Structural Tensegrity for Optimized Retention in Microgravity (STORM)

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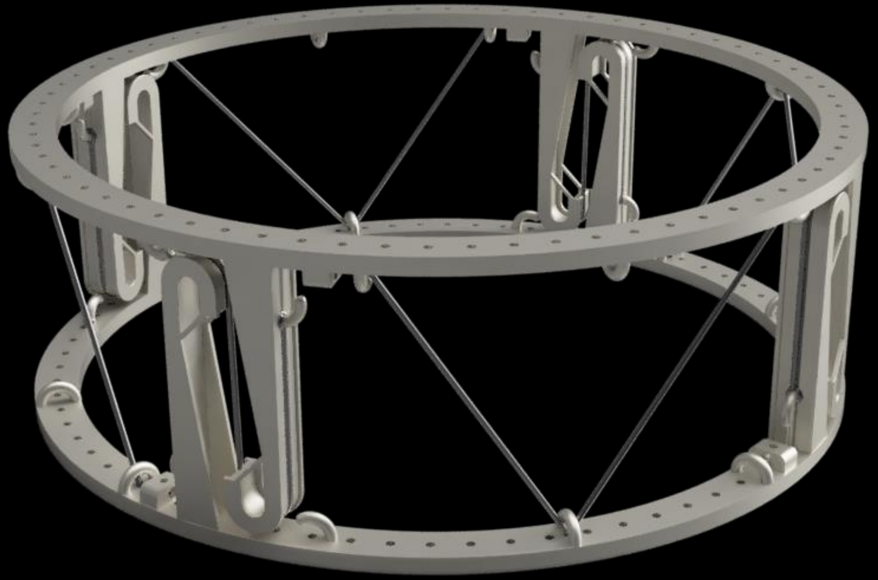


OLD DOMINION UNIVERSITY

2025 HuLC HUMAN LANDER CHALLENGE

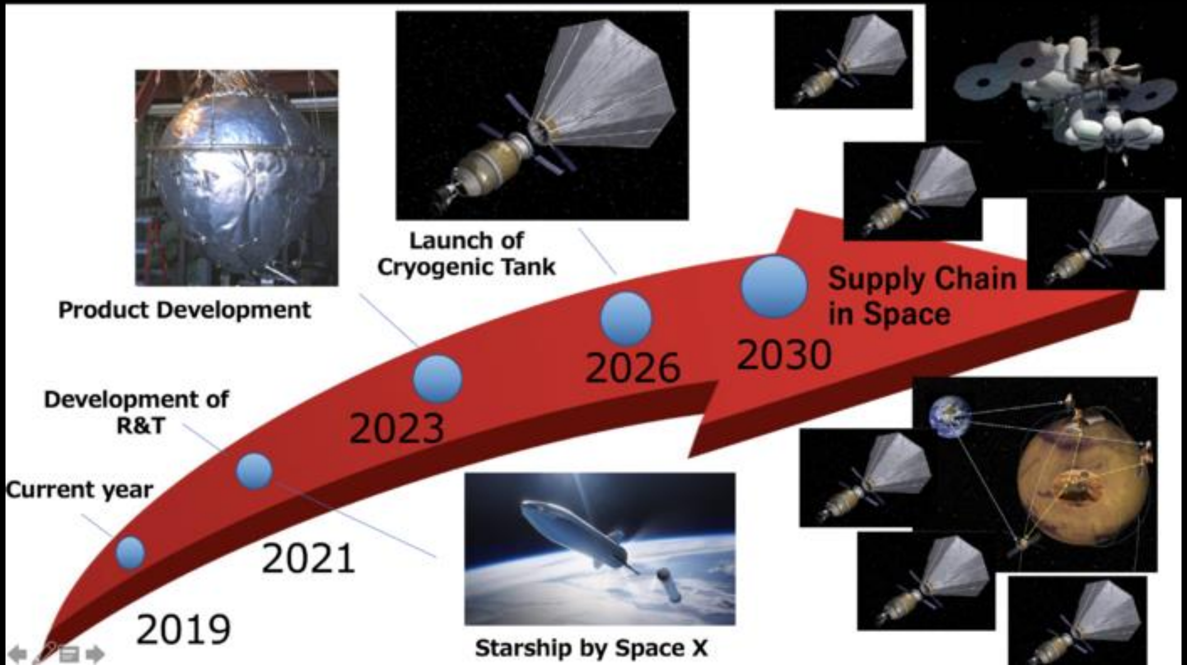
WHY CRYOGENIC SUPPORTS MATTER

Why Cryogenic Storage?

- Cryogenic propellants (LH_2 & LOX) are vital for long-duration missions to the Moon and Mars.

- Traditional metal strut supports create thermal bridges that cause significant boil-off.

- Efficient thermal management is critical for mission sustainability.

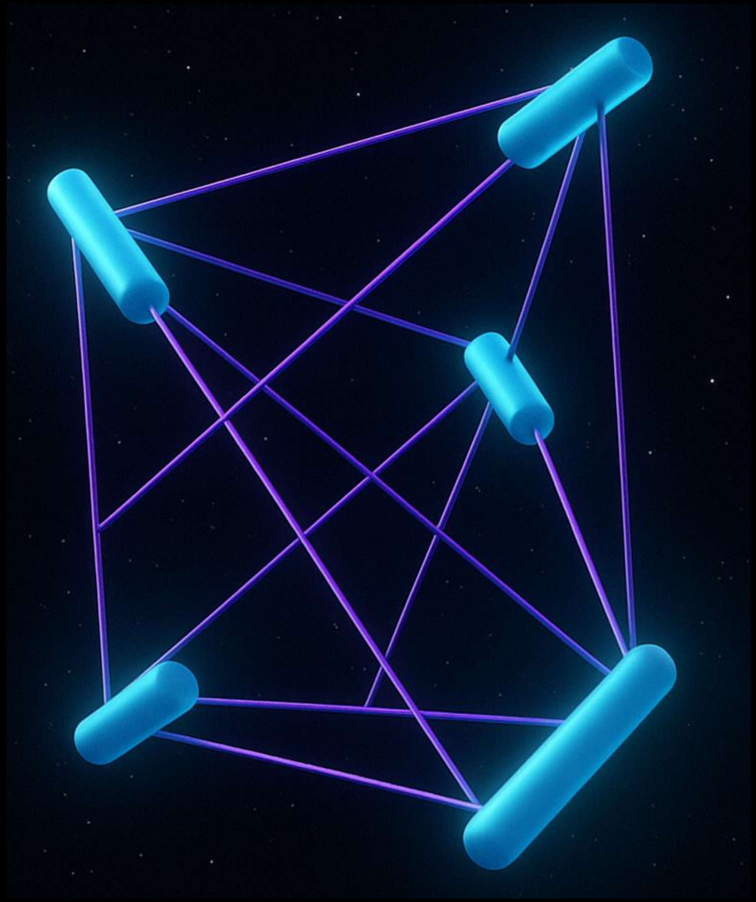


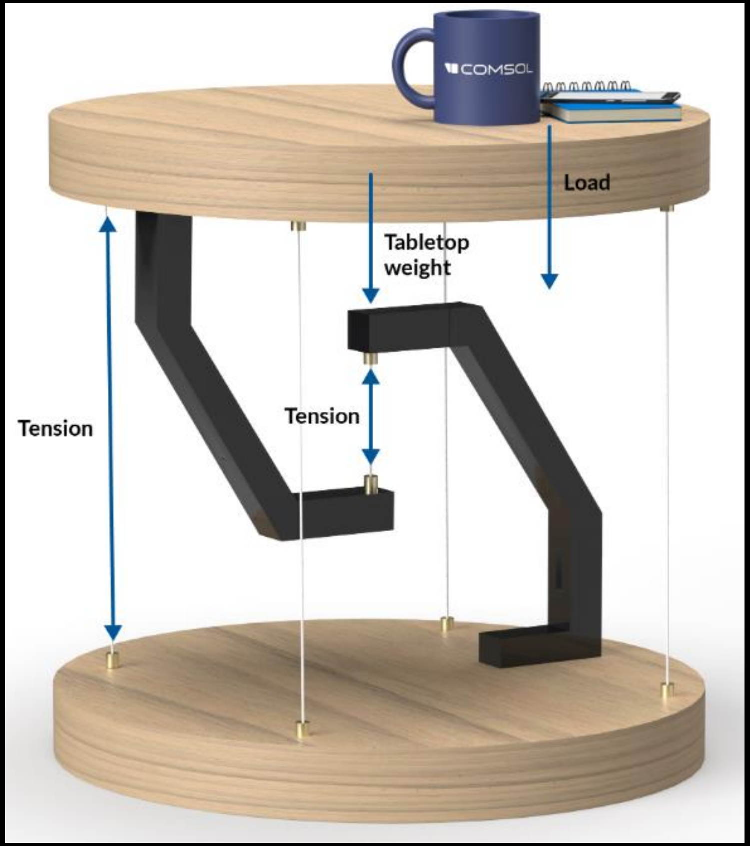
WHAT IS TENSEGRITY?

Definition: A structural principle where isolated compression elements (struts) are held in a network by continuous tension elements (cables).

Key Characteristics:

- **Lightweight & Efficient**
- **Distributed Loads:**
- **Flexibility & Resilience:**

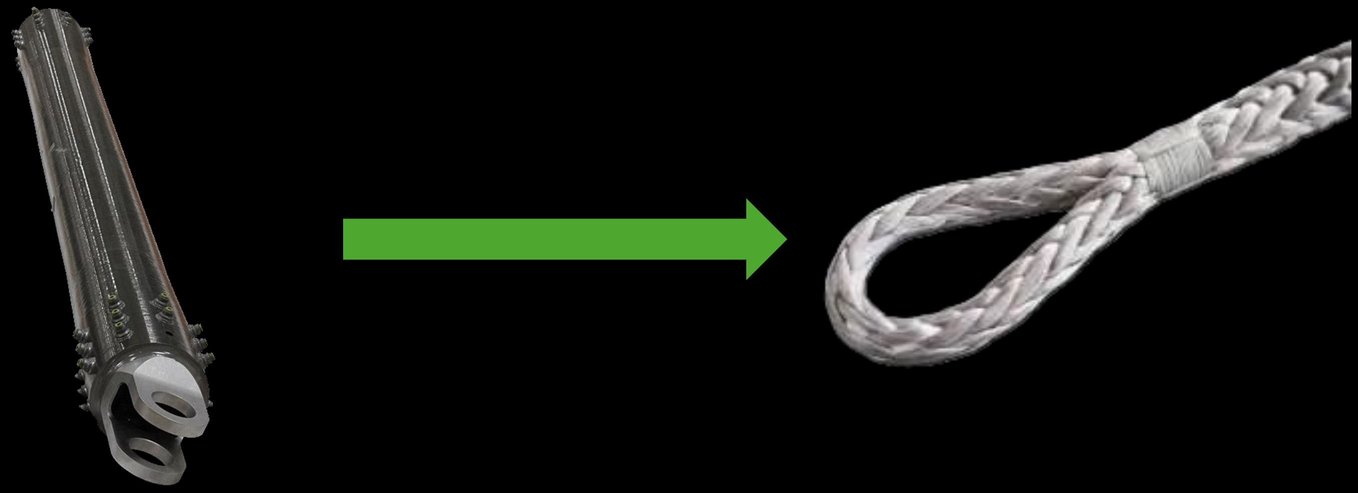




CHALLENGE STATEMENT & OBJECTIVES

Goal: Develop a tensegrity-based support system that reduces heat conduction by 90% (Previously >20%) compared to titanium struts.

- Replace heavy, thermally conductive supports with UHMWPE cables (Dyneema®) in a tensegrity configuration
- Enhance mass-to-volume efficiency and lower boil-off losses.
- Meet NASA’s criteria for efficient in-space cryogenic storage. (>90 days)



Why Current Titanium Struts Won't Close the Boil-off Gap

Traditional metal strut supports create thermal bridges that cause significant boil-off.

Traditional struts conduct around 28 W and weigh 69 Kg.

Exceeds allowable heat-leak by >5×.

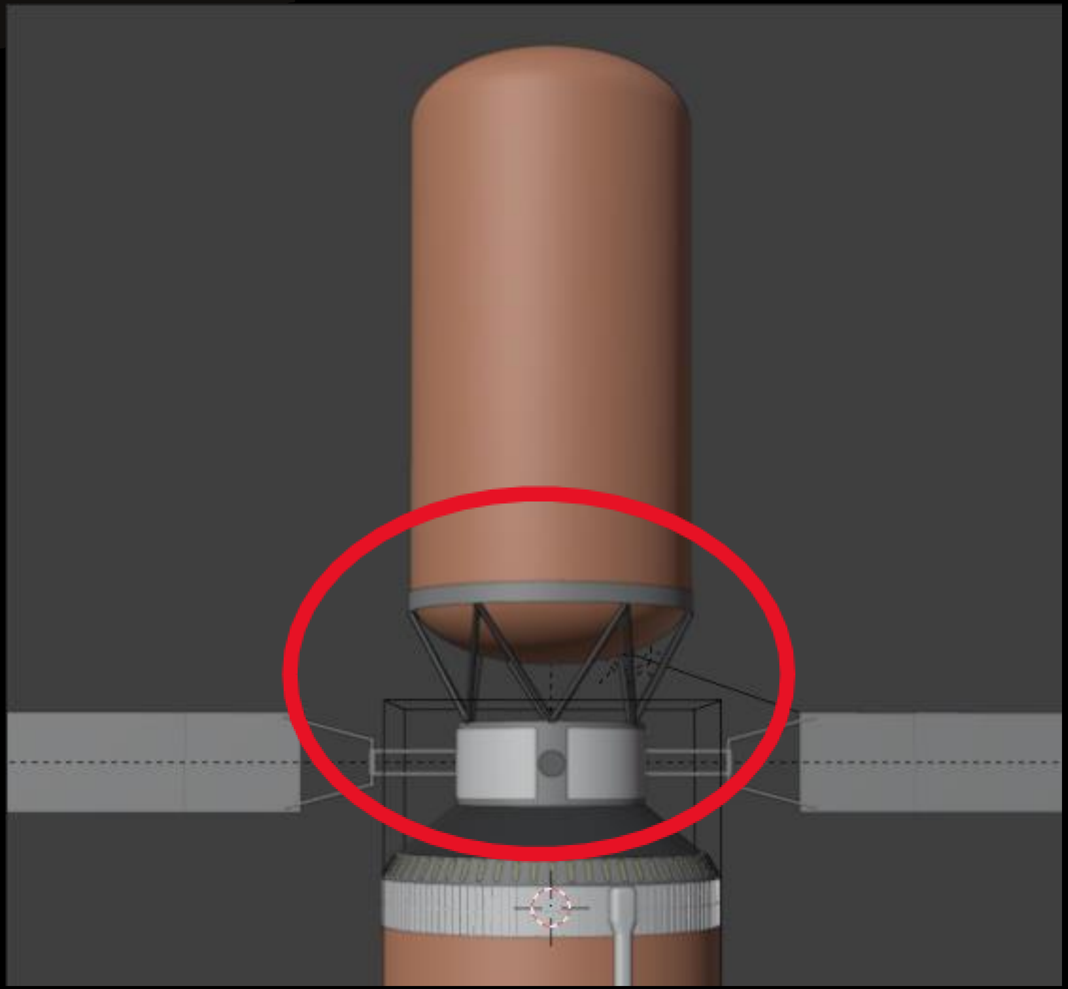


Figure of Merit Trade

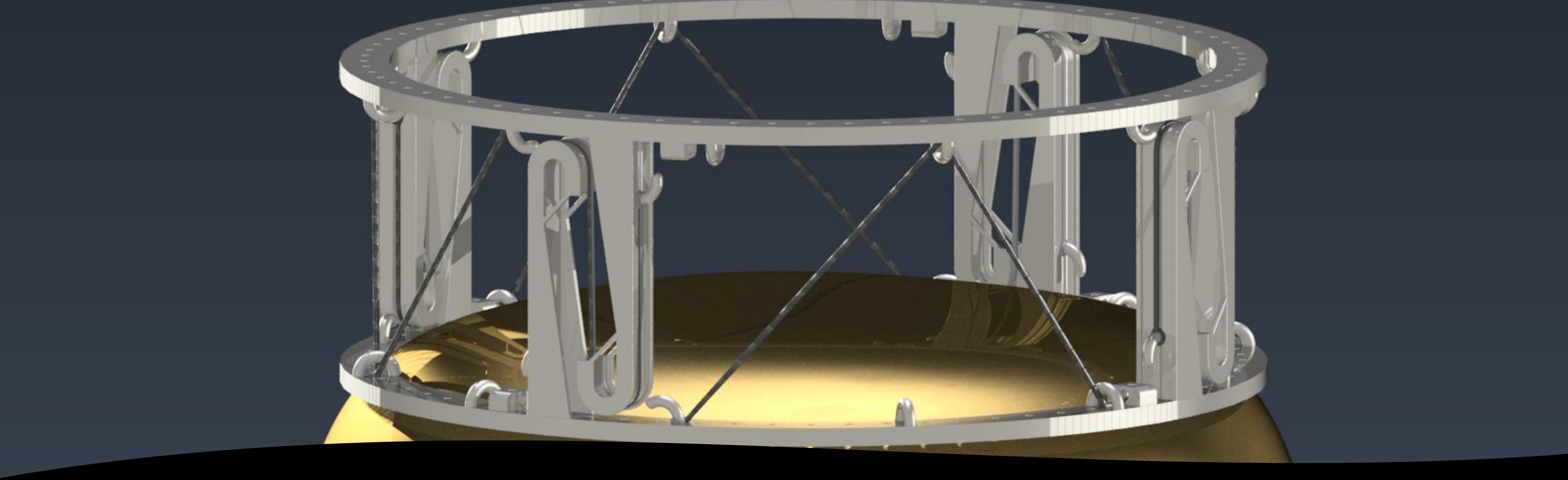
$$FoM = \frac{\sigma}{\rho * \kappa}$$

Material	$\sigma_{f\ @20K}$ (Mpa)	k (W m^{-1} K^{-1})	ρ (kg m^{-3})	σ /ρk
Dyneema SK-99	5300	0.46	970	11.9
Kevlar-49	3200	1.73	1440	1.28
Ti-6AL-4V	1200	6.7	4430	0.04

Dyneema® is an Ultra-High Molecular Weight Polyethylene fiber.

- 100× better strength-to-thermal-conductivity than Ti.
- 10x better than Kevlar

- **[UHMWPE]: ↓Temp = ↓conductivity+↑ Strength**

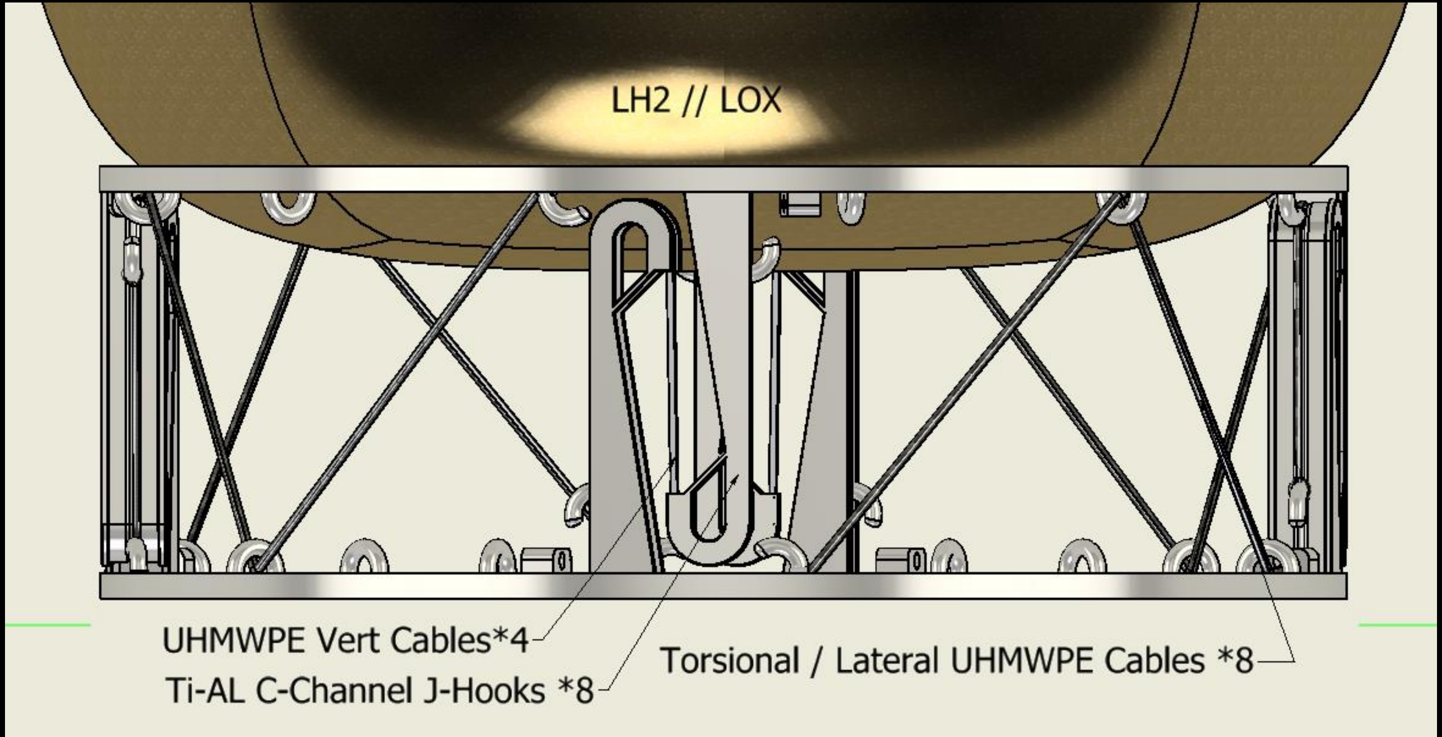


Design Concept

- **STORM** replaces those six conductive struts with a pure-tension tensegrity lattice. Our design provides lateral stiffness and prevent slack after main-engine cutoff. The upper- and lower-ring spacing is 0.37 m, producing a 16° diagonal that satisfies fairing and weld-access limits.

- Ring mass: 28 kg, 2219-T8 Al-Li (10 mm web).
- Cable properties: σ_{ult}, @ 20 K ≈ 5.3 GPa; k ≈ 0.46 W m^{-1} K^{-1} [10].
- Hook geometry: 15 mm × 60
- mm web; shear M.o.S. ≈ 3.3 under wet-launch load (Section 5).

Concept - 5m Tensegrity Ring



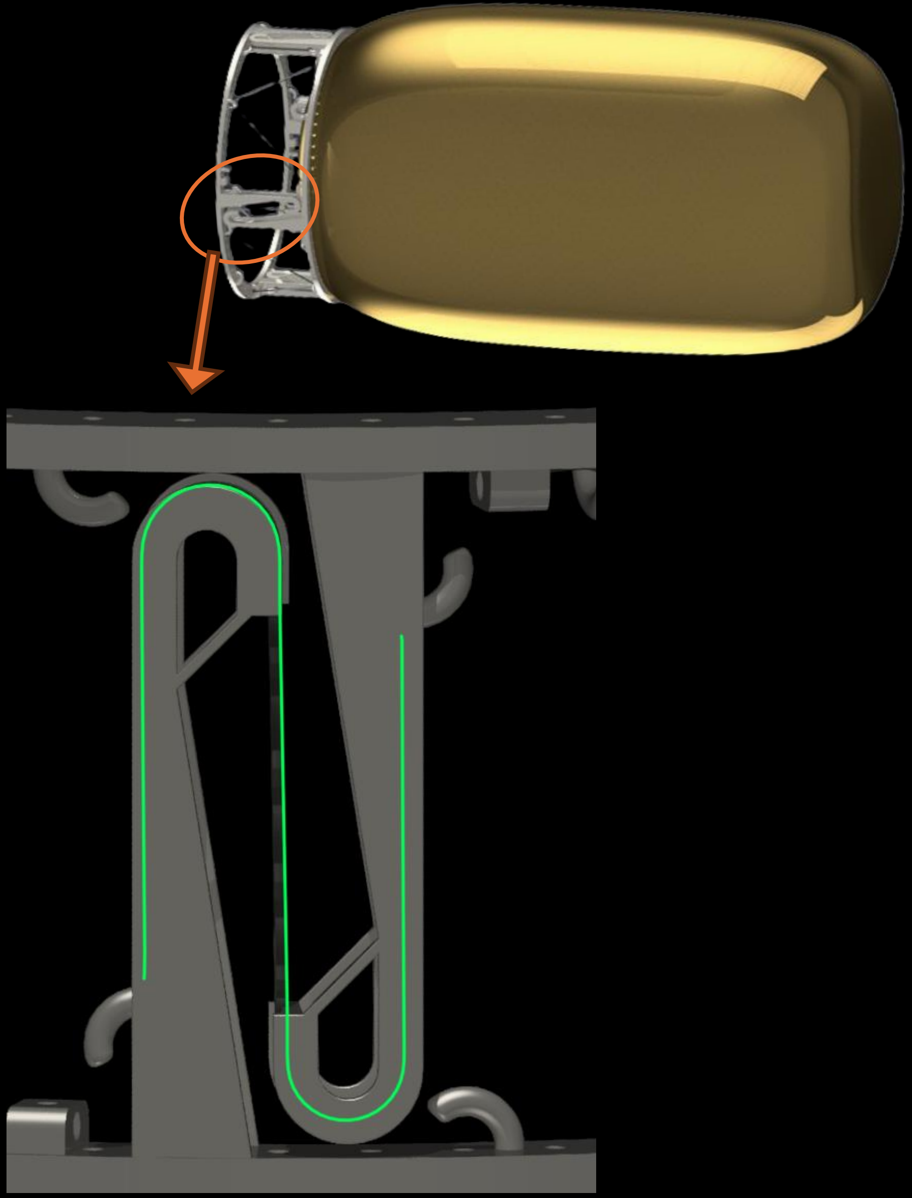
4 mm Dyneema® cables in tension provide lateral stiffness and prevent slack.

Four hollow titanium alloy J-hooks at 90° intervals redirect launch compressive loads.

The upper- and lower-ring spacing satisfies fairing and weld-access limits.

Load Path Converts Launch Compression → Pure Tension

- During ascent, the wet-launch axial load enters the upper ring, transfers through each J-hook into a 180° return leg, and closes at the opposite hook.
- All primary elements therefore operate in tension or short length bearing, eliminating bending concerns.
- Cables never see compression – avoids buckling.



Mass breakdown

Element	Qty	Unit mass (kg)	Sub-total (kg)
2219-T8 Al-Li rings (ϕ 5 m, 10 mm web)	2	14	28
Hollow Ti-6Al-4V J-hooks (15 × 60 × 2 mm C-section)	4	0.65	2.6
PEEK/Torlon sleeves (0.8 mm)	4	0.05	0.2
Dyneema SK-99 loop cables (4 mm Ø, 0.66 m)	4	0.5	2
Dyneema SK-99 diagonal cables (4 mm Ø, 0.74 m)	8	0.125	1
UHMWPE lugs & Ti bolts	—	—	0.6
Total STORM sub-assembly	—	—	31.4 kg
▶ Mass saving vs. six Ti-strut baseline (6 × 4.9 kg) ≈ –38 kg (55 % reduction).			

Thermal payoff: 2.4 W vs 28 W baseline

> 90 % reduction in parasitic heat flow.

Assumptions & Equations

*Conduction dominant transfer

*No direct radiation to cables due to sunshield

*Vacuum Convection ~0

T_H - Payload Conditions ~220K

T_L - Liquid Hydrogen Storage - 20K

Heat Transfer

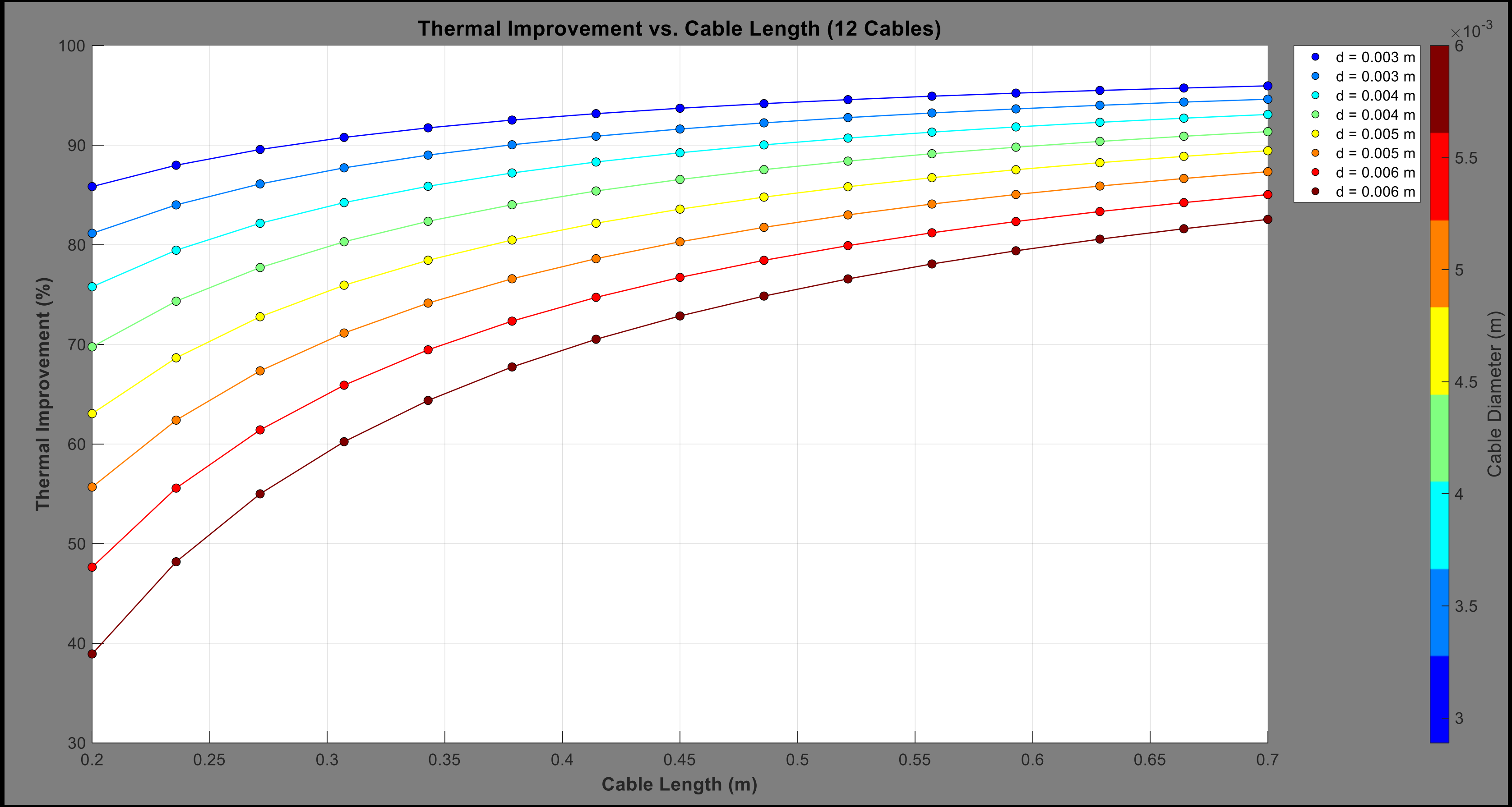
$$Q = \frac{k * A * \Delta T}{L}$$

k: Thermal Conductivity $[W/(m*K)]$

A: Cross Sectional Area $[m^2]$

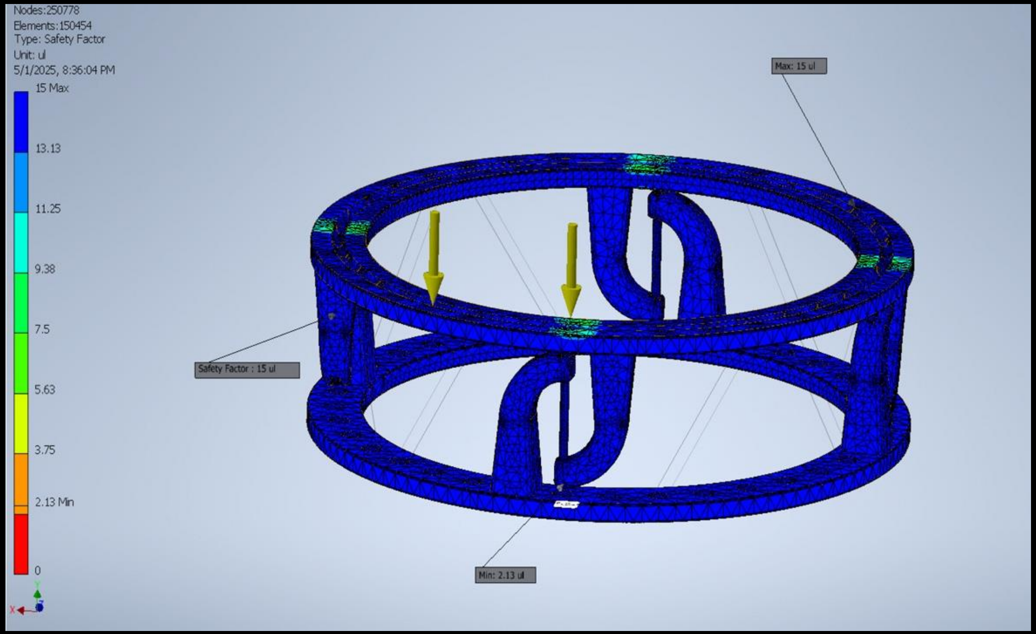
L: Cable Length [m]

ΔT : Temp Differential [K]

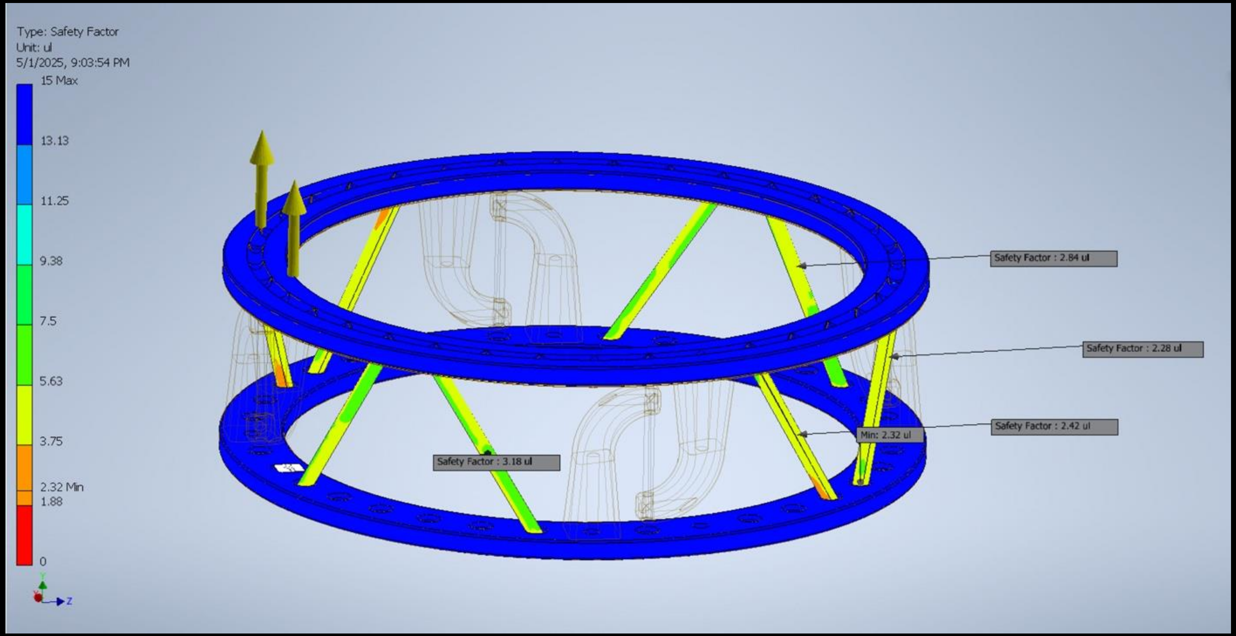


[1] The thermal conductivity of UHMWPE decreases sharply with temperature—dropping from ≈ 0.46 W m^{-1} K^{-1} at 300 K to ≈ 0.25 W m^{-1} K^{-1} at 20 K [10]. To remain conservative, all heat-leak calculations use the higher, room-temperature value (0.46 W m^{-1} K^{-1}); actual boil-off in flight will therefore be lower than the numbers reported.

Structural margins:



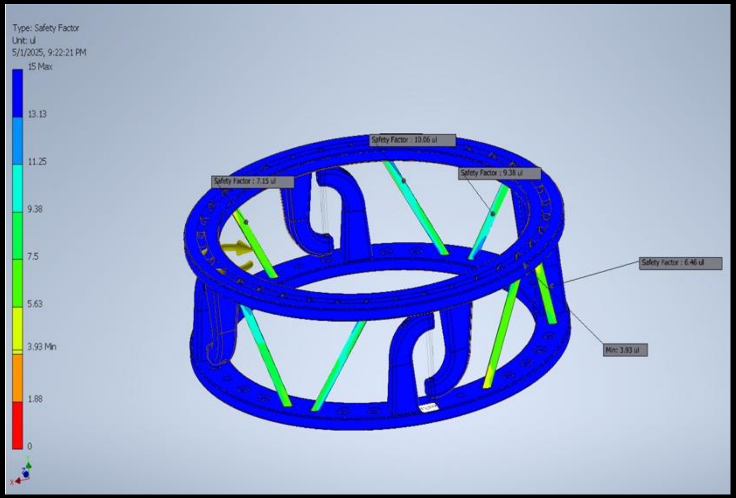
Compression MoS 3.2



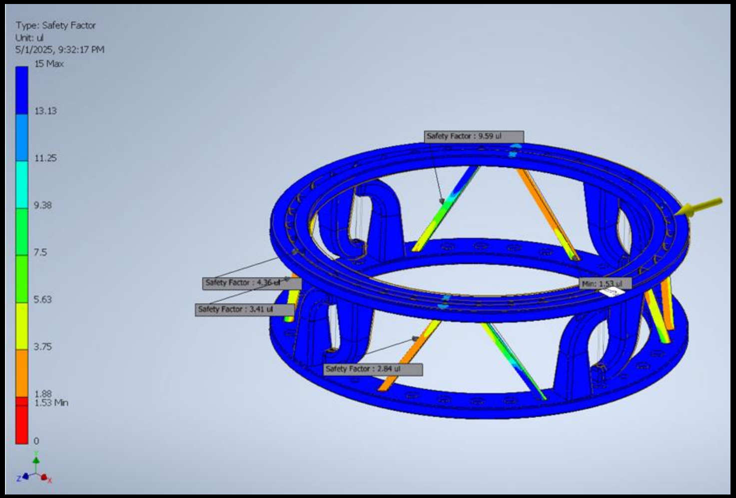
Tension MoS 3.4

2200 kg Tank * 5g Acceleration (Compression / Tension)
0.2g * 2200 kg tank (Maneuvering)-Tension / Shear
Nasa SF – 2.0

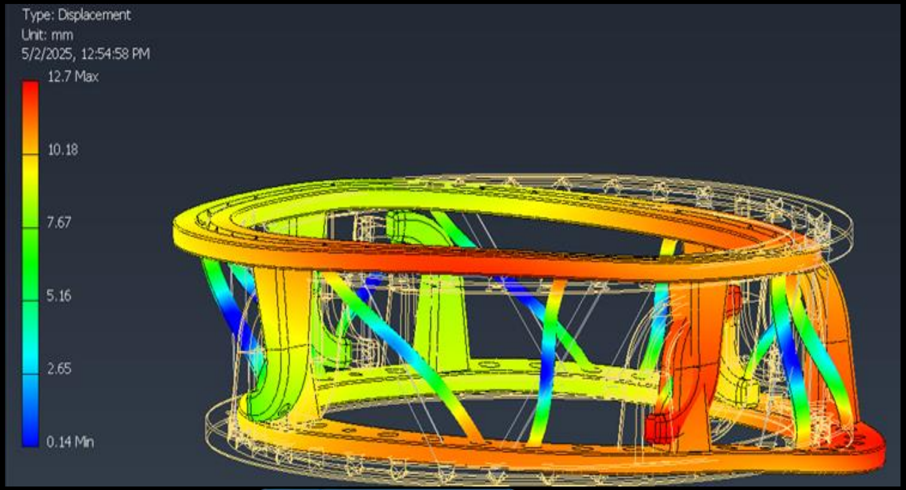
Structural margins:

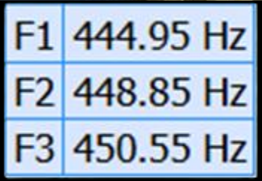


Torsion MoS = 3.93 Strongest



Shear MoS– 1.53 – Weakest
-Pure shear Unlikely, warrants investigation for improvement



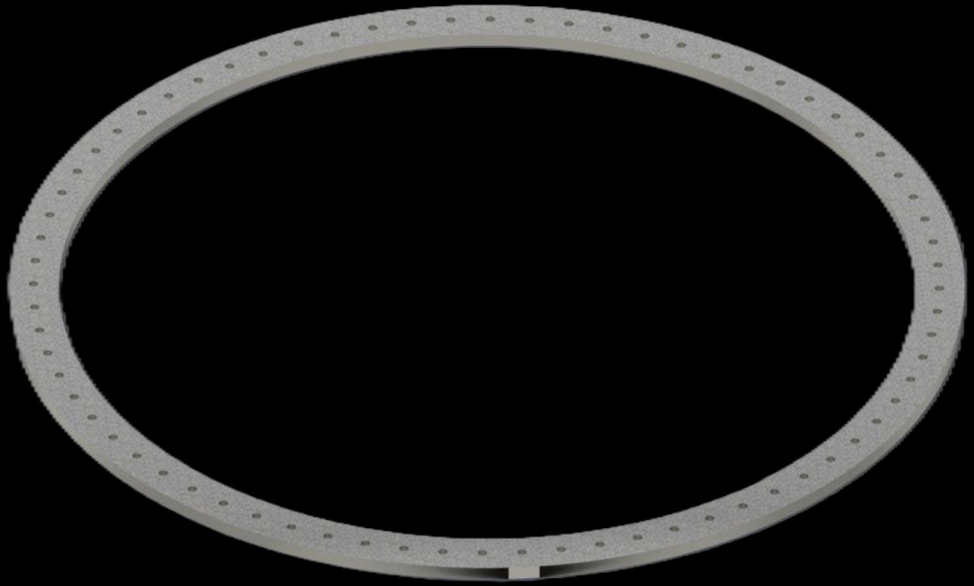


F1	444.95 Hz
F2	448.85 Hz
F3	450.55 Hz

- 2200 kg Tank * 5g Acceleration (Compression / Tension)
- 0.2g * 2200 kg tank (Maneuvering)-Tension / Shear
- Nasa SF – 2.0

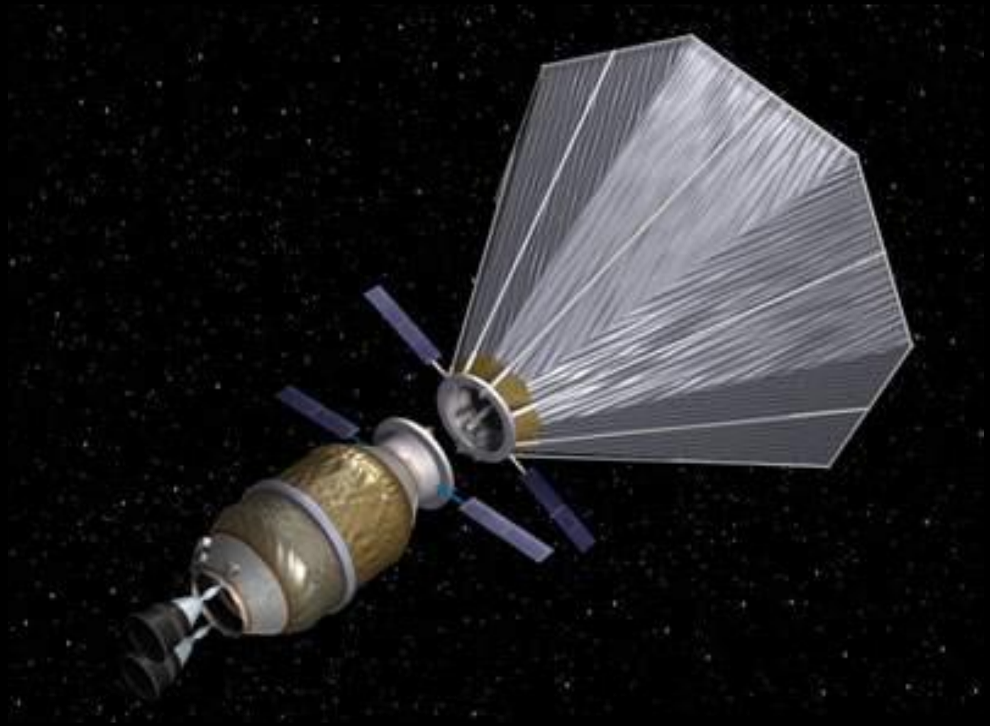
Integration – Fits NASA 5 m Skirt & SLS 8 m Fairing

- The upper- and lower-ring spacing is 0.37 m, producing a 16° diagonal that satisfies fairing and weld-access limits.
- Ring mass: 28 kg, 2219-T8 Al-Li (10 mm web).
- Bolt pattern matches tank skirt.
- Stowed height < 1.1 m inside 8 m fairing



Depot-Level Impact

- Boil-off reduction: 26 W saved equates to 0.25 kg LH_2 day^{-1}, extending dormancy by >30 days for a 30-t depot.
- Cryocooler sizing: A 2.2 W conductive load plus 1.5 W radiative load keeps total <4 W—inside the 20 W capacity of a single 4 K-class pulse-tube cooler, eliminating the need for dual-cooler redundancy.



Cryogenic propellant depot with single sunshade.
Image credit: United Launch Alliance, B. Kutter, 2008

Verification & Path To Flight

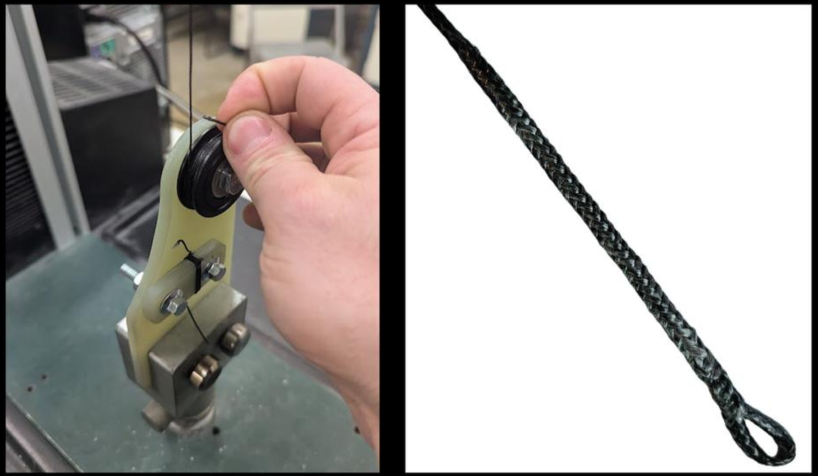
- **Coupon Testing**
  - Validate materials, joints, and thermal models
  - Supports entry to **TRL-5**
- **Full-Scale Ground Vibration Testing**
  - Structural dynamics, modal validation, system integration
  - Targeting **TRL-6**
- **Flight Demo on ISS Pallet**
- → Full environmental exposure in microgravity
- → Demonstrate operational performance and durability
- → Enables qualification for flight missions

Verification Plan to Reach TRL-6 by FY-29

- FY-26 subscale thermal-vac test
- FY-27 micro-gravity flight demo
- FY-29 structural cert on Artemis-IV

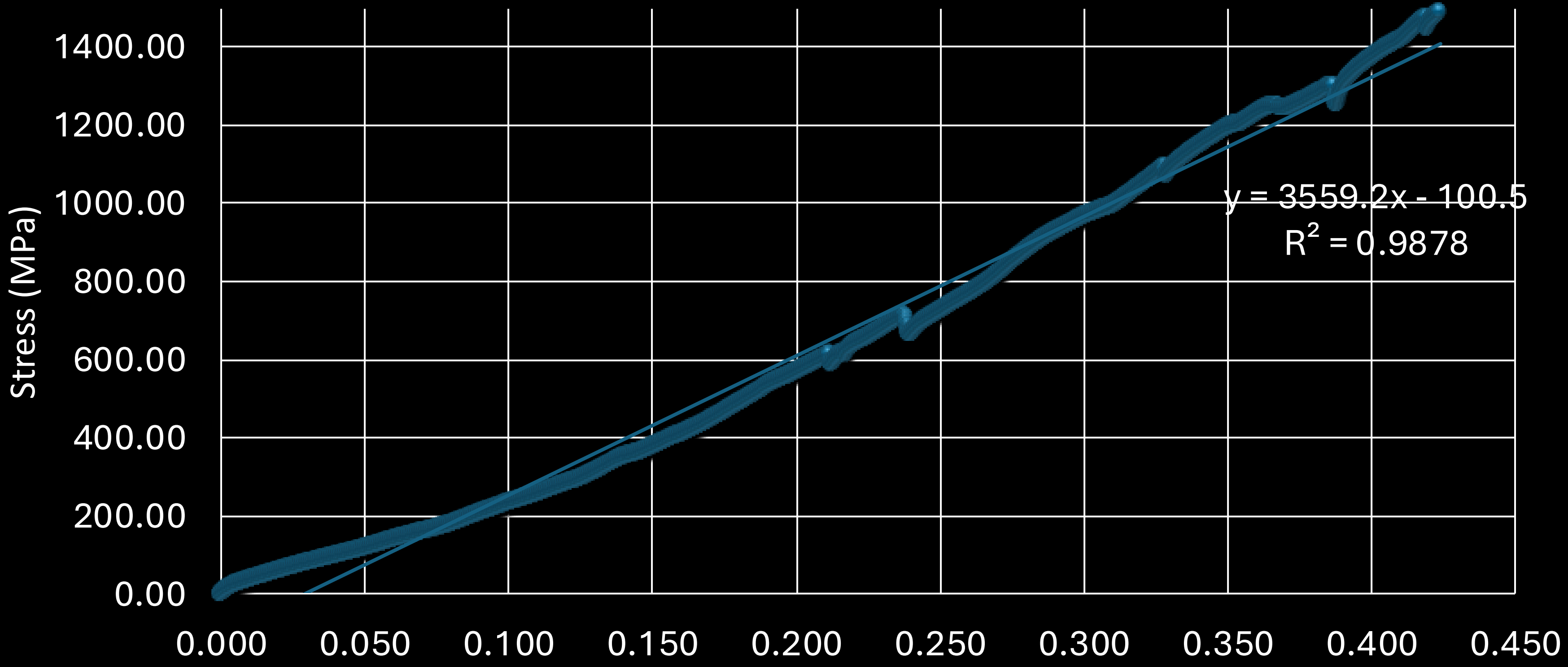
Level (NASA TRL)	Milestone	Facility	FY	Exit criteria
Coupon (→ 4)	LN_2 shear of hollow hook • SK-99 loop tensile & 105-cycle creep	ODU Materials Science Lab	25 Q4	FS ≥ 1.5 × LC-2 • $\Delta L \le 2$ %
¼-scale sub-assembly (→ 5)	90° ring sector + 2 loops, cryo sine-burst (5 g / 2 g)	GSFC-STD-7000 Shaker	26 Q1	M.o.S. ≥ 1.25 • no slack
Full-scale ground (→ 5)	Complete ring pair: cryo sine-vibe + boil-off calorimetry	GSFC Shaker + MSFC J-Tank	27 Q3	$Q \le 2.5$ W
Flight demo (→ 6)	1 m STORM on CLD pallet, 180-day LH_2 dwell	ISS CLD rideshare	29 Q1	$Q \le 3$ W • $\Delta L < 0.5$ %
Certification (→ 6)	NASA LCB FRR & CDR closeout	—	29 Q3	TRL 6 declaration per NPR 7123.1C

Tensile Testing



(Left)Tensile Testing Adapter Setup
(Right) Dyneema Sample with
Brummel eye splice

UMMWPE 0.8mm Stress Vs Strain @ ~23° C



Risk Matrix: Top 3 Items & Mitigations

ID	Risk	L*	C*	Rating	Mitigation
R-1	Cable creep > 2 % over 10 yr	2	3	**M**	Long-term creep rig + 4.5 mm Cable oversize
R-2	J hook internal flaw	2	2	**L**	X-Ray + LN_2 proof test
R-4	Faulty cable anchor splice or in-service SK-99 loop break (manufacturing defect, micrometeoroid, or creep rupture)	1	**5**	**M**	• Proof-load each loop to 1.5 × LC-2 before installation • Install dual parallel loops at each of the four axial stations (load ≤ 50 % on each) • Embed fiber-Bragg-grating (FBG) strain sensors; drop in cable tension triggers safe-mode vent. • Shield diagonals and loops with micrometeoroid bumper inside vehicle shroud

Footnote on L and C**

L = Likelihood and C = Consequence per the NASA 5×5 risk matrix (NPR 7120.5):

1 = Remote/Negligible, 5 = Almost Certain/Catastrophic. The ratings shown are post-mitigation.

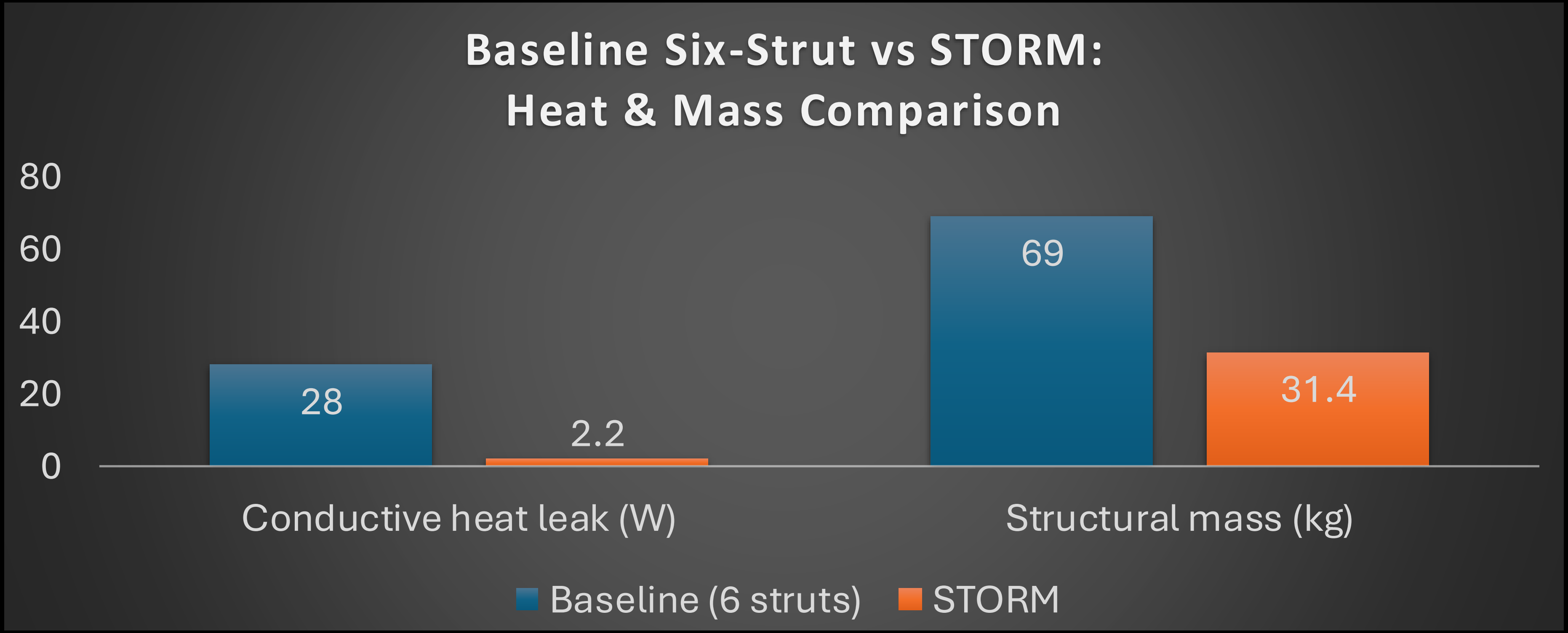
Path-to-Flight Cost Snapshot

- Phase A-C total: $23 M
- Per-unit recurring: $2.1 M

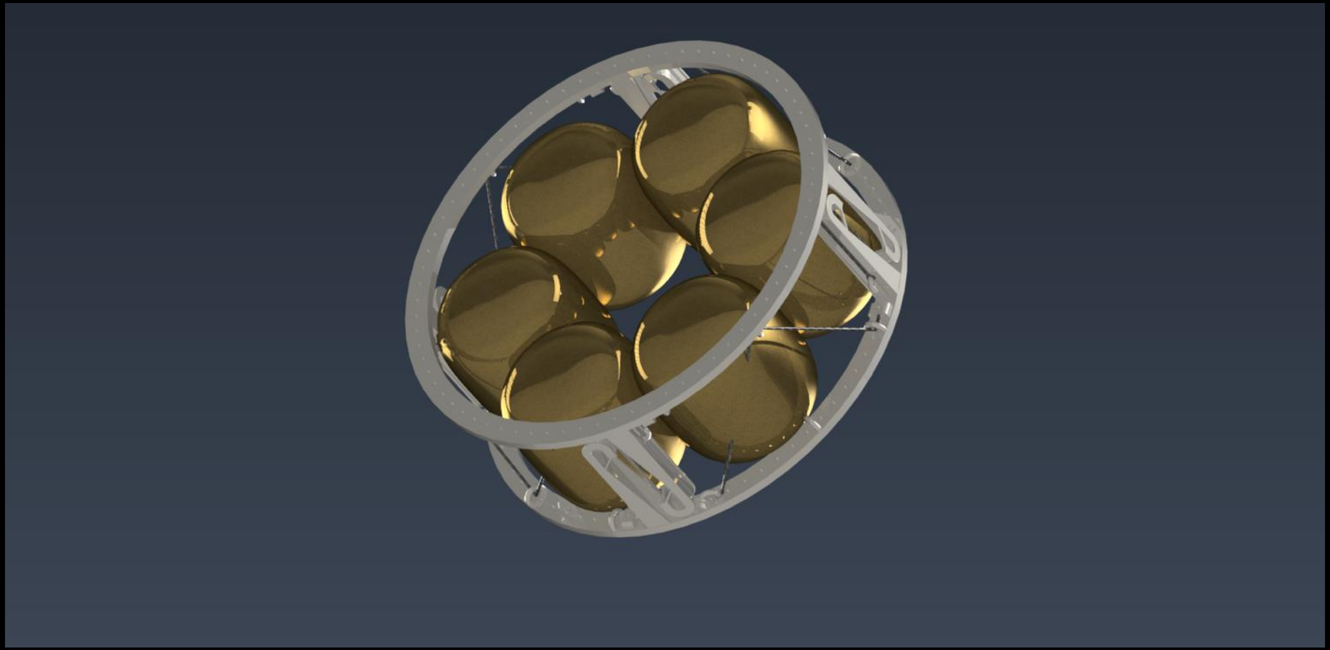
WBS	Phase A	Phase B/C	Phase D (flight demo)	Total
1.1 Concept & Req.	**0.25**	—	—	0.25
1.2 Design	—	**1.05**	—	1.05
1.3 Fabrication	—	**0.8**	0.45	1.25
1.4 Ground testing	—	**0.3**	1.1	1.4
1.5 Flight demo pallet	—	—	**5.1**	5.1
1.6 Mission ops & data	—	—	**0.6**	0.6
1.7 PM / QA / SE	0.05	0.23	1.1	1.38
Subtotal (w/ 30 % reserve)	0.3	2.38	8.35	**11.03**
Launch services (ISS CLD rideshare fee)	—	—	**12**	12
Grand Total	**$23.0 M**			

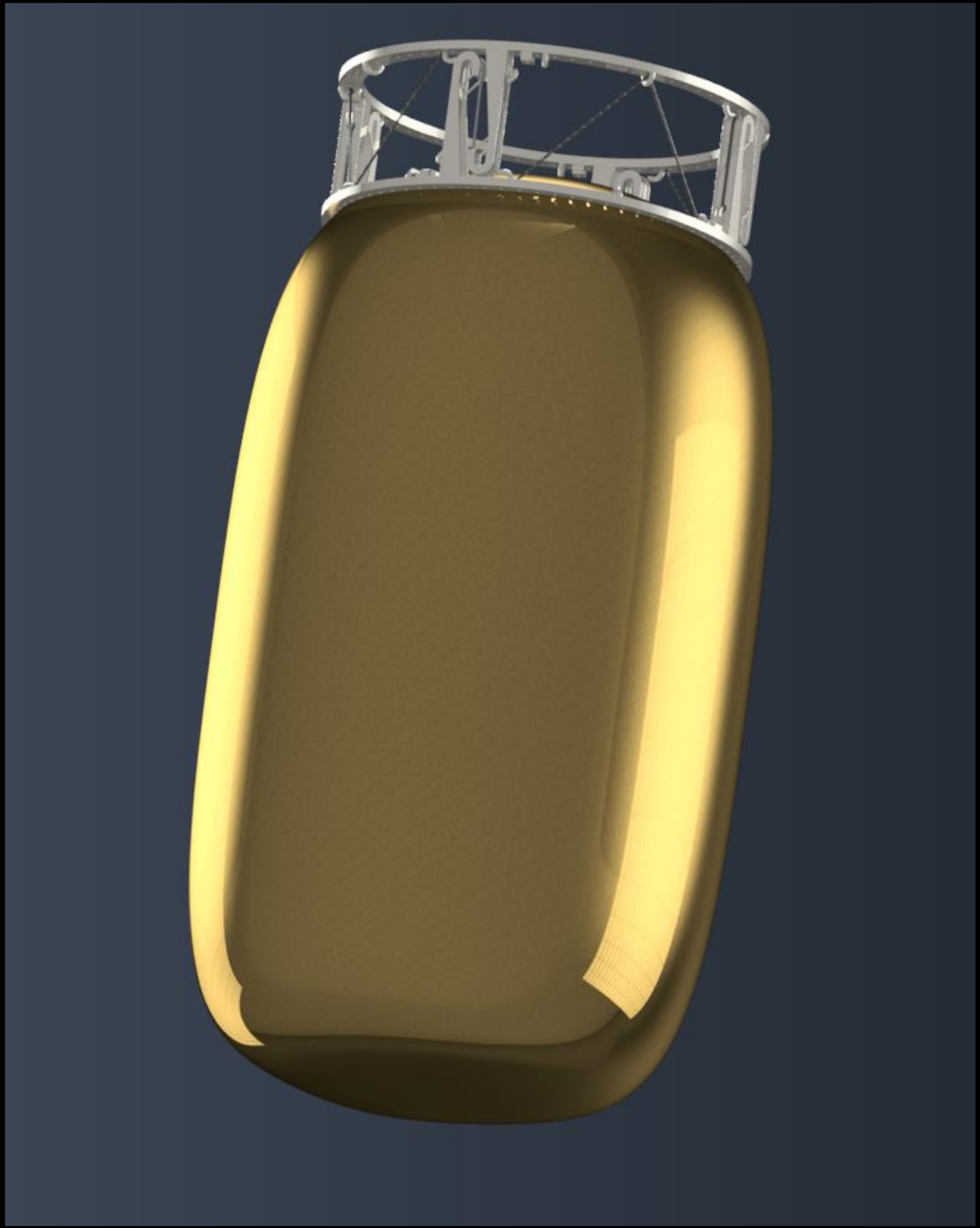
$23 M dev vs $150 M LH_2 saved in 10 years

Value Proposition – STORM Makes Lunar Cryogenic Logistics Lighter, Cheaper, Sooner



90 % heat-leak cut • 38 kg mass save • TRL-6 by 2029





Beyond Propellant Depots – Other Users

- Orbital fuel depots
- Lunar ISRU plants
- Deep-space cryo stages

Conclusion

STORM demonstrates that a pure-tension, hollow-hook tensegrity support can meet NASA’s structural safety factors, slash conductive heat leak, and mature to flight readiness on a realistic schedule and budget.

- Structural Credibility – Finite-element analysis shows minimum ultimate safety factors of MoS ≥ 3.0 (loop cables) and 3.3 (hollow Ti hooks) under the 5 g wet-launch load; the first global mode is 445 Hz, over 22× the HuLC 20 Hz target.
- Thermal Performance – Four 4 mm Dyneema SK-99 loops, eight diagonals, and hollow J-hooks conduct only 2.2 W at 20 K—> 90 % less than a titanium-strut baseline, extending depot dormancy by ~30 days and enabling single-cooler architectures.
- Mass Advantage – The complete assembly masses 31.4 kg, saving ≈ 38 kg vs. metal struts; secondary fairing and adapter knock-on savings raise the total vehicle benefit to ~50 kg.

ODU
Frank Batten College of Engineering and Technology

Structural Tensegrity for Optimized Retention in Microgravity

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Mechanical and Aerospace Engineering Department Old Dominion University, Norfolk, VA

S.T.O.R.M

Purpose & Challenge

- **Tensegrity** = isolated compression nodes suspended in a continuous tension network
- Six Ti struts conduct **≈ 28 W at 20 K**, forcing costly boil-off on lunar depots
- **HuLC goal**: keep conductive leak **≤ 5 W** and survive **5 g axial / 2 g lateral** loads
- Aim: **> 90 % heat-leak cut** and **≥ 38 kg mass saving** without redesigning the tank

Methods

- Replace six Ti struts for a **pure-tension tensegrity lattice of 4 mm Dyneema SK-99 cables**
- **C-Channel Ti-6Al-4V J-hooks** redirect 607 kN launch compression into axial cable tension—no bending
- **Figure-of-Merit: [$Str/(k*\rho)$] trade** singled out SK-99: **100× better** than titanium
- CAD-driven FEA shows global mode **445 Hz** and **MoS ≥ 2.0** in all load cases
- Eye-splice pull **confirms splice efficiency**; next step is LN_2 coupon tests (FY-26)

(Left)Tensile Testing Adapter Setup
(Right) Dyneema Sample with Brummel eye splice

Figure of Merit [$\sigma/\rho*\kappa$] Material Comparison

Material	$\sigma_{f\ @20K}$ (MPa)	k (W m^{-1} K^{-1})	ρ (kg m^{-3})	σ /ρk
Dyneema SK-99	5300	0.46	970	11.9
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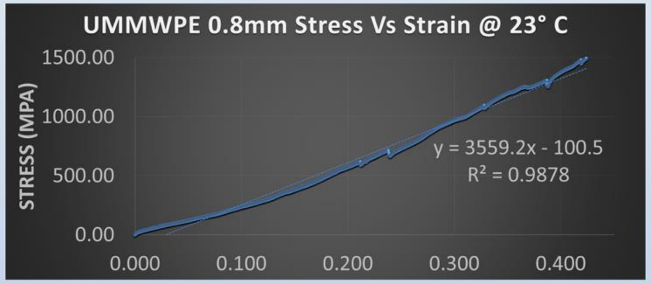
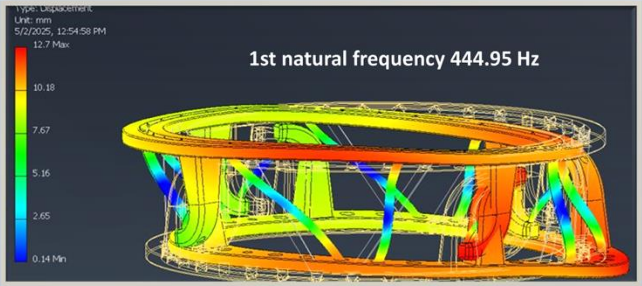
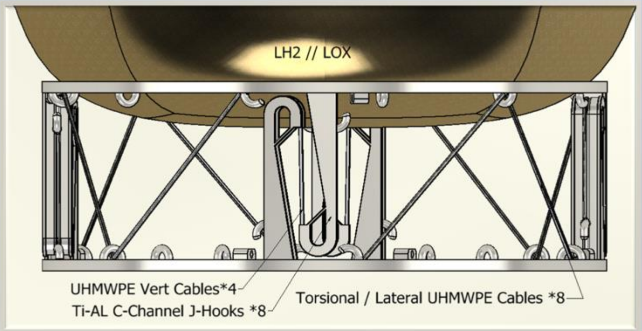


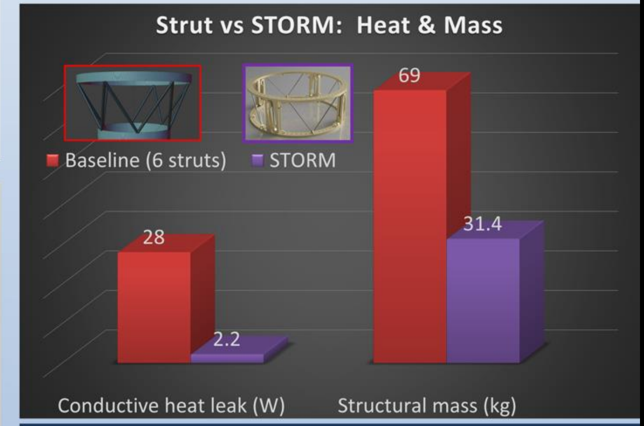




Proposed Tensegrity Support System (S.T.O.R.M.)

Results & Conclusions

- Conduction drops to **2.2 W** → **> 90 % heat-leak reduction** versus baseline
- **[UHMWPE]: ↓Temp = ↓conductivity+↑ Strength**
- **Mass: 31 kg** assembly saves **≈ 38 kg** vs. metal struts—plus cryocooler downsizing
- First mode **22× above** the HuLC 20 Hz requirement; launch safety factors **all > 2**
- Path-to-flight: coupon tests ’25 → TRL-5 ground vibration ’27 → **TRL-6 ISS Pallet demo ’29**



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Lastly, thank you to the sponsors

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