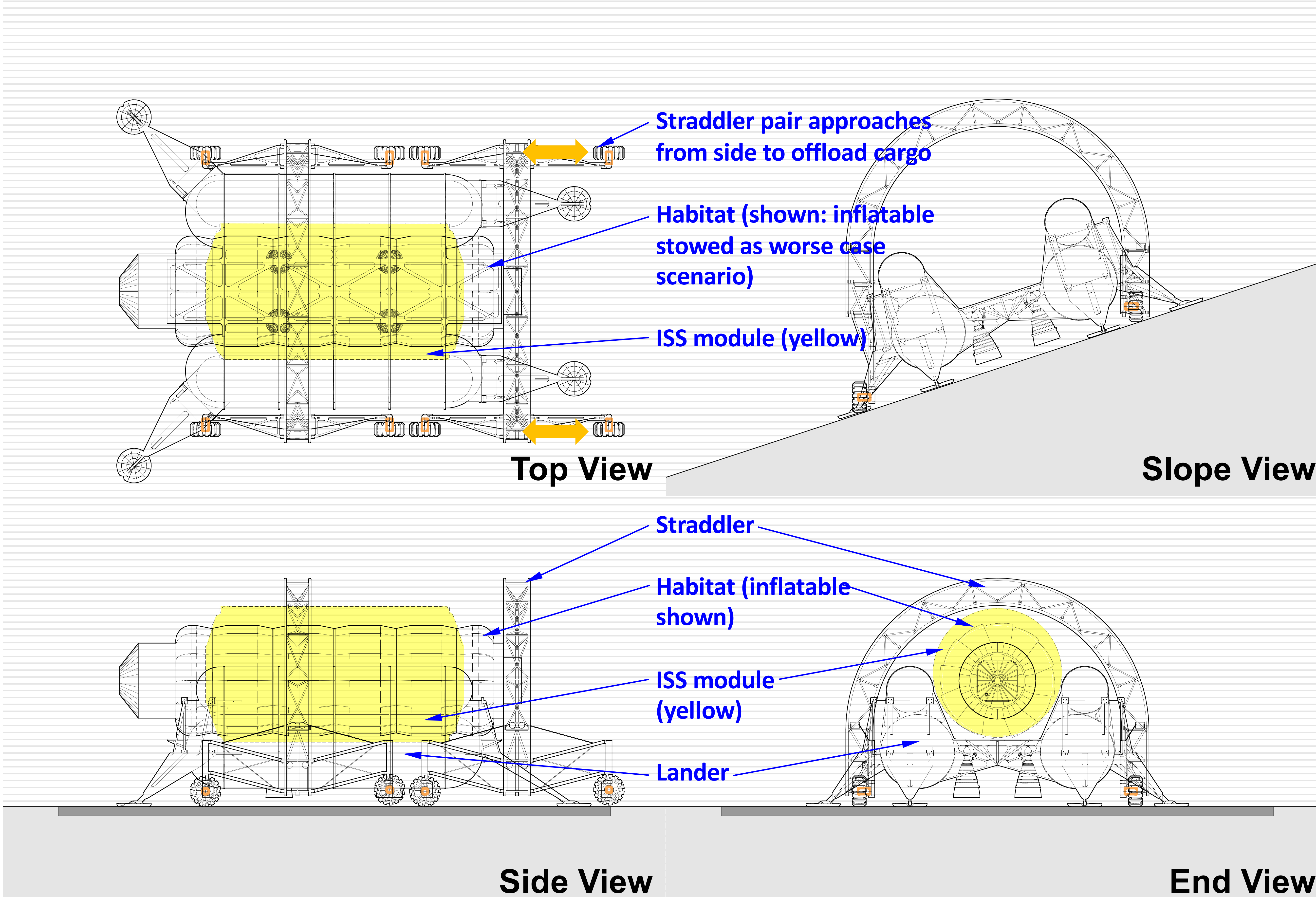
Lunar Lander MEL

Element	Percentage		Unit Mass		Units	Total Mass	
Structure	32	%				2,475	kg
Frame			1,231	kg	1	1,231	kg
H2 Prop Tanks (2mm alum 88.5 m3)			394	kg	2	788	kg
O2 Prop Tanks (2mm alum 33.1 m3)			228	kg	2	457	kg
Landing Gear	5	%				400	kg
Foot Pads			8	kg	4	34	kg
Landing Strut			92	kg	4	366	kg
Mechanisms	7	%				554	kg
Landing Strut Actuators			136	kg	4	544	kg
Deck Latch Mechanisms			1	kg	10	10	kg
Thermal Protection	19	%				1,470	kg
Structure Insulation MLI (0.8 kg/m2 of surface area)						139	kg
Propellant Tank Insulation (80% of prop tank mass)						996	kg
Radiator (10m2)			30	kg	2	60	kg
Cryocooler			225	kg	1	225	kg
Tubing & Fluid Loop						50	kg
Attitude Control	1	%				76	kg
Avionics & Control	1	%				76	kg
Power System	6	%				462	kg
Solar Array	0	%	0	kg	1	0	kg
Batteries	1	%	76	kg	1	76	kg
Water Tank			19	kg	2	39	kg
LH2 Tank (fuel cell)			38	kg	4	150	kg
LO2 Tank (fuel cell)			26	kg	4	103	kg
Fuel Cell			18	kg	1	18	kg
Electrolysis System			159	kg	0	0	kg
Power Avionics	1	%	76	kg	1	76	kg
Propulsion System	29	%				2,267	kg
P&W RL10 Engine			301	kg	4	1,204	kg
Propellant Management Device (15% of prop tank mass)						187	kg
Propulsion Subsys Components (43% of engine mass)						518	kg
Pressurant Tanks (He pressurant x4)						358	kg
Vehicle Dry Mass	**100**	**%**				**7,780**	**kg**
Growth Margin	25	% Vehicle Mass				1,945	kg
Vehicle Dry Mass with Growth Margin						9,725	kg
Cargo						30,000	kg
Total Dry Mass with Growth Margin						39,725	kg
Main Propellant						37,922	kg
Residuals						3,792	kg
Helium Pressurant (50psi in prop tanks)						90	kg
Attitude Control Prop	3	% Vehicle Mass + Margin				292	kg
Volatiles Storage (fuel cell double capacity)						712	kg
LH2 3000psi			71	kg			
LO2 3000psi			641	kg			
Vehicle Wet Mass (w/ growth margin)		(	5,348	kg over)		**82,532**	**kg**

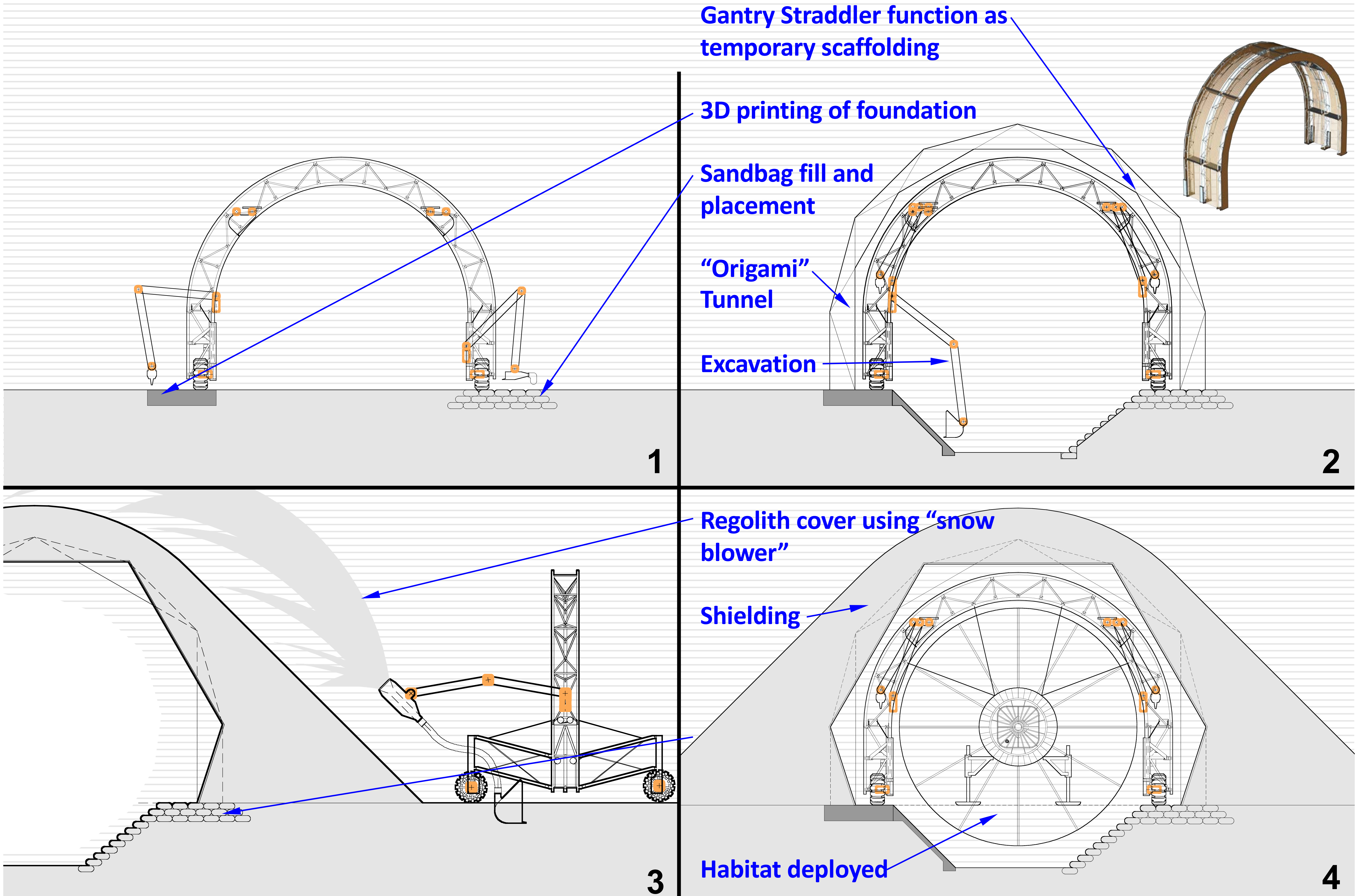
Horizontal Lander






Straddler pair approaches from side to offload cargo
Habitat (shown: inflatable stowed as worse case scenario)
ISS module (yellow)
Top View
Slope View
Straddler
Habitat (inflatable shown)
ISS module (yellow)
Lander
Side View
End View

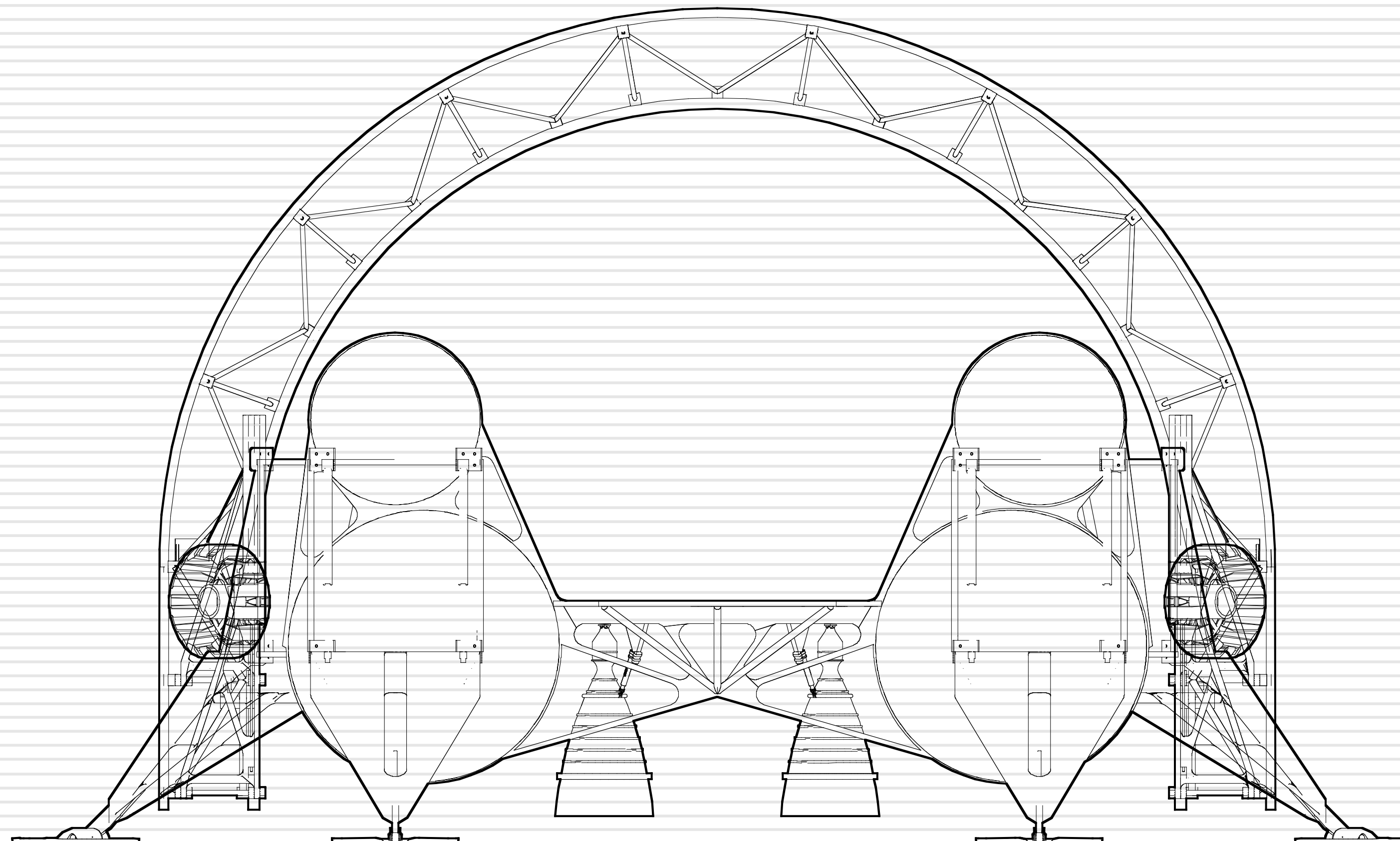
Tunnel Construction (prefabricated)



References

- AFJ Abercromby; SP Chappell; ML Gernhardt; DE Lee; AS Howe (2015). Human Exploration of Phobos. *2015 IEEE Aerospace Conference*, Big Sky, Montana, USA, 7-14 Mar 2015. New York, New York, USA: Institute of Electrical and Electronics Engineers.
- JT Celentano; D Amorelli; GG Freeman (1963). Establishing a Habitability Index for Space Stations and Planetary Bases, AIAA 1963-139. AIAA/ASMA Manned Space Laboratory Conference, Los Angeles, California. New York, New York, USA: AIAA.
- MM Cohen (2009). Testing the Celentano Curve: An Empirical Survey of Predictions for Human Spacecraft Pressurized Volume (SAE 2008-01-2027). 38th International Conference on Environmental Systems (ICES), San Francisco, California, USA, 30 June - 2 July 2008. In, SAE International Journal of Aerospace (vol. 1, no. 1, p. 107-142). Warrendale, Pennsylvania, USA: Society of Automotive Engineers.
- B Drake (2009). Human Exploration of Mars: Design Reference Architecture 5.0. NASA/SP-2009-566
- B Griffin; R Lepsch; J Martin; R Howard; M Rucker; E Zapata; C McCleskey; AS Howe; N Mary; P Nerren (2015). Small Habitat Commonality Reduces Human Mars Mission Costs (AIAA-2015-4455). *AIAA Space 2015 Conference & Exhibition*, Pasadena, California, USA, 31 Aug – 2 Sep 2015. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.
- BN Griffin; D Smitherman; KJ Kennedy; L Toups; T Gill; AS Howe (2012). Skylab II: A Deep Space Habitat From a Space Launch System Propellant Tank (AIAA2012-5207). *AIAA Space 2012 Conference & Exhibition*. Pasadena, California, USA, 11-13 Sep 2012. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.
- TW Hall (2009). Chapter 12: Artificial Gravity, pp133-152. In AS Howe & B Sherwood (eds) *AIAA History of Spaceflight series, Out of This World: The New Field of Space Architecture*, ISBN 978-1-56347-982-3. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.
- AS Howe (2015). A Modular Habitation System for Human Planetary and Space Exploration (ICES-2015-4). *45th International Conference on Environmental Systems (ICES2015)*, Belleview, Washington, USA, 12-16 July 2015. Lubbock, Texas, USA: Texas Tech University.
- AS Howe; A Austin; T Colaprete; J Elliott; T Fong; S Magnus; P Metzger; A Parness; R Polit-Casillas; HH Schmitt; B Sherwood; M Sims; MW Smith; G Voecks; K Zacny (2019). Planetary Autonomous Construction System (P@X). *70th International Astronautical Congress IAC2019*, 21-25 October 2019, Washington DC, USA.
- AS Howe; TW Hall; A Vogler; M Downard (2002 October). Education for Aerospace Architects (AIAA 2002-6121). *1st Space Architecture Symposium* (SAS 2002), Houston, Texas, USA, 10-11 October 2002. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.
- AS Howe; R Howard (2010). Dual Use of Packaging on the Moon: Logistics-2-Living (AIAA2010-6049). Proceedings of the *40th International Conference on Environmental Systems*, Barcelona, Spain, 11-16 July 2010. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.
- AS Howe; K Kennedy; T Gill; et al (2013). NASA Habitat Demonstration Unit (HDU) Deep Space Habitat Analog (AIAA2013-5436). *AIAA Space 2013 Conference & Exhibition*. San Diego, California, USA, 10-12 Sep 2013. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.
- AS Howe; MA Simon; S Wald (2016). Sizing a Common Habitat for Multiple Environments and Mission Durations. *AIAA Space 2016 Conference & Exhibition*, Long Beach, California, USA, 13 – 16 Sep 2016. Virginia, USA: American Institute of Aeronautics and Astronautics.
- NASA (1995). Man-Systems Integration Standards (NASA STD-3000, Revision B). Washington, DC, USA: National Aeronautics and Space Administration.
- SA Shull; R Polit-Casillas; AS Howe (2012). NASA Advanced Exploration Systems: Concepts for Logistics to Living (AIAA2012-5252). *AIAA Space 2012 Conference & Exhibition*. Pasadena, California, USA, 11-13 Sep 2012. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.
- M Yashar; N Chenniuntai; S Nefedov; C Ciardullo; M Morris; R Pailes-Friedman; A Day; J Aronis; S Pender (2019). Robotic Construction & Prototyping of a 3D-Printed Mars Surface Habitat. *70th International Astronautical Congress IAC2019*, 21-25 October 2019, Washington DC, USA.

Jet Propulsion Laboratory
California Institute of Technology



A Scott Howe <a.scott.howe@jpl.nasa.gov>

THANK YOU