LEVITATE

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Lunar Exploration Objectives

- Science of solar system, universe, and our place therein
- Preparation for deeper exploration: Mars
- Enable human lunar settlement

--Lunar Exploration Analysis Group

How to best explore the Moon?

Apollo Style

\+ Access entire globe

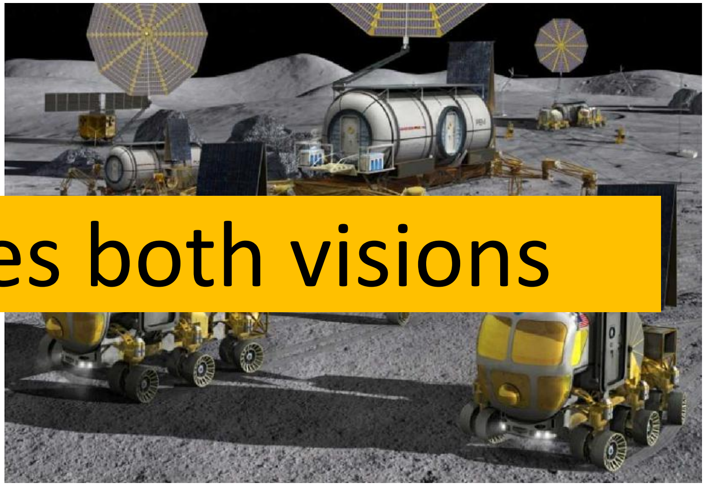
– No reuse of launched mass

Outpost

\+ Reuse every launched kg

– Exploration limited to walkback range (~15 km)

Courtesy Culbert, 2008



Courtesy Cooke, 2007

LEVITATE enables both visions

LEVITATE Enables Global Exploration

Provides Access to Entire Lunar Surface

Fueled by Lunar Resources

Flies from Lunar Base

Returns 500 kg to Outpost

Supports 2 Astronauts

Missions Last 14 Earth Days

Design Intent

- Show concept feasibility
  - Orbital calculations
  - Mass estimates
- Design within codes and standards
  - Part and assembly drawings

Design Approach

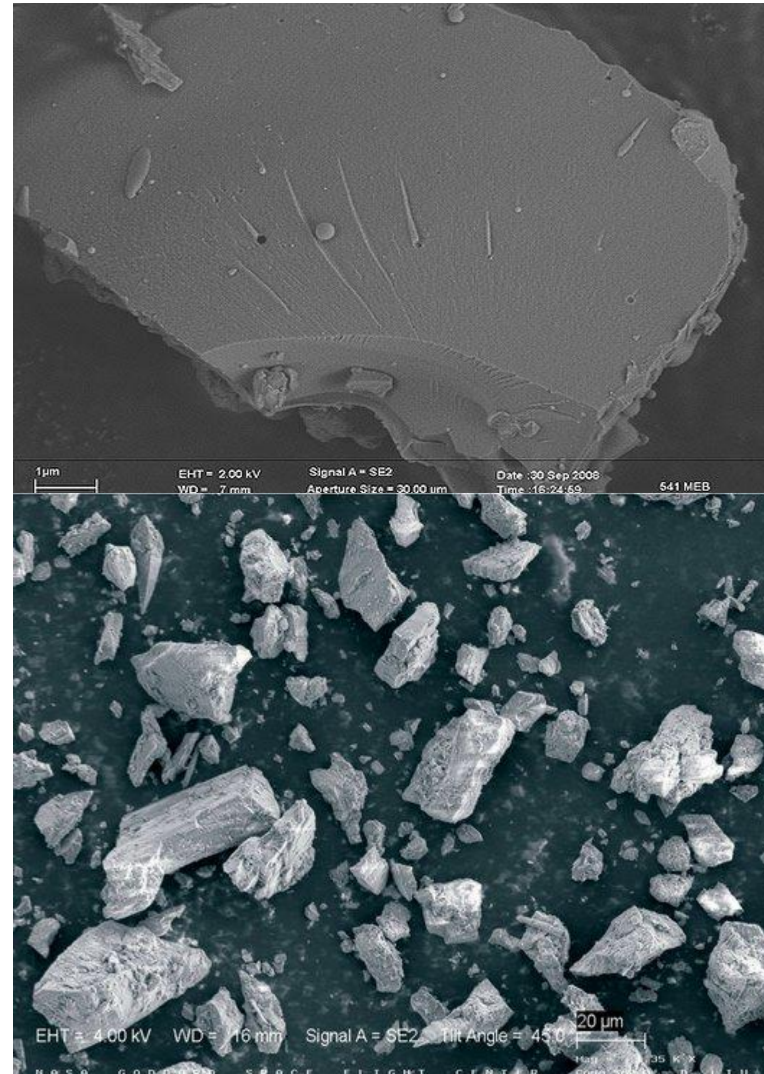
- Identify major systems:
  - Propulsion, structure, habitat, life support
- Research:
  - Combine heritage & new ideas
  - Codes and Standards
- Iterative design:
  - Frequent test integrations of subsystems
  - Compliance with codes and standards
  - Verification through analysis
- High-level systems integration

Design Objectives

- Minimize mass
- Simple operation
- System redundancy
- Long service life
- Repairability
- Integrate with lunar architecture

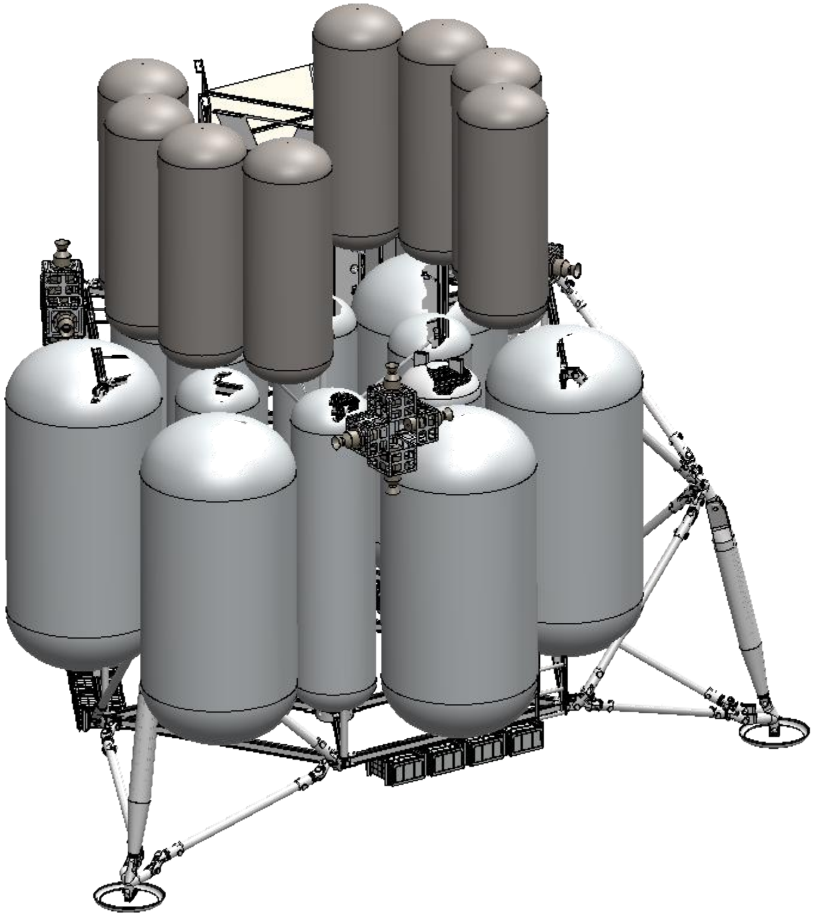
Major challenges

- Regolith
  - Corrosive
  - Health hazard
  - Sticks to everything
- Thermal extremes
- Energetic radiation
- Micrometeoroids and orbital debris



Lunar regolith
Courtesy Canadian Lunar Research Network

LEVITATE

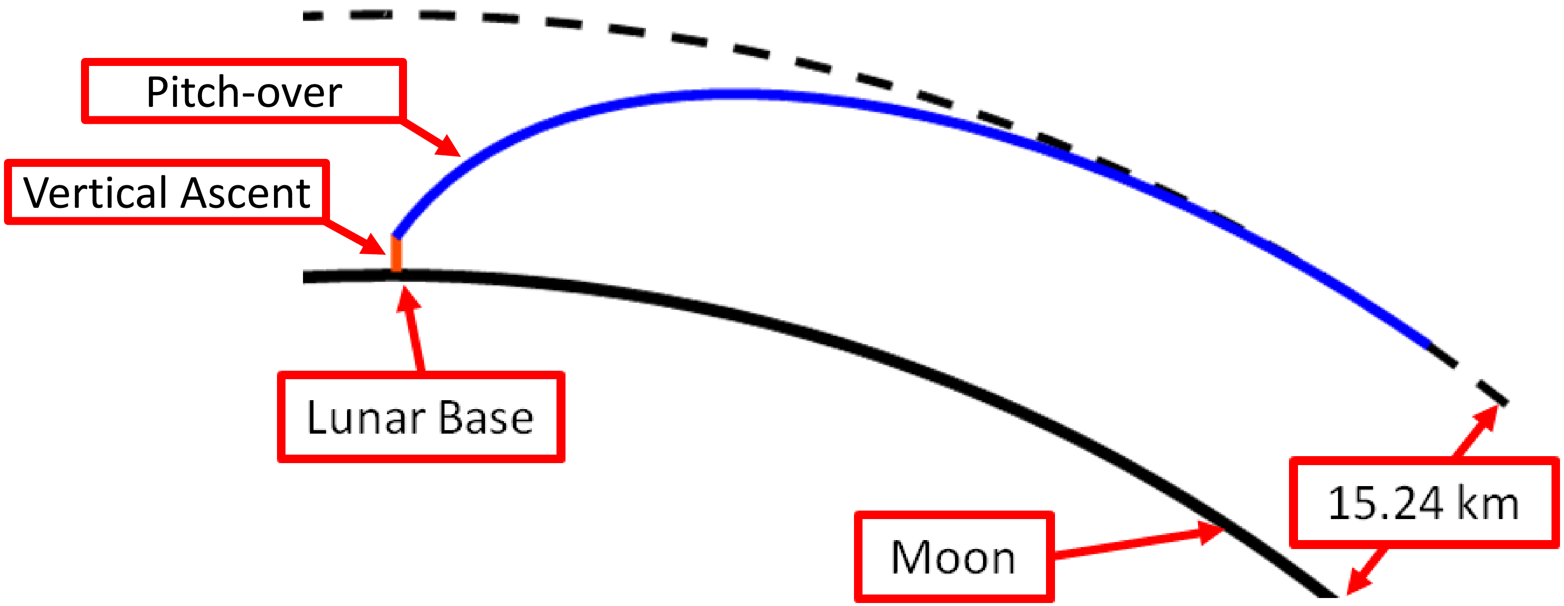


Propulsion
- Tanks
- RCS thruster
- Engine

Structure

Habitat
- Life Support

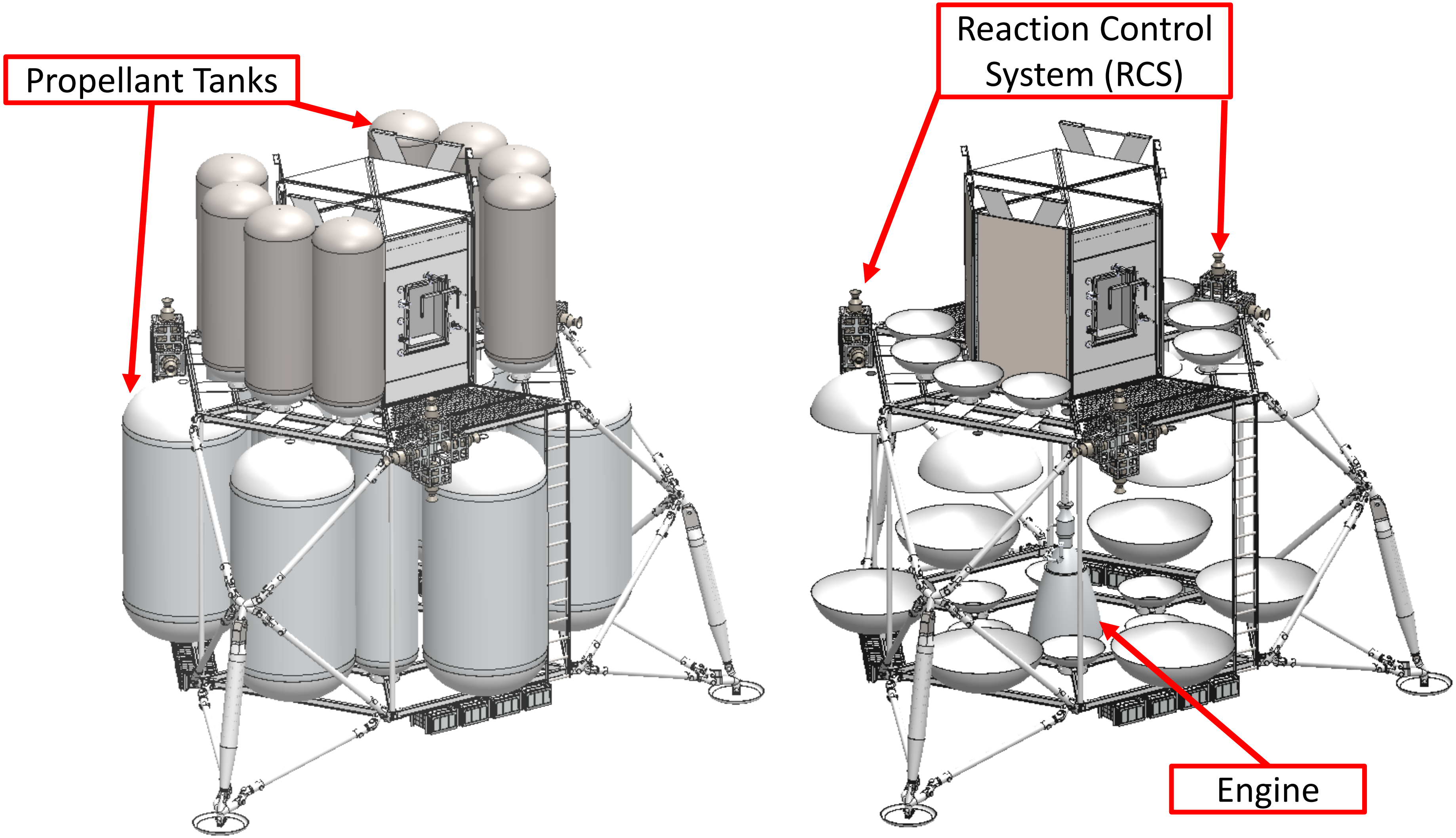
Efficient Trajectory



LEVITATE's trajectory from the lunar surface to orbit

- Fuel efficient trajectory developed for Apollo
- Pole-to-pole transfer time: 64 minutes
- Orbital altitude of 15.24 km

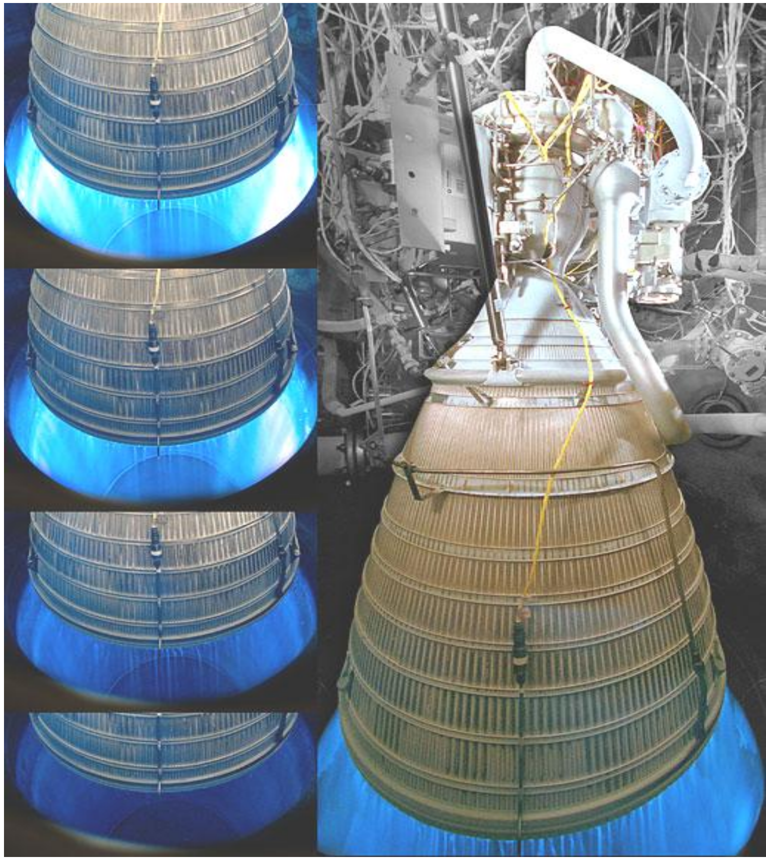
Propulsion Subsystems



Reliable Propulsion

- Engine requirements:
  - In-situ propellants
  - Throttling capability
  - Heritage

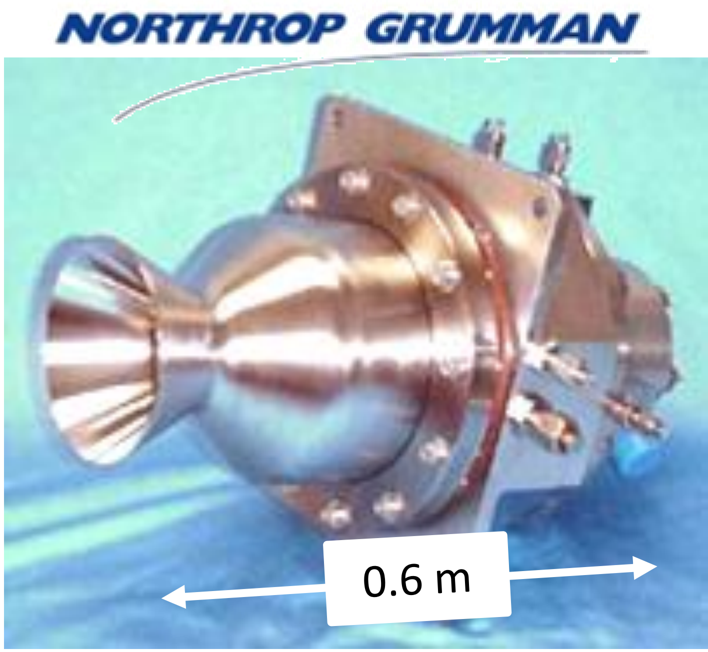
- We chose the P&W CECE
  - Thrust: 66.7 kN
  - Fuel: LOX/LH2
    - 5.5:1 mixture ratio
  - Throttle range: 9%-102%



Pratt and Whitney Common Extensible Cryogenic Engine (CECE)

Efficient Reaction Control System

- RCS requirements:
  - Powerful for pitch maneuver
  - Same fuel as CECE
- We chose the Northrop Grumman 1000 lbf bipropellant thrusters
  - Thrust: 4.45 kN
  - Fuel: LOX/LH2 (3.5:1 mixture ratio)
- Provide redundant propulsion for emergency landing



Bipropellant thruster

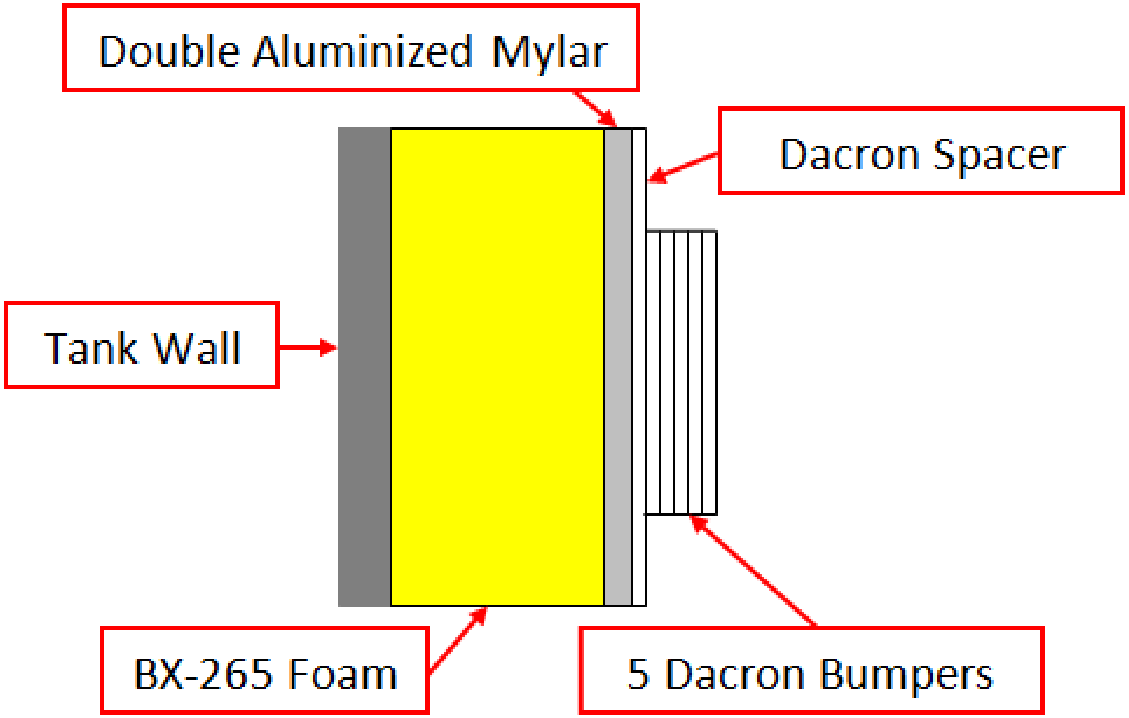
Optimal Fuel Tank Construction

- Fuel tanks requirements:
  - Store cryogenic fuel
  - Withstand operational and launch loads
- Materials
  - LH2: Titanium, grade 5
  - LOX: Inconel 718
- Mil-1522A Factor of Safety (SF)
  - 1.5 on the ultimate stress
  - 1.25 on the yield stress

LOX tank　　LH2 tank

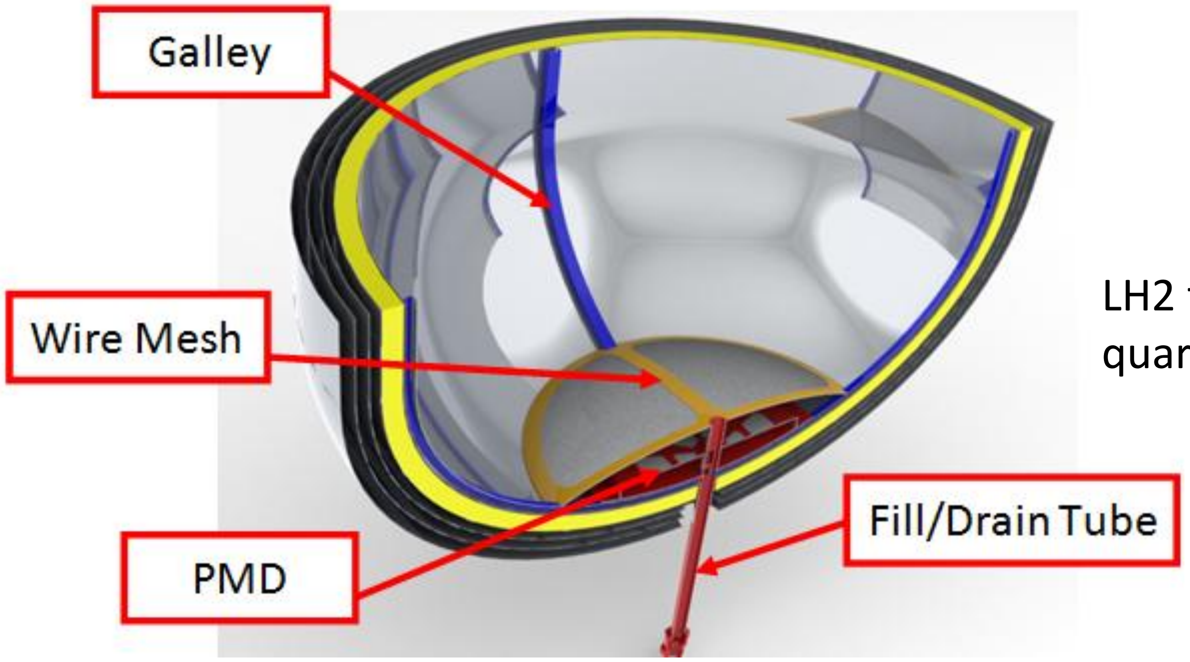
Fuel Tank Thermal Insulation

- Insulation Concept
  - BX-265 foam: 1”
  - Multi-layer insulation: 1.8” (45 layers)



Design derived from Martin Marietta Astronautics

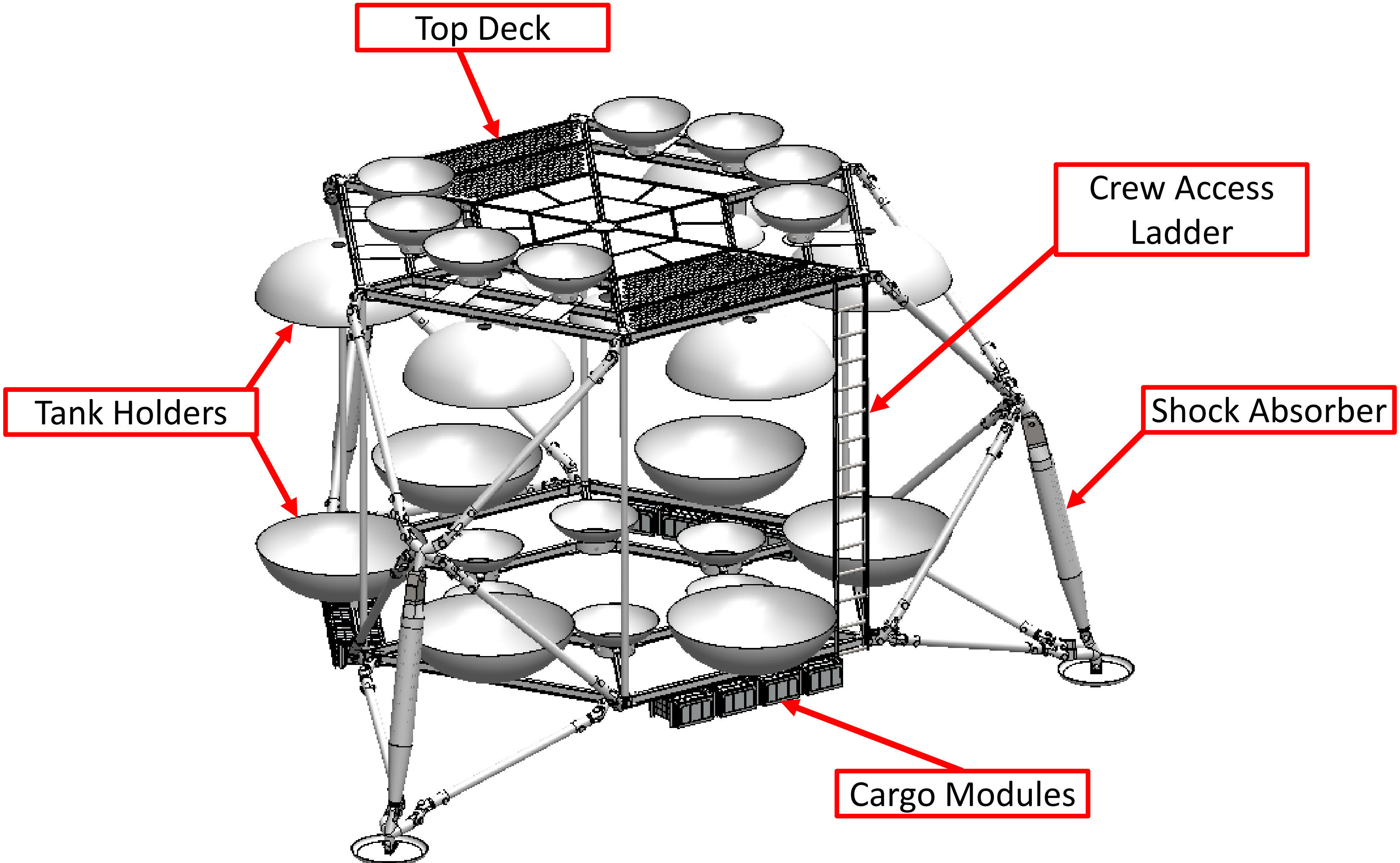
Propellant Management Device



LH2 fuel tank
quarter section

- PMD retains fuel at drain ports
- Uses surface tension
- Flight-proven technique

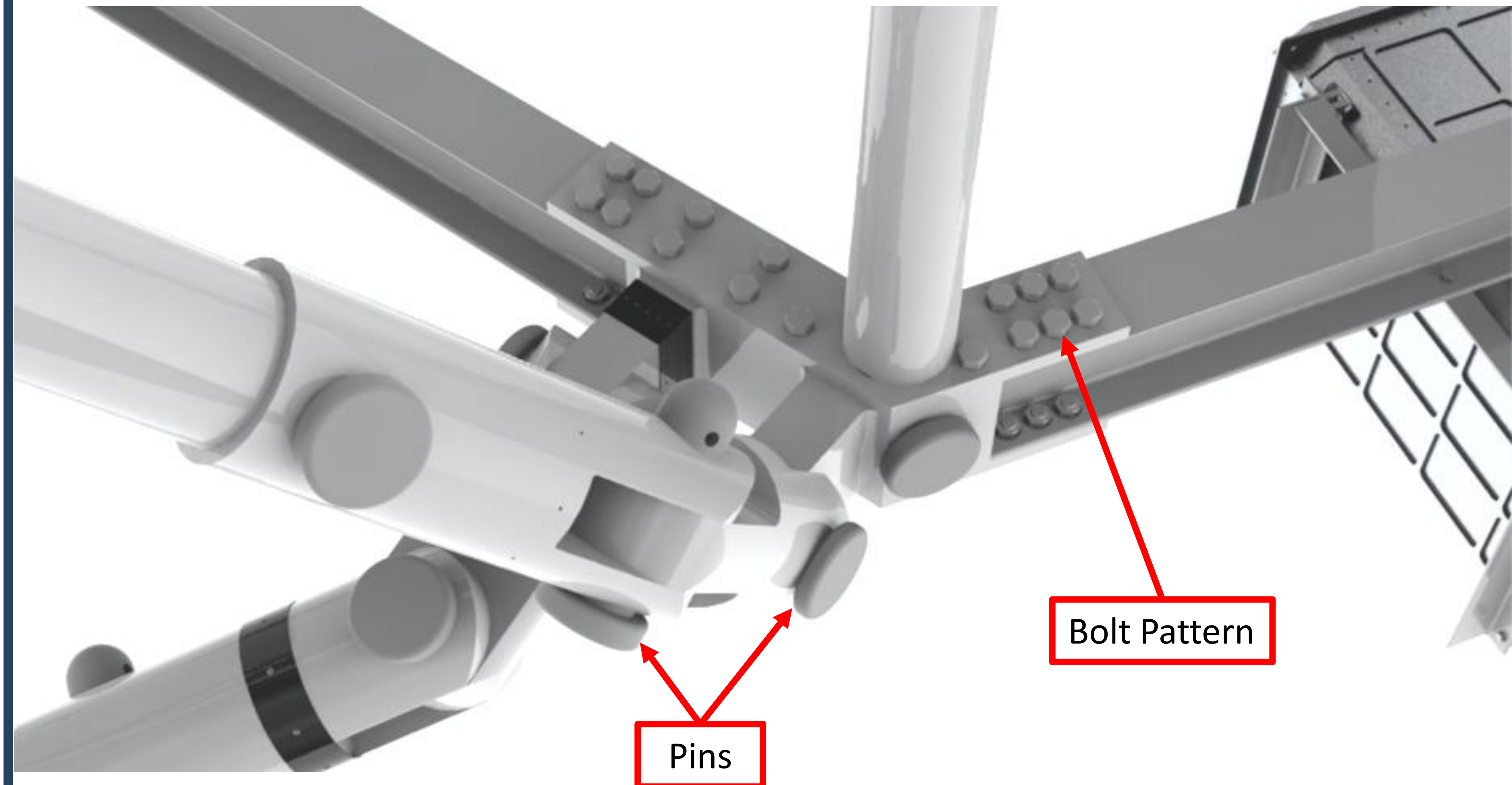
Major Structural Elements



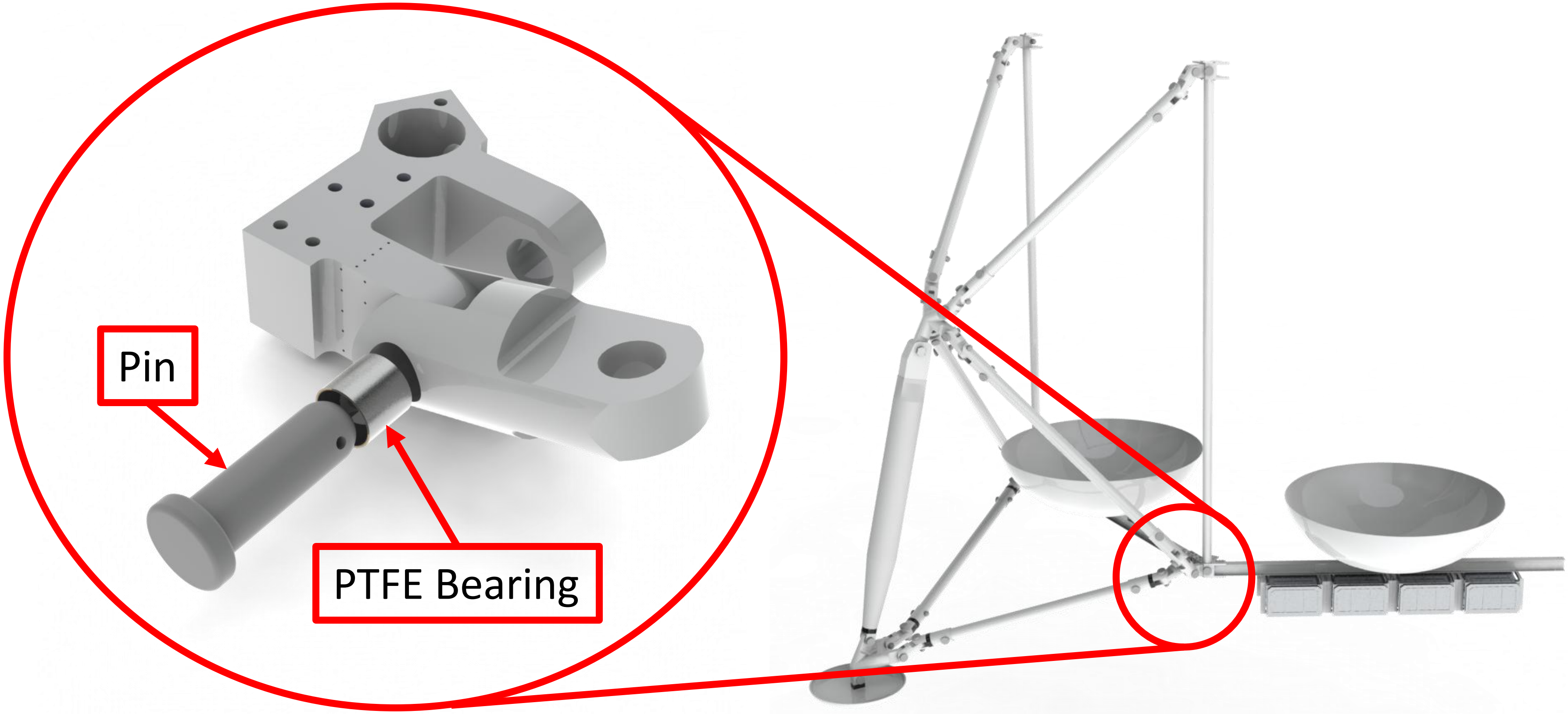
Superior Aluminum Alloy

- Main structural material: Aluminum Weldalite 049-T8
  - Better than traditional alloys (7075-T6)
    - 25% increase in yield strength
    - 3% decrease in mass
  - Easily forged, extruded, machined
- Bolts and pins made of stainless steel
  - Prevents joint fusing
  - High strength
  - Corrosion resistant

Pinned and Bolted Connections

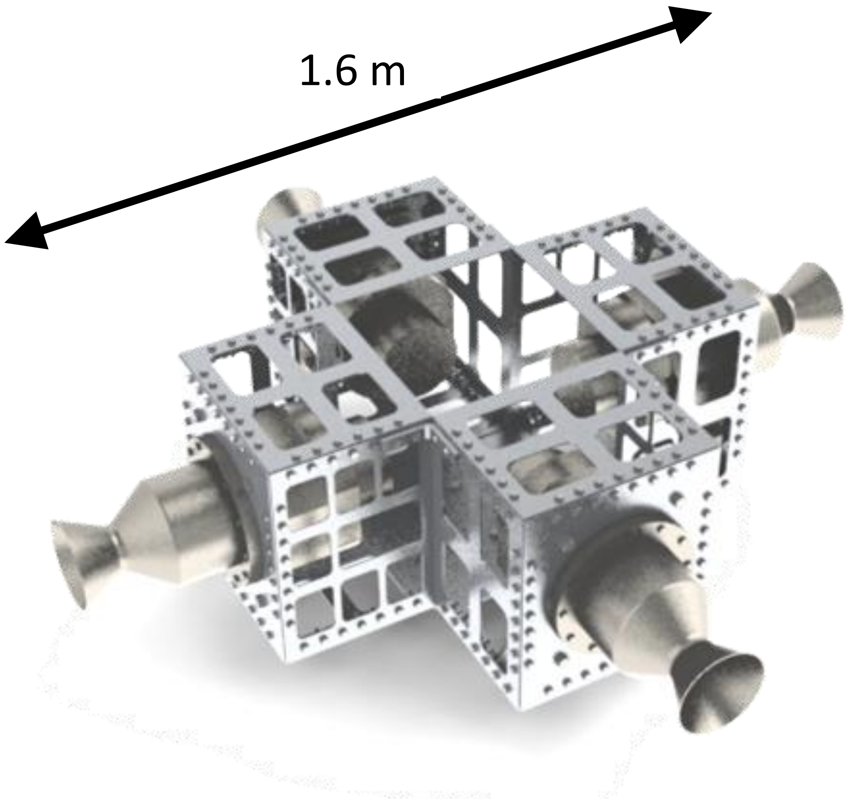


Bearings Prevent Seizure

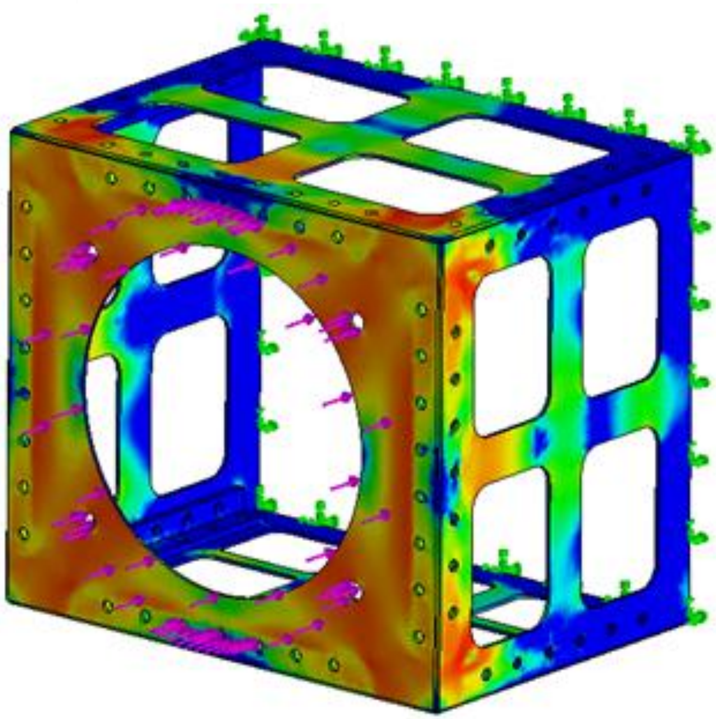


Exploded view of pinned connection showing pin, joint and bearing.

Finite Element Analysis Verifies Structure

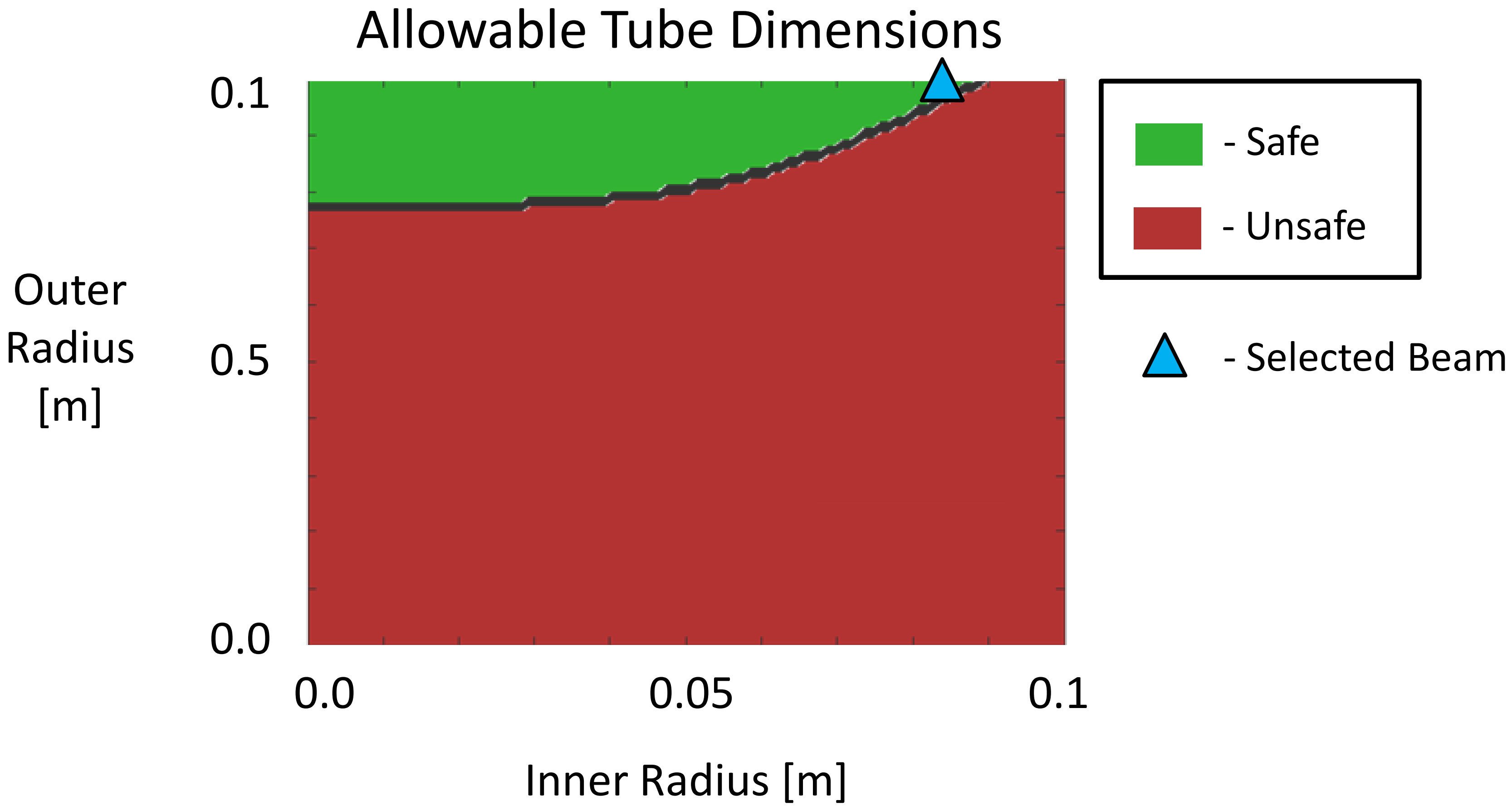


RCS housing assembly



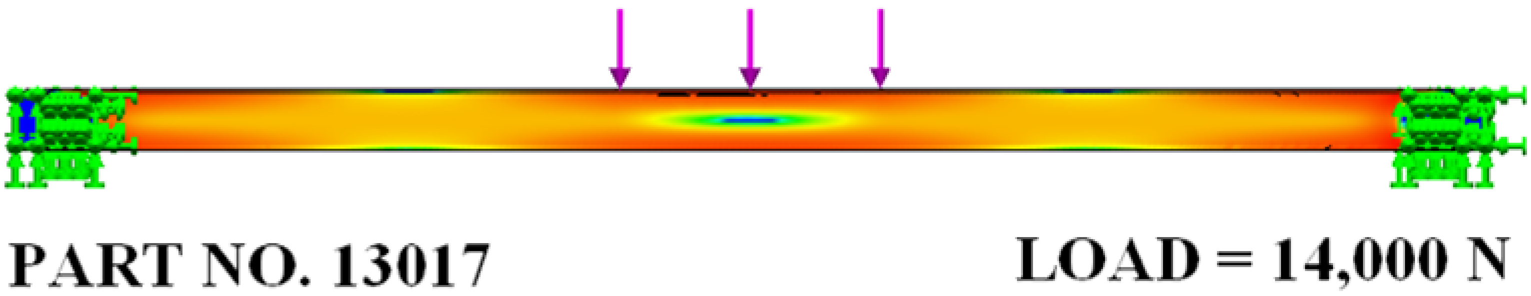
FEA on part no. 23100 shows SF of 1.93

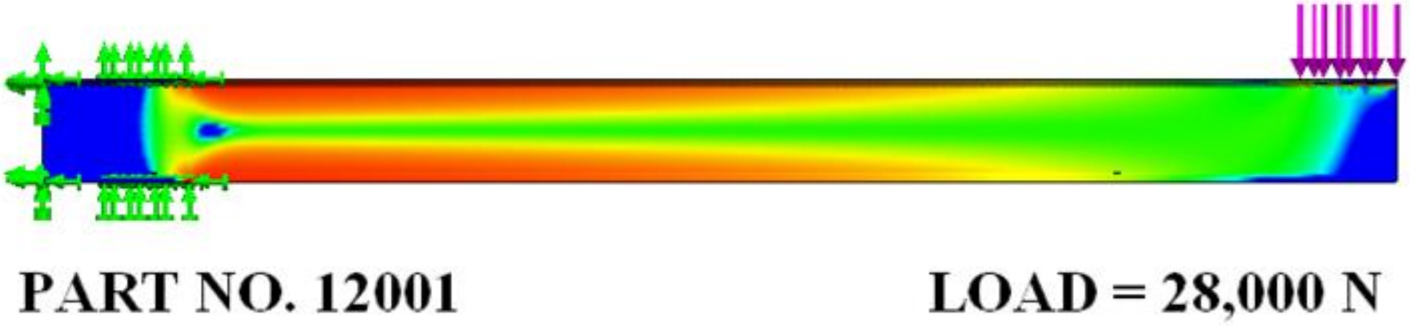
Optimized Tubular Beams



Analysis of critical tubular beam in compression; buckling and yield

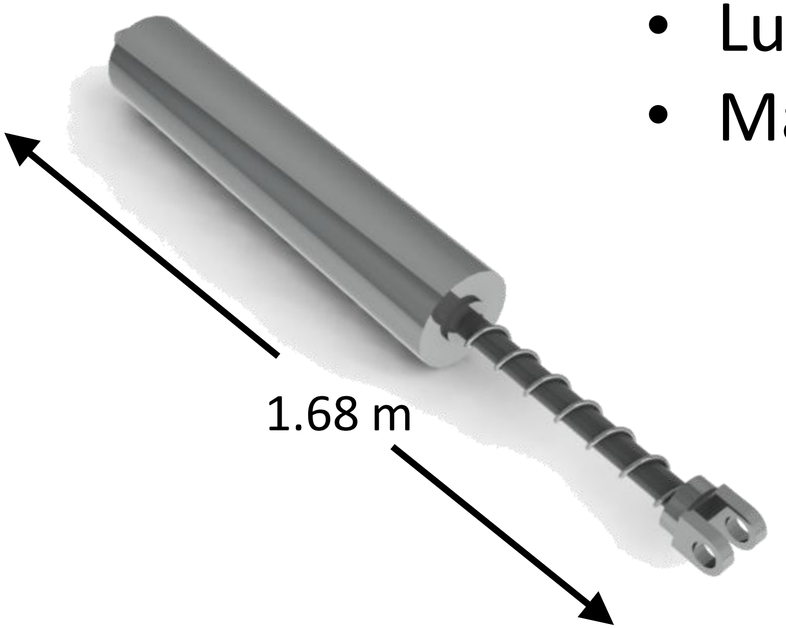
Strong and Light I-Beams





Lowest I-beam factor of safety 2.24

Landing Shock Absorber



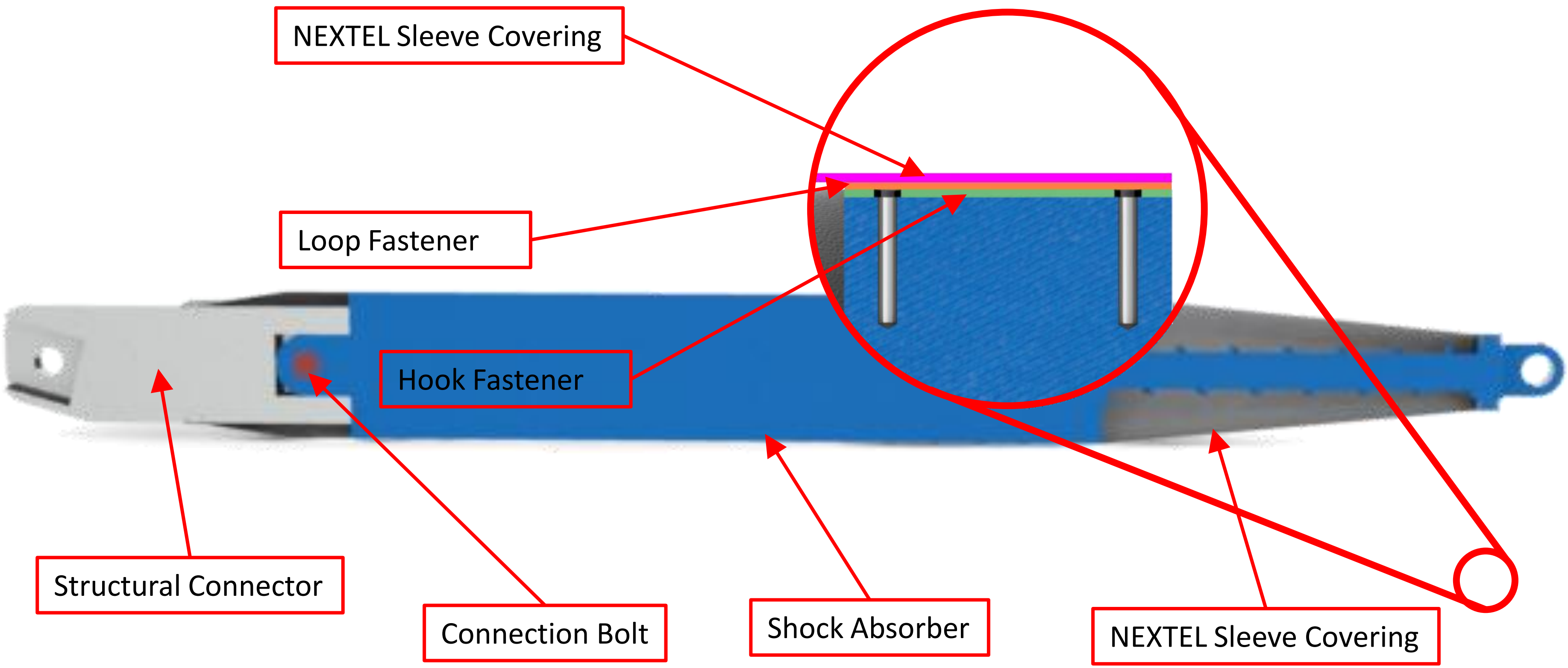
Requirements:

- Lunar Temperatures (-330F to 250F)
- Massive Structure (<25,000 kg)

We chose an EFDYN Inc. shock absorber

- Working Fluid: Silicone-oil
- Bore Diameter: 10 mm
- Stroke: 80 mm
- Weight Equivalent: 40-250 kN

Regolith Protection

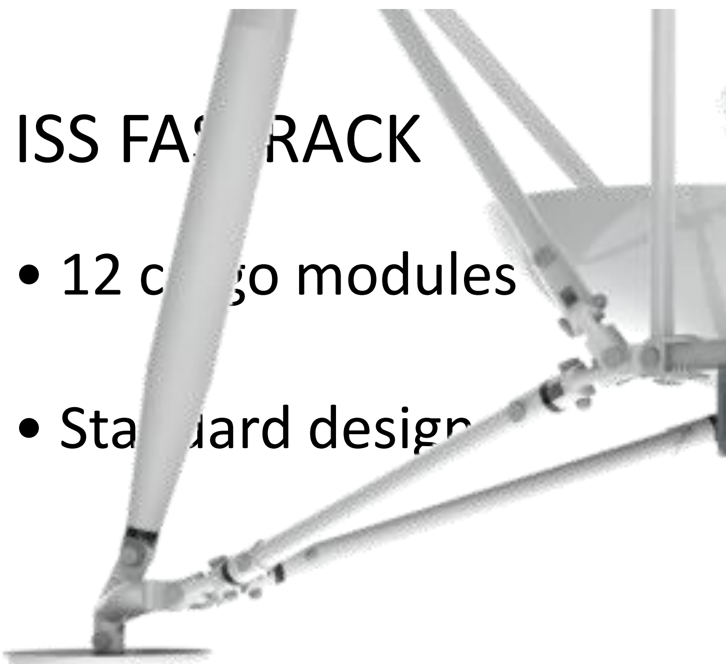


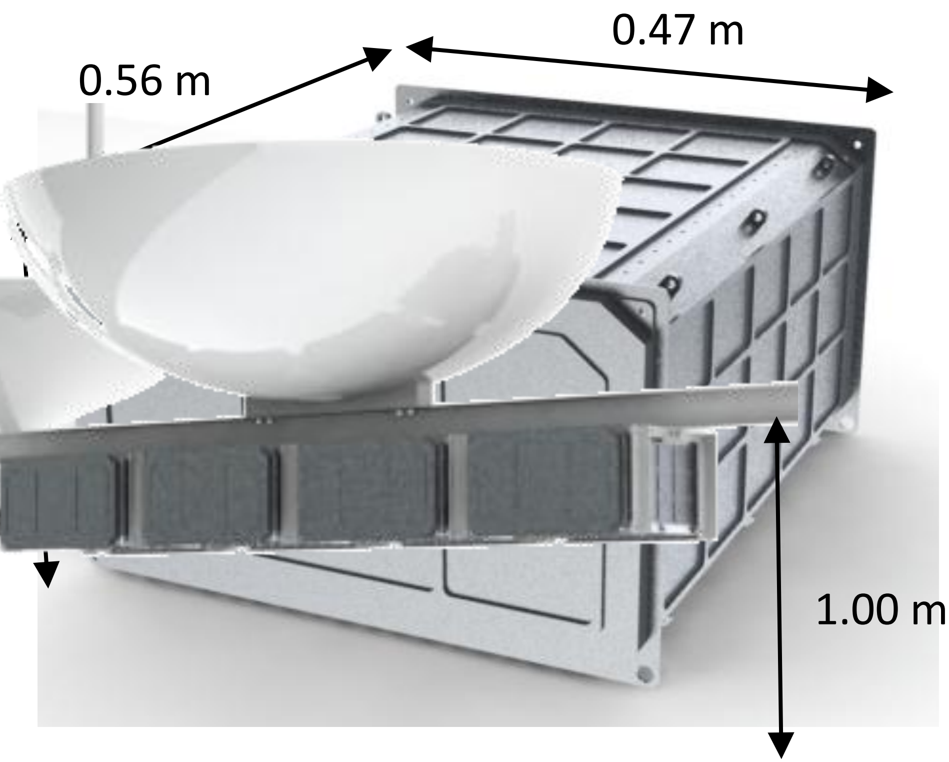
Cross section of shock absorber assembly, covered by NEXTEL sleeve

Easily Accessible for EVAs

ISS FA RACK

- 12 c go modules
- Sta dard design



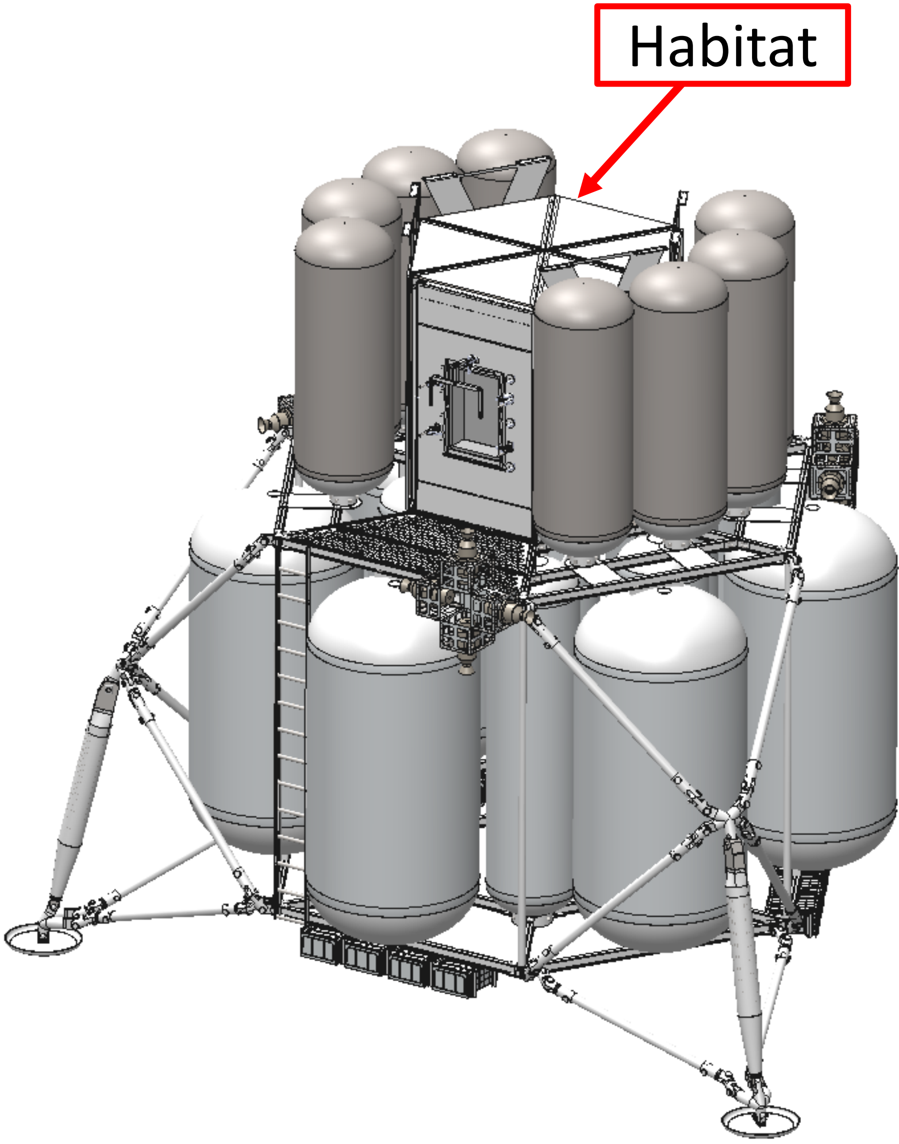


There are twelve total cargo modules

ISS FASTRACK module

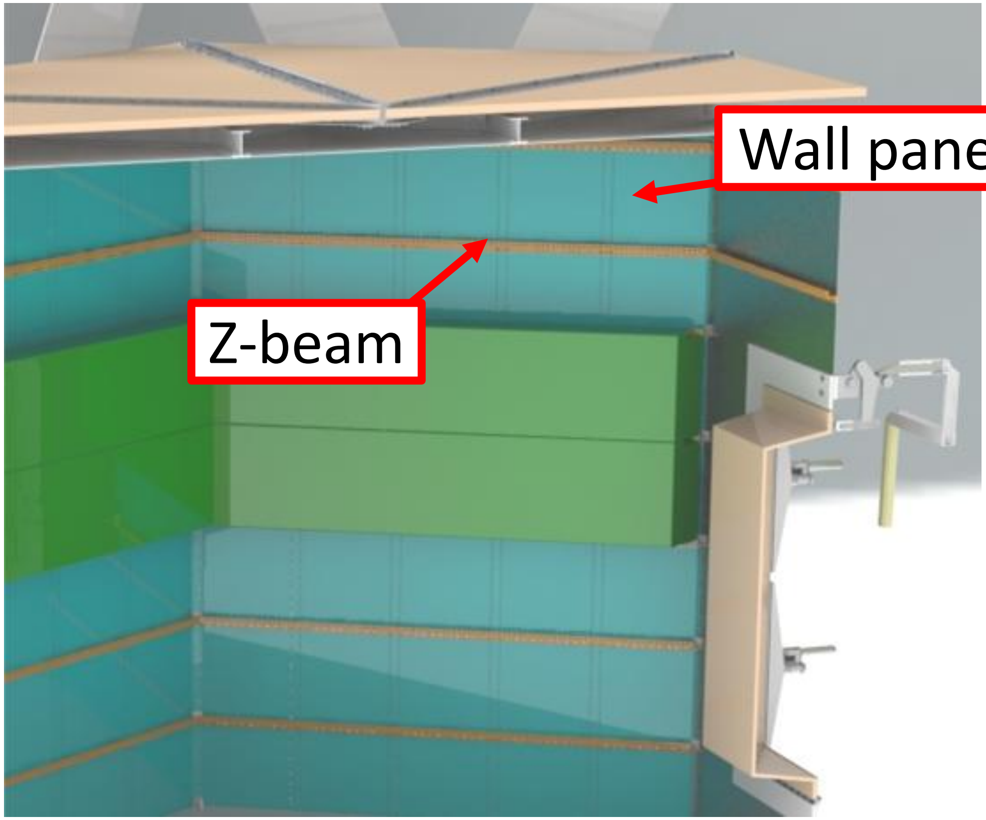
Habitat

- Pressure vessel
  - Wall and roof design
  - Design verification
- Protects from:
  - Thermal transfers
  - Energetic radiation
  - Regolith entrance
  - Micrometeoroid impacts

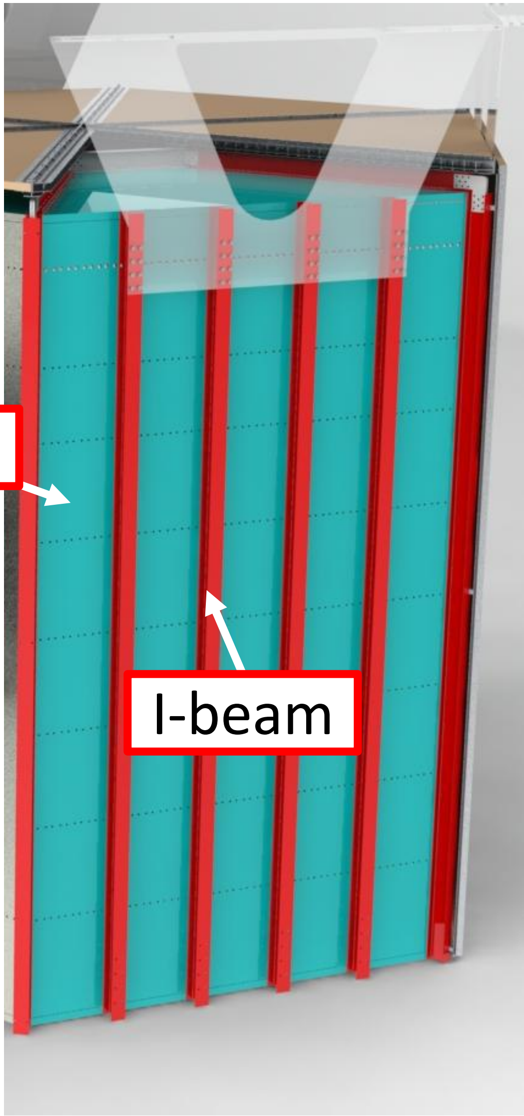


Habitat Wall Construction

- 2.8 mm thick Aluminum Weldalite panels



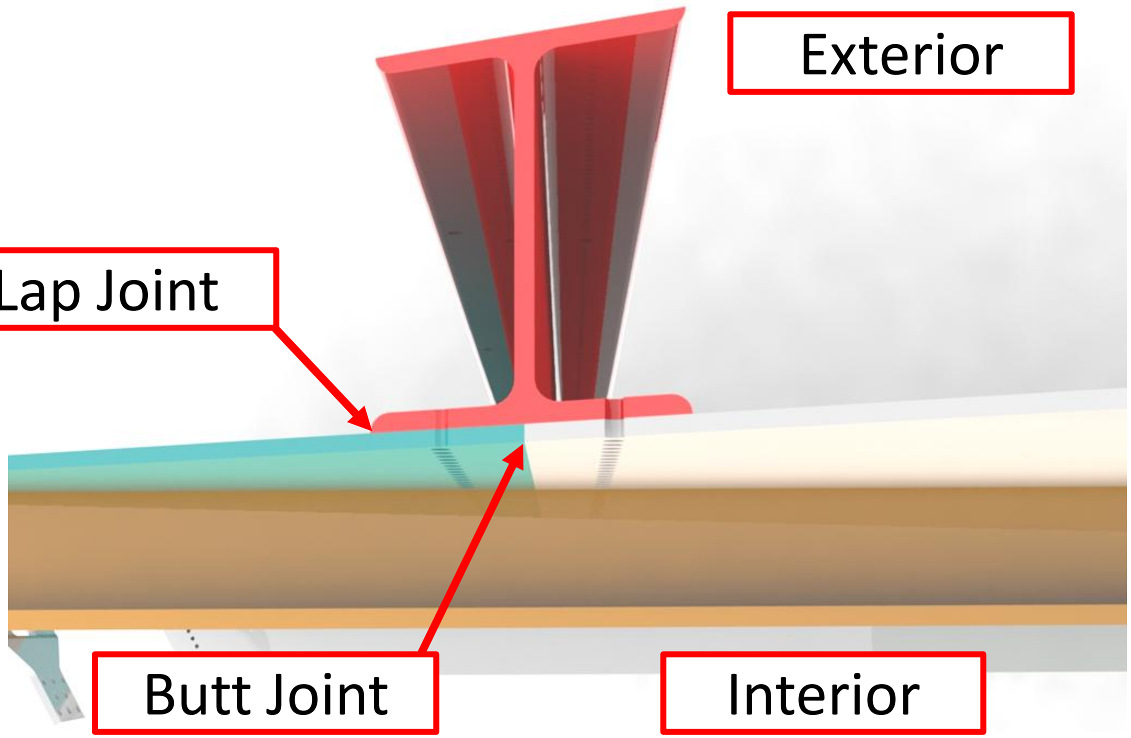
Habitat interior



Habitat exterior

Flight-Proven Riveted Construction

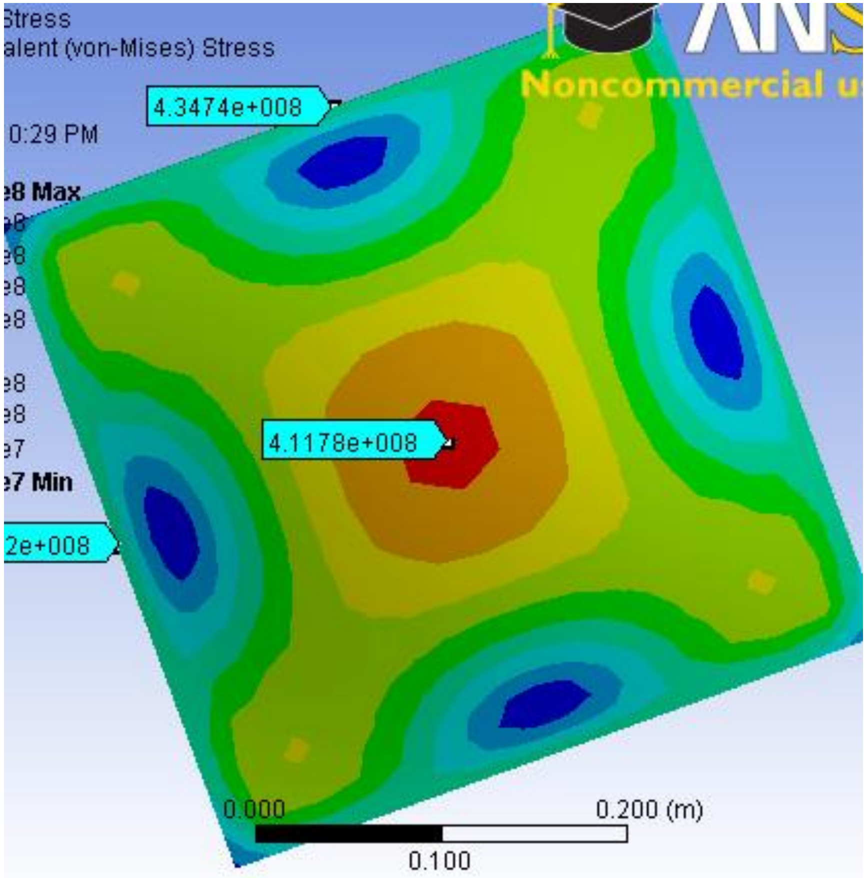
- Hybrid butt/lap joints prevent atmosphere loss



Wall panel section view showing I-beams and adjacent pressure panels

Structure Withstands Pressure

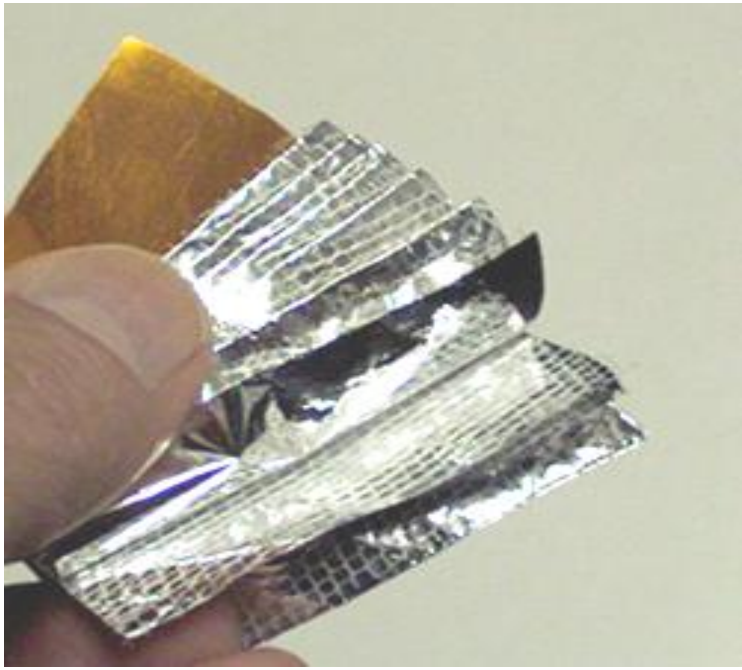
- Maximum 14.7 psi internal pressure
- AIAA S-110-2005 requires a 1.4 factor of safety
- SF 1.67



Finite element analysis of representative wall panel.

Heat Loss Minimized

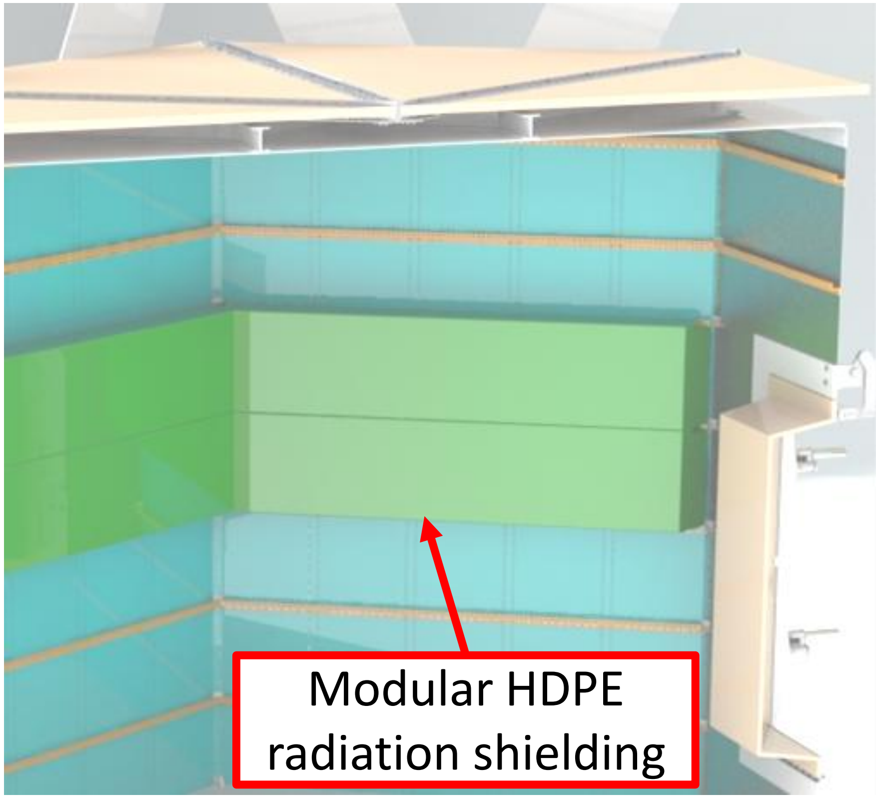
- 15 layers insulation blankets
- Double-aluminized polyimide
- Embossed pattern separates layers
- Heat loss limited to ±50 W



Multi-layer insulation

Energetic Radiation Protection

- NASA Man-Systems Integration Standard 5.7.2.2.1-1
  - 50 rem/yr limit



- Shielding provided by Aluminum and Borated HDPE
- Validated with HZETRN transport code

Astronaut Egress/Ingress

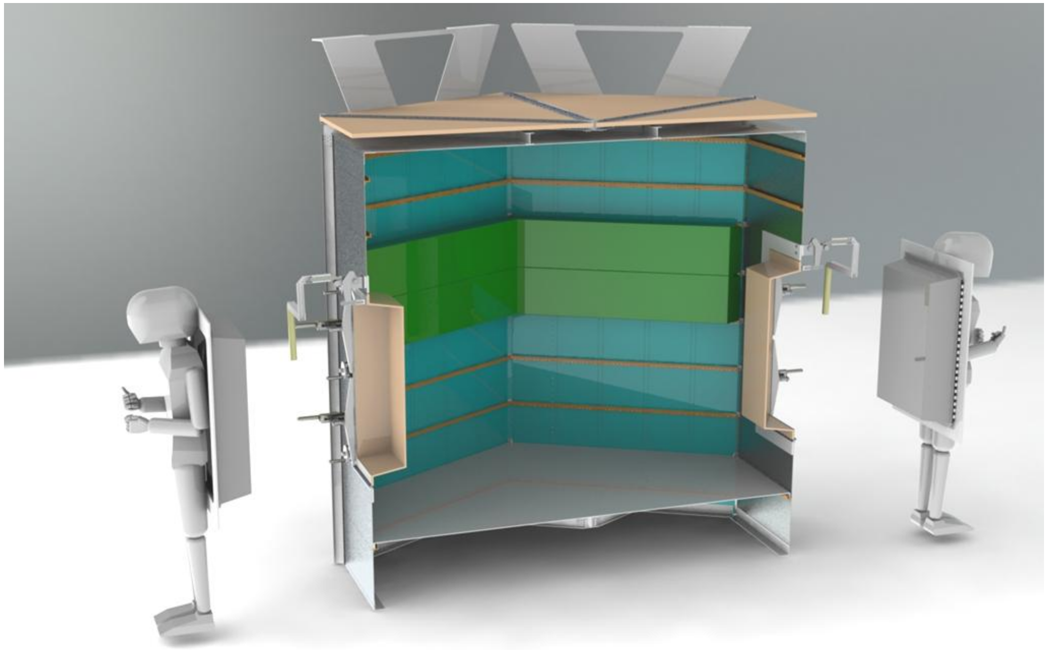
- Suitport airlock keeps suit outside
- Egress/ingress through hatch in back

Illustration courtesy Ford et al., 2008

Prototype suitport testing, courtesy Gernhardt, 2008

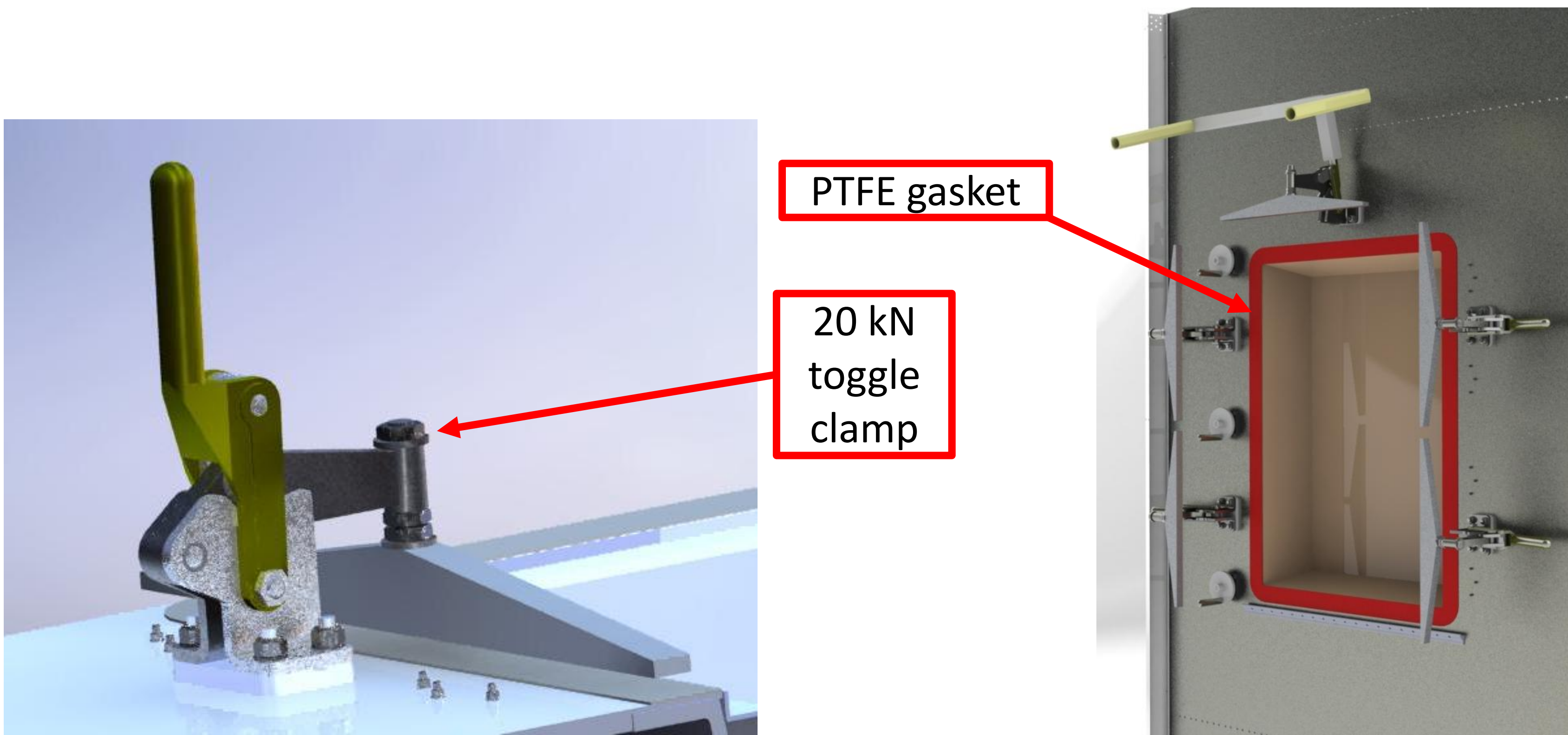
Suitport Ideal for LEVITATE

- No traditional airlock, minimizes space
- One suitport for each astronaut
- Keeps regolith outside



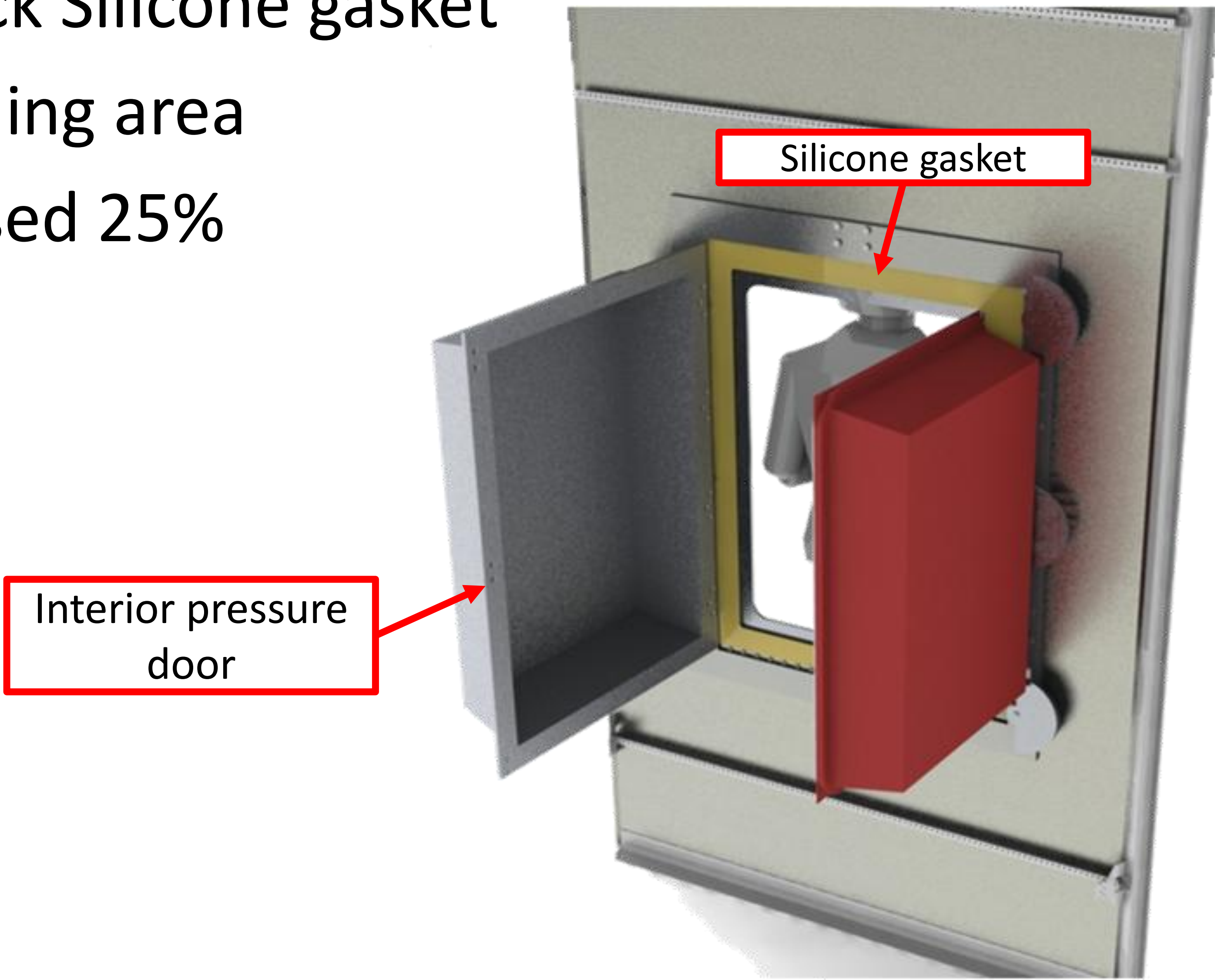
Outer Seal Withstands Environment

- Large temperature swings require PTFE gasket
- 1.8 mm thick
- Seal created by five 20 kN toggle clamps



Inner Seal Minimizes Atmosphere Loss

- 1 mm thick Silicone gasket
- Large sealing area
- Compressed 25%

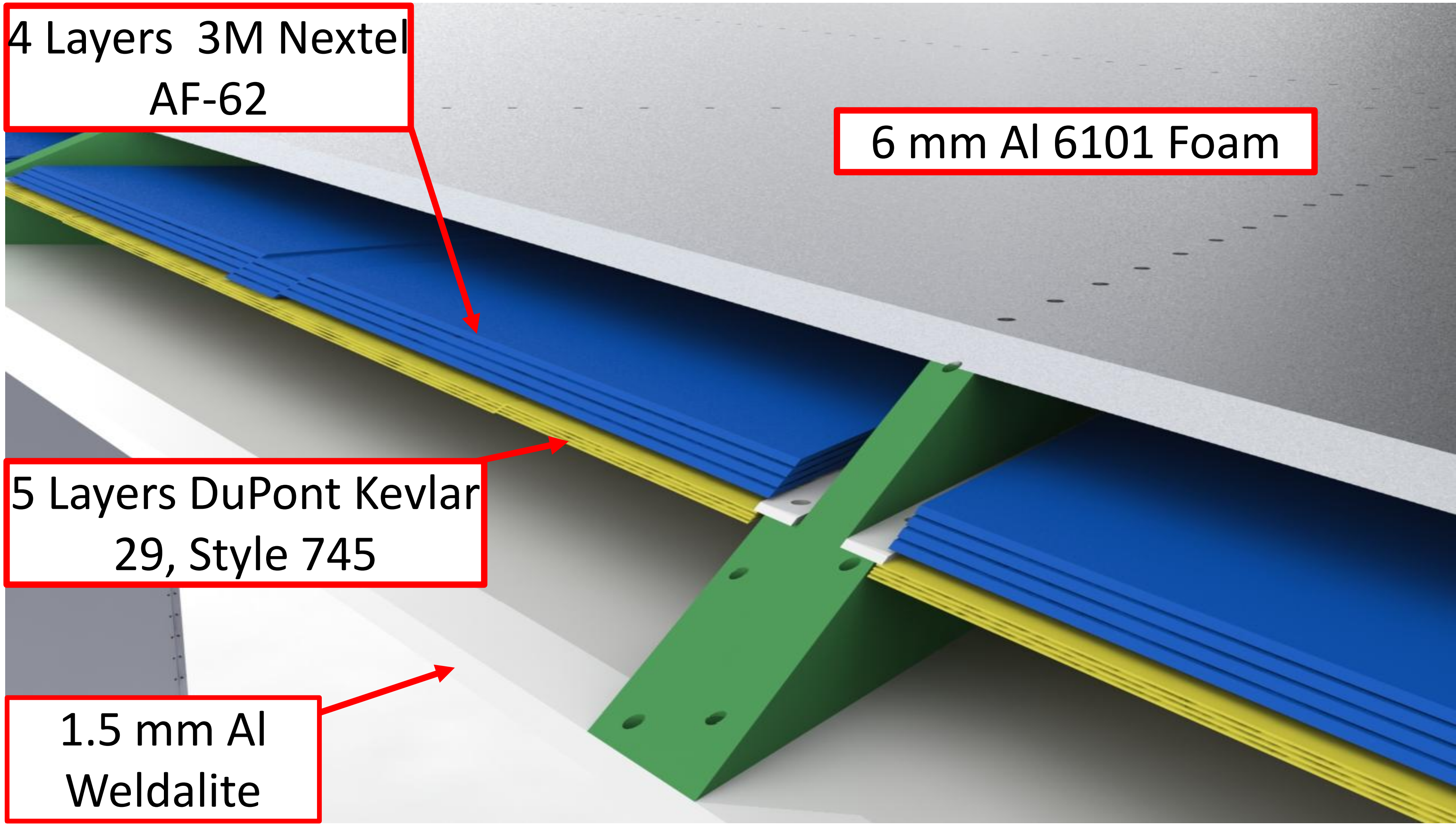


LEVIATE Withstands Meteorite Impacts

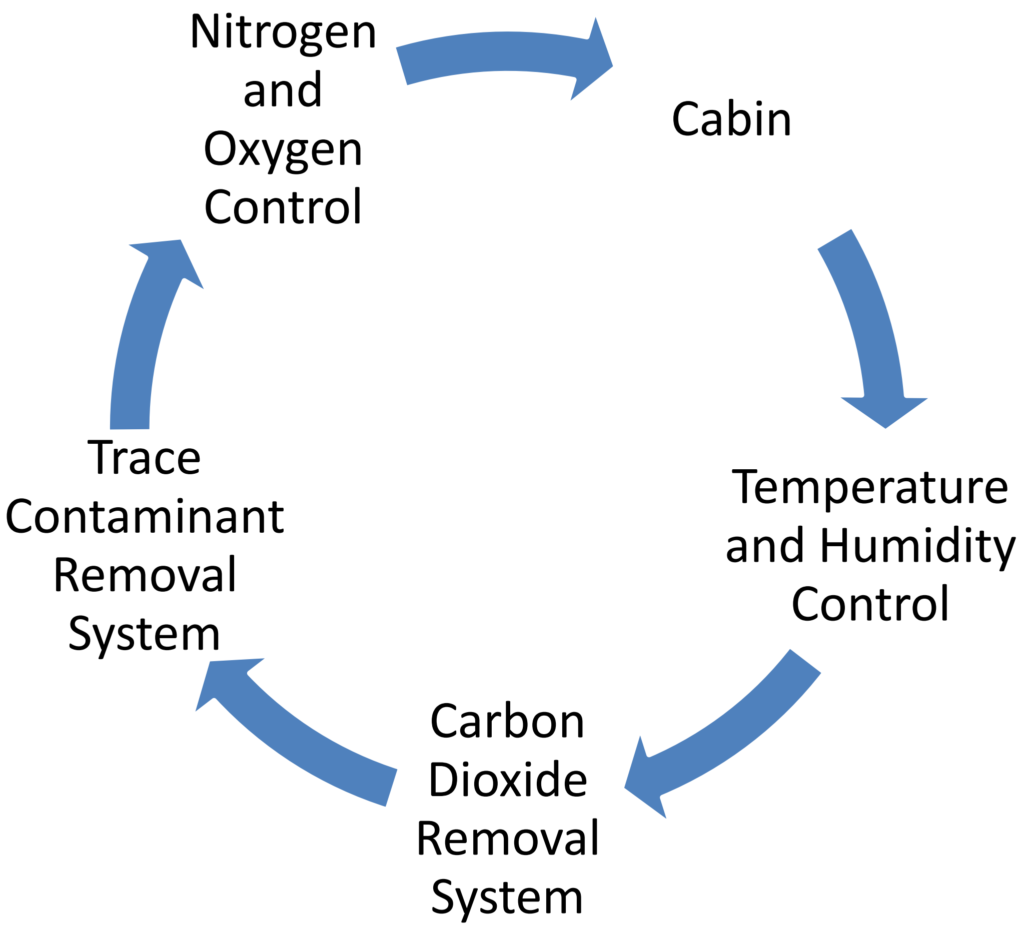
- 17 km/s average impact velocity
- Based on ISS shielding configuration

Micrometeoroid shield that surrounds habitat

LEVIATE Withstands Meteorite Impacts



Environmental Control System (ECS)



- Two Crew
- Fourteen Day Mission
- Simulated Earth Environment

Codes and Standards - NASA

- NASA Std 3000-5.1.3.1-1

Parameter	Units	Operational	90-day degraded (1)	28-day emergency
CO_2 partial press	N/m^2	400 max	1013 max	1600 max
Temperature (7)	deg. K	291.5-299.9	288.8-302.6	288.8-305.4
Dew point (2)	deg. K	277.6-288.7	273.9-294.3	273.9-294.3
Ventilation	m/sec	.076-.203	.051-.508	.050-1.016
O2 partial pressure (3)	kP_2	19.5-23.1	16.5-23.8	15.9-23.8
Total pressure	kP_2	100-101.4	100 -101.4	100-101.4
Dilute gas	———	N_2	N_2	N_2
Trace contaminants (6)	mg/m^3	TBD	TBD	TBD
Micro-organisms	CFU/m^3 (4)	500 (5)	750 (5)	1000 (5)
Particulates > 0.5 micron	$counts/m^3$	3,530,000 max	TBD	TBD

Codes and Standards - SMAC

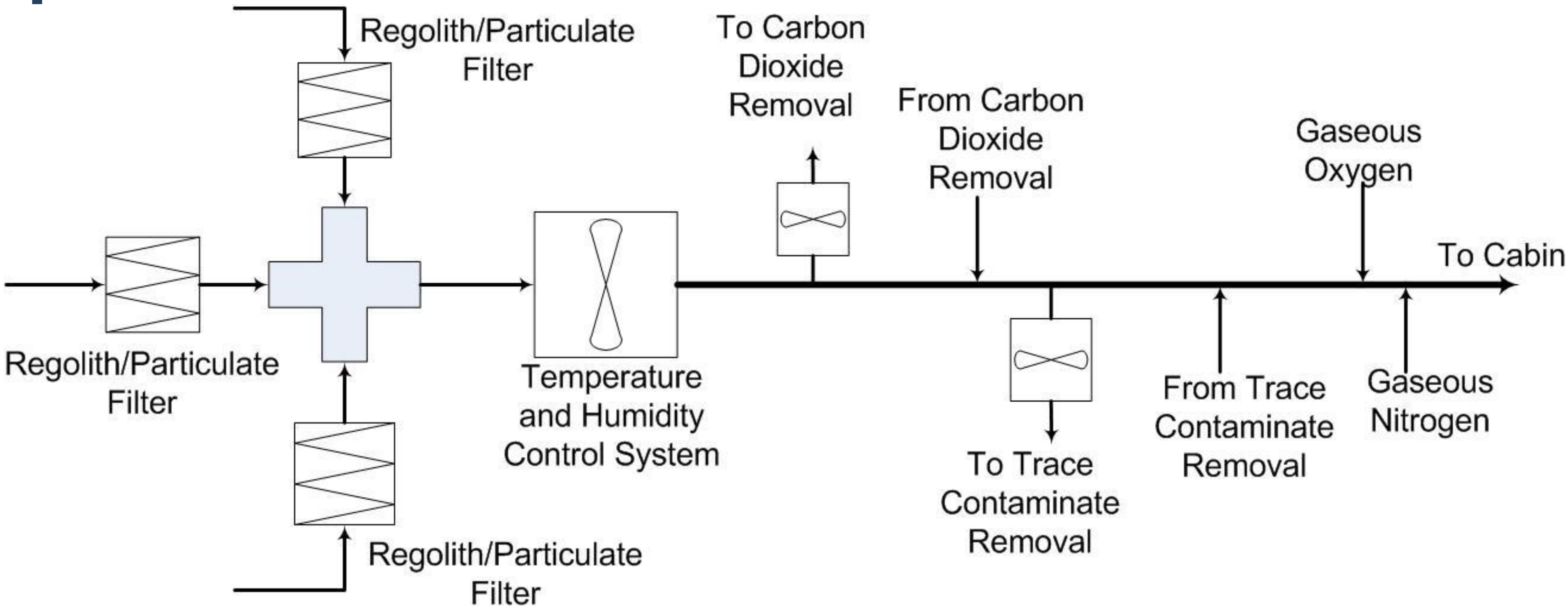
- Spacecraft Maximum Allowable Concentrations (SMAC)

Compound	Equipment Rate (mg/kg-day)	Metabolic Rate (mg/man-day)	Total (mg/day)	30-Day SMAC (mg/m^3)	SMAC PPM
Ethanol	7.85E-03	4	47.3	2000	1062
methanol	1.27E-03	1.5	9.4	90	70
2-propanol	3.99E-03	0	20.0	150	60
n-butanol	4.71E-03	1.33	26.2	80	Varies
toluene	1.98E-03	0	9.9	60	16
xylene	3.67E-03	0	18.4	217	50
chlorobenzene	1.54E-03	0	7.7	0.326	0.1
dichloromethane	2.15E-03	0	10.8	24	7
trifluoroethane	1.89E-02	0	94.5	20	4
tricholorofluoromethane	1.41E-03	0	7.1	790	140
methane	6.39E-04	160	323.2	3800	5300
acetone	3.62E-03	0.2	18.5	52	22
2-butanone (Methyl Ethyl Keytone)	6.01E-03	0	30.1	30	10
4-methyl-2-pentanone	1.41E-03	0	7.1	143	35
cyclohexanone	6.62E-04	0	3.3	4.89	25 (TLV)
carbon monoxide	2.03E-03	23	56.2	11	10
ammonia	8.46E-05	321	642.4	7	10
Carbon Dioxide	0.00E+00	1000000	2000000	12600	7000
Based on two persons and 5000kg of equipment off gassing				TLV = Threshold Limit Value	

Four Major Subassemblies

- Driven by NASA Std 3000-5.1.3.1-1
  - Carbon Dioxide Removal System (CDRS)
  - Temperature and Humidity Control (THC)
  - Nitrogen and Oxygen Control (NOC)
- Driven by SMAC
  - Trace Contaminate Removal System (TCRS)

ECS Airflow Inlet/Circulation



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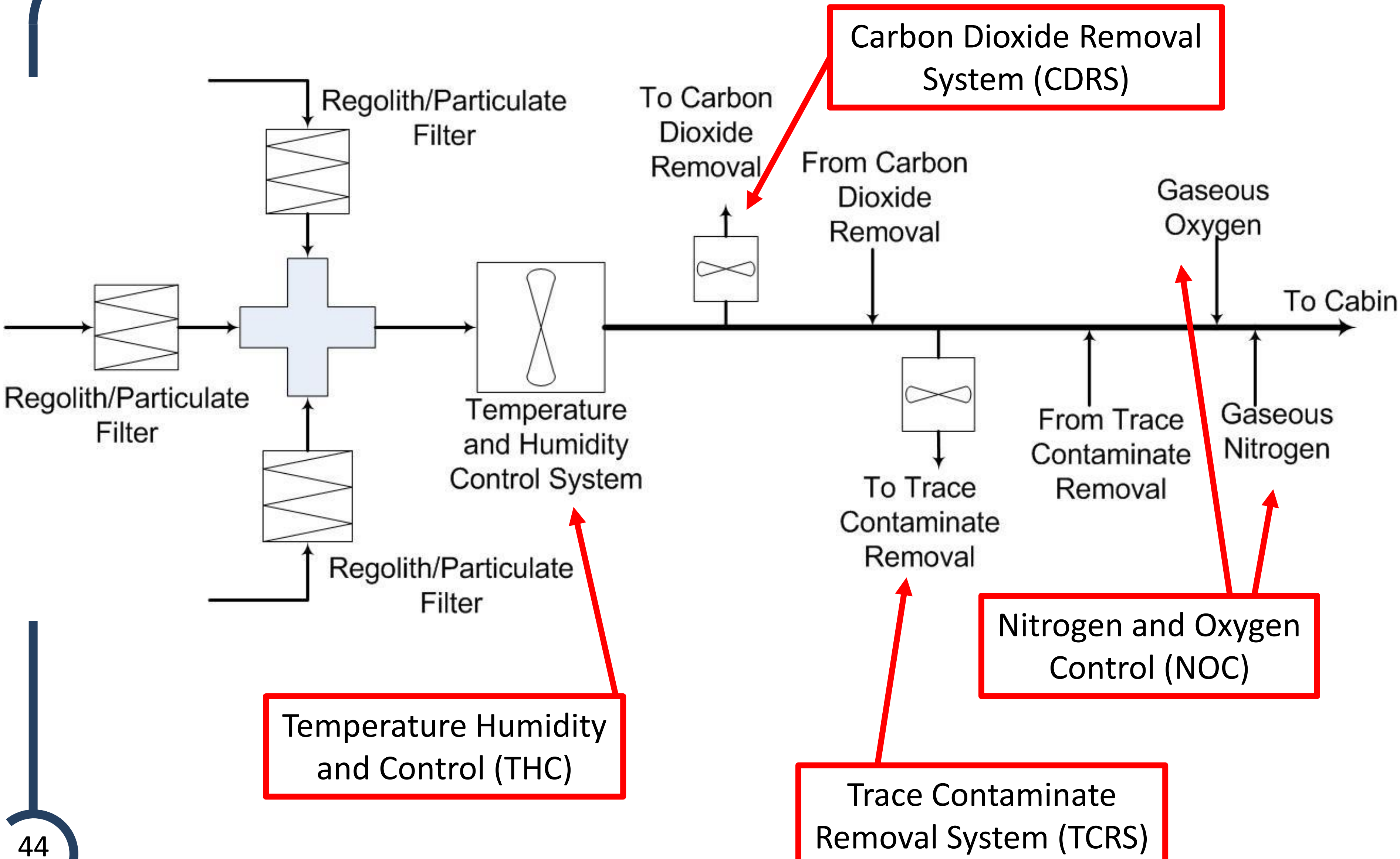

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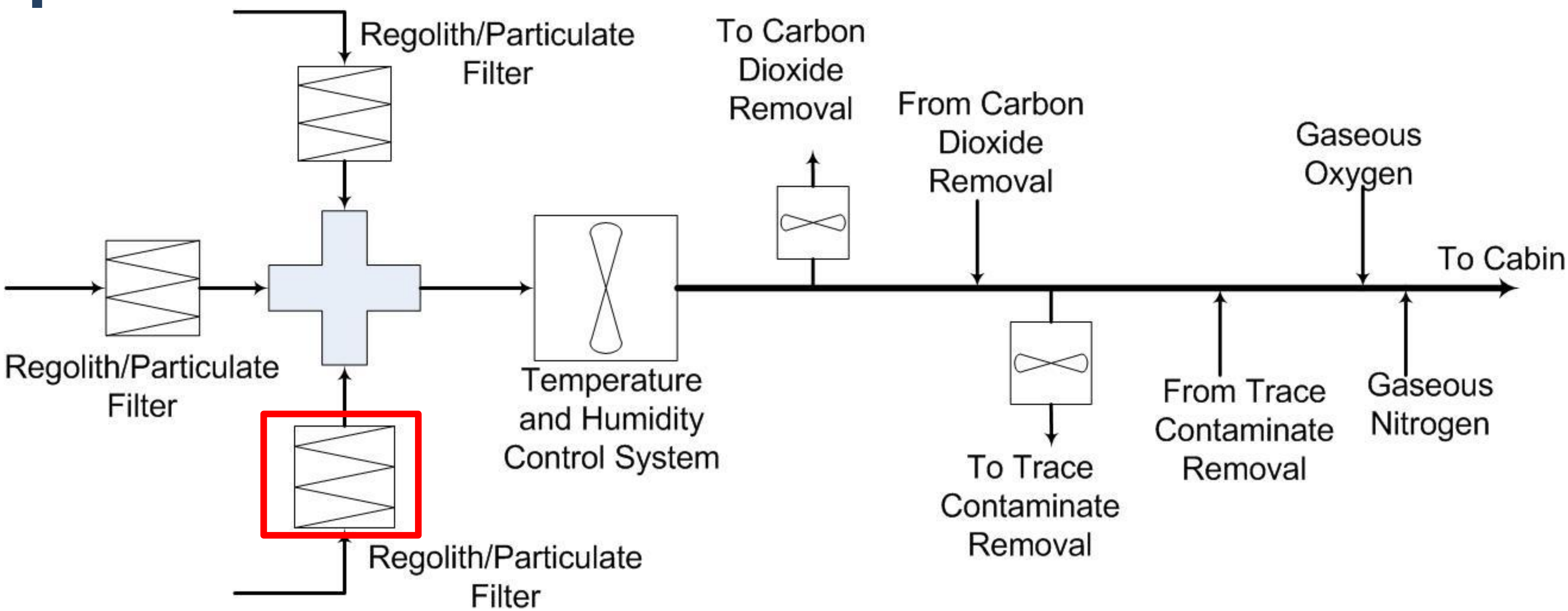
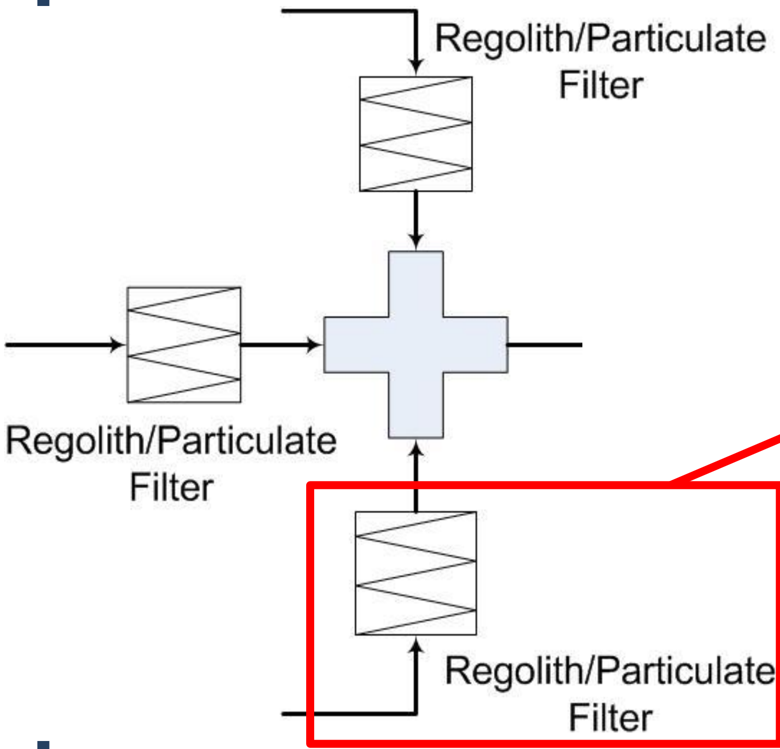


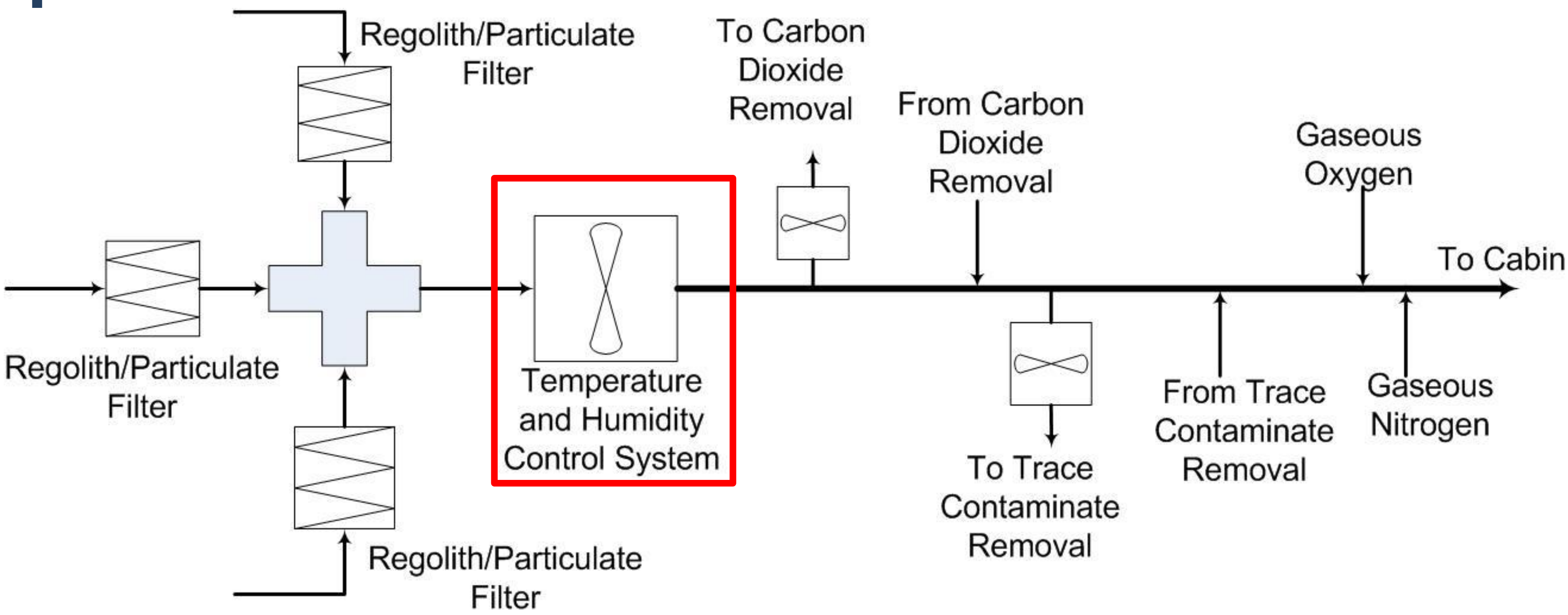
Regolith Filtration



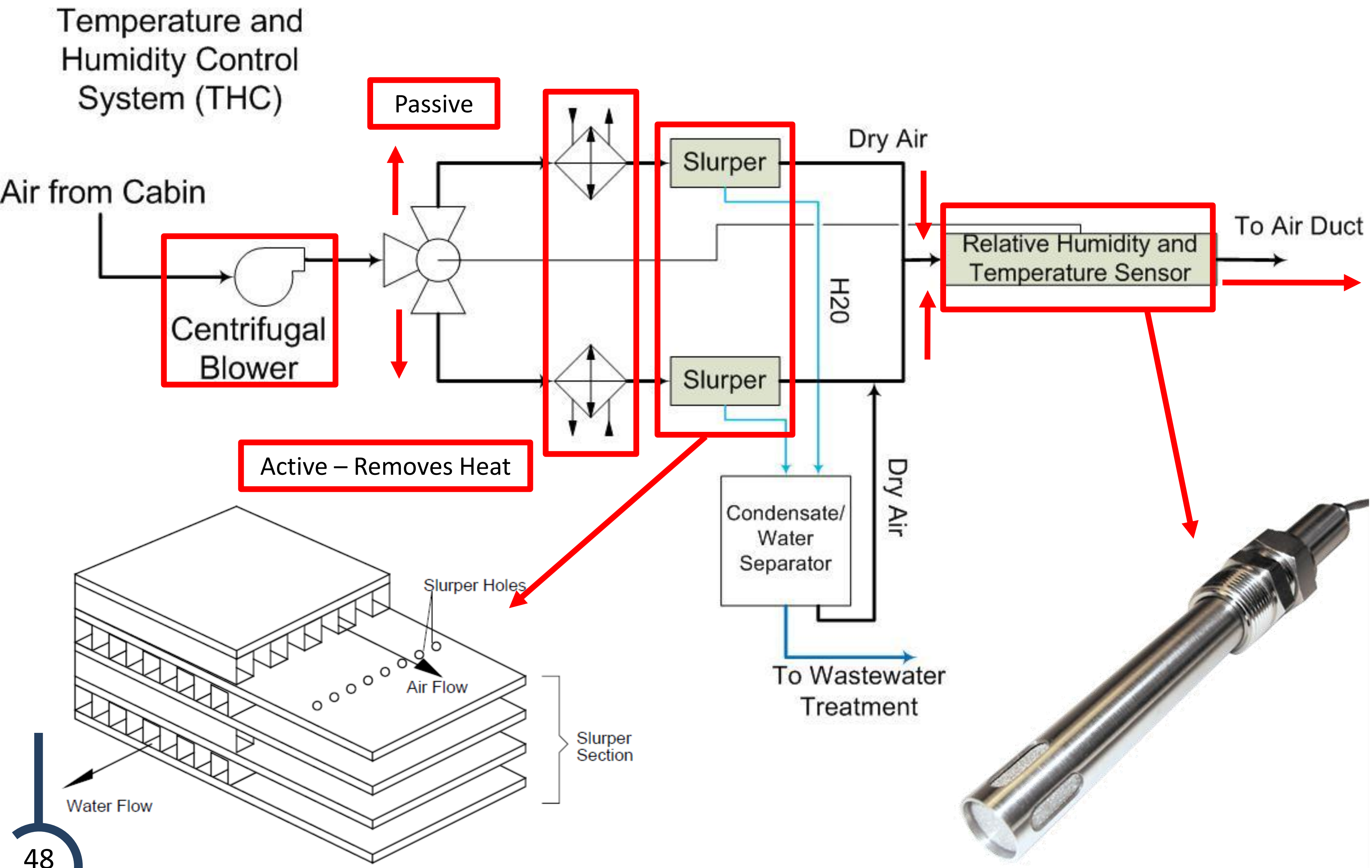
Swagelok Ultra-High Purity Gas Filter with Membralox Ceramic Filtration Insert

- Stops 99.9999999% of particulates (regolith) 0.3 µm or larger
- Easy to replace

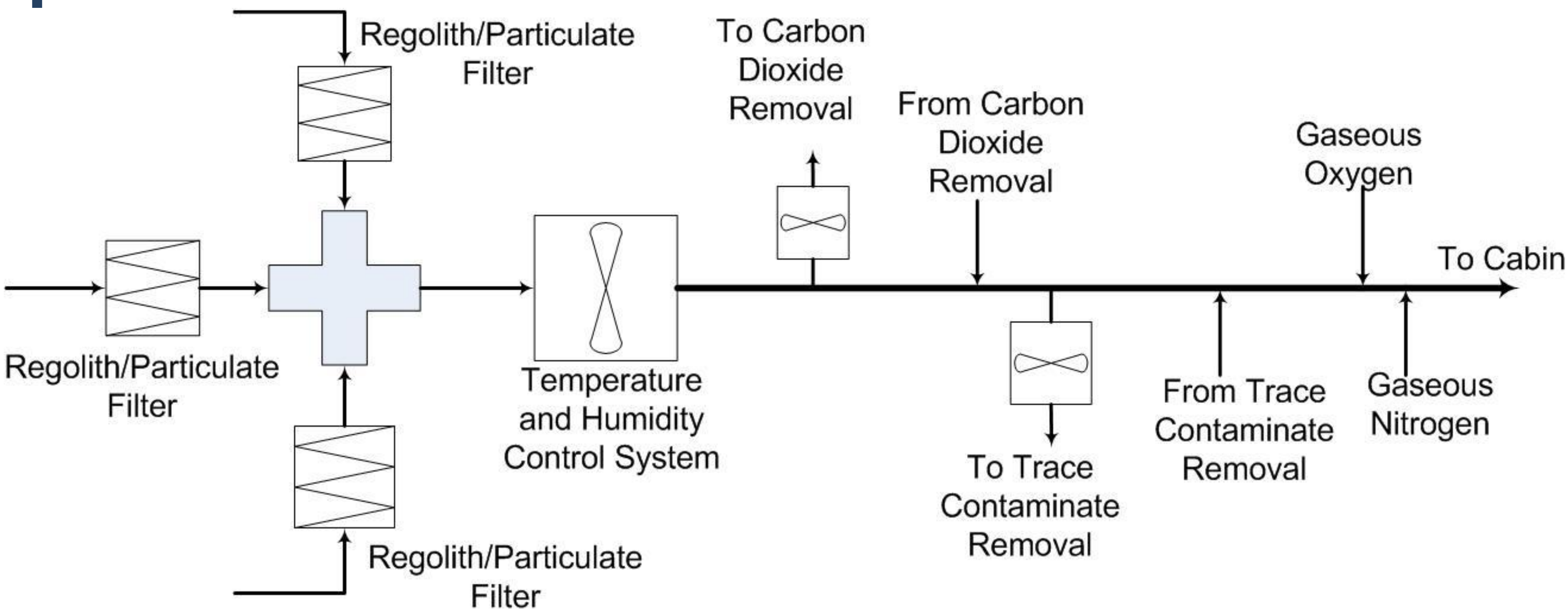
Temperature and Humidity Control (THC)



Temperature and Humidity Control (THC)



Carbon Dioxide Removal System (CDRS)



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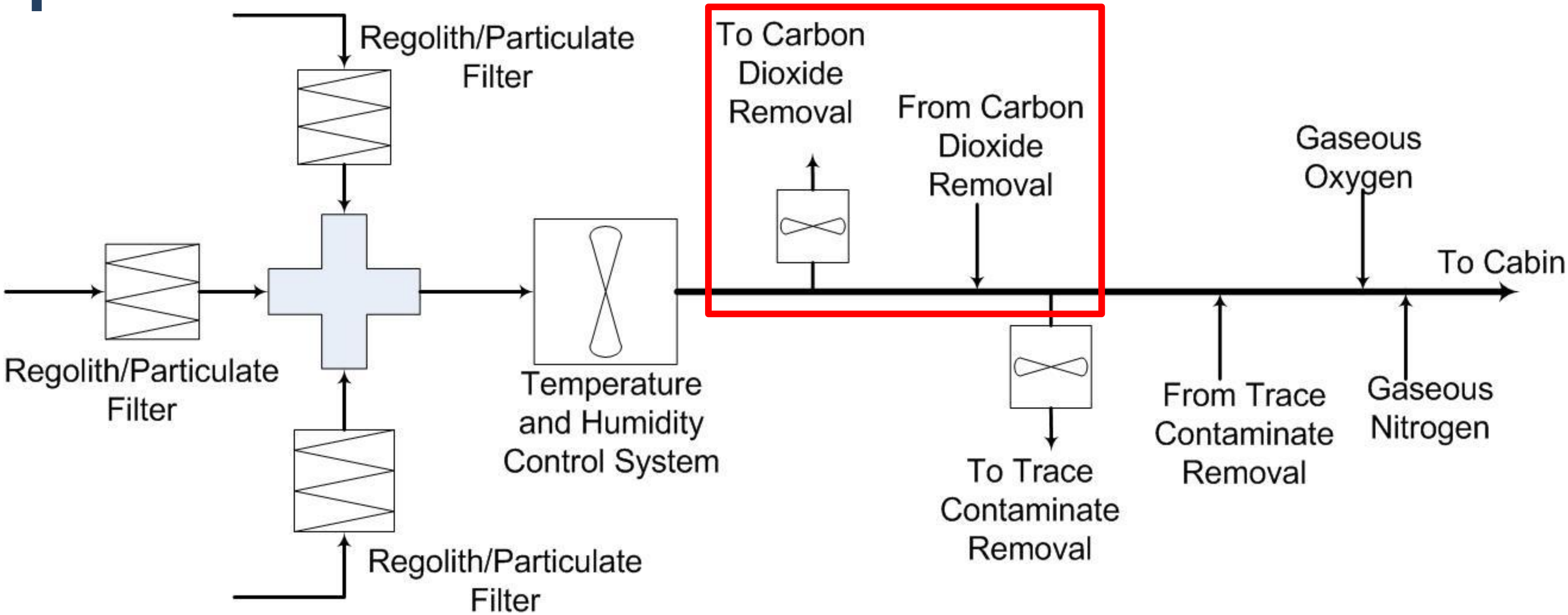

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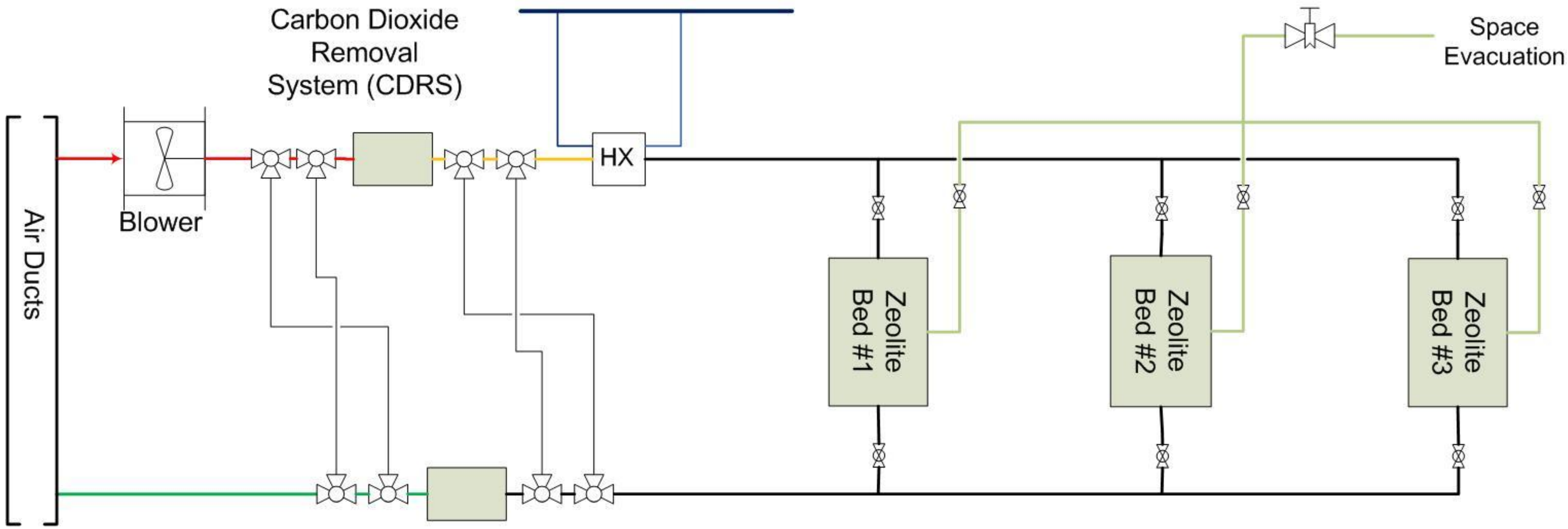

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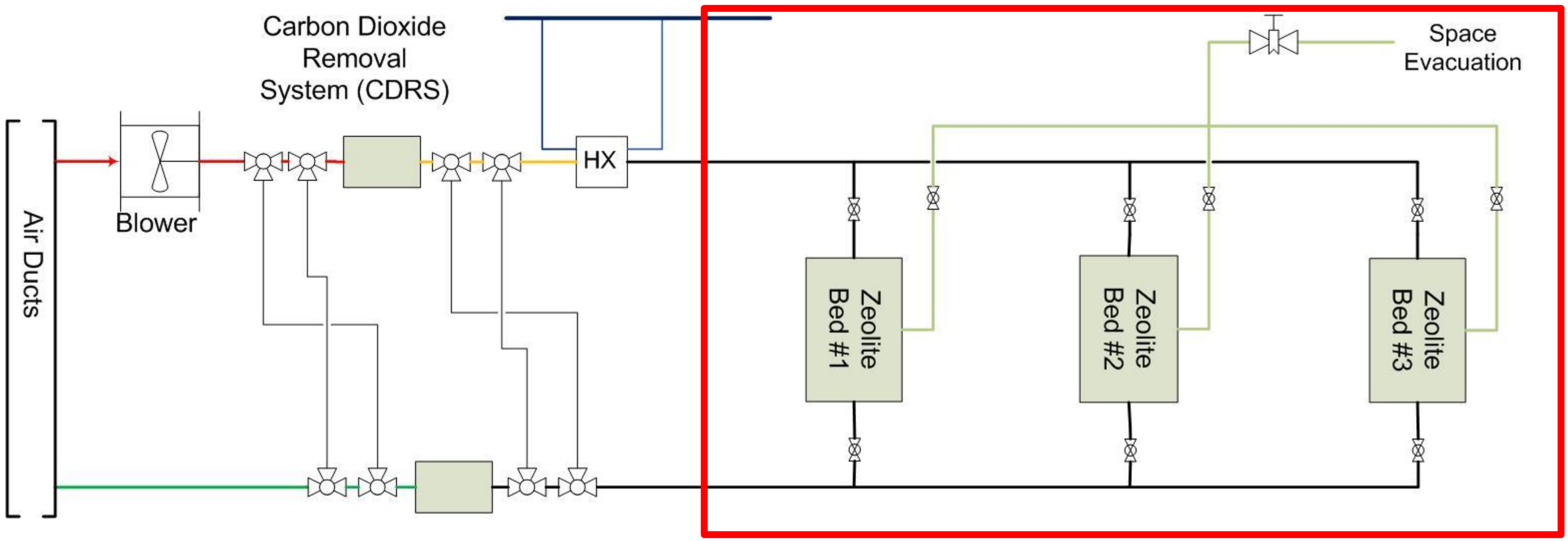

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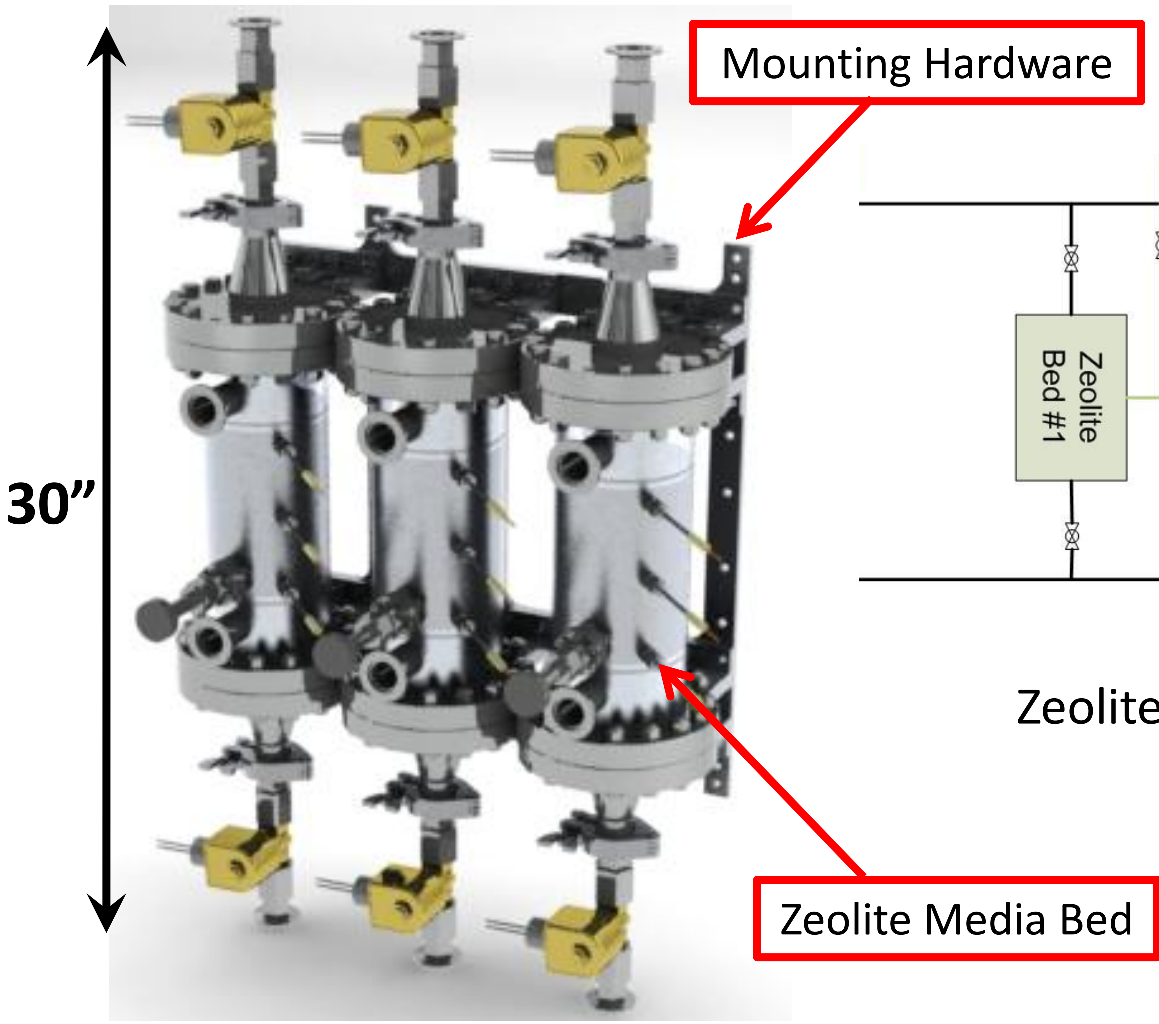
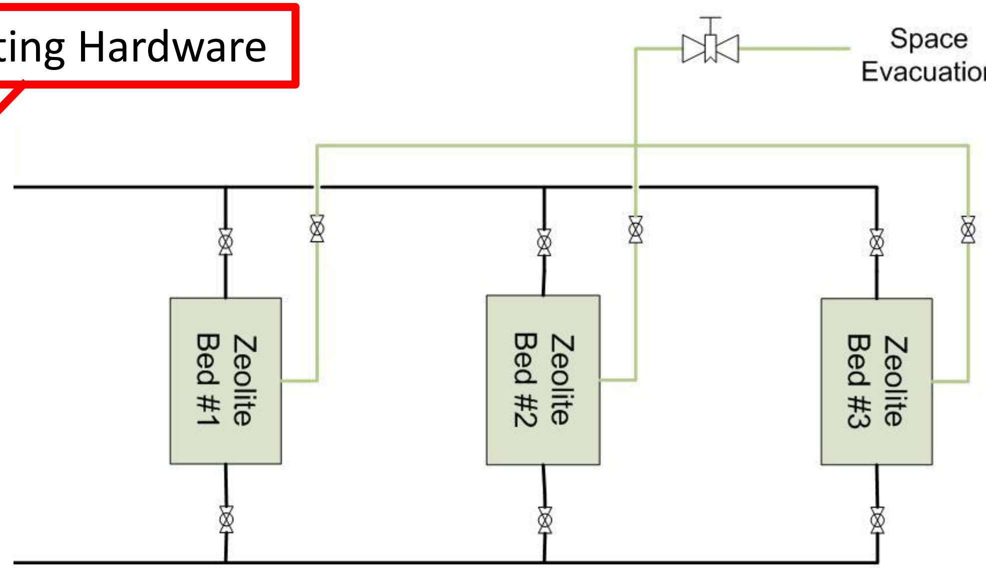




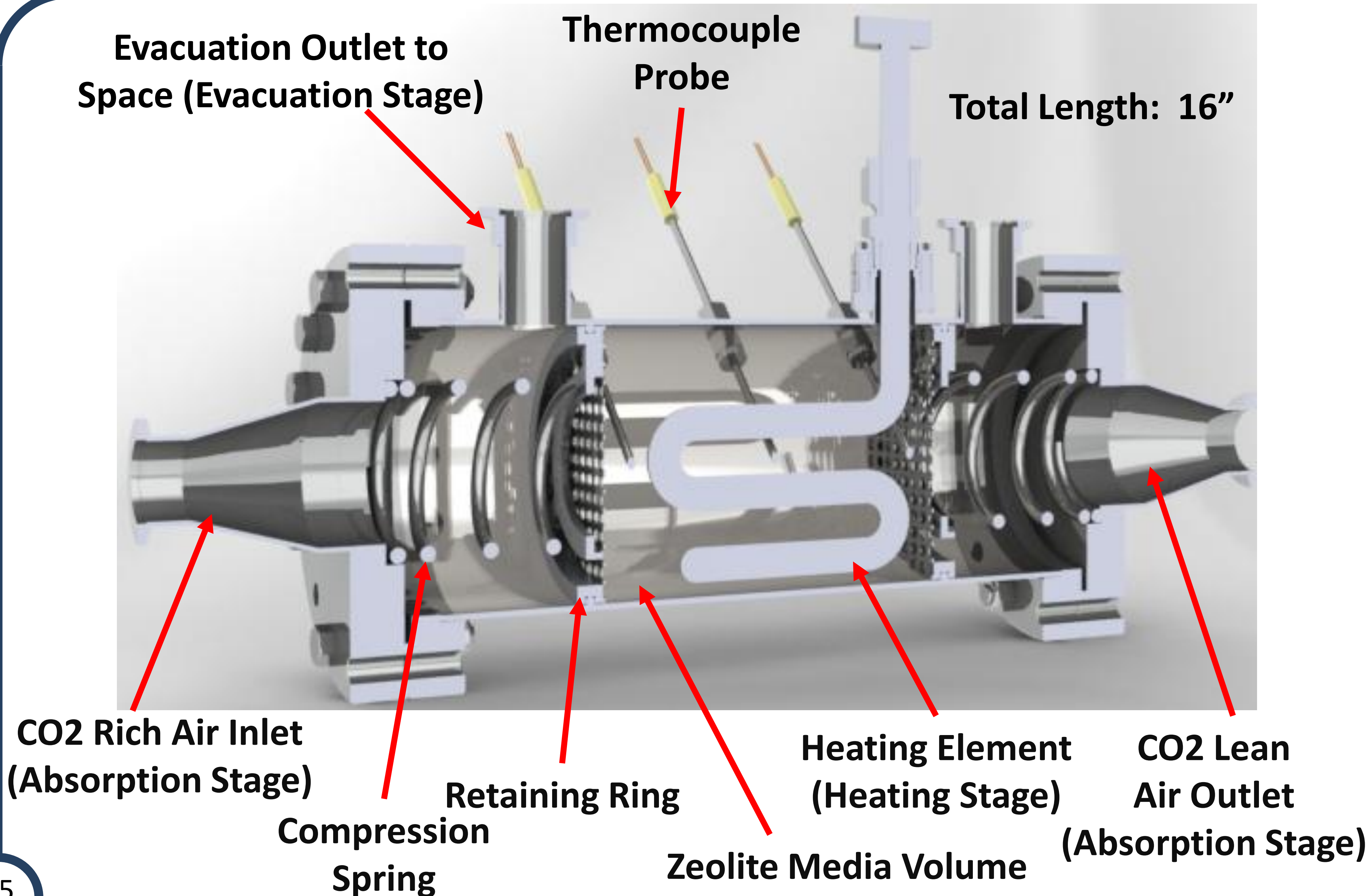
Zeolite Media Bed Assembly

Regenerative Zeolite 5A Media

- Small beads (Ø ~4 mm)
- Specifically targets CO_2
- Removes ~2 kg CO_2 per day
- Regenerates at 135 °C
- Flight-proven

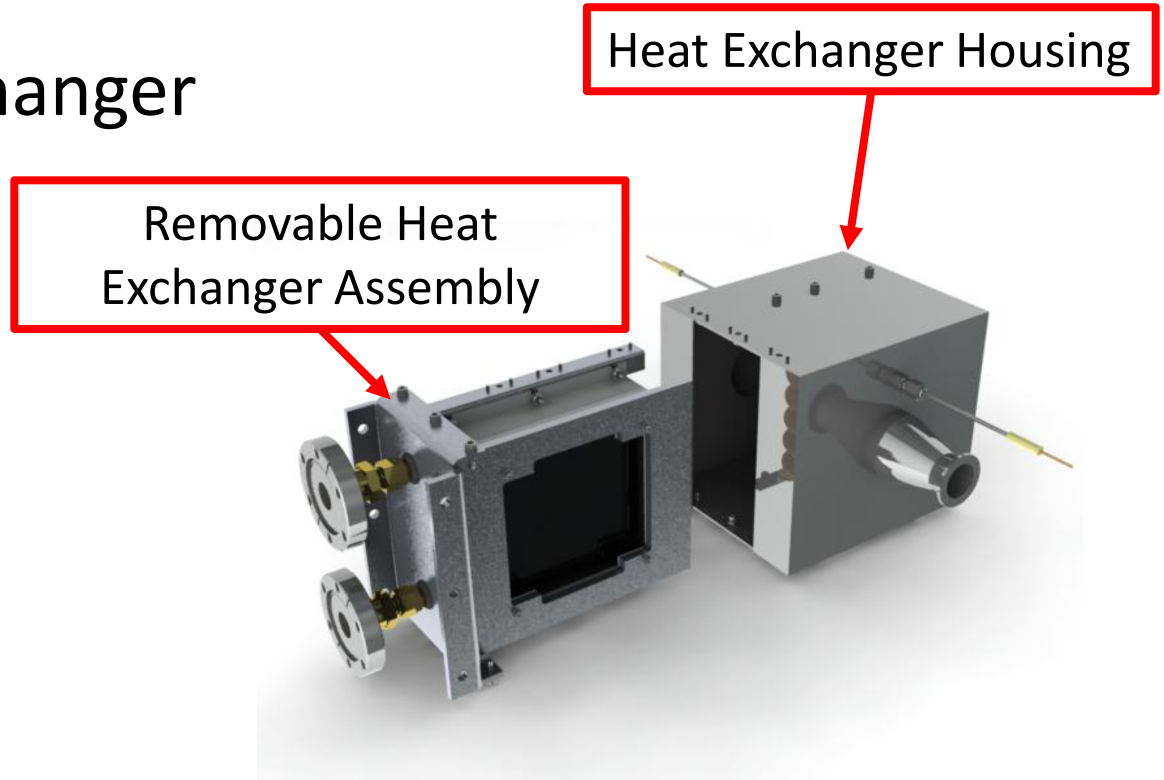
Zeolite 5A Media

Zeolite Media Bed Cross Section



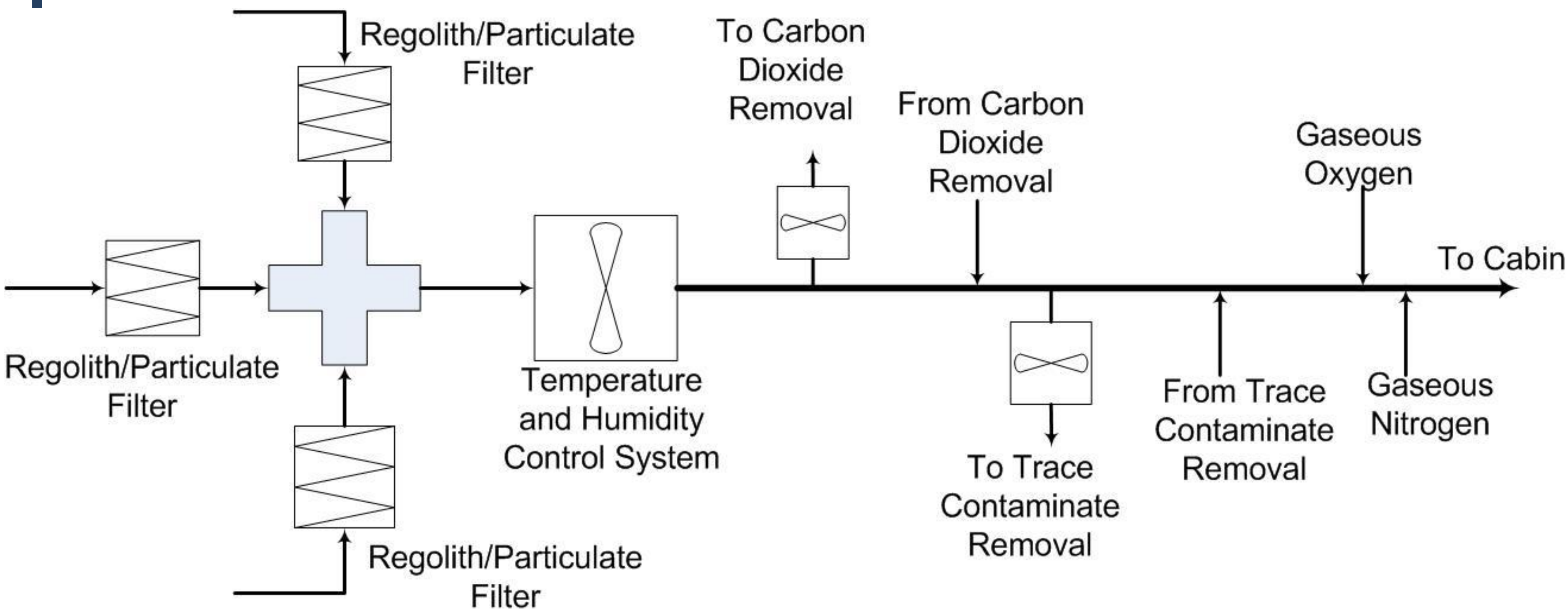
Moisture And Heat Removed

- Air/fin heat exchanger
  - Lytron 6110-SB

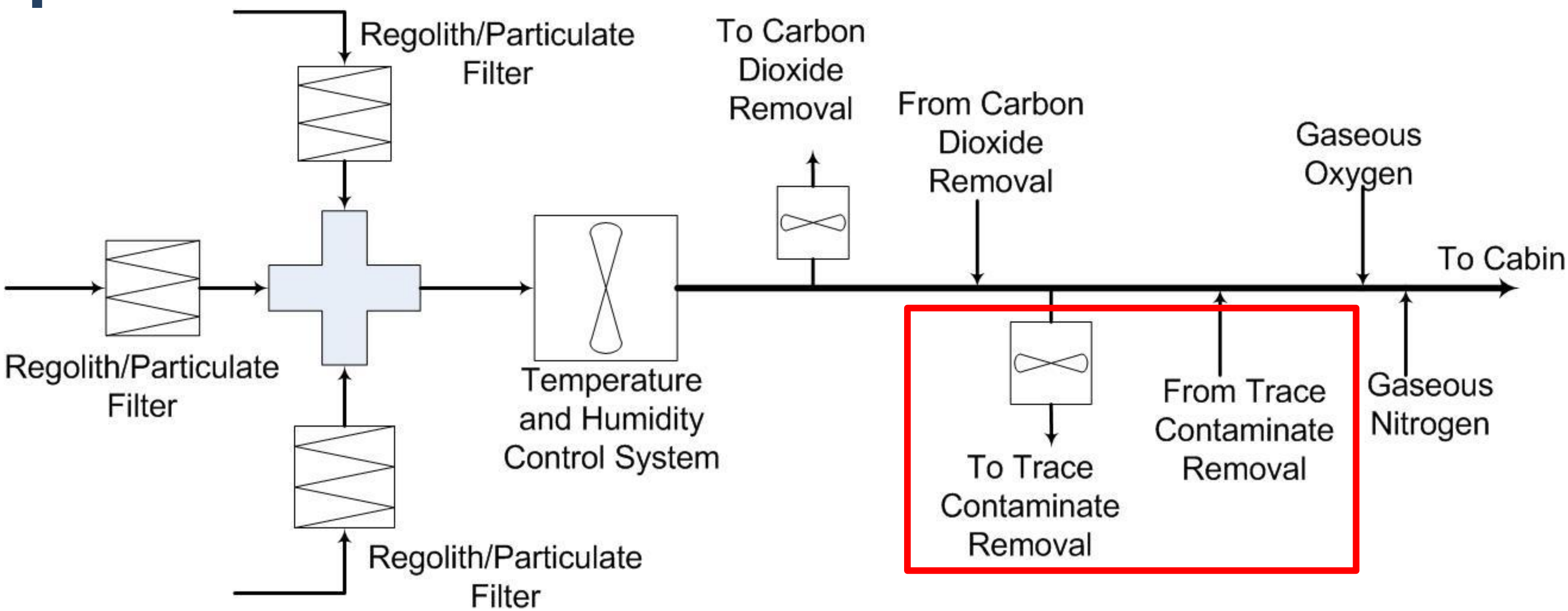


- Desiccant Bed Assembly
  - Silica Gel Beads

Trace Contaminate Removal System (TCRS)



Trace Contaminate Removal System (TCRS)



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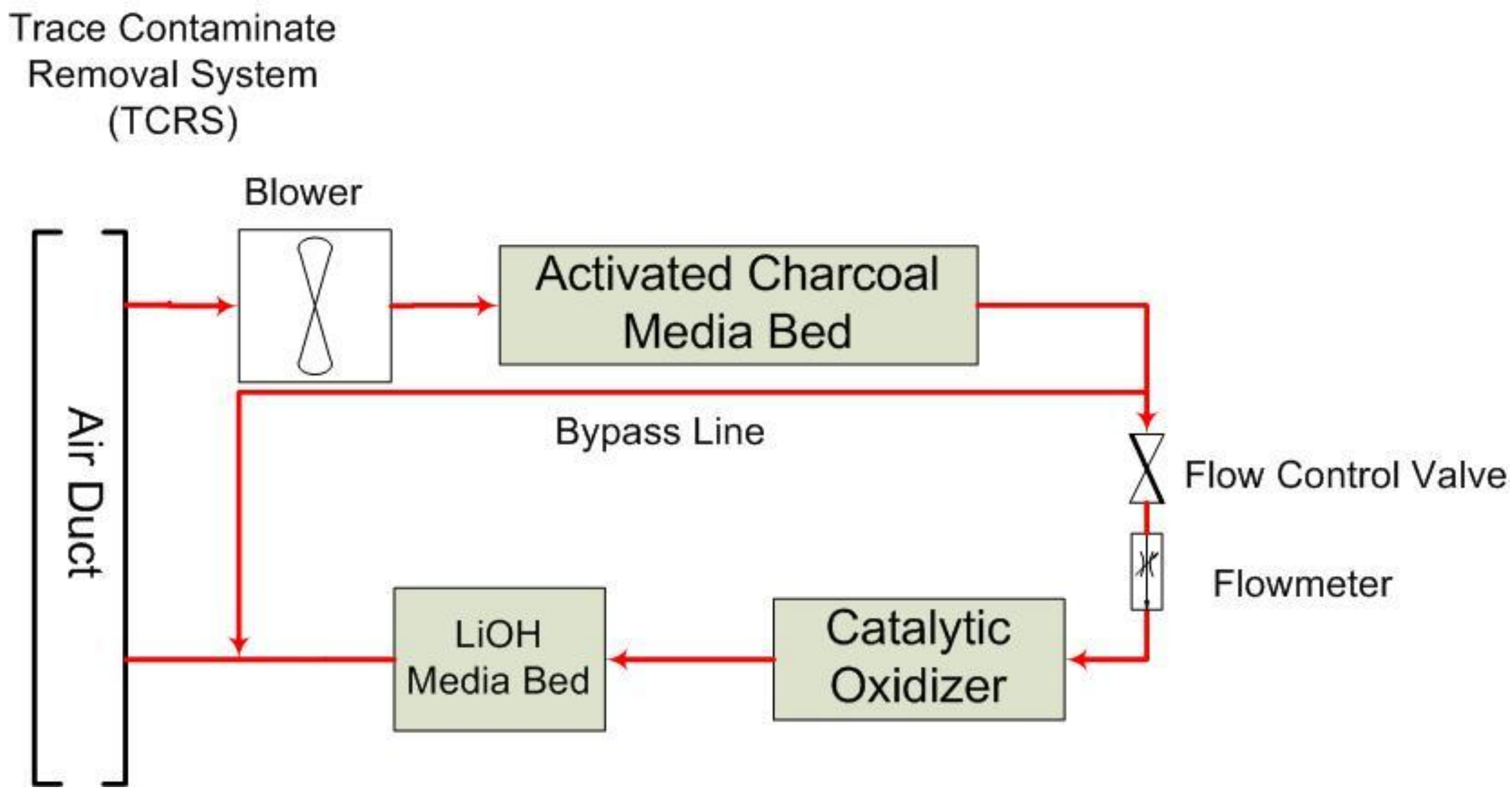

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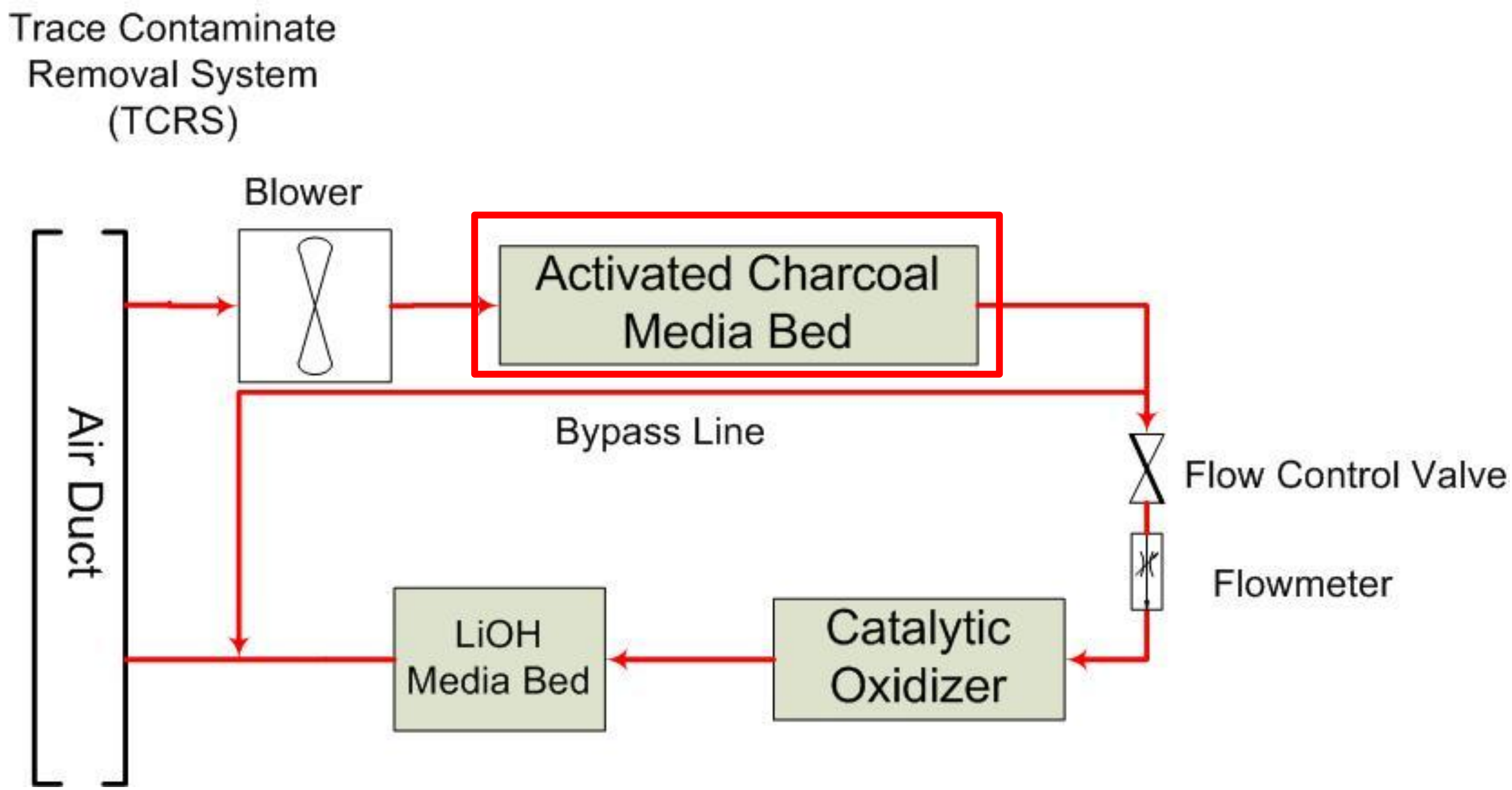
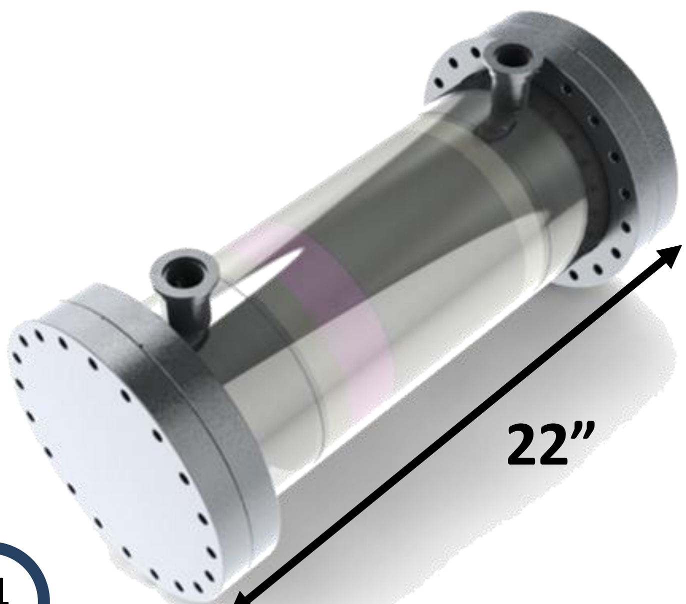


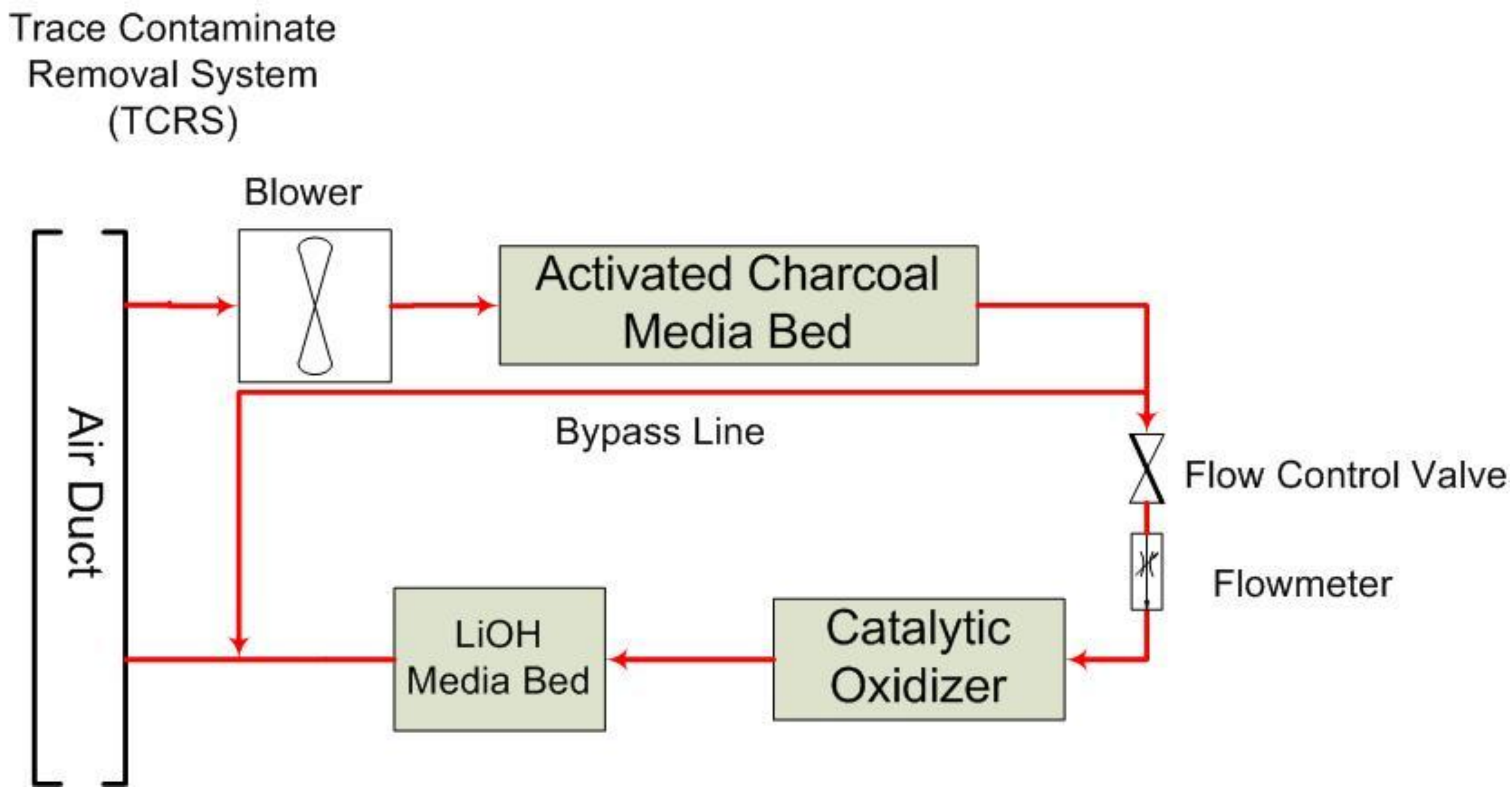
TCRS Activated Charcoal Media Bed

Charcoal media



- Removes high molecular weight components
  - Toluene, dichloromethane, ammonia, etc…

Trace Contaminate Removal System (TCRS)



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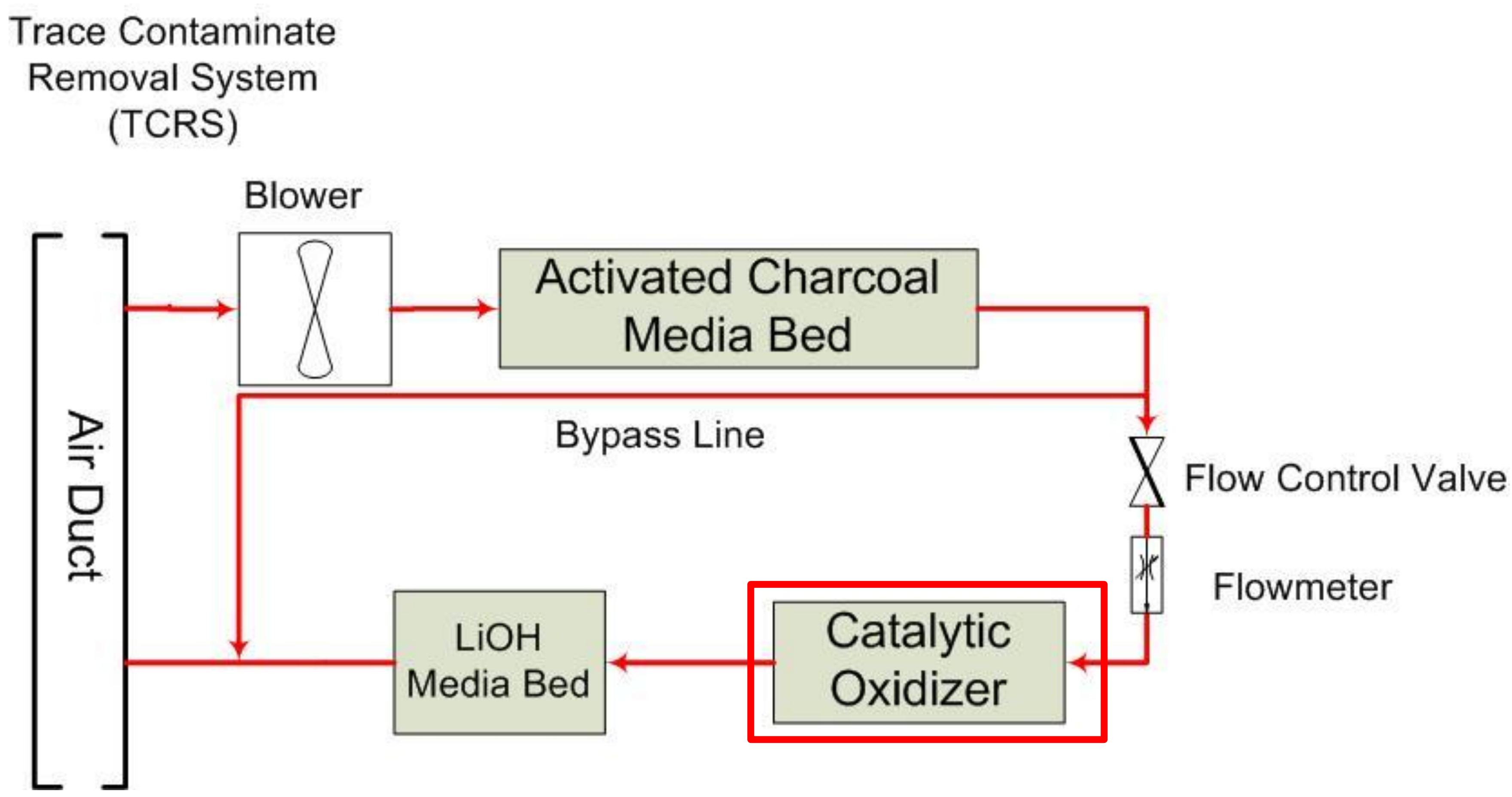
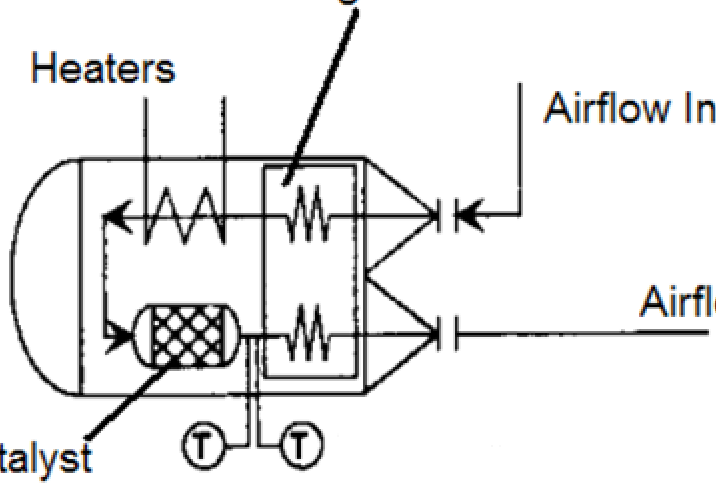


TCRS High Temperature Catalytic Oxidizer



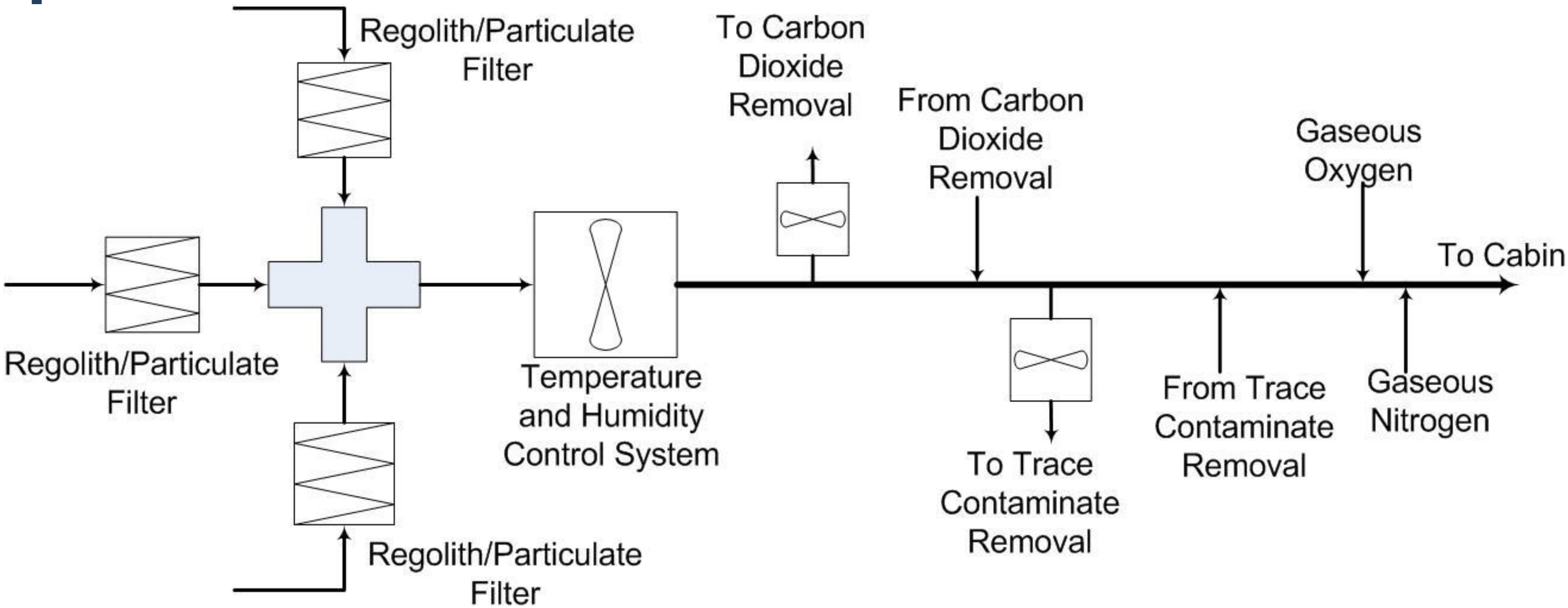
$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + 891$ KJ/mol

(Methane Combustion)

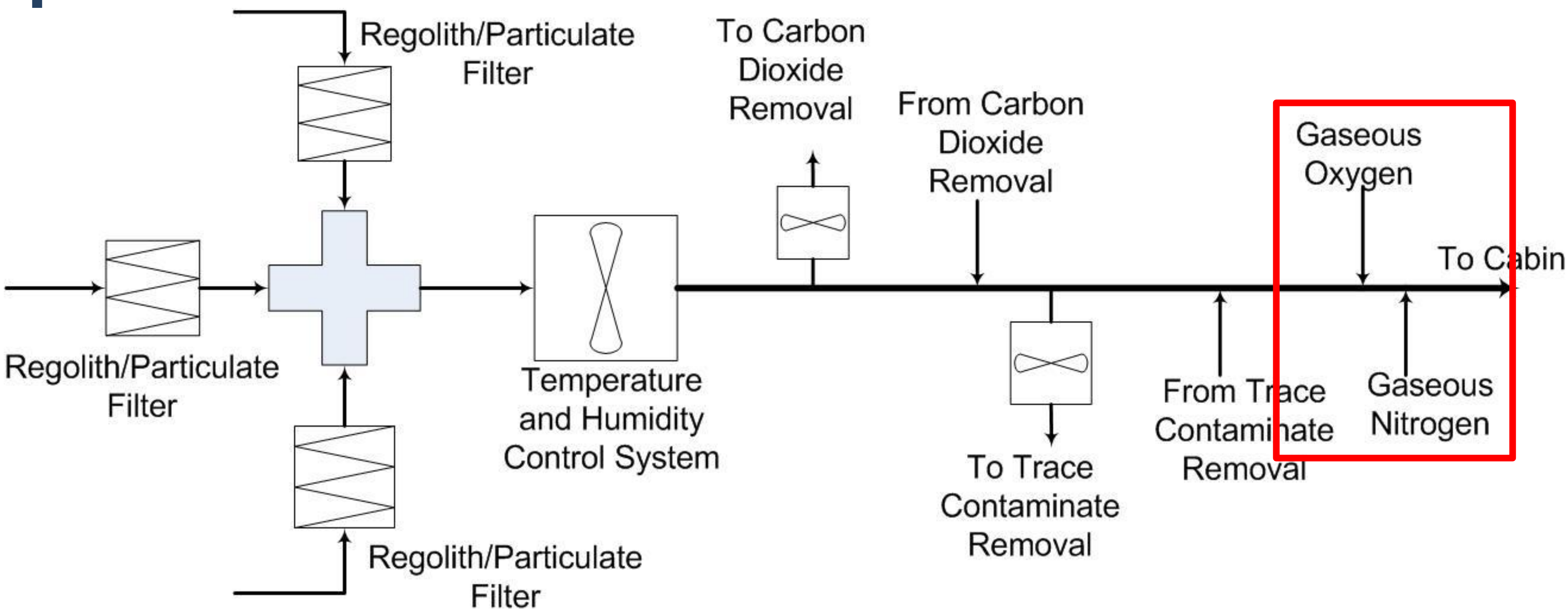
Design based on Perry, et al., 1999

- Removes low molecular weight components
  - Methane, carbon monoxide, etc…

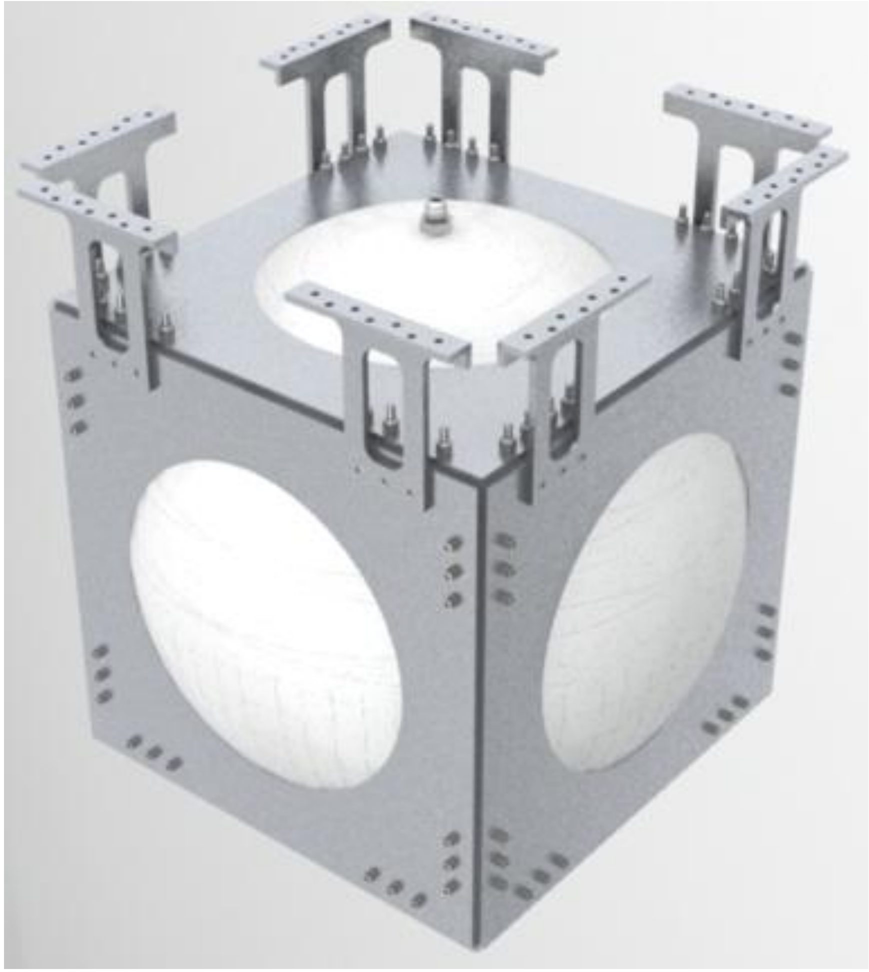
Nitrogen and Oxygen Control (NOC)



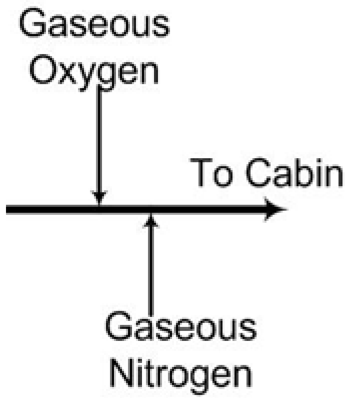
Nitrogen and Oxygen Control (NOC)



Nitrogen and Oxygen Control (NOC)



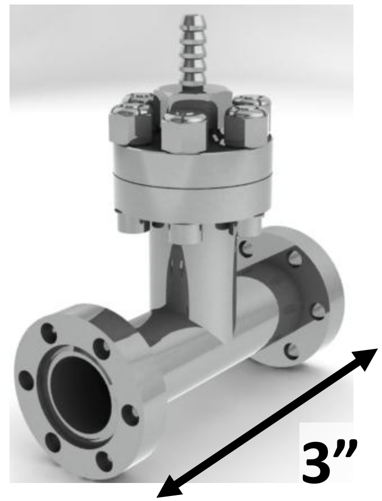
Cryogenic LOX tank

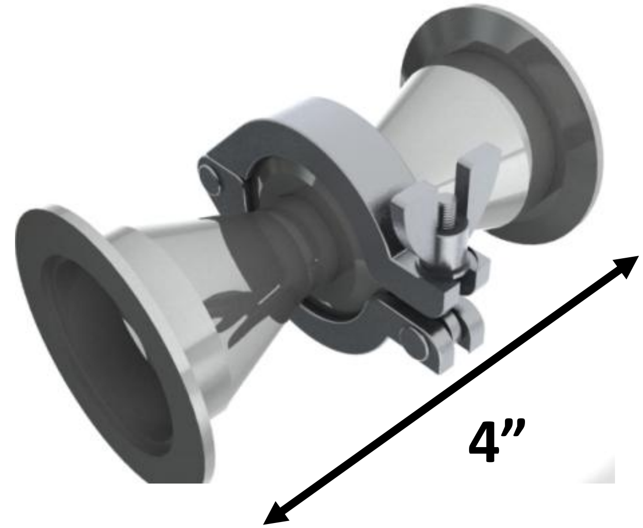


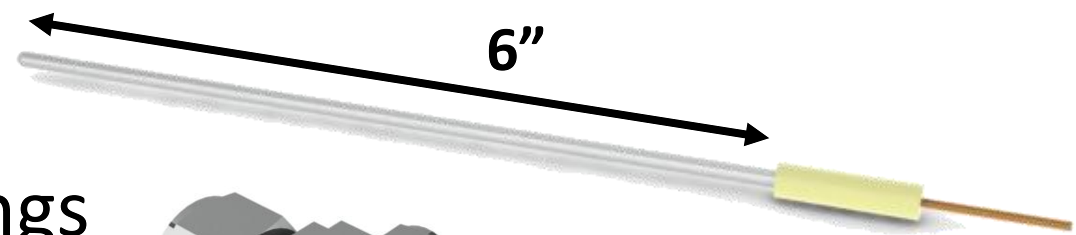
- Stored as liquid
- Refilled for each mission
- Replaces oxygen generation system

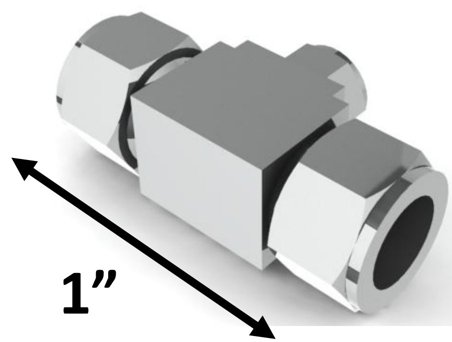
Flight-Proven Technologies

- Routing components
  - MDC-Vacuum
- Electronics
  - OMEGA Engineering
- Compression Fittings
  - Swagelok



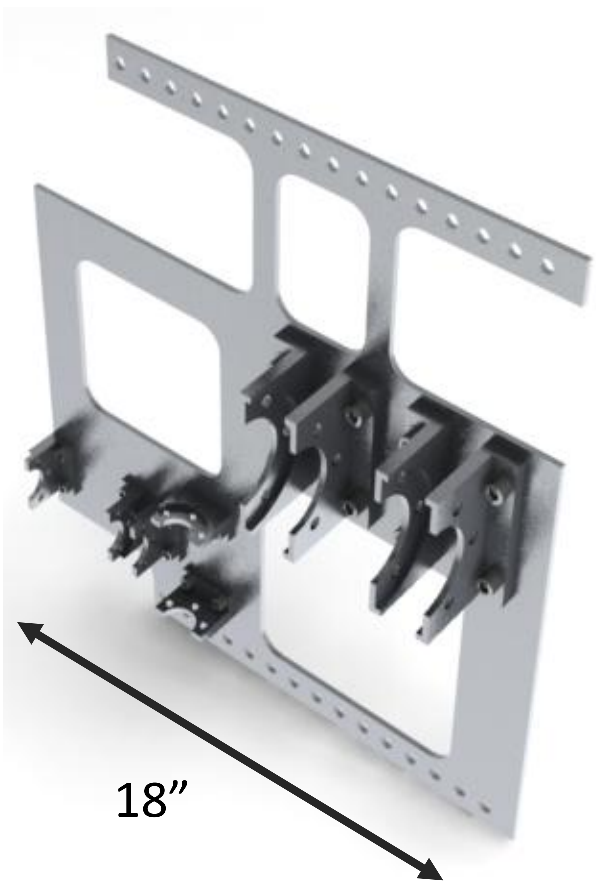


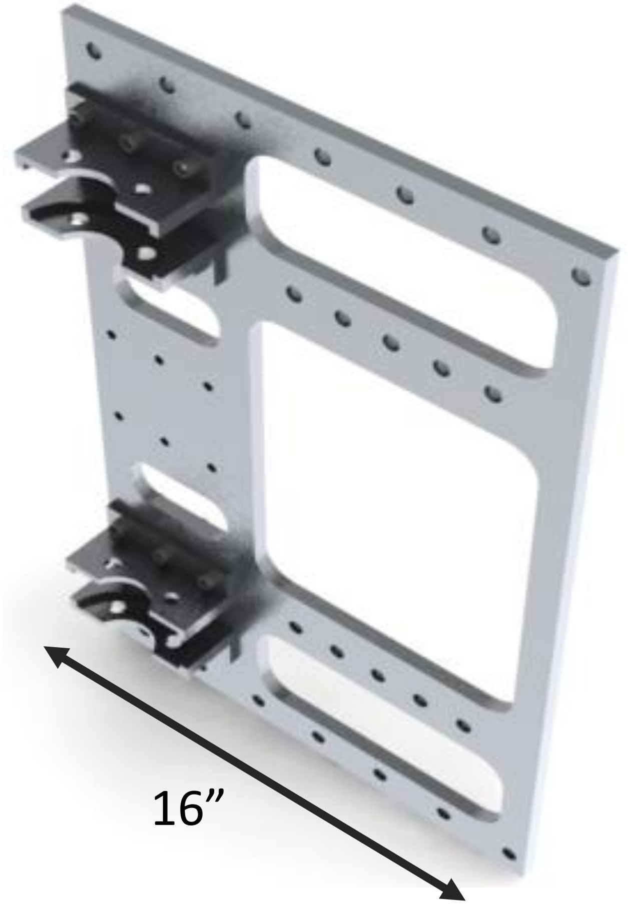




ECS Component Mounting

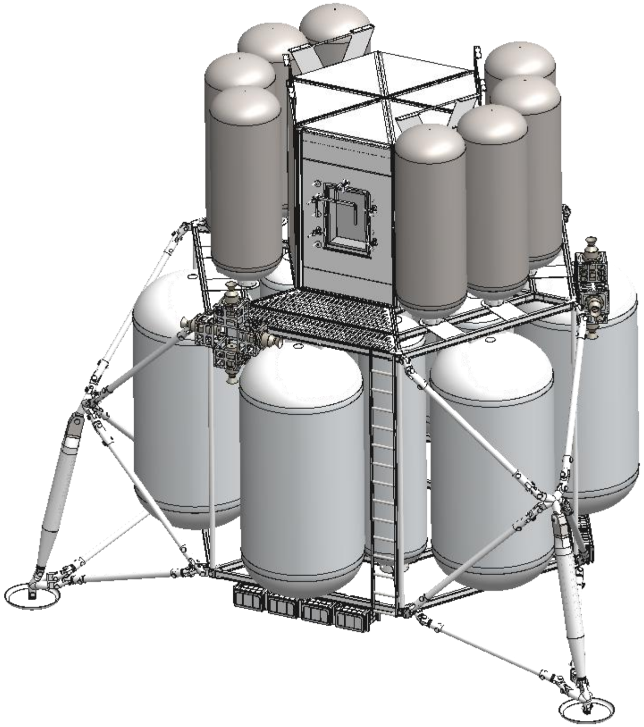
- Al 7075-T6: Lightweight, strong, machinable





Design Summary

- Mass: 24,871 kg
- Height: 8.15 m
- Fuel: LOX/LH2



- Technology Readiness Level (TRL) summary:

Major Subsystem	TRL
Propulsion	6
Structure	6
Habitat	**4**
Life Support	6

Next Design Iteration

- Feasibility proven, next step to integrate with lunar architecture and refine existing design
- Primary goals for the next iteration:
  – Guidance, Navigation and Control (GNC)
  – Communications
  – Power Supply
  – Fuel Distribution
  – Vehicle Interior Systems

Objectives Achieved

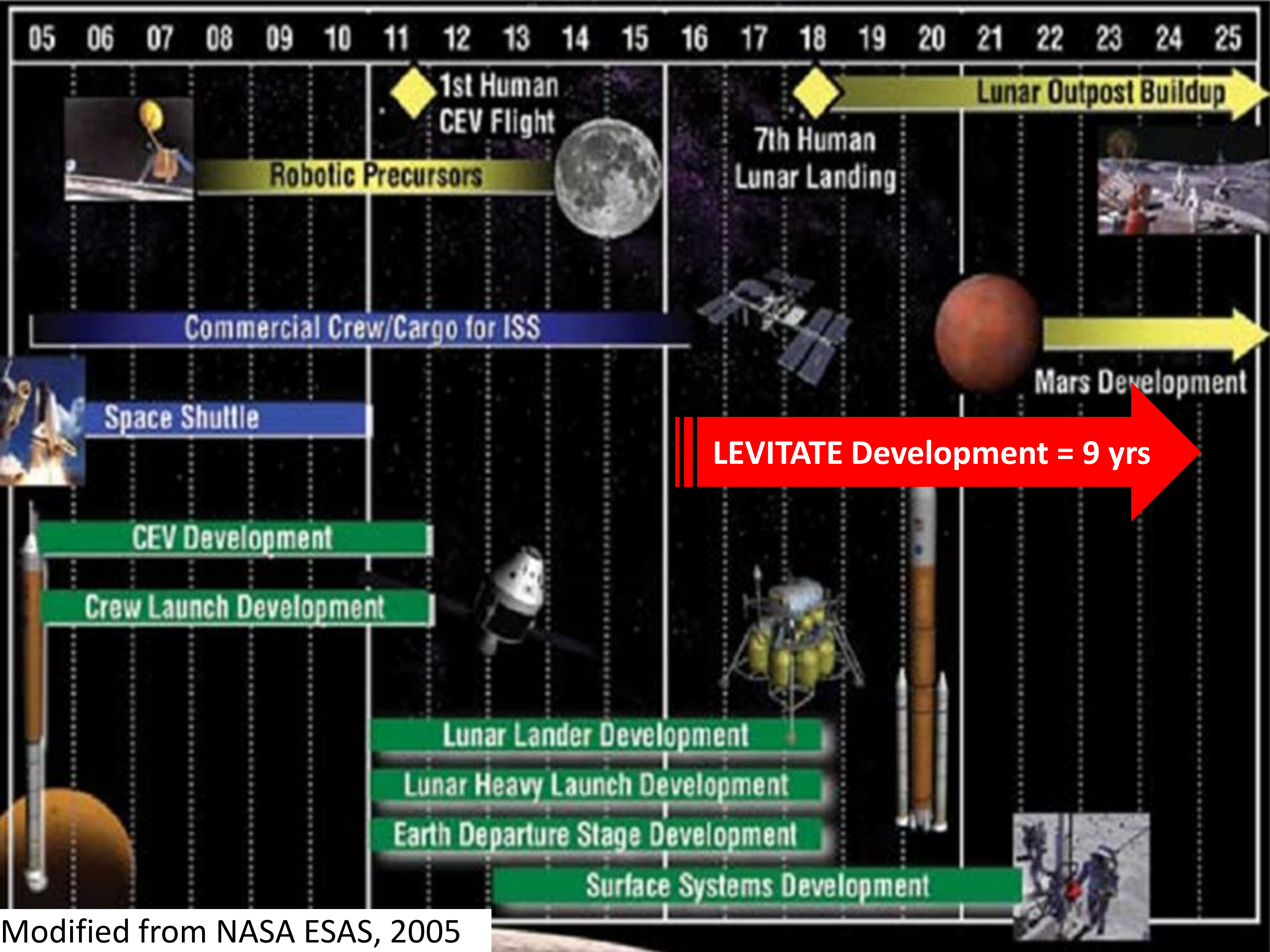
Design Goals	Proven With:
Access entire lunar surface	Orbital calculations, vehicle mass

NAFCOM Cost Estimate

- NASA-Air Force COst Model – 2007
- Vehicle specifics wherever possible
- Shuttle, ISS, Apollo analogues for unspecified

- DDT&E $3.1 billion
- Unit Cost $280 million

- No benefit from similar systems development



Modified from NASA ESAS, 2005

Community Education

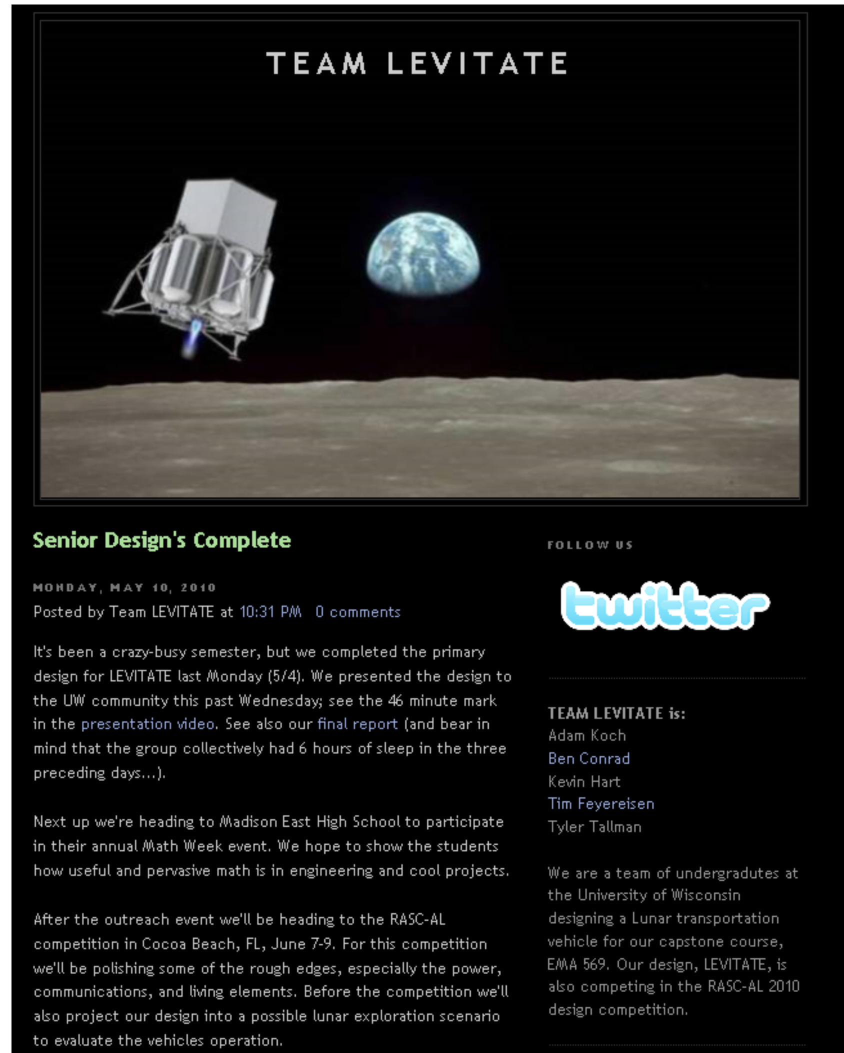
- Cross Plains Elementary
  - ~100 Elementary students and parents

- Madison East High School
  - ~100 Advanced Math Students

- University presentations

Public Outreach

- Website
  - uw-levitate.blogspot.com
- Twitter
  - @uw_levitate



Thanks to

- University of Wisconsin
  - Dr. Frederick Elder
  - Prof. Noah Hershkowitz
  - Prof. Michael Corradini
- Industry
  - Eric Benson, ERG Aerospace
  - Steve McQueen, ALCAN Rolled Products
  - Victor Giuliano, Pratt & Whitney Rocketdyne

Questions?

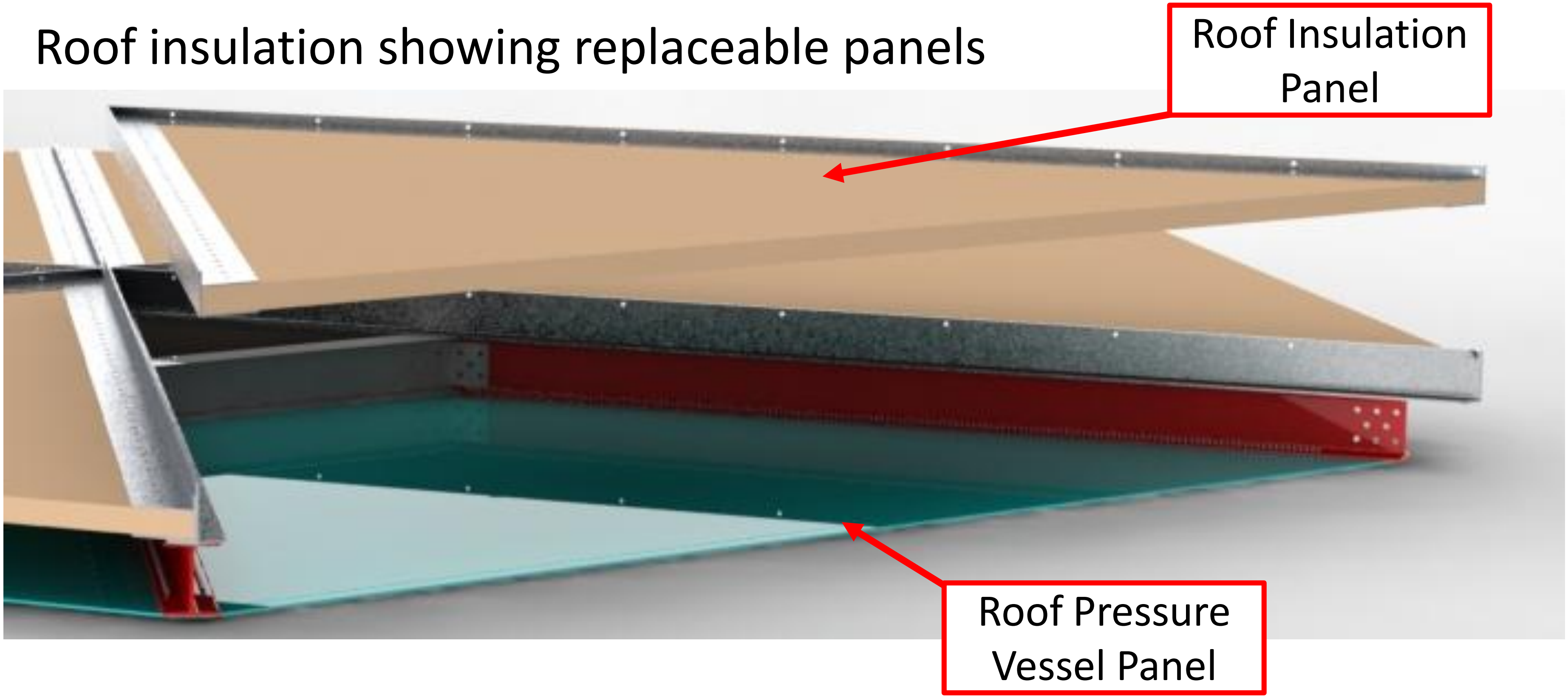
Backup Slides

Resupply via suitport cargo transfer modules

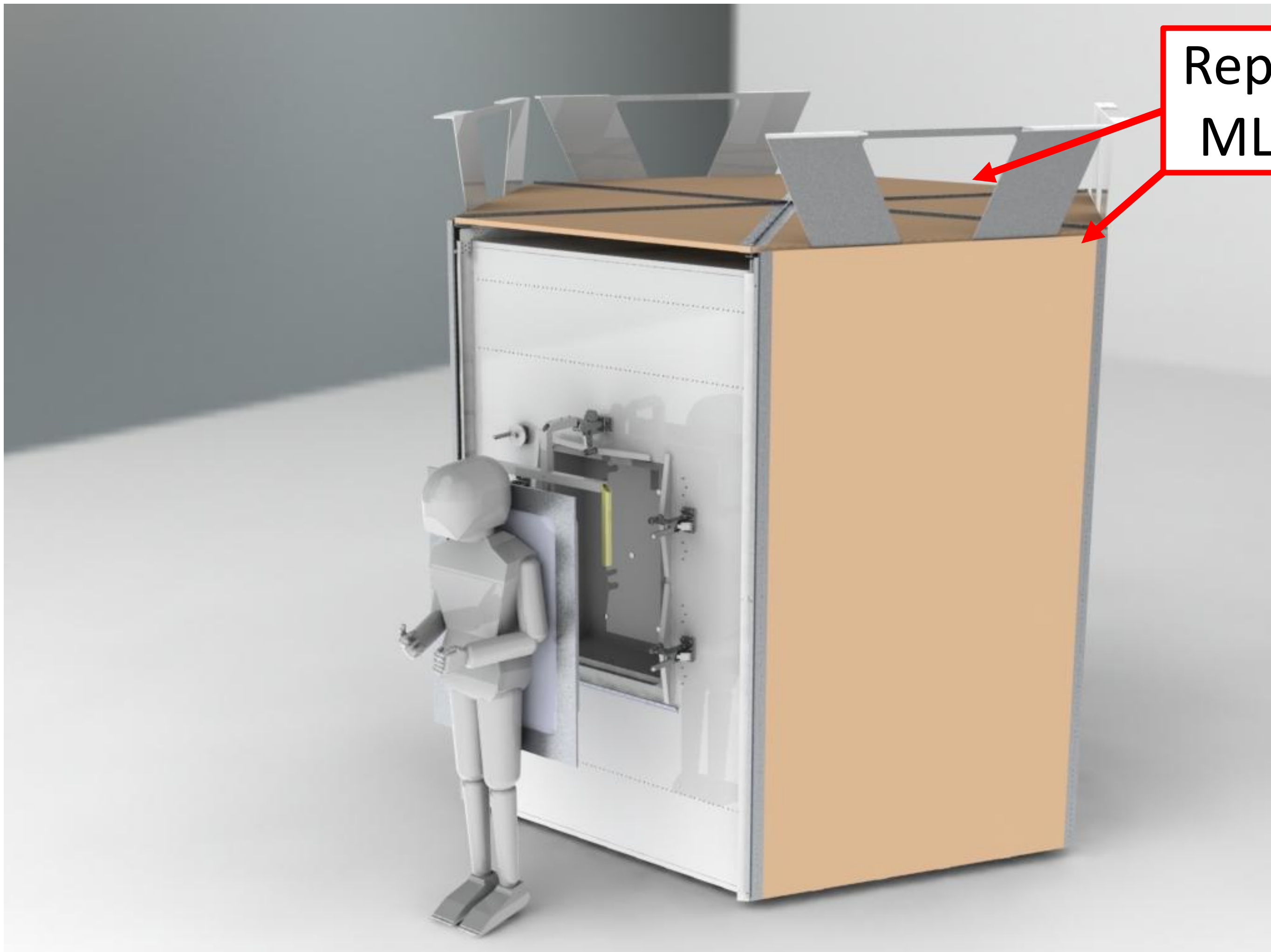
- Same interface as spacesuit
- Spacesuited astronaut seats, locks module
- Astronaut enters vehicle through other suitport
- Empties cargo

Field Replaceable Insulation

Roof insulation showing replaceable panels



Habitat With Multi-layer Insulation



Mass Tally

Subsystem	Component	Mass (kg)	
Structure	Leg Assemblies	1875	2741
	Top Deck	290	
	Engine Box	76	
	RCS Assemblies	230	
	Tank Caps	210	
	Misc Fasteners	60	
Propulsion Hardware	CECE Engine	150	1240
	Fuel Tanks	1090	
Fuel	LOX	16923	20000
	LH2	3077	
Life Support	Life Support System	270	270
Habitat	Wall Panels	236	620
	Roof Panels	130	
	Suitports	234	
	MLI	20	
	Total	**24871**	

TCRS Activated Charcoal Media Quantities

Media	Removes	Est. Yearly Load (kg)	With Factor Of Safety, 1.5 (kg)	Media Capacity (kg VOC / kg media)	Required Media Mass (kg)	Media Bulk Density (kg/m^3))	Required Media Volume (m^3)
Puracarb AM	Ammonia	0.23448	0.35173	0.058	6.064	720	**0.0084**
Purafil SP Blend	VOCs	0.10971	0.16456	0.1	1.646	640	**0.0026**

TCRS Residence Times in Activated Charcoal

Activated Charcoal Bed Cross Section Sizing and Residence time (5.0 CFM Flow Rate)							
Media	**Bed Radius (ft)**	**Cross Section (ft^2)**	**Required Volume of Media (ft^3)**	**Required Length (ft)**	**Air Velocity (ft/min)**	**Residence Time (min)**	**Residence Time (s)**
Puracarb AM	0.250	0.196	0.297	1.513	25.47	0.06	**3.56**
Purafil SP	0.250	0.196	0.091	0.462	25.47	0.02	**1.09**

Nitrogen and Oxygen Control (NOC) Cabin Partial Pressures

Component	Required Partial Pressures (%)	Partial Pressure (psia)	Initial Atmospheric Requirements (L)	Metabolic Regeneration Required (L)	Total Gaseous Volume Required (L)	Total Required (mol)	Total mass Required (kg)	Liquid Density (kg/L)	Liquid Volume Required (L)
Oxygen (O_2)	0.203	3.0	11165	16380	27545	1229.7	39.4	1.141	**34.5**
Nitrogen (N_2)	0.785	11.5	43175	0	43175	1927.5	54.0	0.807	**66.9**
			Gaseous					Liquid	

Life Support Power Requirements

System	Operational Power (W)	Stand-by Power (W)
CDRA	368	162
TCRS	461	154
THC	551	451
NOC [1]	50	50
WWCP [1]	654	380
TOTAL	**2084**	**1197**