



Cryogenic Insulation Solutions for the Surface of Mars with Its Unique Environments

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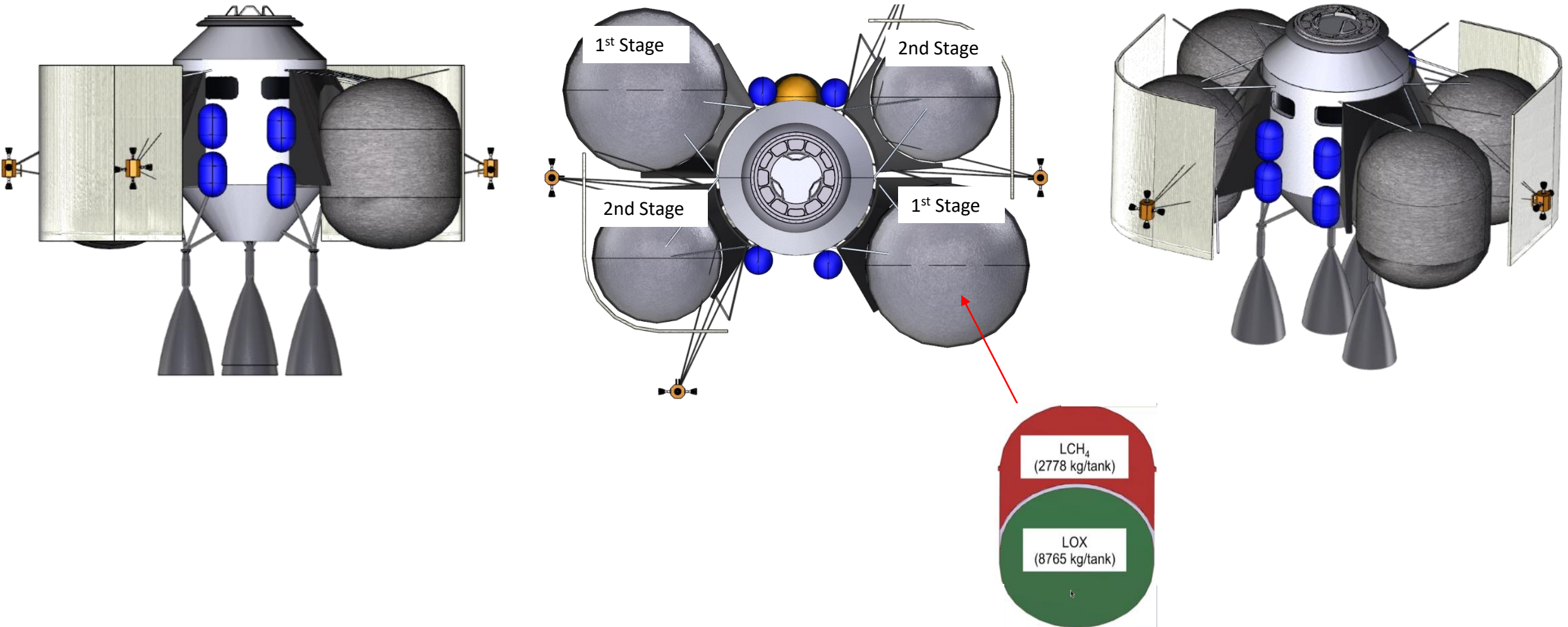
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Introduction

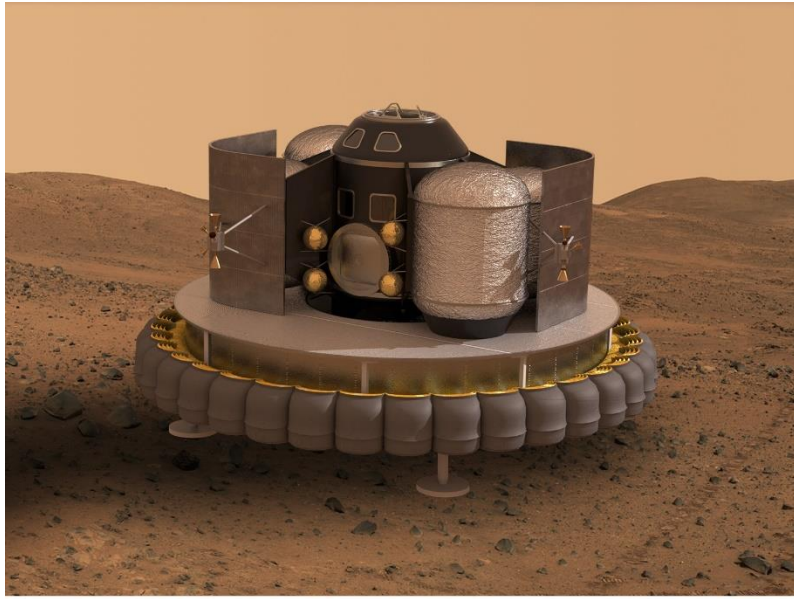


- NASA would prefer to use cryogenic propellants due to the increased propulsive efficiency and the possibility for producing them using the atmosphere and/or regolith. [1]
- Fluids being stored for the proposed Mars Ascent Vehicle:
 - Liquid Oxygen: $\sim 95\text{ K}$ ($-290\text{ }^{\circ}\text{F}$)
 - Liquid Methane: $\sim 120\text{ K}$ ($-250\text{ }^{\circ}\text{F}$)
- Gear factor for Mars is around 200 [2]
 - This means that for every kg you land on Mars, you would need to launch 200 kg.
 - Minimization of all mass becomes a high priority.
- Most space applications use the free vacuum of space to help performance.
- Mars has several unique environmental challenges
 - Atmosphere, dust storms, no people to fix things that break
 - Operational time on Martian surface ~ 3 years
- System may need to operate for up to five years

Mars Ascent Vehicle Typical Design

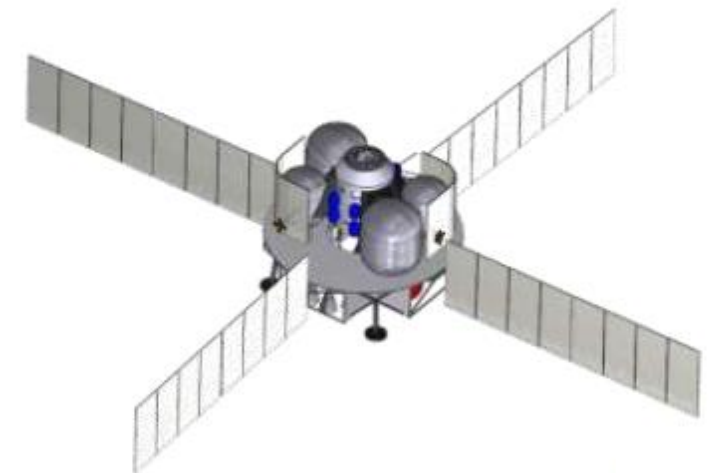


Environmental Challenges

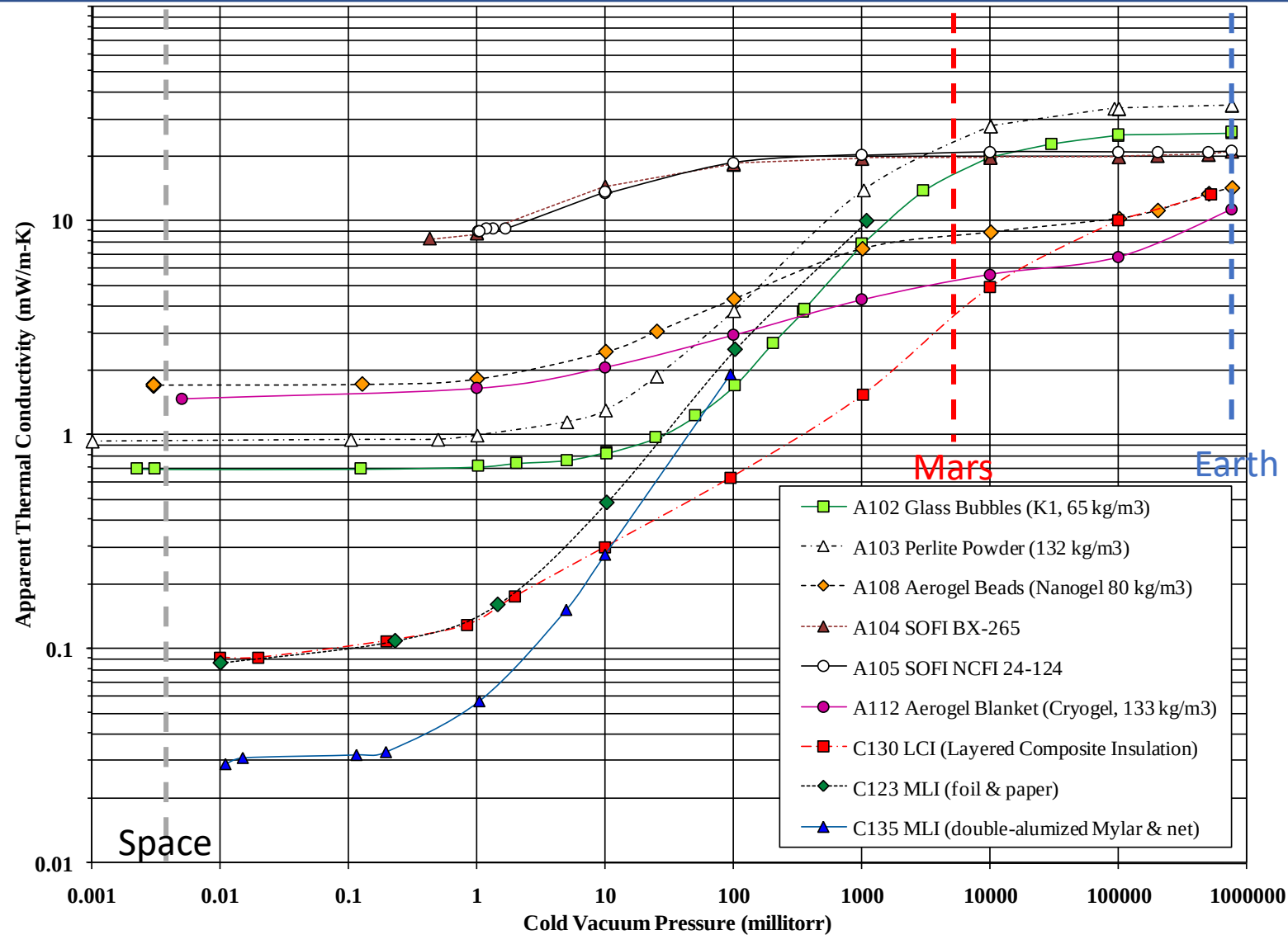


- Mars
 - Atmosphere: Soft Vacuum
 - Surface pressure between 5 – 8 Torr (0.1 to 0.15 psia)
 - 95% Carbon Dioxide
 - Prevent solid formation if no hermetically sealed outer layer
 - Dust Storms
 - UV exposure
 - Cold Surface Temperatures (150 to 225 K or -190 to – 55°F)

- Earth
 - Nitrogen purged vacuum annulus on the launch pad
 - Handling by personnel (wrench drop scenario)
 - Relatively high surface temperatures (~310 K or 100°F) and humidity experienced at Cape Canaveral
- In transit
 - Hard vacuum is free
 - Cooler surface temperatures (based on surrounding radiative environment)



Insulation Performance as a Function of Vacuum



Fluid and Mechanical Challenges

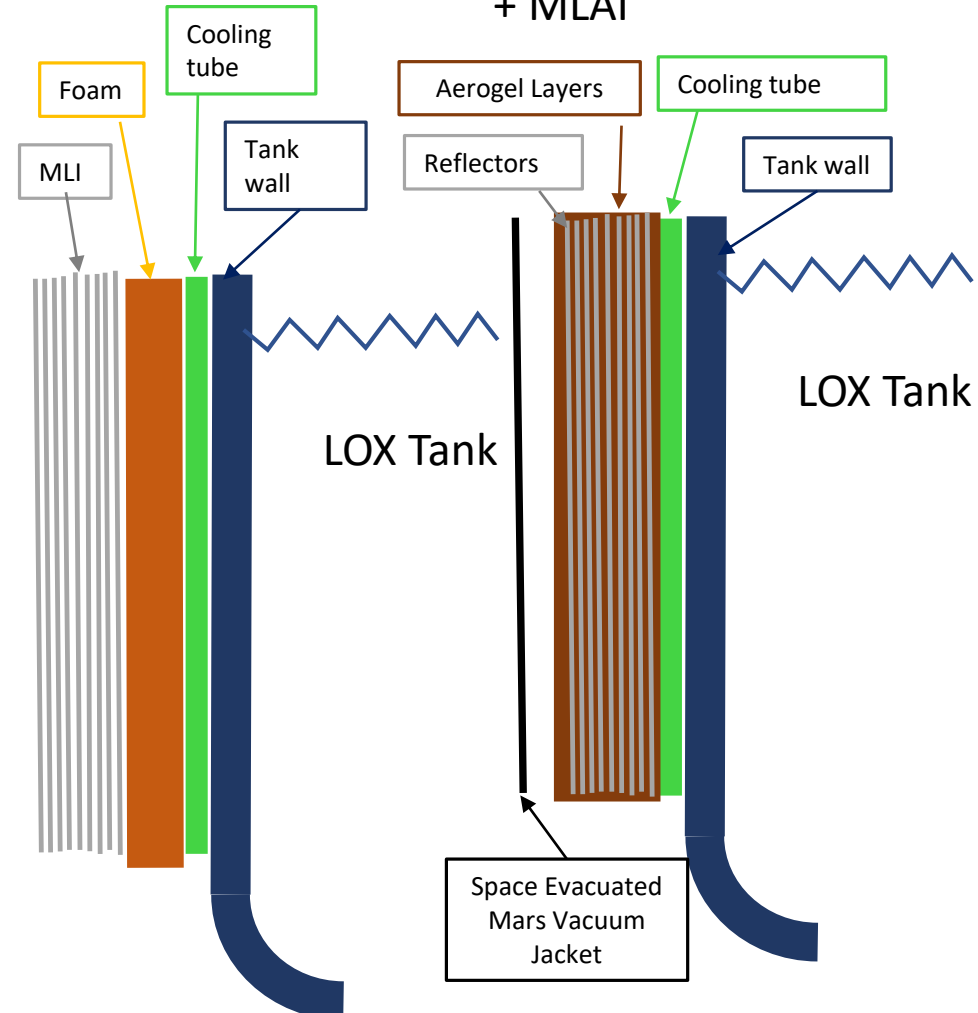
- Insulate around structural members
 - Allow for shrinkage of members and skin
- Fluid lines into and out of cryogenic tank
- Cryocooler (large refrigerator) integration onto tank surface
- Evacuation of vacuum space on orbit
- Isolation of vacuum space prior to landing
- What happens in case of failures?



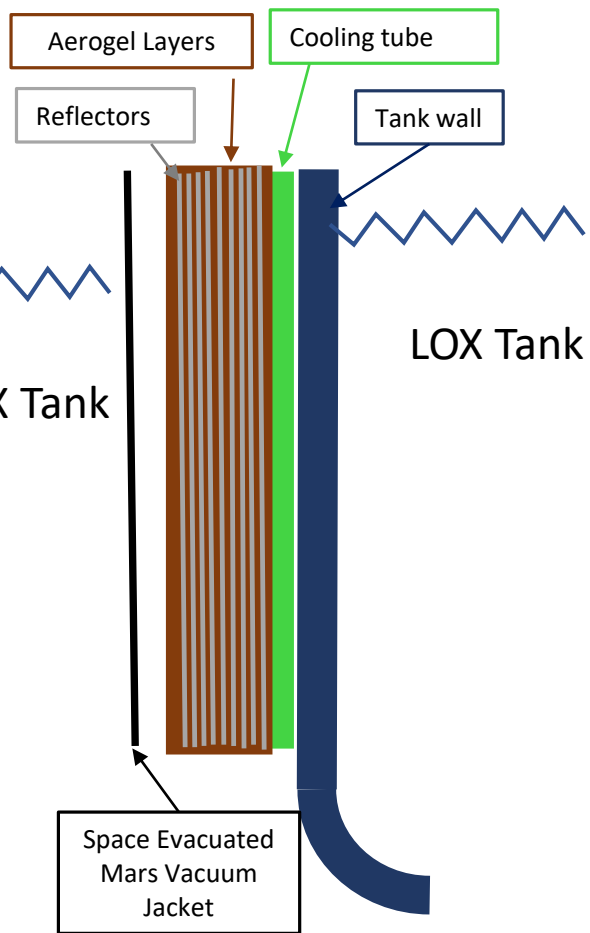
Insulation Options (ref 3)



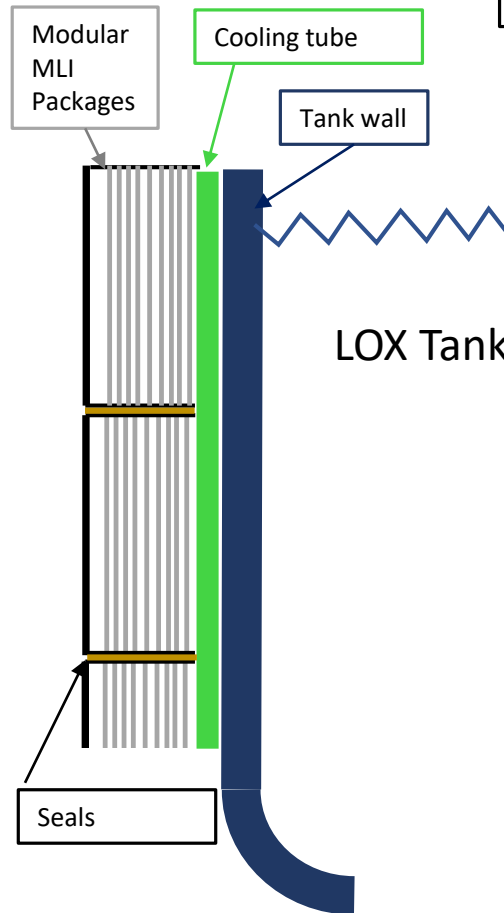
SOFI/MLI



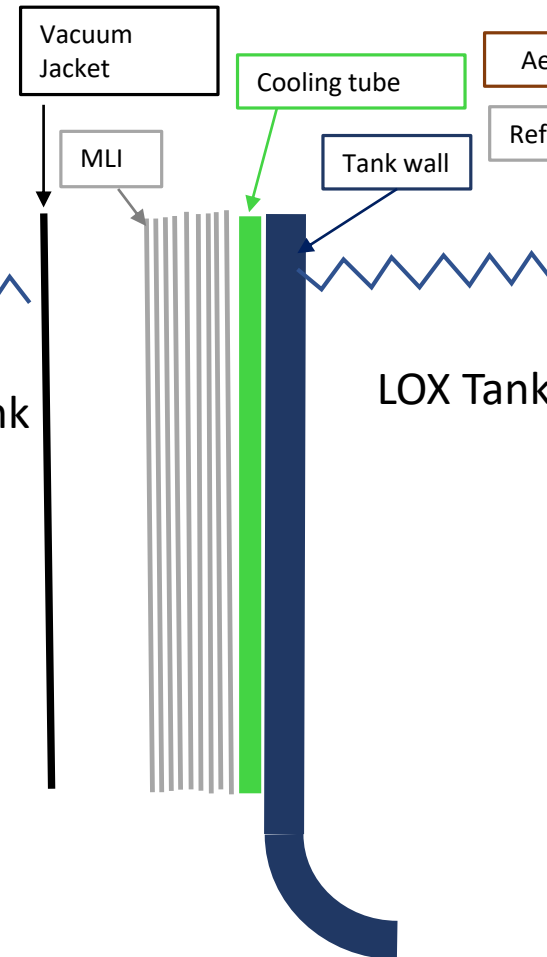
Vacuum Jacket + MLAI



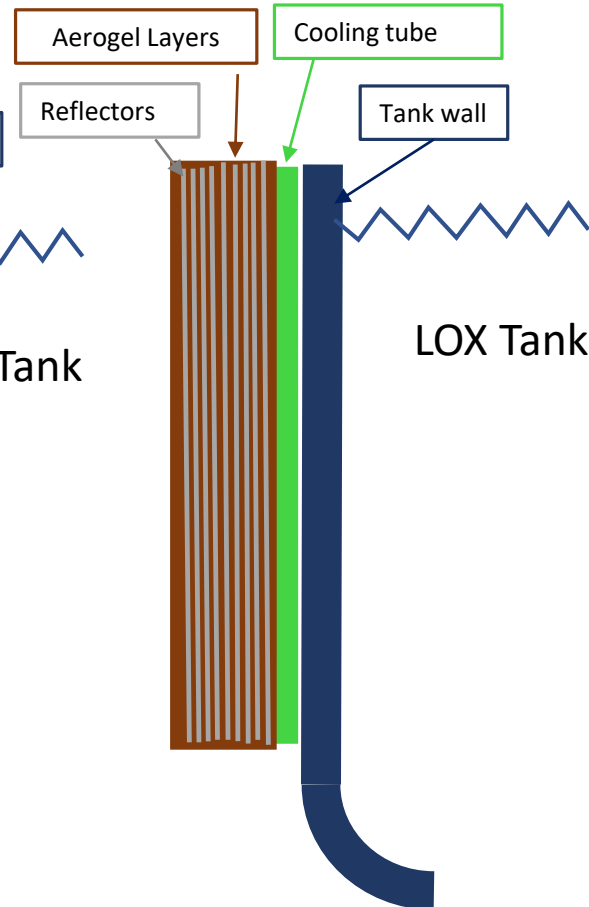
Quest LR-MLI/MEMLI



Vacuum Jacket



Multilayer Aerogel Insulation (MLAI)



Insulation Trade Results



Relative Scoring Results	Insulation System Mass	Active System Power	Insulation System Cost	Insulation System Manufacturability	Insulation System Operational Flexibility	Insulation System Reliability	% of total points scored
Quest LRMLI	0.0976319	0.0573333	0.0002327	0.0005248	0.0582015	0.0025097	22
Improved 2016 MLI/VJ	0.0131803	0.0811321	0.0002433	0.0054227	0.0753195	0.0221692	20
MLAI	0.0392968	0.0035157	0.0026652	0.0264139	0.0188299	0.1087544	20
VJ + MLAI	0.0012204	0.0573333	0.0002327	0.0054227	0.0582015	0.0644161	19
SOFI/MLI	0.0515008	0.0035157	0.0037017	0.0306121	0.0017118	0.1087544	20

From the results above, there was no clear “winner” or even separation between the options.

However, there was one clear issue:

- Systems with good mass/power have a low reliability.
- Systems with high reliability have high mass/power.

The conclusion of the team was that in order to lower the mass of the insulations system significantly (~500 kg + multiple cryocoolers), there needs to be some development and investment in the Lightweight Vacuum Jacketed options to drive up the reliability and team understanding of these options.



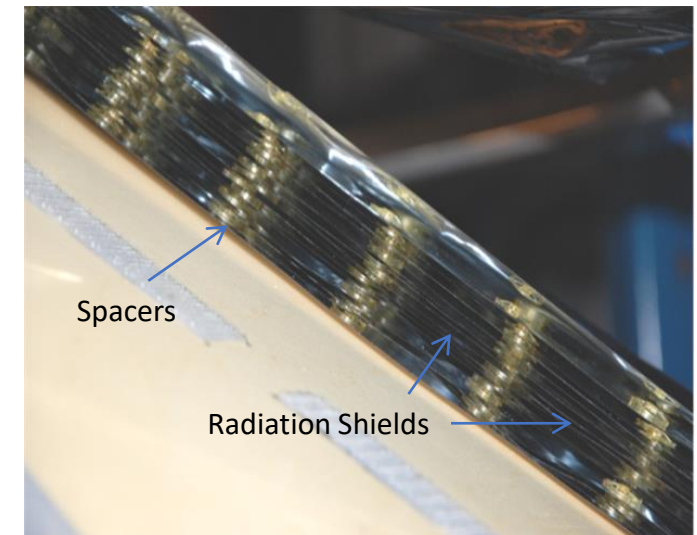
Insulation Development Approach

- Further testing by Fesmire demonstrated that Aerogels would physi-sorb large quantities of CO₂ in the temperature range we were interested in. [5]
 - This increased the mass and also increased the thermal conductivity.
 - Could still be made to work with external barrier, as long as it doesn't fail.
- Determined to use a multi-pronged development approach, competitive procurements gave awards to:
 - Quest Thermal Group (Arvada, CO) developing their Multi-Environment Multilayer Insulation (MEMLI), a derivative of LR-MLI, to assess the lowest mass possible solutions.
 - Lockheed Martin (Palo Alto, CA) developing a solution based on previous space-flight dewar systems developed for superfluid helium.

Quest Thermal Group MEMLI

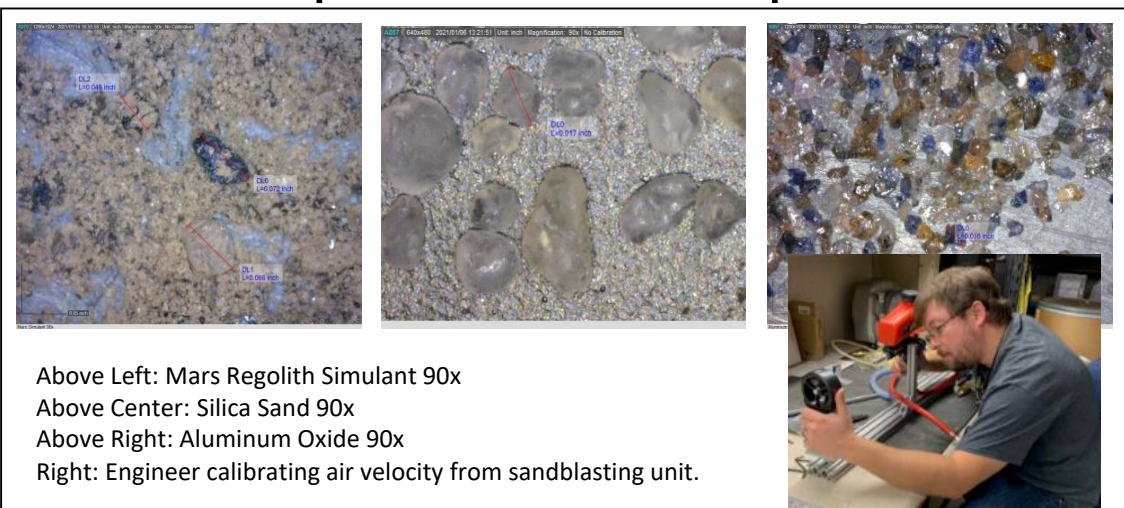
- Use Quest Thermal Group's micro-molded insulation spacers to provide structural support to the vacuum jacket.
- Need to improve structural models of insulation system to validate structural elements.
- Demonstrate conceptual performance on ~ 400 liter tank (30" diameter)

Layers	Q (W/m ²) 77 - 295K	Q (W/m ²) 105 - 210K	Blanket Thickness (in)	Blanket Areal Mass (kg/m ²)	Aluminum VS thickness (in)	Alum shell Areal Mass (kg/m ²)	Total Areal Mass (kg/m ²)
2	5.00	1.40	0.144	0.233	0.015	1.034	1.27
5	2.06	0.574	0.36	0.395	0.015	1.034	1.43
10	0.997	0.28	0.72	0.801	0.015	1.034	1.83
15	0.657	0.185	1.08	1.206	0.015	1.034	2.24
20	0.49	0.138	1.44	1.612	0.015	1.034	2.65



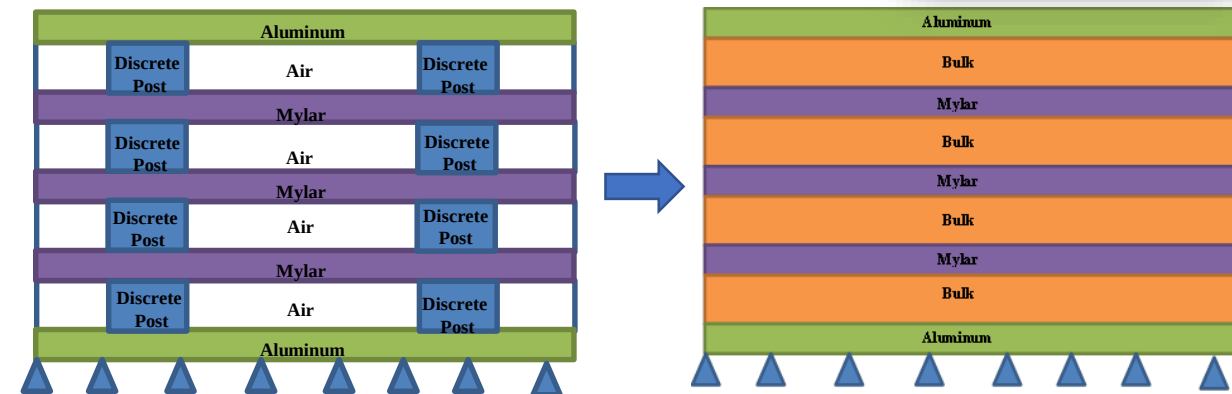
Quest - Abrasion Testing & Structural Testing

- Quest performed “sandblasting” using Martian simulant
 - Adjusted air speed of sandblaster
 - Multiple different media
 - Determined erosion rate of thin wall aluminum
- NASA performed structural testing to better predict and model system level performance in compression.
 - 3-point bend, compression, shear testing



Above Left: Mars Regolith Simulant 90x
 Above Center: Silica Sand 90x
 Above Right: Aluminum Oxide 90x
 Right: Engineer calibrating air velocity from sandblasting unit.

Ref 6



Quest - Results

- Didn't have time for full bake out prior to test.
- Heat load not as low as predicted, but better than required.
- Didn't fully eliminate leaks in welds, used attached vacuum pump to shell in Tests 2/3.

Test number	1	2/3	4
Environment	High-vacuum	Surface, transition	Cooled boundary
Average flow rate [sccm]	1732	2030	1476
Average vacuum [mbar]	3.6 E-05	4.3 E-05	N/A
Total heat leak [W]	6.647	7.799	5.671
Total heat flux [W/m ²]	2.340	2.717	1.976
Calculated e*	5.48 E-03	6.40 E-03	4.60 E-03
Calculated heat flux [W/m ²]	0.583	0.677	0.493



Lockheed Martin MarVACS Concept



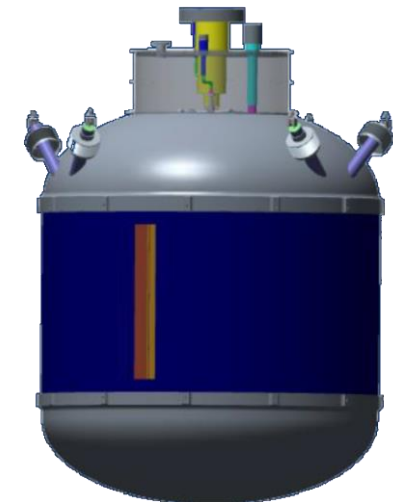
- Flight cryogenic storage systems have historically utilized hard metallic vacuum shells driven by external 1 atm pressure during ground servicing
- A MarVACS concept extends these designs with similar but lower weight approach taking advantage of lower external pressure
 - Concept design for a large approach being demonstrated on smaller ZBO ground test unit



WIRE
(Solid Hydrogen)



Gravity Probe B
(Liquid Superfluid Helium)

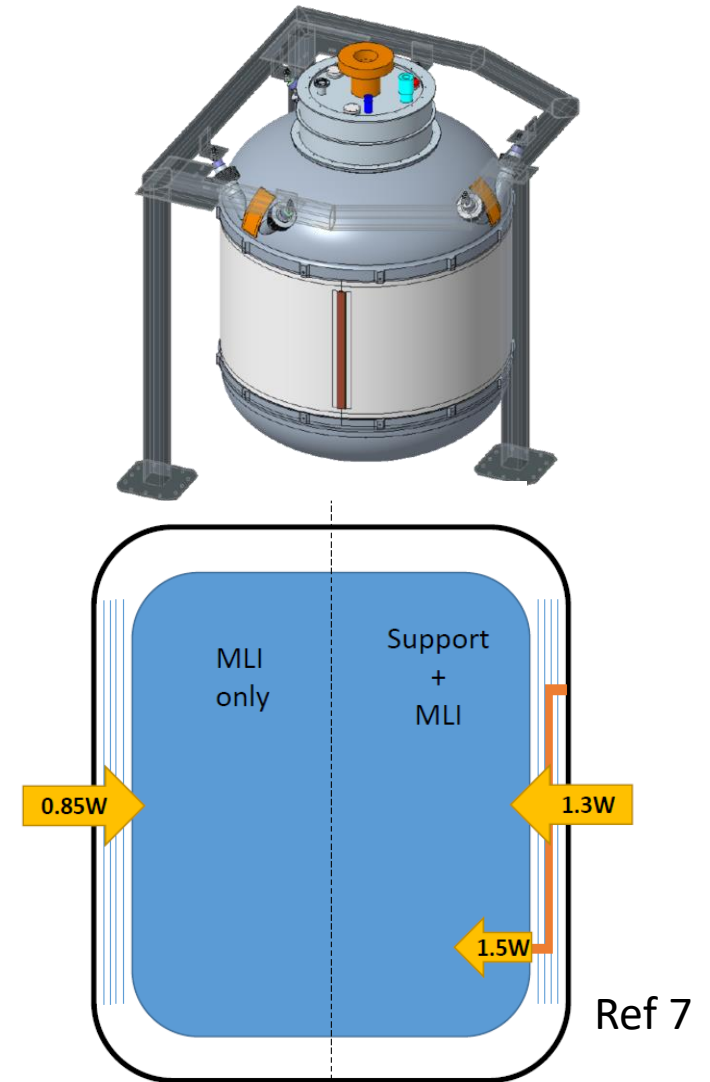


Lockheed ZBO MarVACS concept (ref 7)
(liquid Oxygen and Methane)

Lockheed Martin ZBO Approach



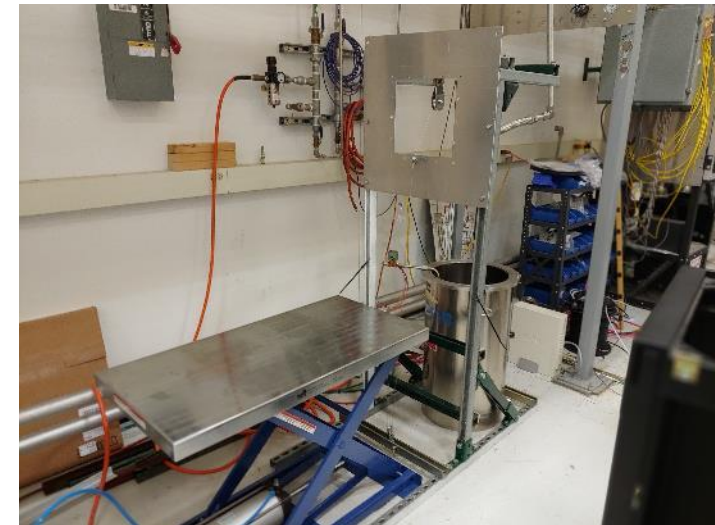
- Segmented approach installed around tank that is supported by struts to vehicle (ZBO tank to stand)
 - Requires special strut penetration accommodations
- Final closeouts use epoxy as opposed to welding.
- Composite structural skirt support around periphery of tank to support vacuum jacket.
- Total insulation and skirt heat load on tank about 3 W.
- Further work needed for better understanding of complete design.



Risks and NASA Internal Risk Reduction

Several concerns/risks identified internally:

- Sustained impact due to wind/dust storms.
 - Any standards for dust impact/erosion for beach/desert locations on Earth?
- Impact due to orbital debris falling from the sky.
 - Analysis of statistical data available suggested that this was not worth concern now.
- Failure of welds/epoxy seams due to repeated thermal cycling (i.e. day/night)
 - Vacuum pump development of interest to mitigate failure scenarios.



Conclusions



- Demonstrations have suggested that proposed concept of operations is workable.
 - Identified fall back capability requirements such as evacuation capabilities that may be required.
- Multiple possible options are in work based on the perceived trade between mass and reliability.
 - Both Quest and Lockheed Martin appear to have developed workable solutions.
- Further work required to delineate between the system level performances of each system and separate the theoretical from the actual.



Future Work

- Perform testing on actual cryogenic tank with structural attachments, tubing on tank, and other more difficult integration components.
 - Determine mass and thermal performance.
 - Prefer to perform relatively similar tank tests with both concepts for comparison.
- Scale up concepts to full size tank to measure performance.
- Demonstrate full operations sequences, including long duration hold in soft vacuum environment.
- Look for opportunities to use concepts as dust shield for lunar systems.

References



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4. J E Fesmire *et al*, Spray-on foam insulations for launch vehicle cryogenic tanks, *Cryogenics*, vol 52, pp 251-261, 2012.
5. J E Fesmire *et al* 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **278** 012198
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7. D J Frank, I Nason, and V Mistry, "MarVACS Final Report", Contract 80GRC019C0038, June 30, 2020.

Questions

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