THERMOS

Translunar **HE**at **R**ejection and **M**ixing for **O**rbital **S**ustainability

Beverly Ma '26, Daniel Rojas '27, Stone Smith '27, Pranav Bala '27, Nicole Ding '27
Faculty advisors: Dr. George Lordos, Prof. Jeffrey Hoffman, Prof. Olivier de Weck

Massachusetts Institute of Technology

NASA'S HUMAN LANDER CHALLENGE
2025 THEME: ADVANCED CRYOGENICS
23-26 June 2025, Huntsville AL

HuLC
HUMAN LANDER CHALLENGE

Without boiloff management, the 120-day Artemis III mission would be infeasible, and NASA would be unable to return to the Moon.

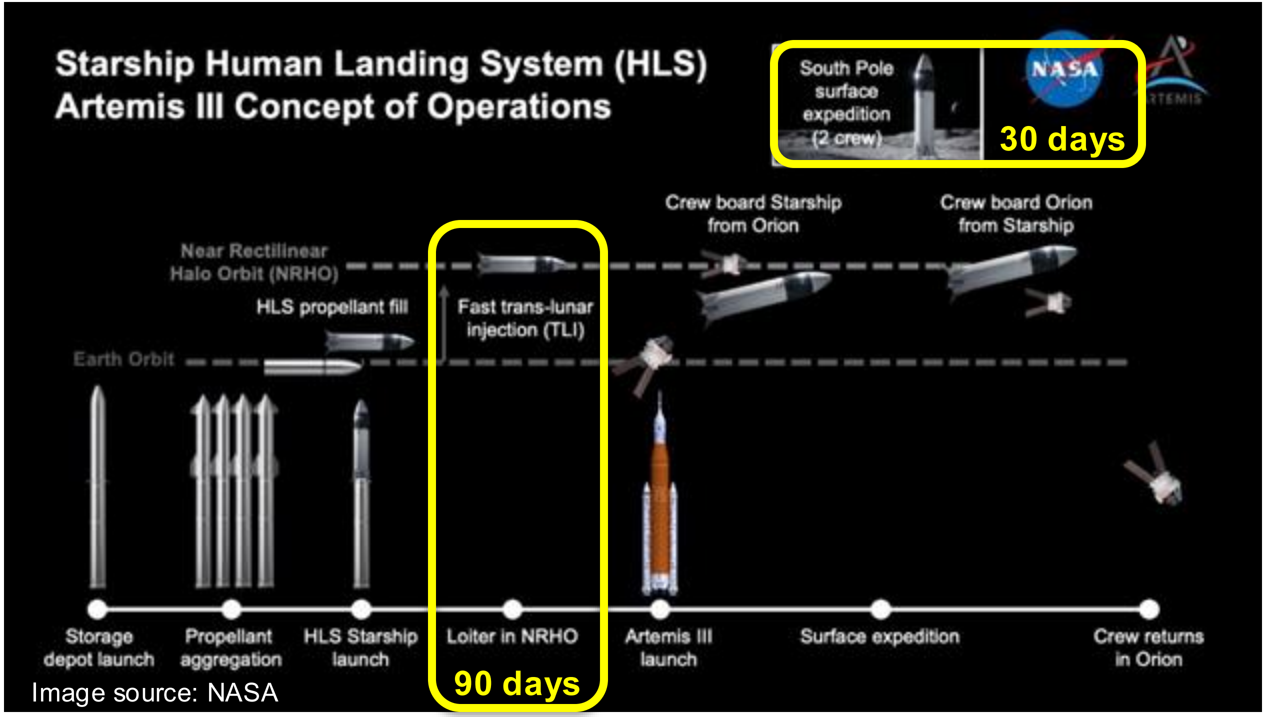


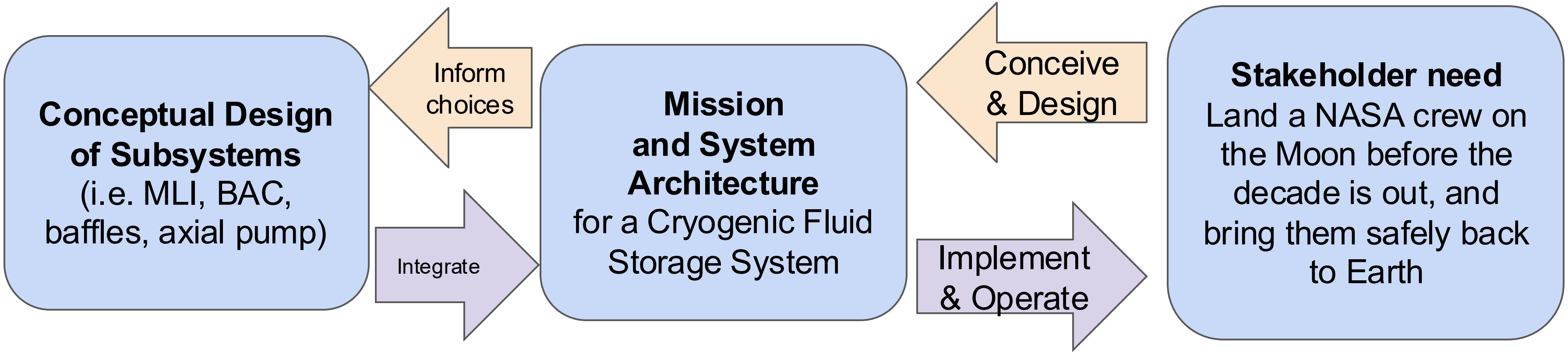
Image source: NASA

Propellant capacity of HLS
Starship V3 = **2,300 t**

NRHO boiloff with bare steel
90d x 38 t/day = **3,420 t**

LSP boiloff with bare steel
30d x 273 t/day = **8,190 t**

To solve the issue of storing cryogenic fluids for Artemis III, we used NASA's systems engineering approach to 'architect from the right'.



- Model subsystem performance and effects on mass and delta-v budgets
- Model mission modes and alternative architectures (i.e. active, passive, hybrid, ….)
- Select Figures of Merit for benefit, cost and risk

We developed a model (see demo at poster session) to justify our architectural decisions by quantifying our key Figures of Merit.

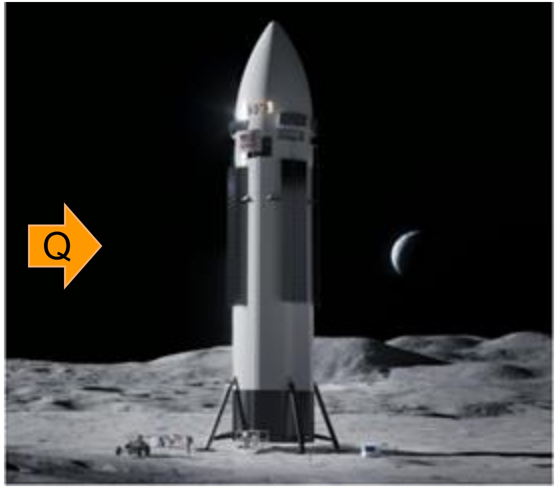
Major Decision	Decision Options
Earth Departure Orbit	LEO, TLI-1000 m/s
Starship Version	V2, V3
Structural MLI	None, 20, 40, 60 layers
Cryocoolers	None, Petach, Creare
Take deployable arrays?	No, Yes
Twisted baffles for mixing?	No, Yes

Stress testing: option to increase degradation factor of MLI from DF4 to DF8, and option to fail 0-7 Cryocoolers.

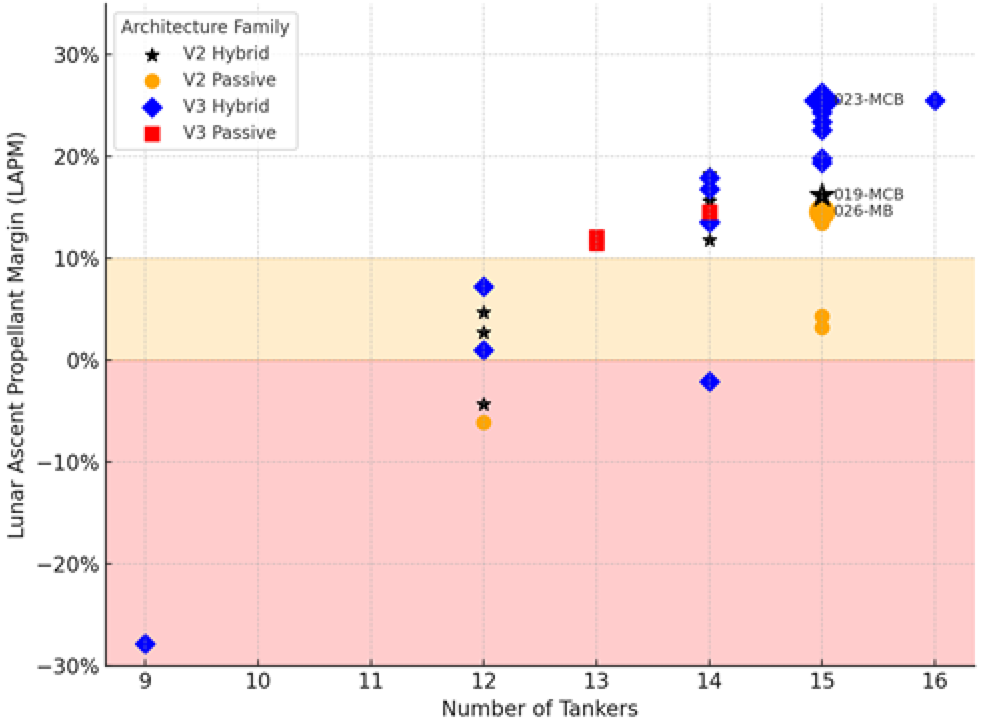
Figure of Merit	Definition	Rationale
Lunar Ascent Propellant Margin (LAPM)	Propellant mass after return to Orion, divided by propellant before lunar ascent	More propellant margin increases mission robustness and crew safety
Number of Tankers	Number of tanker launches required for mission	A proxy for mission operating cost and complexity
Relative Schedule Risk	Sum of “TRL gap” for required technologies	The more techs and the lower TRL, the higher the schedule risk

Thorough analysis of propellant burns and modeled boiloff led to three major realizations that guided our design.

Earth Departure Orbit	LAPM	Tankers
TLI-3200 (i.e. LEO)	-22.6%	8
TLI-1600	17.8%	14
TLI-1300	22.3%	14
TLI-1040	25.5%	15



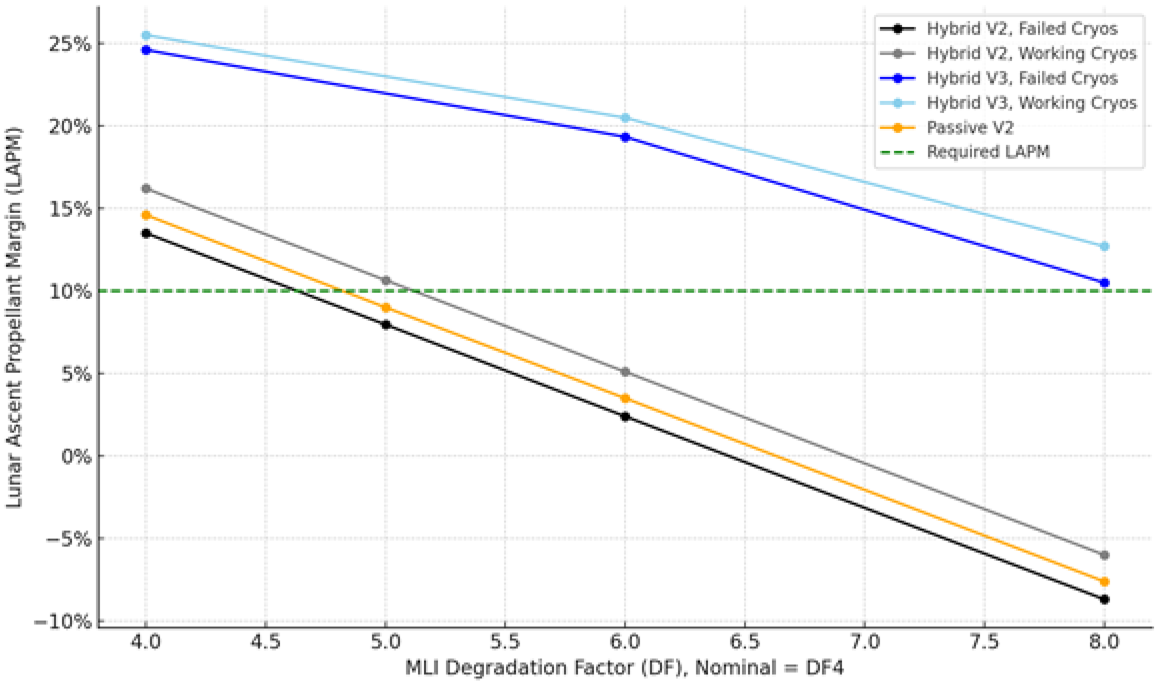
To select attractive system concepts, we traded off Lunar Ascent Propellant Margin (LAPM) vs. tanker launches and schedule risk.



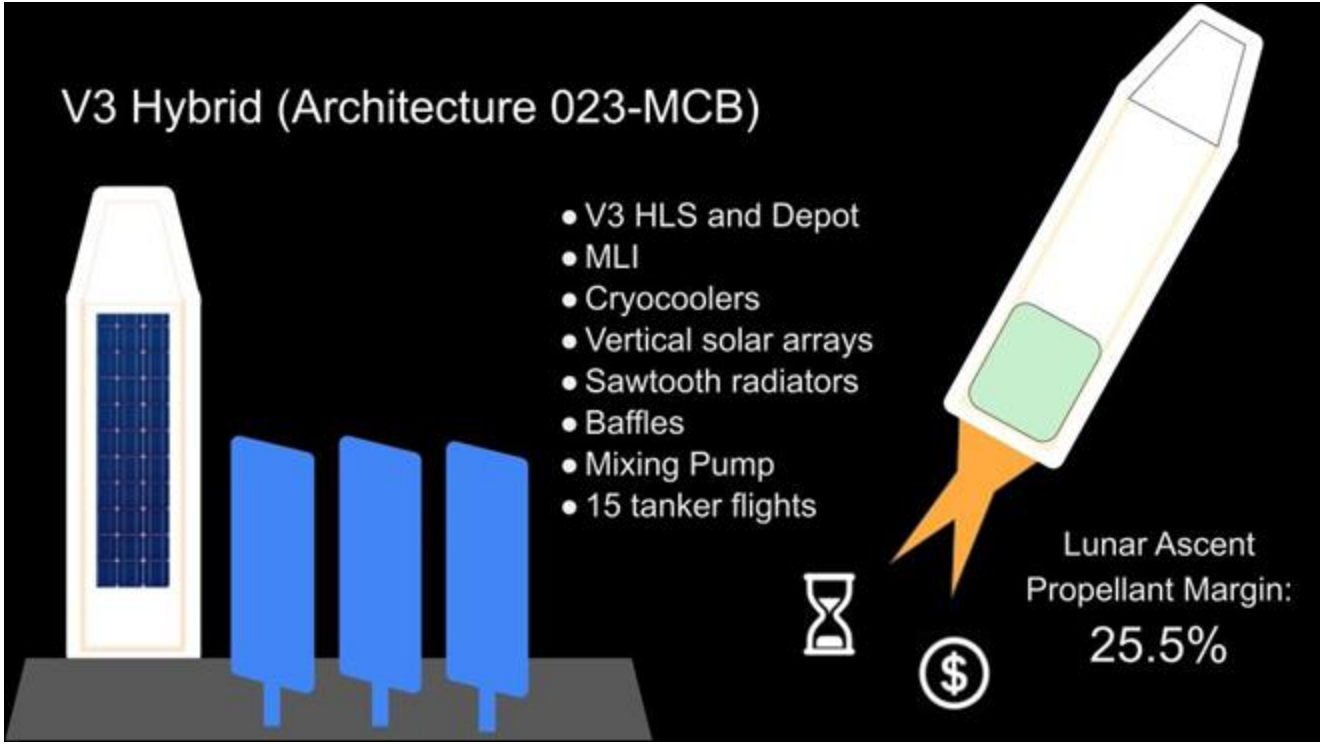
	Hybrid V3 (023-MCB)	Hybrid V2 (019-MCB)	Passive V2 (026-MB)
Nominal LAPM	25.5%	16.2%	14.6%
Can withstand DF up to	~8	~4.5	~5
Req. Techs	6	5	3
Relative Schedule Risk Index	29	26	16
# Tankers	15	15	15

THERMOS enables NASA to choose between increased mission robustness and lower schedule risk.

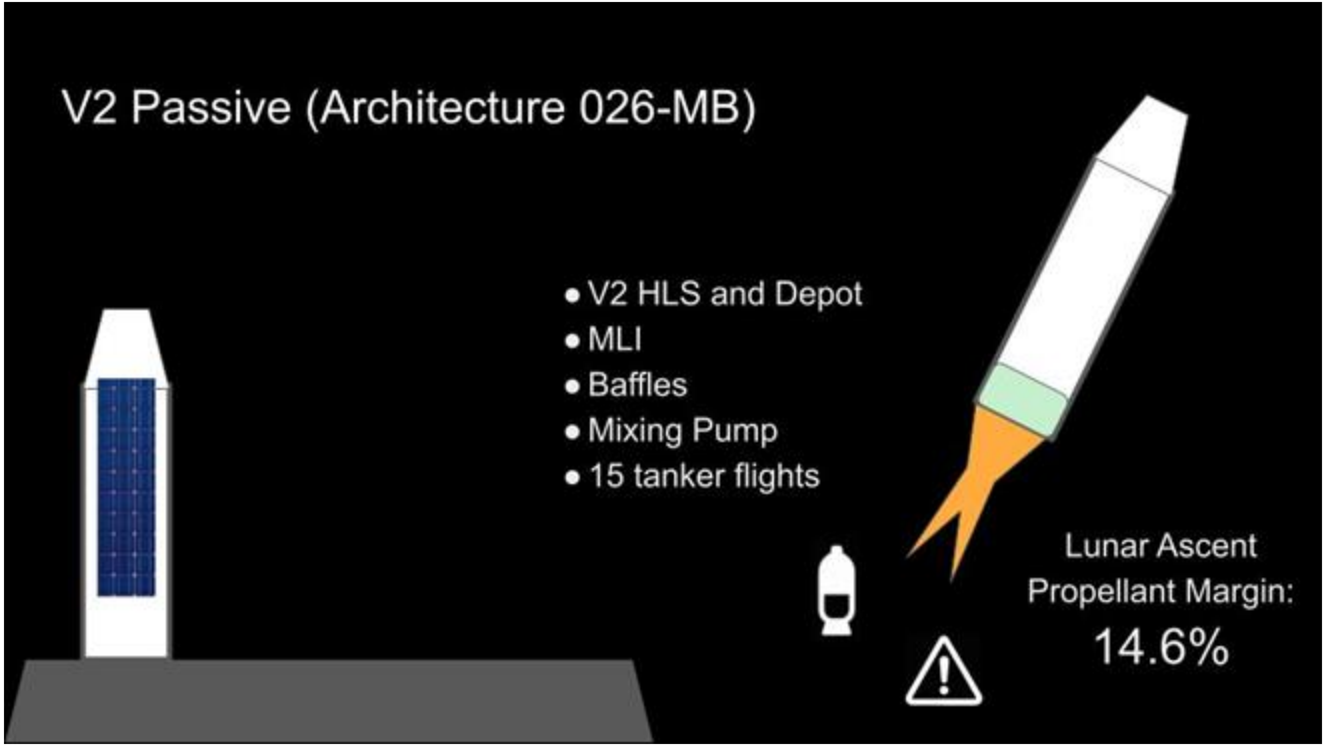
	Hybrid V3 (023-MCB)	Hybrid V2 (019-MCB)	Passive V2 (026-MB)
Best-case LAPM	25.5%	16.2%	14.6%
Can withstand DF up to ~	~8	~4.5	~5
# Key Techs	6	5	3
Relative Schedule Risk Index	29	26	16
# Tankers	15	15	15



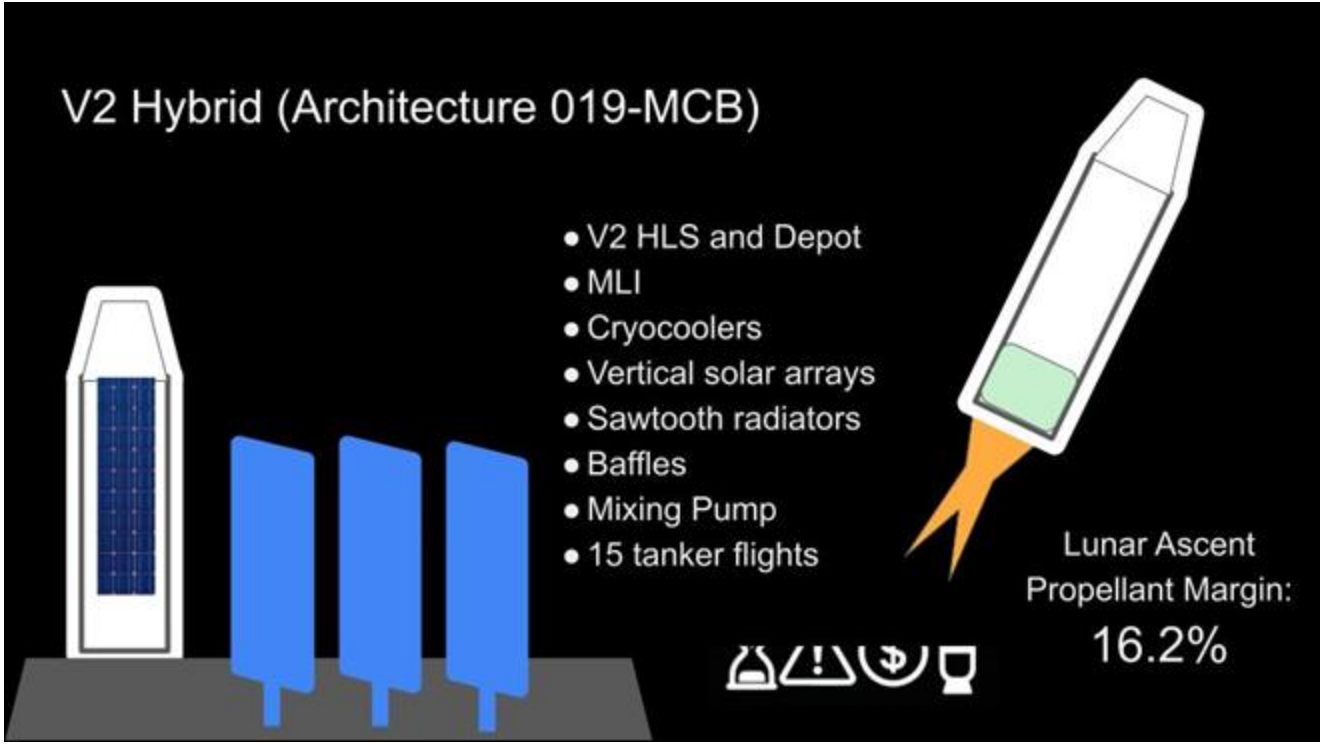
Option 1 summary: best LAPM performance.



Option 2 summary: simplest → lowest schedule risk.

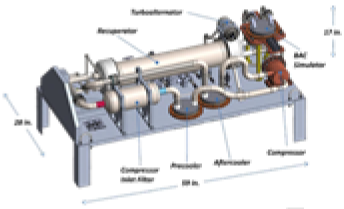


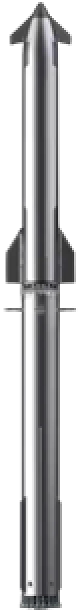
Option 3 summary: Somewhere in Between.



For conceptual design of subsystems, we selected 023-MCB with Multi Layer Insulation (MLI), Broad Area Cooling (BAC) and our novel concept for hydrodynamic mixing baffles ‘ETHER’.

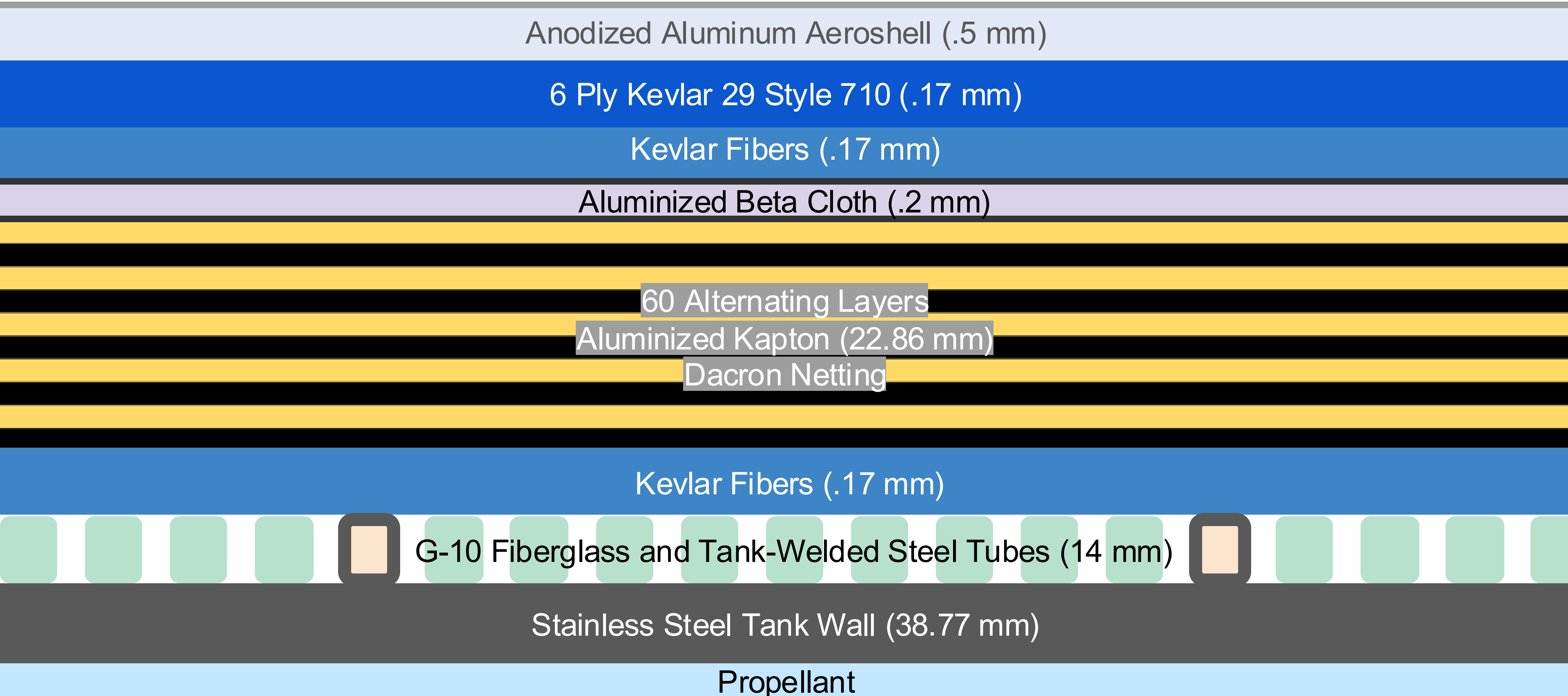
Item	Mass (kg)
V3 HLS	138,767
MLI System	12,797
BAC System	5,389
Synergy	(-1,979)
Other	2,100
Payload leave	13,152
Payload return	30,000



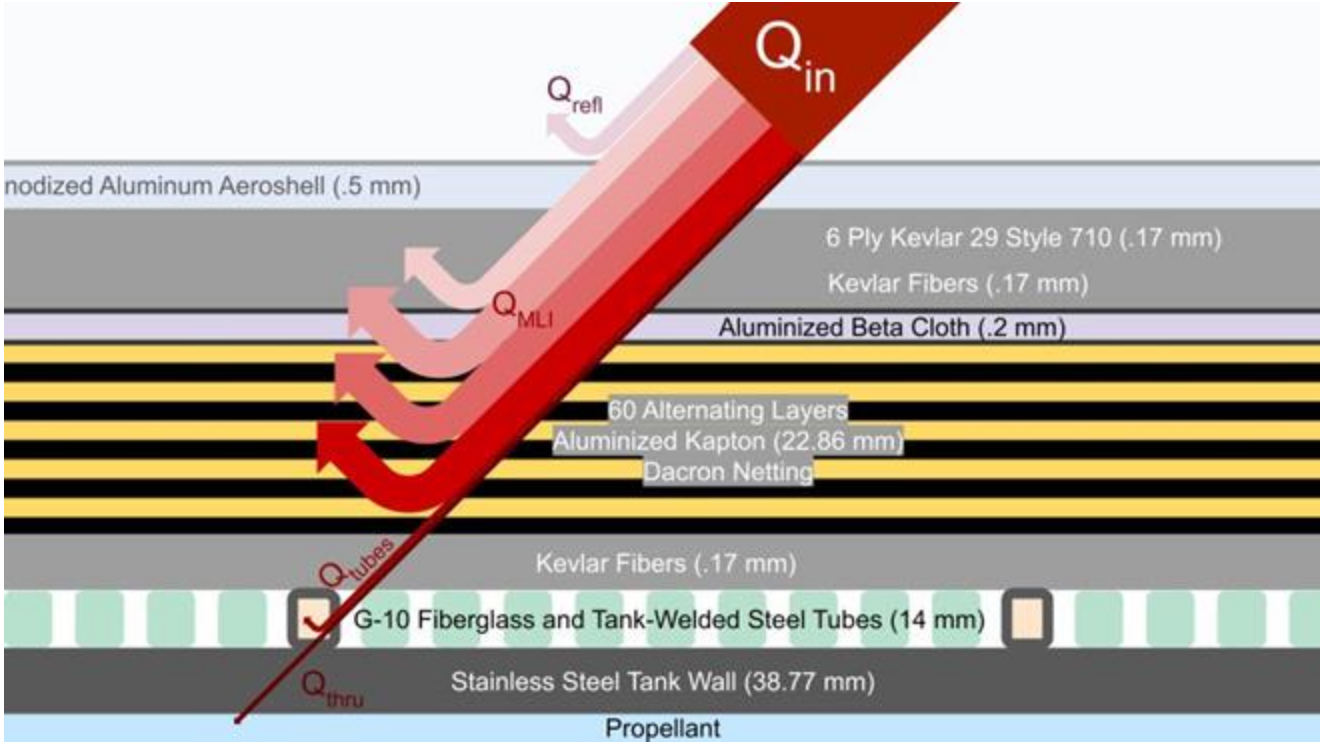


Major Decision	Architecture 023-MCB
Earth Departure Orbit	TLI-1040 m/s
Starship Version	V3 for both HLS and Depot
Structural MLI	40 layers front, 60 layers side
Cryocoolers	7x Creare 150W / 90K
Deployable arrays?	Yes (8.4 kW)
ETHER baffles?	Yes
Mass of 023-MCB HLS	157 tons

MLI and Shielding deter anything--heat, ionizing radiation, micrometeoroids, orbital debris-- from ever reaching the tanks

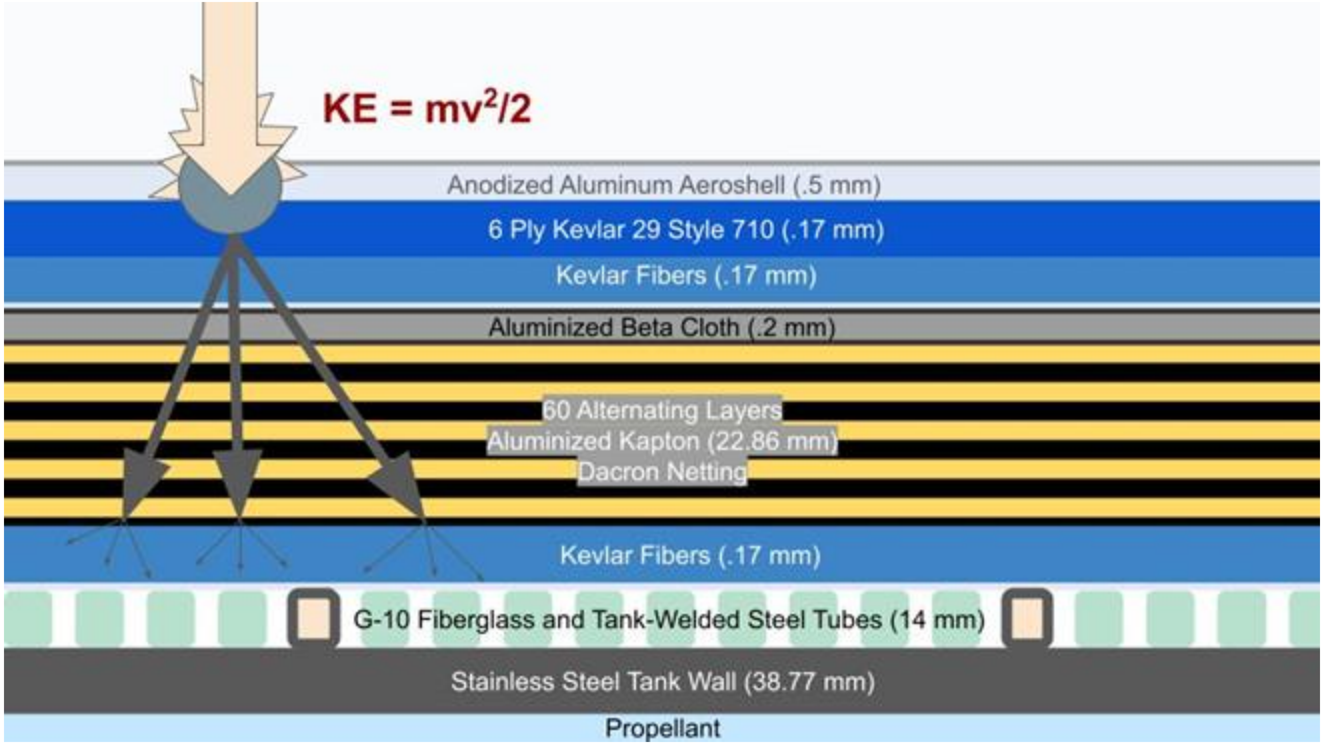


The THERMOS MLI design is mounted on the BAC cooling tubes, helping to prevent some of the heat from reaching the tanks.



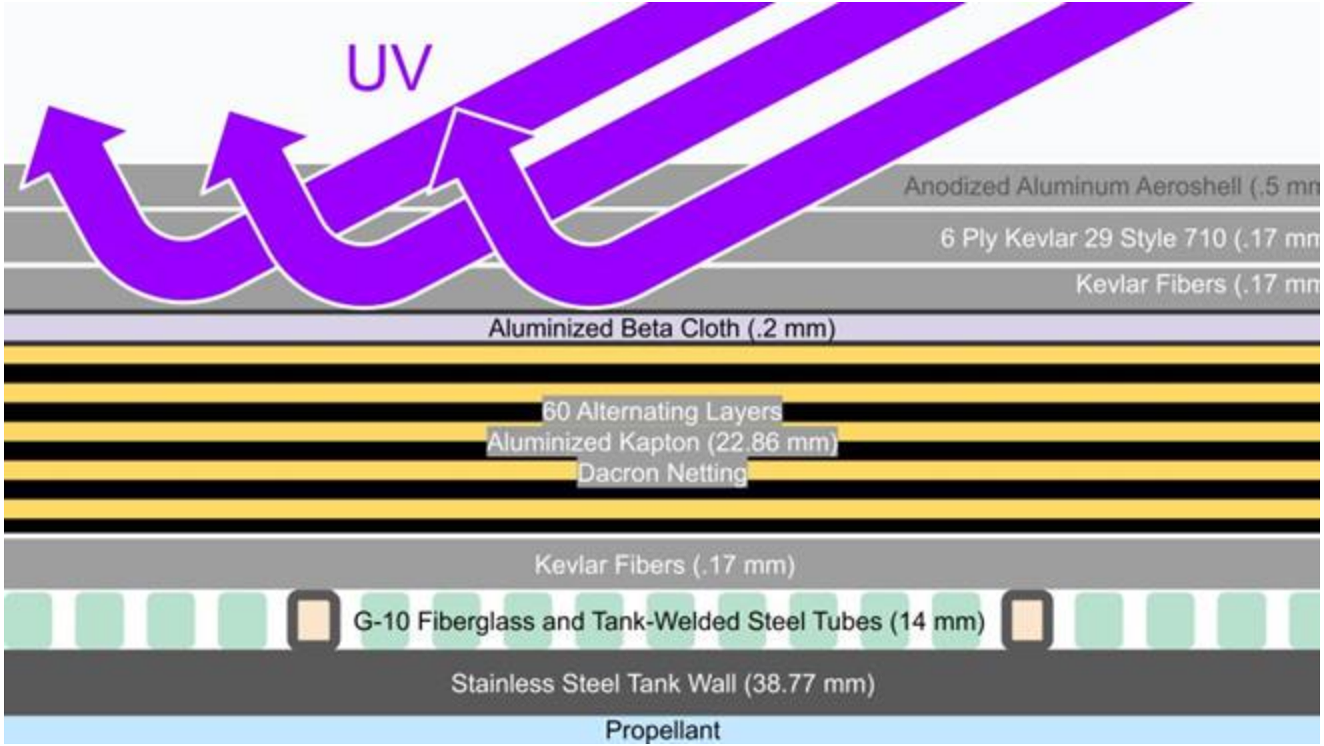
Specific mass	6.47 kg/m^2
Ideal performance	99.54%
Realistic performance	98.15% (DF4)
Reference	A144 (Johnson thesis, 2010)

Kevlar fibers at both ends of the blanket and an aluminum aeroshell serve as a double Whipple shield and add strength to survive launch.

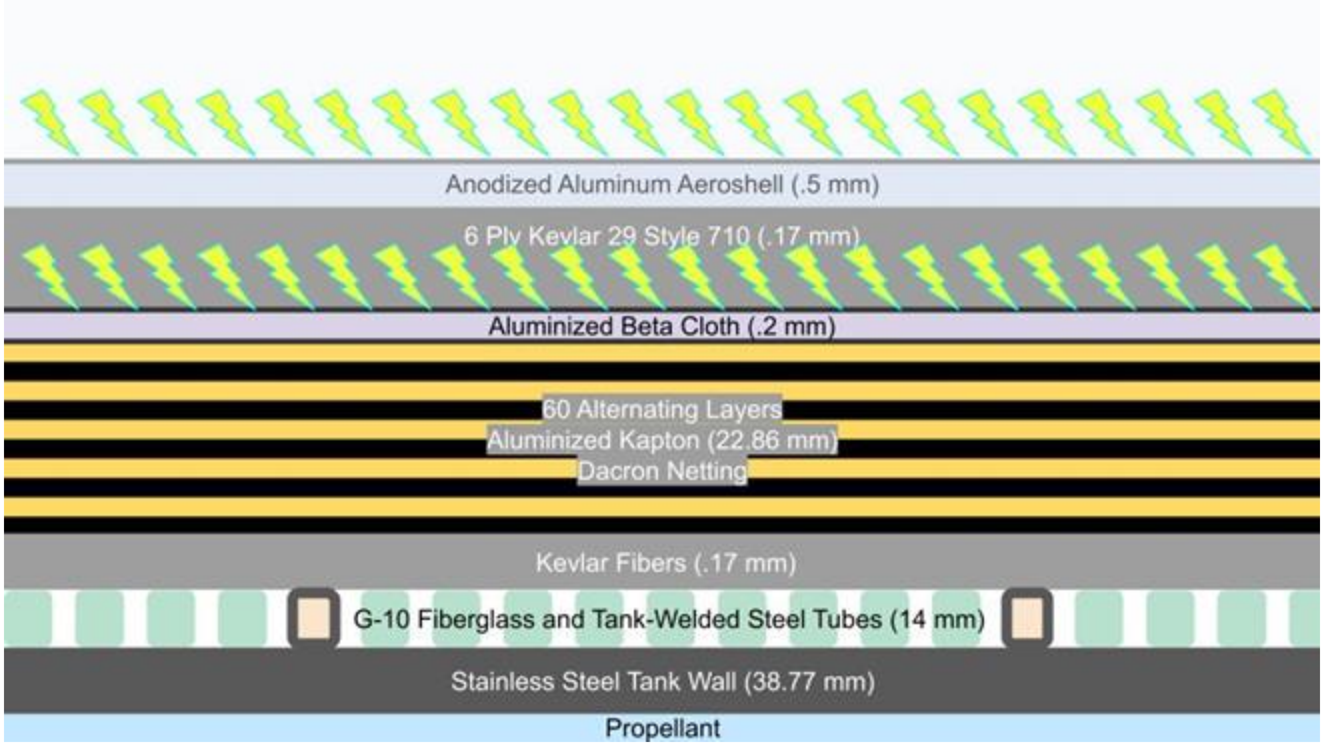


Aluminum + double Kevlar (warm side)	0.84mm, 3.99 kg/m^2
Gap for debris cone dispersal	23mm
Single Kevlar (cold side)	0.17mm, 1.32 kg/m^2
Gap to tank wall	14mm

Beta cloth protects the aluminized kapton layers from ultraviolet radiation.



Aluminum aeroshell and aluminized beta cloth protect the HLS and Depot from charging when traveling through the radiation belts.



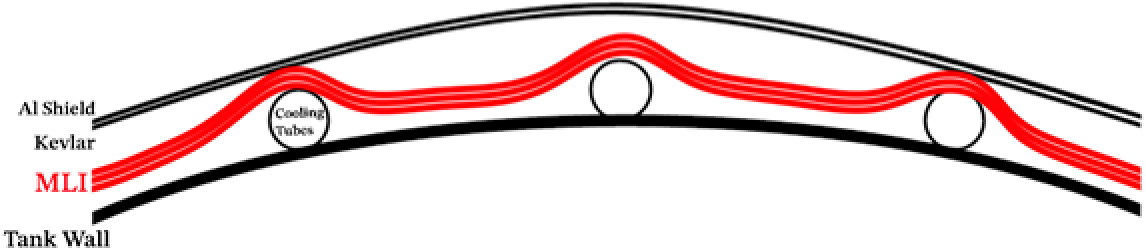
The BAC will employ seven Creare 150W cryocoolers which together serve 28 cooling tubes that are flat welded onto the tank.

Red lines represent coolant tubes

Cryocoolers under crew compartment, internal MLI shielding the tanks

Cryocooler Specifications	
Number of Coolers	7
Number of Coolant Tubes	28
Coolant Tube Spacing	1 m
Type of Coolant	Neon Gas
Cooler Model	Creare
Thermal Lift per Cooler	150 W
Cooler Set Point	90 K
Total Power Requirement	8.4 kW
Total Mass	3.4 t

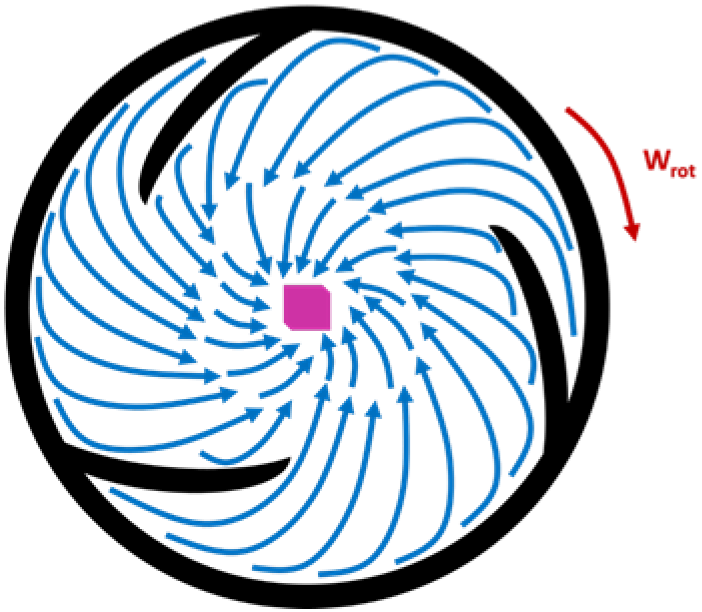
Hybrid MLI and BAC on a V3 Starship (concept # 023-MCB) yields a robust architecture delivering the required 10% LAPM performance, even in case of 2x MLI degradation and complete cryocooler failure.

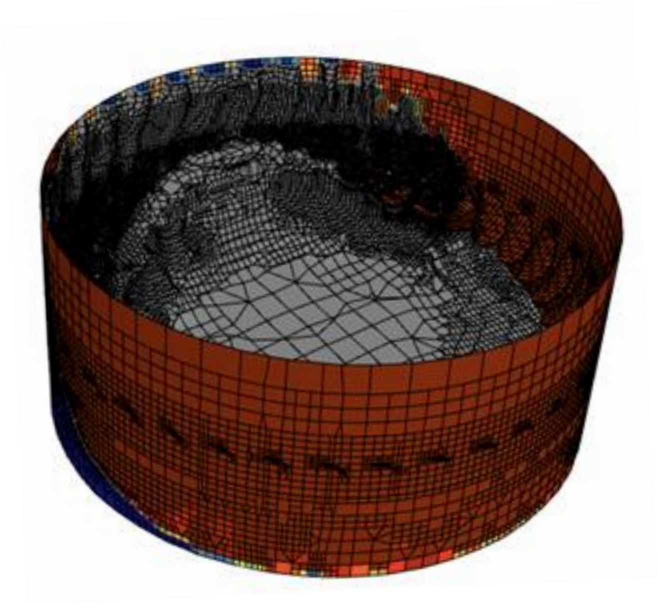


Architecture and Failure Mode	Starship Version	Boiloff Rate at Lunar South Pole (tons per day)	LAPM
Hybrid 023-MCB-DF4-FC0 (Nominal)	**v3**	**4.5**	**25.5%**
Nominal MLI, failed Cryos	v3	4.7	24.6%
Doubled heat leak, working Cryos	v3	9.0	12.7%
Doubled heat leak, failed Cryos	v3	9.3	10.5%
Passive 026-MB-DF4 (Nominal)	**v2**	**3.4**	**14.6%**
+25% heat leak (DF 5)	v2	4.2	9.0%
+50% heat leak (DF 6)	v2	5.1	3.5%
Doubled heat leak (DF 8)	v2	6.7	-7.6%

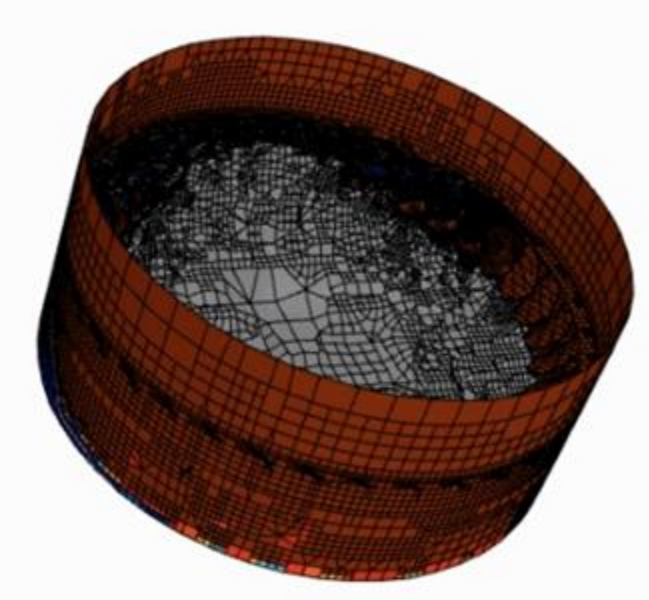
To prevent temperature stratification we modified existing baffles within the fuel talk into hydrodynamic geometries.

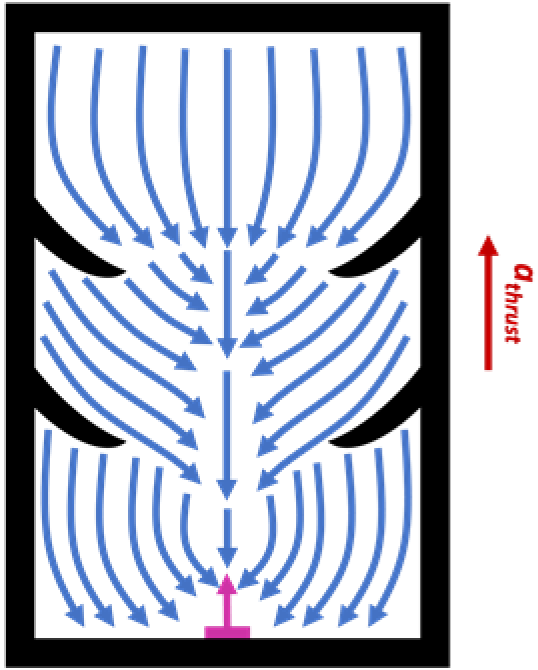
The modified baffles will induce mixing by taking advantage of centrifugal forces from axial rotation.





Our novel propeller-shaped baffles retain their original anti-sloshing function, and our cryopump provides a redundant mixing capability.

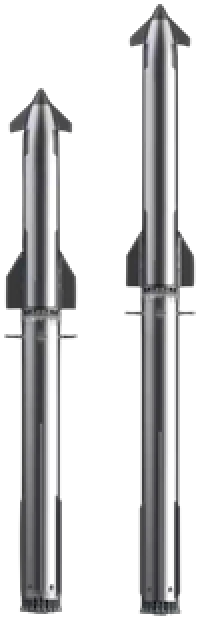


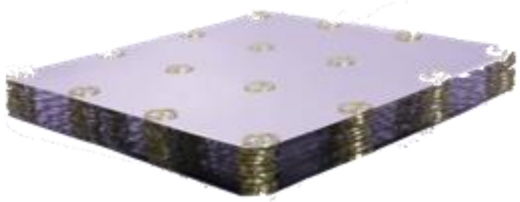


A technology maturation plan has been designed to lead to rapid integration and implementation.

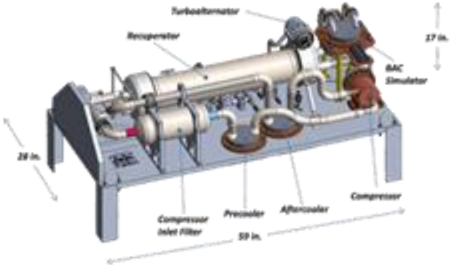
		Technology Readiness Level				
Category	**Technology**	**2025**	**2026**	**2027**	**2028**	**2029**
Active Cooling	Creare Cryocoolers	4	6	7	8	8
Passive Cooling	Double Whipple Shield	9	9	9	9	9
	Sawtooth Radiators	4	6	7	8	8
	Large MLI Blanket	6	7	8	9	9
Power Generation	LVSAT	6	6	7	8	8
	LUNAR SABER	4	5	6	6	8
ETHER	Mixing Pump	6	7	8	8	8
	Twisted Baffles	3	5	6	7	8

The THERMOS project has been architected to support trade-off of technical vs. schedule risk during detailed design in H2 of 2025.





Structural MLI only (faster, simpler?), or can also add **Creare BAC** (higher-performing)

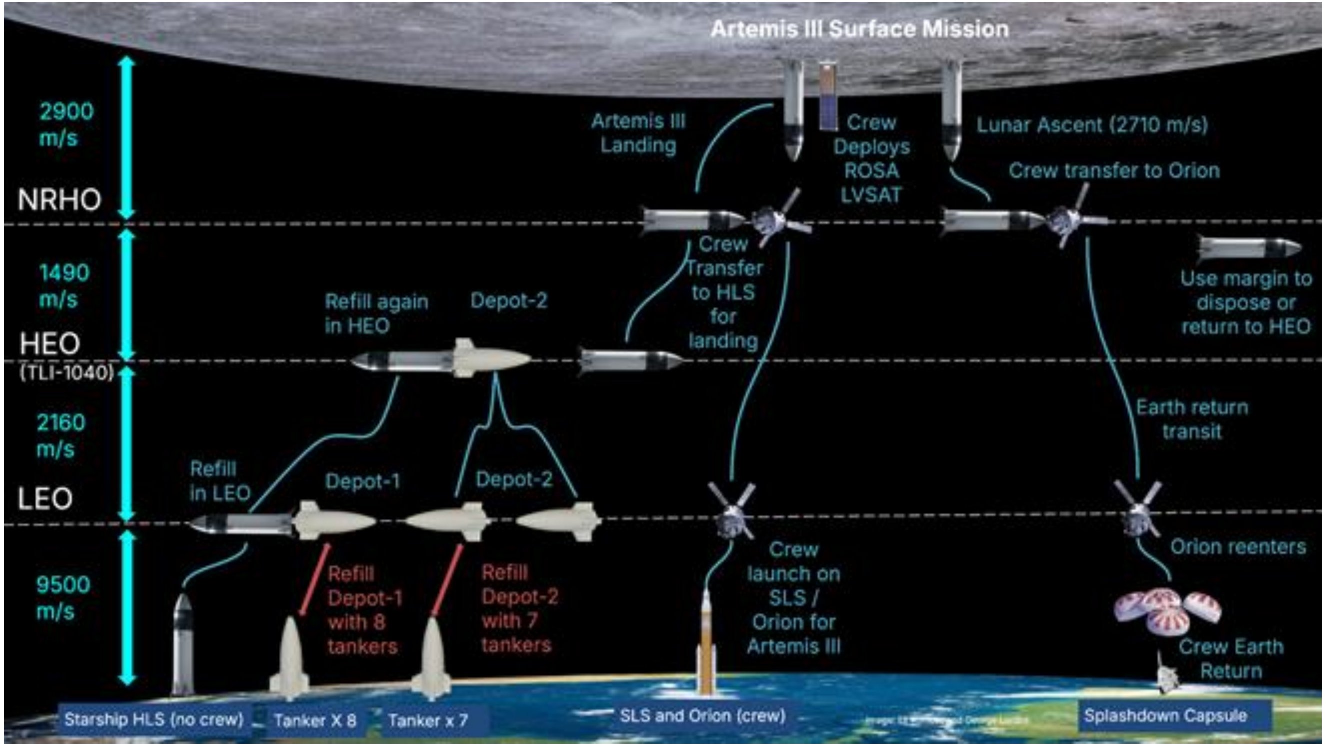


Year	Milestones
2025 H1	Present at HuLC
2025 H2	Detailed Design and Project Planning
2026 H1	Build tanks with new MLI, cryocoolers & Baffles
2026 H2	Flight test aboard one of the regular Starship tests
2027 H1	Incorporate flight learnings; uncrewed HLS flight to LEO / HEO
2027 H2	Uncrewed HLS to HEO, NRHO & LSP, uncrewed Depot to LEO
2028 H1	Incorporate changes to HLS and Depot
2028 H2	Repeat all uncrewed flight tests
2029 Q1	Conclude human-rating certification of THERMOS
2029 Q2-Q4	THERMOS available for use in crewed Artemis III mission

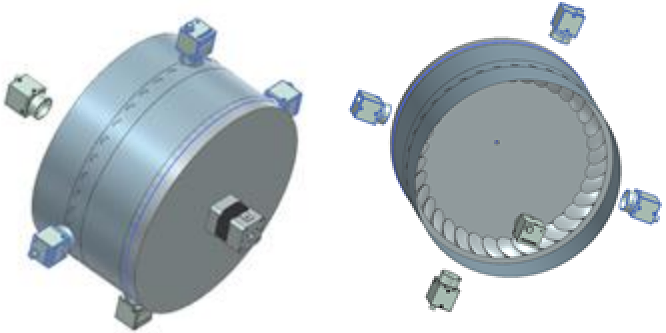
Starship V2 (faster?) or **V3** (higher-performing)

Images credit: SpaceX; Sampson et al, IAC-19.D2.5.9x48999; Creare

The overall cost of THERMOS is affordable, and the 15 tanker launches per Artemis mission are within range of past estimates.



Design and development is currently underway for a baffle prototype manifested for launch on an Oligo satellite in February.



Preliminary, high-level design of sub-scale space prototype of THERMOS ETHER subsystem.

THERMOS X OLIGO SPACE

Beyond our prototype, to facilitate mitigating risks, THERMOS was designed around proven and well-understood technologies.

Likelihood → Impact ↓	Very Unlikely	Unlikely	Possible	Likely	Very Likely
Severe	R6, R16	R1			
Major	R2, R10	R4, R15, R20	R3, R11, R13, R17		
Moderate	R14	R9	R7, R8, R12, R18, R19	R5	
Minor	R21	R22	R23		
Negligible		R24	R25		

Overall, THERMOS delivers sufficient long-term cryogenic propellant storage performance to not only meet the needs of Artemis III, but also return to HEO for refilling and then return to LEO for reuse.

Starship HLS Delta V and Prop Boiloff Budget for Artemis III													
Starship version:	V3	Dep. Orbit: TLI -	1040	m/s	PROPNEEDHEO	1,100,363							
Endurance NRHO:	90	Endurance LSP:	30	days									
Front insulation:	MLI40-A139	1-Way Payload:	13,152	kg									
Side insulation:	MLI60-A144	Return Payload:	30,000	kg									
Event - STAGE or Burn #	From	To	Purpose	Event Start at Mission Elapsed Time (MET) (seconds)	Event Ends at Mission Elapsed Time (MET) (seconds)	Wet mass before Event (kg)	Propellant mass before Event (kg)	Delta V (m/s)	Total Propellant Received during event (kg)	Total Boiloff during Event (kg)	Wet mass after Event (kg)	Propellant Mass Change	Propellant mass after Event (kg)
1	LEO 250	HEO	Enter HEO	0	300	2,500,226	2,300,000	2,160	0.0	4.3	1,399,838	-1,100,388	1,199,612
REFILL	HEO	HEO	Refill propellant	300	9103	1,399,838	1,199,612	0	1,100,388.1	25.6	2,500,201	1,100,363	2,299,974
2	HEO	TLI	TLI Manuever	9103	268303	2,500,201	2,299,974	1,040	0.0	752.8	1,890,239	-609,962	1,690,013
3	TLI	NRHO	Enter NRHO	268303	268483	1,890,239	1,690,013	450	0.0	0.5	1,675,087	-215,152	1,474,861
LOITER	NRHO	NRHO	Loiter at NRHO	268483	8044483	1,675,087	1,474,861	0	0.0	22,584.4	1,652,503	-22,584	1,452,276
DOCK	NRHO	NRHO	Dock with Orion	8044483	8048083	1,652,503	1,452,276	100	0.0	10.5	1,608,708	-43,794	1,408,482
4	NRHO	LLO 50	Enter LLO	8048083	8062483	1,608,708	1,408,482	750	0.0	41.8	1,315,219	-293,489	1,114,993
5	LLO	LSP	Landing Burn	8062483	8066083	1,315,219	1,114,993	2,050	0.0	10.5	758,438	-556,781	558,212
SURF MISSION	LSP	LSP	Operations during Surface Missio	8066083	10658083	758,438	558,212	0	0.0	134,049	624,389	-134,049	424,163
6	LSP	LLO 50	Enter LLO	10658083	10661683	611,237	424,163	1,860	0.0	10.5	370,923	-240,315	183,848
7	LLO 50	NRHO	Enter NRHO	10661683	10676083	370,923	183,848	750	0.0	41.8	303,220	-67,703	116,146
DOCK	NRHO	NRHO	Dock with Orion	10676083	10679683	303,220	116,146	100	0.0	10.5	295,176	-8,044	108,101
8	NRHO	TEI	TEI Manuever	10679683	10938883	295,176	108,101	450	0.0	753	260,826	-34,350	73,751
9	TEI	HEO	HEO	10938883	10938903	260,826	73,751	1,040	0.0	0	197,272	-63,554	10,197
PROP XFER	HEO	HEO	Prop xfer at HEO	10938903	11025303	197,272	10,197	0	0.0	251	397,021	199,749	209,946
10	HEO	HEO	Phasing at HEO?	11025303	11111703	397,021	209,946	0	0.0	251	396,770	-251	209,695
11	HEO	LEO 250	Enter LEO	11111703	11154903	396,770	209,695	2,160	0.0	125	222,146	-174,624	35,071

The THERMOS system and mission architecture are enabling for Starship HLS to perform its Artemis III mission by 2029.

Image credit: NASA

Appendix Slides

Parameter or Intermediate Variable Name	Excel Variable Name	Value	Units
LCH4 to LOX mass ratio	LCH4LOXRATIO	0.28	none
Sea level Raptor ISP	SLRAPISP	327	s
Vacuum Raptor ISP	VACRAPISP	380	s
g	GEE	9.80	m/s^2
Duration of landing burn	LANDBURN	10.00	s
Delta V needed Starbase to LEO 250 x 250 (incl 2,000 m/s losses)	DVEARTHTOLEO	9,500	m/s
Delta V LEO 250 x 250 to TLI	DVLEOTOTLI	3,200	m/s
Delta V LEO 250 x 250 to HEO 250 x ????	DVLEOTOHEO	2,200	m/s
Delta V HEO 250 X ???? to TLI	DVHEOTOTLI	1,000	m/s
Delta V HEO 250 X ???? to LEO 150 x ? (reentry)	DVHEOTOLEO	50	m/s
Delta V TLI to NRHO	DVTLITONRHO	450	m/s
Delta V Orion docking burn	DVORIONDOCK	100	m/s
Delta V NRHO to LLO 50 x 50	DVNRHOTOLLO	750	m/s
Delta V LLO 50 x 50 to lunar South pole	DVLLOTOLSP	2,050	m/s
Delta V NRHO to TEI	DVNRHOTOTEI	450	m/s
Delta V TEI to HEO 300 x ????	DVTEITOHEO	1,000	m/s
Delta V TEI to LEO 250 x 250	DVTEITOLEO	3,000	m/s
Delta V Lunar South Pole to LLO 50 x 50	DVLSPTOLLO	1,860	m/s
Delta V deorbit burn from LEO 250 x 250	DVDEORBITLEO	100	m/s
Delta V budget for orbital maneuvers of tanker	DVTNKORBMAN	50	m/s
Delta V budget for landing burn	DVLANDBURN	196	m/s
Super Heavy dry mass (excluding upper stage)	SHDRYMASS	250,000	kg
Super Heavy propellant mass (note - not tracking LCH4/LOX for SH)	SHPROPMASS	4,050,000	kg
Super Heavy propellant remaining at MECO	SHPROPREMMECO	400,000	kg
Total wet mass of upper stage being boosted if boosting tanker	MASSUPPERSTAGETNK	2,638,767	kg
Total wet mass of upper stage being boosted, if boosing depot	MASSUPPERSTAGEDEP	2,668,990	kg
Total wet mass of upper stage being boosted if boosting lunar cargo s	MASSUPPERSTAGECARGO	2,578,499	kg
Delta V imparted on upper stage by SH	STARSHIPDVATSTAGING	2,393	m/s
Terminal velocity of tanker (for belly flop maneuver)	TNKTERMVEL	80	m/s
Tanker dry mass (structures only, excl. payload)	TNKDRYMASS	138,767	kg
Tanker propellant mass (all)	TNKPROPMASS	2,500,000	kg
Tanker LOX "payload"	TNKLOXPAYLOAD	0	kg
Tanker LCH4 "payload"	TNKLCH4PAYLOAD	0	kg
Tanker propellant delivered to HLS at HEO (max)	MAXPROPDELHEO	200,000	kg
HLS dry mass (structures only, excl. Artemis crew/eqpmt)	HLSDRYMASS	178,499	kg
HLS propellant mass (all)	HLSPROPMASS	2,300,000	kg
HLS LOX mass	HLSLOXMASS	1,800,000	kg
HLS LCH4 mass	HLSLCH4MASS	500,000	kg
Tanker propellant transferred to Depot per trip	TNKPROPDELIVERED	287,647	kg
Number of tankers required to fully refill tanks of a LEO Depot	NOTANKERS	15	number
Depot dry mass	DEPDRYMASS	168,990	kg
Depot propellant mass (all)	DEPPROPMASS	2,500,000	kg
Depot LOX "payload"	DEPLOXPAYLOAD	1,956,522	kg
Depot LCH4 "payload"	DEPLCH4PAYLOAD	543,478	kg

Delta V imparted on Depot by SH	DEPDVATSTAGING	2,377	m/s
Time for propellant transfer for Depot	DEPPROPXFERTIME	20,000	s
Propellant transfer rate	PROPXFERRATE	125.0	kg/s
Density for steel 301	ST301RHO	7,930	kg/m^3
Area of Starship solar panels		250	m^2
Solar conversion efficiency (MOL)		37%	
Power system efficiency		80%	
Electrical power available in HEO / NRHO orbit (facing Sun)		101,158	W e
Electrical power available on lunar surface		50,579	W e
Excess power available in NRHO to run cryocoolers	EXCESSPOWERNRHO	50,579	We
Boiloff Rates			
HLS boiloff rate at LEO	BORATELEO	0.00758	kg / s
Depot boiloff rate at LEO	BORATELEO_DEP	0.00018	kg / s
Tanker boiloff rate at LEO	BORATELEO_TNK	0.16897	kg / s
HLS boiloff rate at NRHO	BORATENRHO	0.00000	kg / s
Depot boiloff rate at NRHO / HEO	BORATENRHO_DEP	0.00000	kg / s
HLS boiloff rate at LSP	BORATELSP	0.03331	kg / s

			HLS	DEP	TNK	
Starship Version			V3	V3	V3	
Passive Insulation solution - SS front			MLI40	MLI40	301STEEL	
Passive Insulation solution - SS sides			MLI60	MLI40	301STEEL	
Cryocooler technology			PETACH	PETACH	NONE	
Max thermal lift per cryocooler			1500	600	0	
Number of Cryocoolers to use			4	4	0	
Custom Baffles for Prop Mixing			2D Curved	1D Curved	Regular	
Net heat flux into propellant tanks	**NETHEATFLUX**	LEO	3713	86	82778	W
Net heat flux into propellant tanks	**NETHEATFLUX**	NRHO / HEO	0	0		W
Net heat flux into propellant tanks	**NETHEATFLUX**	LSP	163/17			W
	HVAPLOX	214000.00				W*s/kg
Boiloff rate LOX tank		LEO	0.00867	0.00020	0.19341	kg / s
Boiloff rate LOX tank		NRHO / HEO	0.00000	0.00000		kg / s
Boiloff rate LOX tank		LSP	0.03812			kg / s
	HVAPMETH	511000.00				W*s/kg
Boiloff rate LCH4 tank		LEO	0.00363	0.00008	0.08100	kg / s
Boiloff rate LCH4 tank		NRHO / HEO	0.00000	0.00000		kg / s
Boiloff rate LCH4 tank		LSP	0.01597			kg / s

Net Heat Flux Calculations

			HLS	DEP	TNK	
Projected area front	FRONTAREAPROJ		63.6	63.6	63.6	m2
Area side	SIDEAREA		1,747.4	1,747.4	1,747.4	m2
Orbit-average front area looking at Sun	OAFRONTSUN	LEO	59%	59%	59%	
Orbit-average side area looking at Sun	OASIDESUN	LEO	0%	0%	0%	
Orbit-average front area looking at Earth	OAFRONTEARTH	LEO	41%	41%	41%	
Orbit-average side area looking at Earth	OASIDEEARTH	LEO	29.5%	29.5%	29.5%	
Orbit-average front area looking at Sun	OAFRONTSUN	NRHO	100%	100%		
Orbit-average front area looking at Sun		LSP	0%	0%	0%	
Orbit-average side area looking at Sun		LSP	50%	50%	50%	
Orbit-average side area looking at Moon		LSP	50%	50%	50%	
Front absorptivity			0.02	0.005	0.25	
Front effective emissivity			0.02	0.005	0.58	
Side absorptivity			0.016	0.005	0.25	
Side effective emissivity			0.016	0.005	0.58	
Environmental heat flux reaching exterior tank	ENVHEATFLUX	LEO	6460	1947	77771	W th
Environmental heat flux reaching exterior tank	ENVHEATFLUX	NRHO	1739	435		W th
Environmental heat flux reaching exterior tank	ENVHEATFLUX	LSP	20763			W th
Environmental heat flux reaching tanks	ENVHEATFLUX	LEO	6460	1947	77771	W th
Environmental heat flux reaching tanks	ENVHEATFLUX	NRHO	1739	435		W th
Environmental heat flux reaching tanks	ENVHEATFLUX	LSP	20763			W th
Internal heat flux conducted to tanks	INTHEATFLUX		500	500	500	W th
Solar panel heat flux onto side of tanks	BACKPANELFLUX	LEO	124	39	4507	W th
Solar panel heat flux onto side of tanks	BACKPANELFLUX	NRHO	211	66		W th
Solar panel heat flux onto side of tanks	BACKPANELFLUX	LSP	1054			W th
Power-limited cooling capacity (in orbit)			3372	3372		
Power-limited cooling capacity (on lunar surface)			7200	7200		
Heat flux removed by CC (in orbit)			-3372	-2400	0	W th
Heat flux removed by CC (on lunar surface)			-6000			W th

Dashboard knobs- Performance goals / decisions	Excel cell name	Value			Units	Notes
Required Endurance at NRHO	REQENDNRHO	[illegible]			days	[illegible]
Required Endurance at LSP	REQENDLSP	[illegible]			days	[illegible]
Starship HLS Payloads staying on Moon	HLS1WAYPAYLOAD	[illegible]			kg	[illegible]
Starship HLS Payloads returning to NRHO	HLSPAYLOADMASS	[illegible]			kg	[illegible]
How much delta V from HEO to TLI?	TLIMINUS	[illegible]			m/s	[illegible]
Dashboard knobs - Technology Choices	**Default Variable Names**	**Value**	**Value**	**Value**	**Propellant Margin LSP - NRHO**	**25.5%**
		For HLS	For Depot	For Tanker	**Total Number of Tankers**	**15**
		default name	**Suffix: _DEP**	**Suffix: _TNK**		
Starship Version	STARSHIPV	[illegible]	[illegible]	[illegible]		[illegible]
Passive insulation solution - SS front	PASSINSULFRONT	MLI[illegible]	MLI[illegible]	[illegible]		[illegible]
Passive insulation solution - SS sides	PASSINSULSIDE	MLI[illegible]	MLI[illegible]	[illegible]		[illegible]
Radiator design - backside of solar panels	PANELRADIATORS	[illegible]	[illegible]	[illegible]		[illegible]
Cryocooler technology	CRYOCOOLERS	[illegible]	[illegible]	NONE		[illegible]
Cryo Sizing: Max Thermal Power of Cryocoolers used, per Cryocooler Unit	CRYOPOWER	[illegible]	[illegible]	[illegible]	W(th)	watts of heat removed by cryocooler (cooling capacity)
Number of Cryocoolers to use	NUMBERCRYOS	[illegible]	[illegible]	[illegible]		[illegible]
Take deployable solar arrays as 1-way payload to power the cryocoolers while landed?	LUNARCRYOS	[illegible]				
Baffles Customized for Prop Mixing	CUSTBAFFLES	[illegible]	[illegible]	Regular		
Dashboard knobs - orientations (locked to optimal)						
Orientation strategy at LEO	ORIENTLEO	FaceSun	FaceSun	FaceSun		
Orientation strategy at HEO	ORIENTHEO	FaceSun	FaceSun			
Orientation strategy at NRHO	ORIENTNRHO	FaceSun				
Dashboard knobs used for stress-testing the HLS mission						
MLI Degradation factor	MLIDEGRADE	[illegible]				[illegible]
Number of failed cryocoolers	FAILEDCRYOS	[illegible]				[illegible]
Dashboard knobs - not used for HuLC						
Lunar Cargo Starship Payload	CARGOPAYLOADMASS	[illegible]			kg	This is used only for calculations of number of tankers required for cargo missions

THERMOS

			HLS	Depot	Tanker	
Starship Version			V3	V3	V3	
Passive Insulation solution - SS front			MLI40	MLI40	301STEEL	
Passive Insulation solution - SS sides			MLI60	MLI40	301STEEL	
Cryocooler technology			PETACH	PETACH	NONE	
Number of Cryocoolers to use			4	4	0	
Custom Baffles for Prop Mixing			2D Curved	1D Curved	Regular	
Baseline Dry Mass			138767	138767	138767	kg
+ Mass of passive insulation (front)	**FRONTAREACONE**	**PASSINSULFRONT**	2785	2785	0	kg
+ Mass of passive insulation (sides)	**SIDEAREA**	**PASSINSULSIDE**	27958	20968	0	kg
+ Delta mass of custom baffles			600	600	0	kg
+ Mass of cryocoolers			4200	1680	0	kg
+ Delta mass of solar panels (if sawtooth radiators used)			1500	1500	0	kg
+ Mass of cooling tubes & manifolds			4669	4669	0	kg
- Mass of MLI supports, if both Cryo and MLI used	FRONTAREACONE	SIDEAREA	-1979	-1979	0	kg
Total Dry Mass of Configured Starship	**SSDRYMASS**		**178499**	**168990**	**138767**	

Mass of Payloads Staying on the Moon

Mass of deployable solar arrays			8055			kg
Consumables			2400			kg
Rovers			3000			kg
Experiments			4000			kg
Total	**PAYLOADS1WAY**		**17455**			kg

MLI Calculations Section

Custom Baffles Calculations Section

Cryocooler Tubes Mass Calculations Section

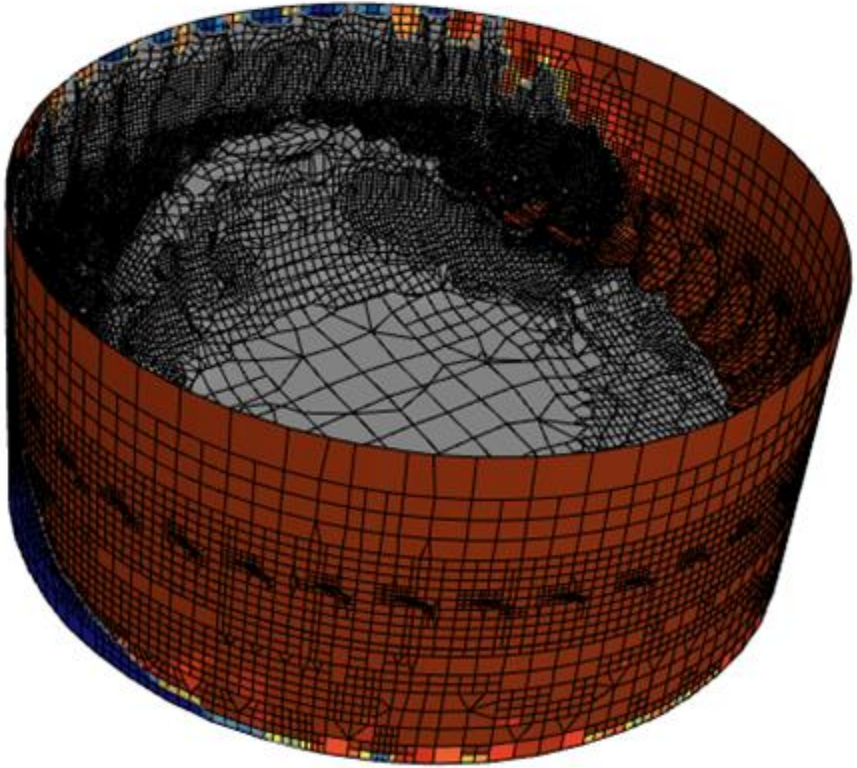
	Variable name	Value	HLS Result	Depot Result	Tanker Result	Unit
Outer diameter of cooling tube	**TUBEOUTERD**	14.00				mm
Inner diameter of cooling tube	**TUBEINNERD**	8.00				mm
Mass of cooling tubes per m of length (incl work fluid)	**LINMASSTUBES**	1.09	1.09	1.09	1.09	kg / m
Lateral spacing of tubes on tank	**TUBESPACING**	1	1	1	1	m
Length of tank	SHIPHEIGHT		69.8	69.8	69.8	m
Number of tubes on tank			28	28	28	#
Total length of tubes			3909	3909	3909	m
Total mass of tubes			4269	4269	4269	kg
Number of manifolds (=2X number of cryocoolers)		8	8	8	8	#
Mass per manifold	MANIFOLDMASS	50	50	50	50	kg
Total mass of cryocooler manifolds and tubes	**MASSTUBEMAN**		**4669**	**4669**	**4669**	kg
Mass of lightweight MLI supports per unit area	**MASSMLISUPP**	2				

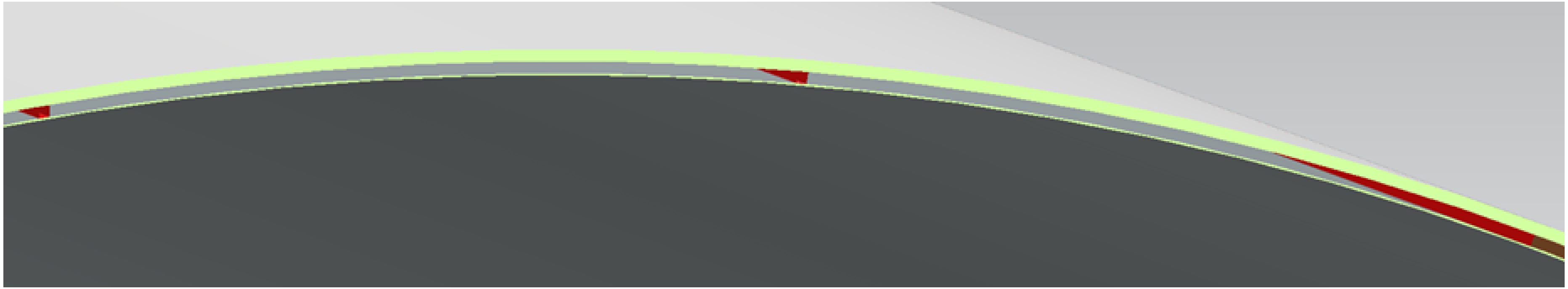
Deployable Solar Panels Calculation

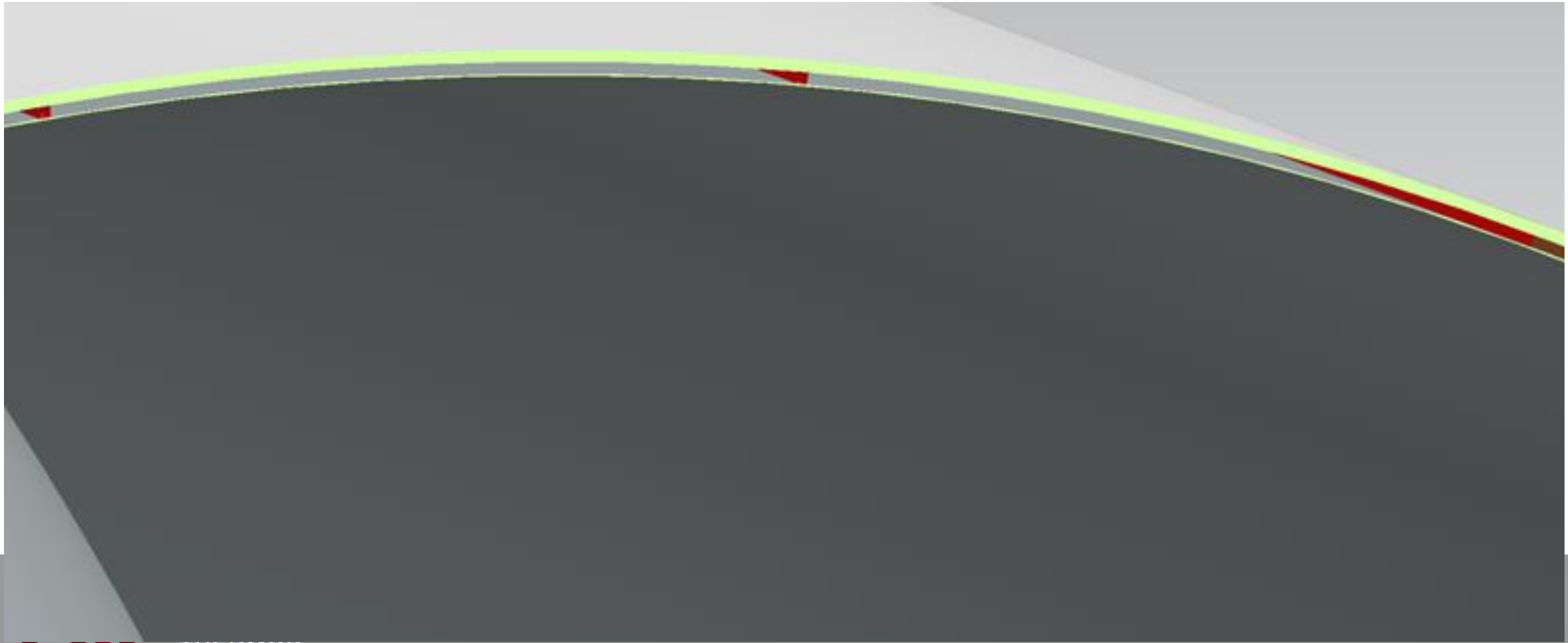
Design power Wth of HLS Cryocoolers (total)			6000			Wth
Electrical power demand of cryocoolers, +20%	**LUNARARRAYSPWR**		108000			We
Area of solar panels required			309.8			m^2
Specific mass of solar arrays per unit area	SPECMASSPANELS	20				kg / m^2
Total mass of deployable solar panels required			6196			kg
Plus overhead mass for tracking and structure		30%	1859			kg
Total mass of deployable arrays	**MASSDEPLARRAYS**		**8055**			kg

Starship HLS Delta V and Prop Boiloff Budget for Artemis III													
Starship version:	V3	Dep. Orbit: TLI -	1000	m/s	PROPNEEDHEO	1,126,819							
Endurance NRHO:	90	Endurance LSP:	30	days									
Front insulation:	MLI40	1-Way Payload:	17,455	kg									
Front insulation:	MLI40	Return Payload:	30,000	kg									
Event - STAGE or Burn #	**From**	**To**	**Purpose**	**Event Start at Mission Elapsed Time (MET) (seconds)**	**Event Ends at Mission Elapsed Time (MET) (seconds)**	**Wet mass before Event (kg)**	**Propellant mass before Event (kg)**	**Delta V (m/s)**	**Total Propellant Received during event (kg)**	**Total Boiloff during Event (kg)**	**Wet mass after Event (kg)**	**Propellant Mass Change**	**Propellant mass after Event (kg)**
1	LEO 250	HEO	Enter HEO	0	300	2,525,955	2,300,000	2,200	0.0	2.3	1,399,136	-1,126,819	1,173,181
REFILL	HEO	HEO	Refill propellant	300	9315	1,399,136	1,173,181	0	1,126,818.8	0.0	2,525,955	1,126,819	2,300,000
2	HEO	TLI	TLI Manuever	9315	268515	2,525,955	2,300,000	1,000	0.0	0.0	1,931,102	-594,853	1,705,147
3	TLI	NRHO	Enter NRHO	268515	268695	1,931,102	1,705,147	450	0.0	0.0	1,711,299	-219,802	1,485,344
LOITER	NRHO	NRHO	Loiter at NRHO	268695	8044695	1,711,299	1,485,344	0	0.0	0.0	1,711,299	0	1,485,344
DOCK	NRHO	NRHO	Dock with Orion	8044695	8048295	1,711,299	1,485,344	100	0.0	0.0	1,665,957	-45,342	1,440,003
4	NRHO	LLO 50	Enter LLO	8048295	8062695	1,665,957	1,440,003	750	0.0	0.0	1,362,067	-303,890	1,136,113
5	LLO	LSP	Landing Burn	8062695	8066295	1,362,067	1,136,113	2,050	0.0	0.0	785,465	-576,603	559,510
SURF MISSION	LSP	LSP	Operations during	8066295	10658295	785,465	559,510	0	0.0	86,332	699,133	-86,332	473,178
6	LSP	LLO 50	Enter LLO	10658295	10661895	681,677	473,178	1,860	0.0	0.0	413,680	-267,997	205,181
7	LLO 50	NRHO	Enter NRHO	10661895	10676295	413,680	205,181	750	0.0	0.0	338,220	-75,460	129,721
DOCK	NRHO	NRHO	Dock with Orion	10676295	10679895	338,220	129,721	100	0.0	0.0	329,259	-8,961	120,760
8	NRHO	TEI	TEI Manuever	10679895	10939095	329,259	120,760	450	0.0	0	291,782	-37,477	83,283
9	TEI	HEO	HEO	10939095	10939115	291,782	83,283	1,000	0.0	0	223,068	-68,714	14,569
PROP XFER	HEO	HEO	Prop xfer at HEO	10939115	11025515	223,068	14,569	0	0.0	0	423,068	200,000	214,569
10	HEO	HEO	Phasing at HEO?	11025515	11111915	423,068	214,569	0	0.0	0	423,068	0	214,569
11	HEO	LEO 250	Enter LEO	11111915	11155115	423,068	214,569	2,200	0.0	0	234,340	-188,729	25,840

Parameter or Intermediate Variable Name	Excel Variable Name	Value	Units
LCH4 to LOX mass ratio	LCH4LOXRATIO	0.28	none
Sea level Raptor ISP	SLRAPISP	327	s
Vacuum Raptor ISP	VACRAPISP	380	s
g	GEE	9.80	m/s^2
Duration of landing burn	LANDBURN	10.00	s
Delta V needed Starbase to LEO 250 x 250 (incl 2,000 m/s losses)	DVEARTHTOLEO	9,500	m/s
Delta V LEO 250 x 250 to TLI	DVLEOTOTLI	3,200	m/s
Delta V LEO 250 x 250 to HEO 250 x ????	DVLEOTOHEO	2,200	m/s
Delta V HEO 250 X ???? to TLI	DVHEOTOTLI	1,000	m/s
Delta V HEO 250 X ???? to LEO 150 x ? (reentry)	DVHEOTOLEO	50	m/s
Delta V TLI to NRHO	DVTLITONRHO	450	m/s
Delta V Orion docking burn	DVORIONDOCK	100	m/s
Delta V NRHO to LLO 50 x 50	DVNRHOTOLLO	750	m/s
Delta V LLO 50 x 50 to lunar South pole	DVLLOTOLSP	2,050	m/s
Delta V NRHO to TEI	DVNRHOTOTEI	450	m/s
Delta V TEI to HEO 300 x ????	DVTEITOHEO	1,000	m/s
Delta V TEI to LEO 250 x 250	DVTEITOLEO	3,000	m/s
Delta V Lunar South Pole to LLO 50 x 50	DVLSPTOLLO	1,860	m/s
Delta V deorbit burn from LEO 250 x 250	DVDEORBITLEO	100	m/s
Delta V budget for orbital maneuvers of tanker	DVTNKORBMAN	50	m/s
Delta V budget for landing burn	DVLANDBURN	196	m/s
Super Heavy dry mass (excluding upper stage)	SHDRYMASS	250,000	kg
Super Heavy propellant mass (note - not tracking LCH4/LOX for SH)	SHPROPMASS	4,050,000	kg
Super Heavy propellant remaining at MECO	SHPROPREMMECO	400,000	kg
Total wet mass of upper stage being boosted if boosting tanker	MASSUPPERSTAGETNK	2,638,767	kg
Total wet mass of upper stage being boosted, if boosing depot	MASSUPPERSTAGEDEP	2,668,990	kg
Total wet mass of upper stage being boosted if boosting lunar cargo s	MASSUPPERSTAGECARGO	2,578,499	kg
Delta V imparted on upper stage by SH	STARSHIPDVATSTAGING	2,393	m/s
Terminal velocity of tanker (for belly flop maneuver)	TNKTERMVEL	80	m/s
Tanker dry mass (structures only, excl. payload)	TNKDRYMASS	138,767	kg
Tanker propellant mass (all)	TNKPROPMASS	2,500,000	kg
Tanker LOX "payload"	TNKLOXPAYLOAD	0	kg
Tanker LCH4 "payload"	TNKLCH4PAYLOAD	0	kg
Tanker propellant delivered to HLS at HEO (max)	MAXPROPDELHEO	200,000	kg
HLS dry mass (structures only, excl. Artemis crew/eqpmt)	HLSDRYMASS	178,499	kg
HLS propellant mass (all)	HLSPROPMASS	2,300,000	kg
HLS LOX mass	HLSLOXMASS	1,800,000	kg
HLS LCH4 mass	HLSLCH4MASS	500,000	kg
Tanker propellant transferred to Depot per trip	TNKPROPDELIVERED	287,647	kg
Number of tankers required to fully refill tanks of a LEO Depot	NOTANKERS	15	number
Depot dry mass	DEPDRYMASS	168,990	kg
Depot propellant mass (all)	DEPPROPMASS	2,500,000	kg
Depot LOX "payload"	DEPLOXPAYLOAD	1,956,522	kg
Depot LCH4 "payload"	DEPLCH4PAYLOAD	543,478	kg
Delta V imparted on Depot by SH	DEPDVATSTAGING	2,377	m/s
Time for propellant transfer for Depot	DEPPROPXFERTIME	20,000	s
Propellant transfer rate	PROPXFERRATE	125.0	kg/s
Density for steel 301	ST301RHO	7,930	kg/m^3
Area of Starship solar panels		250	m^2
Solar conversion efficiency (MOL)		37%	
Power system efficiency		80%	
Electrical power available in HEO / NRHO orbit (facing Sun)		101,158	W e
Electrical power available on lunar surface		50,579	W e
Excess power available in NRHO to run cryocoolers	EXCESSPOWERNRHO	50,579	We
Boiloff Rates			
HLS boiloff rate at LEO	BORATELEO	0.00758	kg / s
Depot boiloff rate at LEO	BORATELEO_DEP	0.00018	kg / s
Tanker boiloff rate at LEO	BORATELEO_TNK	0.16807	kg / s
HLS boiloff rate at NRHO	BORATENRHO	0.00000	kg / s
Depot boiloff rate at NRHO / HEO	BORATENRHO_DEP	0.00000	kg / s
HLS boiloff rate at LSP	BORATELSP	0.03331	kg / s







Lookup table name	*Column range name*		*Excel data range name*	
Coatings Properties Lookup Table	**SURFACETYPES**		**COATINGLOOKUP**	

Surface Material Description	Lookup name	mass in kg / m2	Abs	Emm
	don't use this			
	BLACK	1	0.99	0.98
No coating, 301 steel	**301STEEL**	0	0.25	0.58
White Paint	**WHITE**	1	0.12	0.9
Magnesium Oxide in White paint	**MGOWHITE**	1	0.09	0.9
AZ Tech Inorganic Low Alpha White Paint	**AZTWHITE**	1	0.09	0.91
silver backed, used on skylab, space shuttle, and hubble	**QIOPTIQ**	1	0.06	0.83
SOLEC LO/MIT	**SOLEC**	1	0.23	0.17
MLI, 40 layers	**MLI40**	12	0.005	0.005
MLI, 20 layers	**MLI20**	8	0.006	0.006
MLI, 60 layers	**MLI60**	16	0.004	0.004

Lookup table name			*Excel data range name*	
Cryocooler Version Lookup Table			**CRYOLOOKUP**	

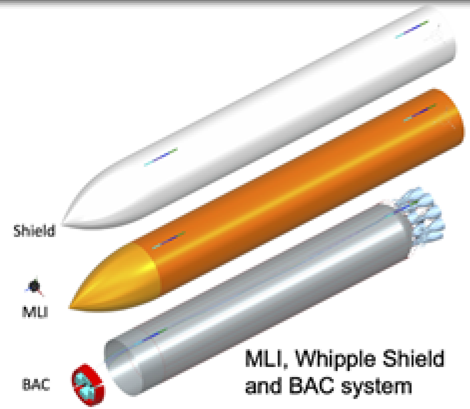
Type of Cryocooler	Model var name	Row No.	SPEC MASS	PWR RATIO
units			kg/W(th)	none
no cryocooler used	**NONE**	2	0	0
generic efficient cryocooler	**GENERIC**	3	2	20
heavy, inefficient cryocooler	**HEAVYGEN**	4	6	60
Petach pulse-tube cryocooler	**PETACH**	5	0.7	15

Translunar Heat Rejection and Mixing for Orbital Sustainability (THERMOS)

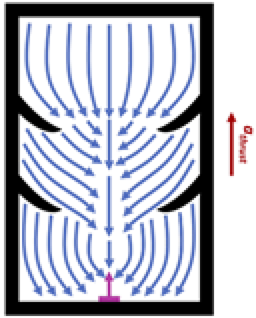
Massachusetts Institute of Technology

Theme Category, Major Objectives & Technical Approach

- **Theme Categories:** (1) Large Surface Area Radiative Insulation and (2) Propellant Mixing Devices
- **Major Objective:** A true systems solution for a healthy Lunar Ascent Propellant Margin of Starship HLS
- **Technical concept:** intercept and reject heat loads, and also mix the propellant for thermal homogeneity (HLS & Depot)
- **Systems approach:** evaluate & stress- test conceptual designs for alternative Boil-off Control Systems, for their impact on Ascent Propellant Margin, number of tanker launches required, *and also* for resilience to unexpectedly high MLI degradation



MLI, Whipple Shield and BAC system


Modified Baffle Geometry + Pump = Propellant Mixing Device

Key Design Details & Innovations of the Concept

- **Model-based engineering:** simultaneous decisions for mission ConOps, technology infusion and system sizing, for CFM technologies which could reduce boil-off *but* also add mass
- **Technical innovation 1**: **modified baffle geometry** plus recirculation pump, leveraging regular flight operations (i.e. spin-stabilizing, settling thrusts) to mix & destratify propellants.
- **Technical innovation 2:** a **combined MLI / Whipple Shield system mounted on tank-welded BAC cryocooler tubes**, saving structural mass and intercepting heat leaks at source
- **A key finding:** contingency operational modes compensate for high MLI Degradation Factor (DF) up to **DF of 9X** if V3 Starship + Cryocoolers are used, vs. just 5X if passive-only V2 Starship

Summary of Schedule & Costs: Design, Build, Fly, Fix & Fly Again!

2025 *H1:* Present at HuLC; *H2:* Detailed Design and Project Planning

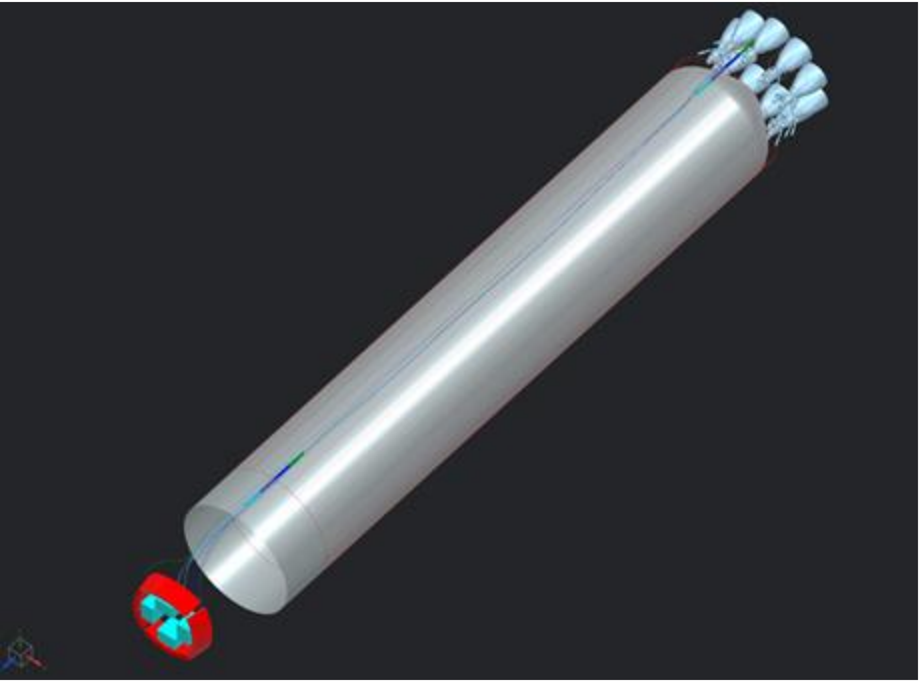
2026 *H1:* Build tanks with new MLI, Cryocoolers & Baffles;
H2: Flight test, aboard one of the regular Starship tests

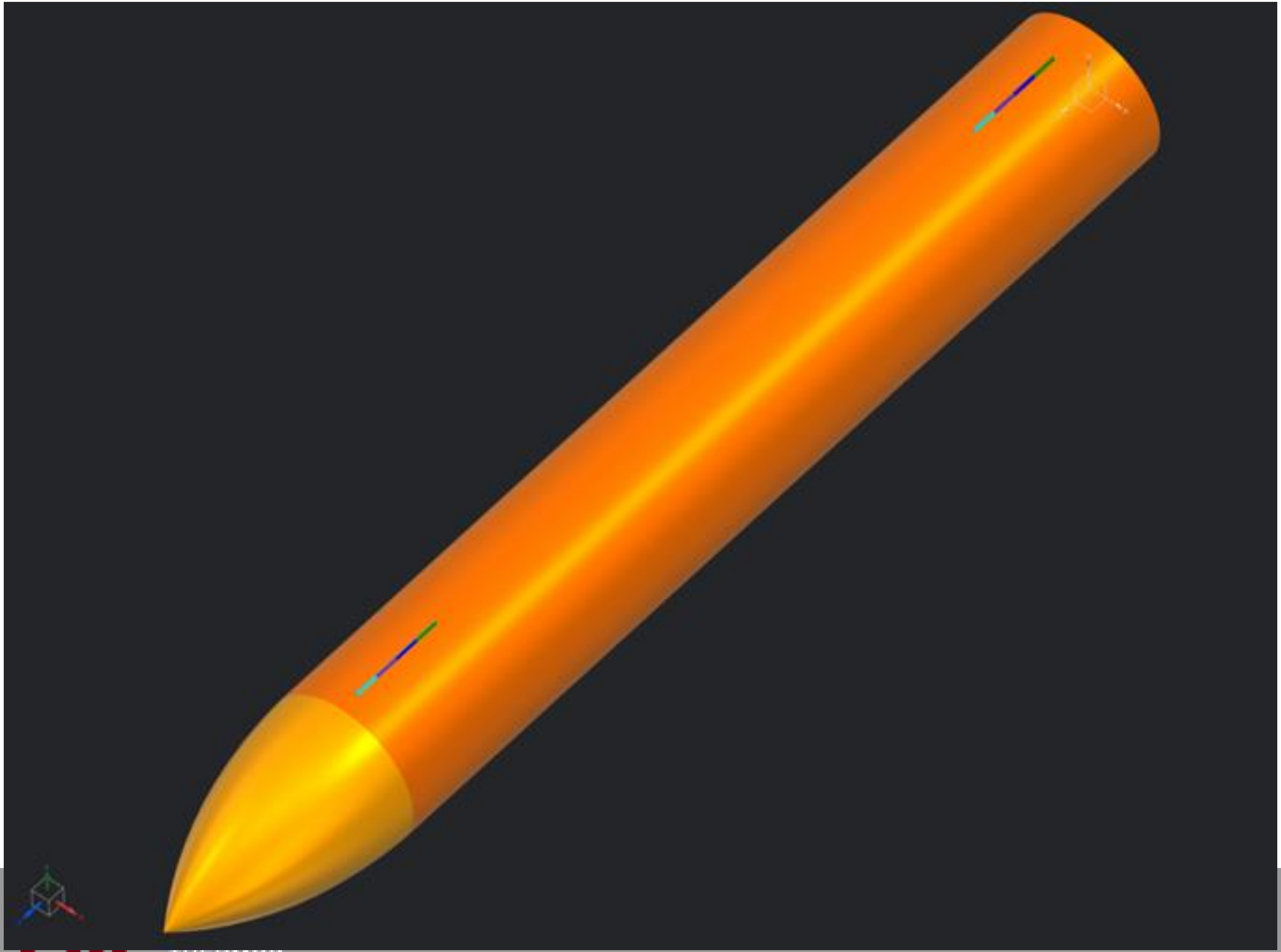
2027 *H1*: Incorporate flight learnings; uncrewed HLS flight to LEO / HEO;
H2: Uncrewed HLS to HEO, NRHO & LSP, uncrewed Depot to LEO

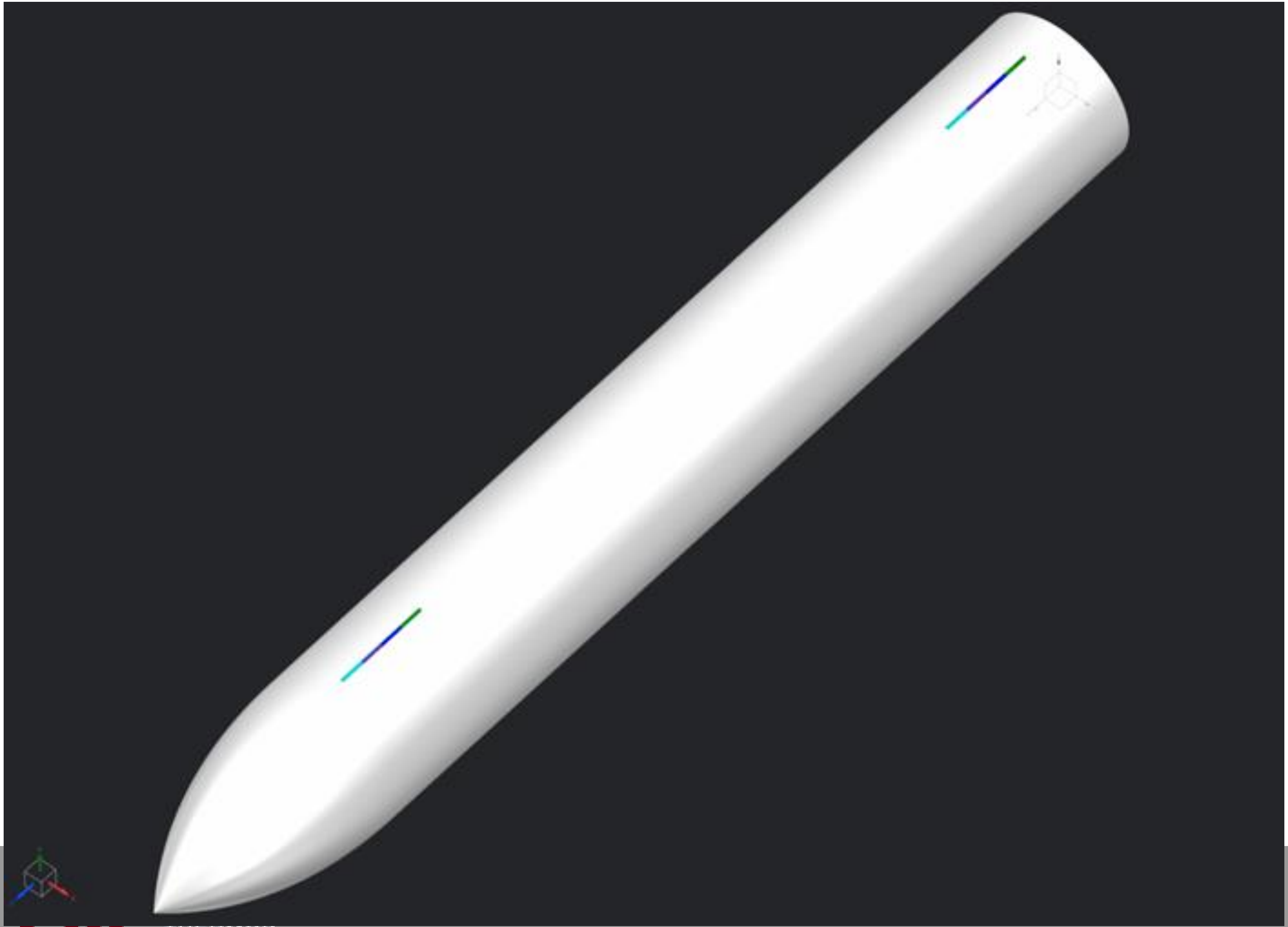
2028 *H1*: Incorporate changes to HLS and Depot;
H2: repeat all uncrewed flight tests

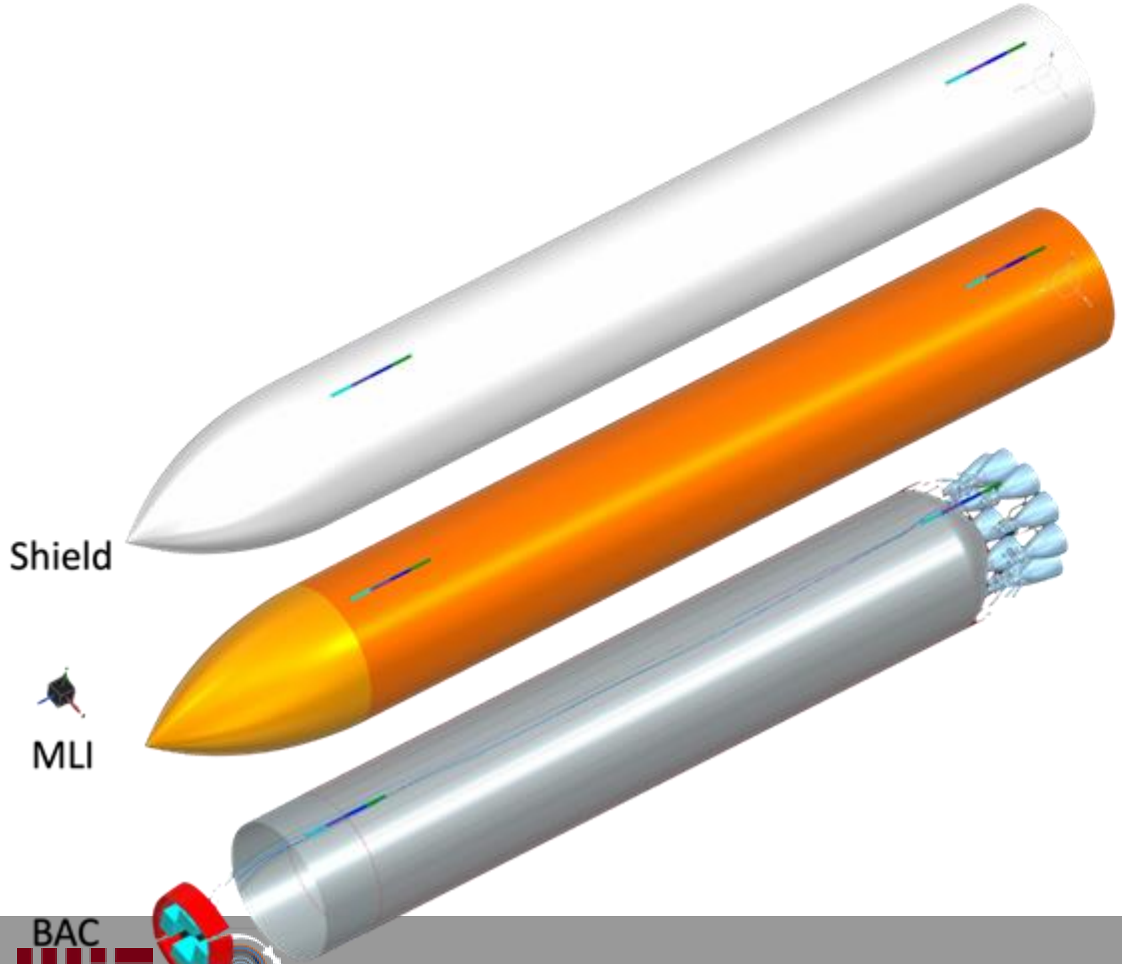
2029 *Q1*: Conclude human-rating certification of THERMOS;
Q2-Q4: THERMOS available for use in crewed Artemis III mission

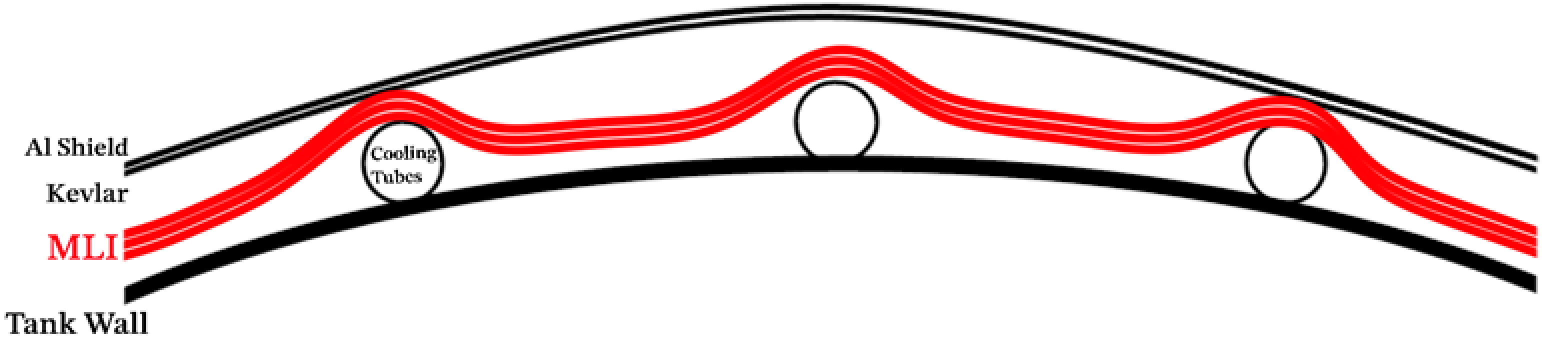
Lifecycle development cost (internal to SpaceX): from **$200M - $500M**
Annual Operating cost during Artemis III: from **$40M - $100M**

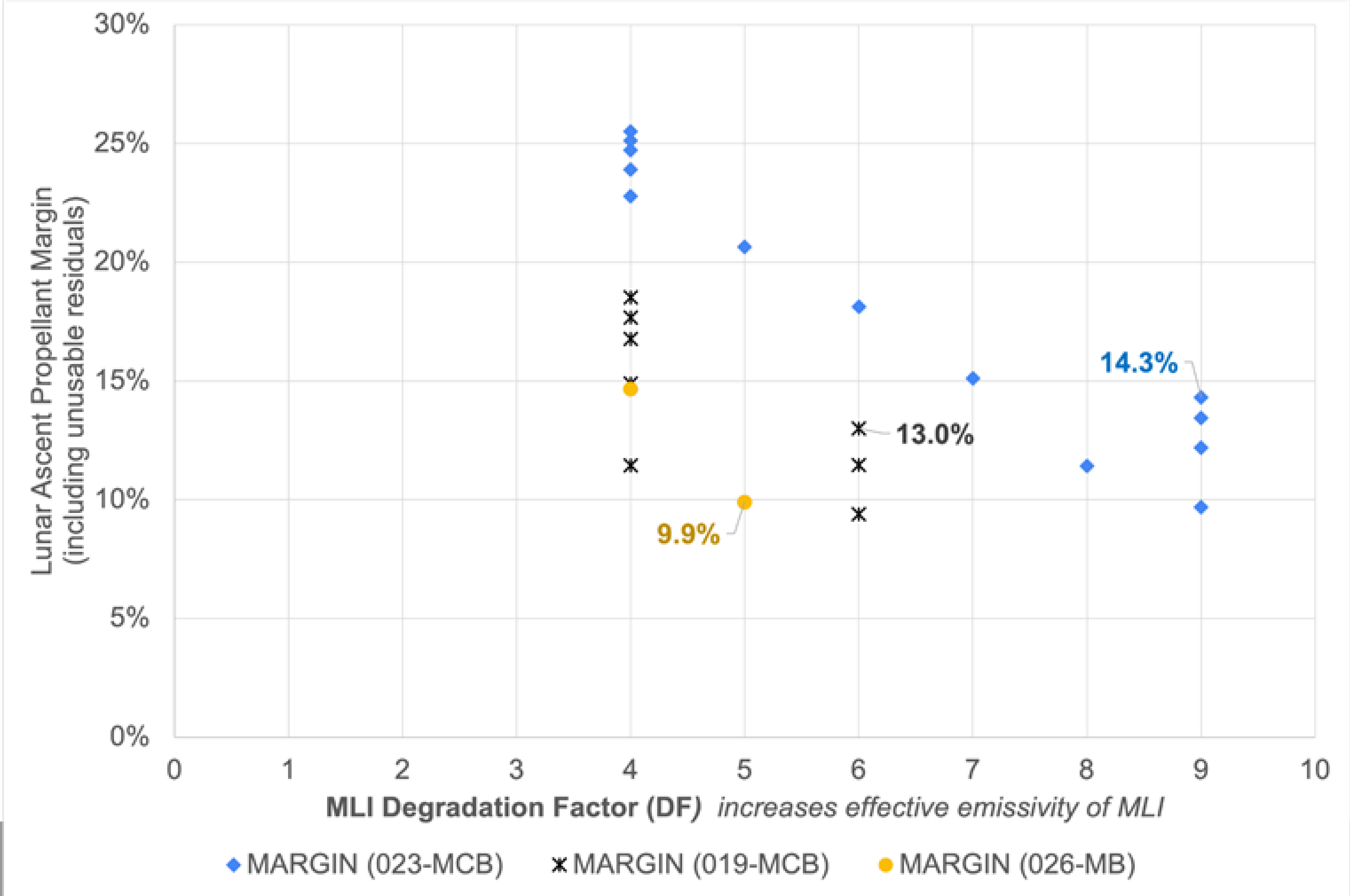




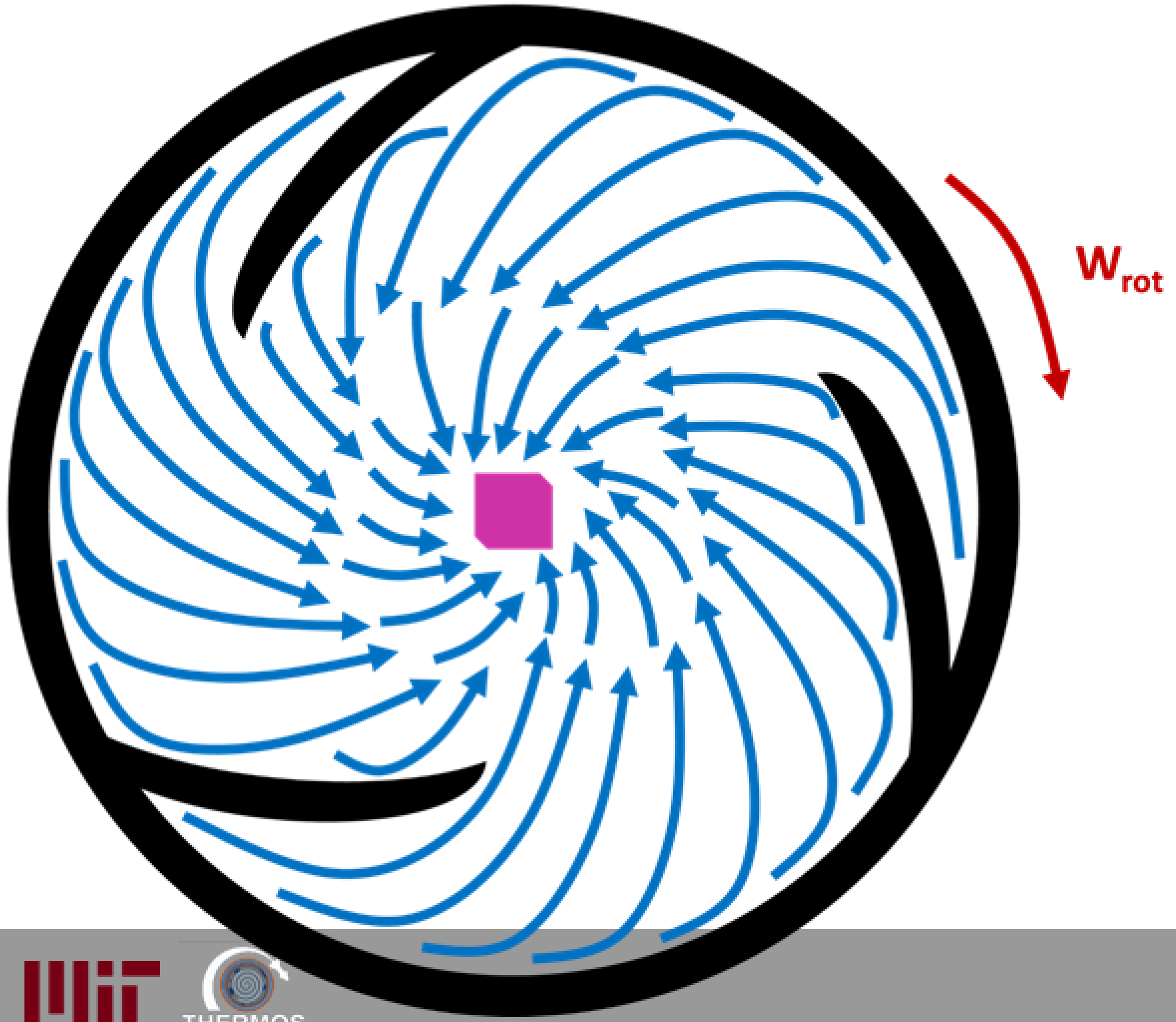



Shield
MLI
BAC

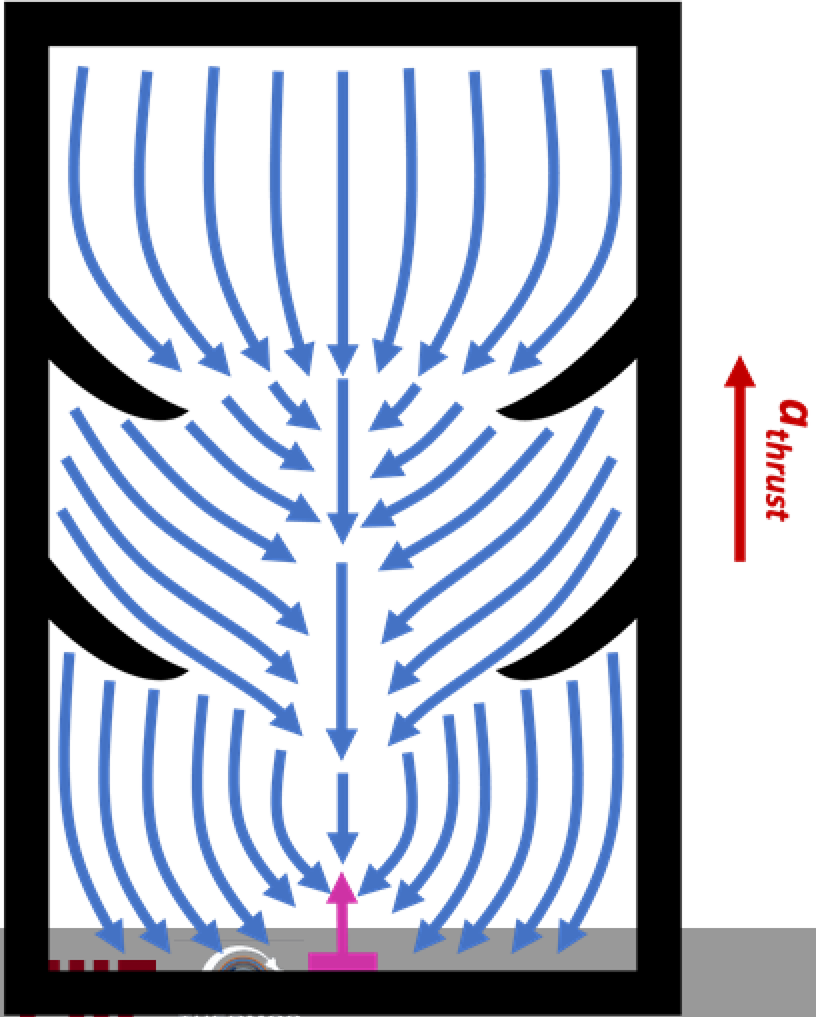

Al Shield
Kevlar
MLI
Tank Wall
Cooling Tubes



30%
25%
20%
15%
10%
5%
0%
Lunar Ascent Propellant Margin (including unusable residuals)
14.3%
13.0%
9.9%
0
1
2
3
4
5
6
7
8
9
10
MLI Degradation Factor (DF) increases effective emissivity of MLI
MARGIN (023-MCB)
MARGIN (019-MCB)
MARGIN (026-MB)



W_{rot}

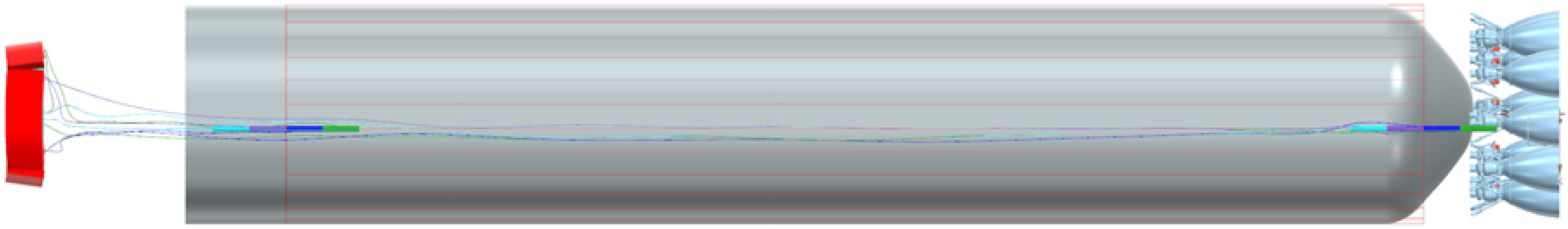

a_{thrust}

Likelihood → Impact ↓	Very Unlikely	Unlikely	Possible	Likely	Very Likely
Severe	R6, R16	R1			
Major	R2, R10	R4, R15, R20	R3, R11, R13, R17		
Moderate	R14	R9	R7, R8, R12, R18, R19	R5	
Minor	R21	R22	R23		
Negligible		R24	R25		

Risk ID	Risk Description	Impact	Likelihood	Mitigation Strategy
R1	Complete cryocooler failure	Severe	Unlikely	Hybrid passive-active system; ETHER ensures mixing; vent gas used for pressure control
R2	MLI degradation exceeds design DF = 8	Major	Rare	MLI alone will keep boil-off low enough
R3	Propellant mixing ineffective due to baffle/pump failure	Major	Possible	CFD-tested geometry; dual-mode mixing via rotation and axial pump
R4	Structural failure of BAC cooling tubes during launch vibrations	Major	Unlikely	Stainless steel tubes; FEA-validated welds; launch vibration testing
R5	Power shortfall at lunar surface limits cryocooler operation	Moderate	Likely	Deployable vertical solar arrays; tolerate minor boil-off; prioritize mixing on surface
R6	Delay in Starship HLS development blocks integration	Severe	Rare	Modular additive design; coordinate early with SpaceX for interface alignment
R7	Internal tank sensor or axial pump failure	Moderate	Possible	Sensor redundancy; fallback to passive mixing and pressure control
R8	Excess conductive heat through MLI mounting brackets	Moderate	Possible	Use low-thermal-conductivity mounts (PEEK/G-10); verify through modeling
R9	Radiator sawtooth panel underperforms under specific sun angles	Moderate	Unlikely	Secondary radiators or alternate geometry under review; validate in thermal modeling
R10	Material incompatibility (e.g., Al in LOX tank, charging risk with Kapton)	Major	Unlikely	Use compatible materials only; incorporate electrostatic discharge path; verify safety standards
R11	CFD predictions do not match true behavior in zero-g	Major	Possible	Validate via parabolic flights and ground rotation tests
R12	Boil-off venting induces unwanted rotational or translational thrust	Moderate	Possible	Vent direction controlled; integrated into RCS logic
R13	Modified baffles amplify slosh during propulsive maneuvers	Major	Possible	CFD and dynamic modeling; shape optimization preserves anti-slosh function
R14	MLI suffers launch damage or displacement during ascent	Moderate	Rare	Perforated MLI design; Kevlar-reinforced outer shield; vibration-tested mount points
R15	TVS (venting system) fails to maintain proper ullage pressure	Major	Unlikely	Redundant venting paths; automated thermal-pressure feedback loop
R16	Excess boil-off jeopardizes LAPM >10% for safe crew return	Severe	Rare	Concept stress-tested for up to 3 cryocooler failures and MLI DF = 9
R17	Overall system mass or volume exceeds Starship integration envelope	Major	Possible	CAD and mass tracking with margin; early interface checks with SpaceX
R18	Ground cryo testing does not represent true lunar/space environment	Moderate	Possible	Flight test campaign in LEO/HEO; simulate NRHO via environmental modeling
R19	Neon leak in BAC loop or fitting contamination	Moderate	Possible	Closed-loop architecture; high-quality fittings; leak testing and pressure monitoring
R20	Cryocooler control software fails or behaves erratically	Major	Possible	Software-in-loop testing; fallback logic; watchdog protocols
R21	Slight misalignment of MLI segments during install affects emissivity	Minor	Rare	Use segment-based blankets with installation tolerance; edge sealing to prevent hot spots
R22	Moisture in test setup skews thermal vacuum results	Minor	Unlikely	Use dry nitrogen purge; redundant thermocouples; flag data uncertainty in results

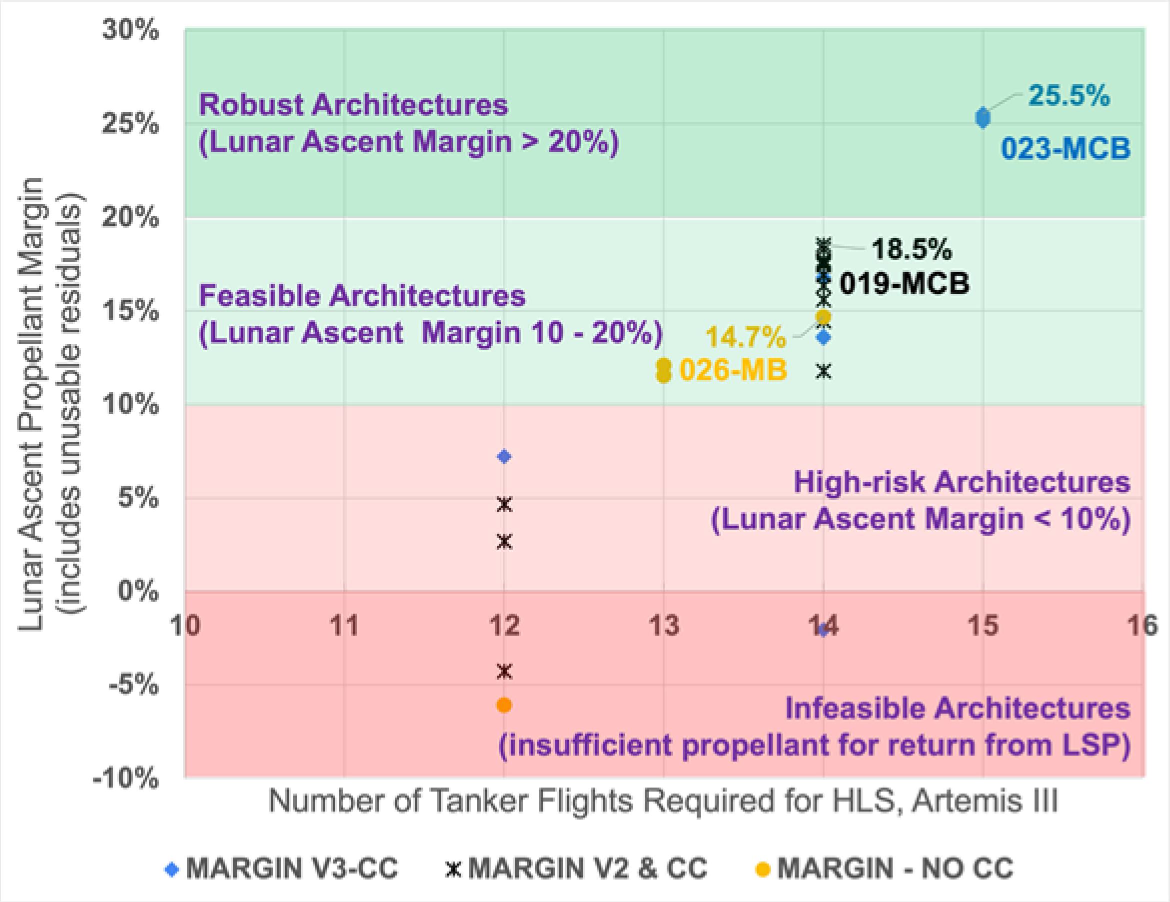
Scenario number	MLIDEGRADE	FAILED CRYOS	BORATE LSP (t/day)	ASCENT MARGIN
023-MCB-DF9-FC0	9	0	7.7	14.3%
023-MCB-DF9-FC1	9	1	8.0	13.5%
023-MCB-DF9-FC2	9	2	8.2	12.2%
023-MCB-DF9-FC3	9	3	8.5	9.7%
023-MCB-DF8-FC4	8	4	7.8	11.4%
023-MCB-DF7-FC4	7	4	6.8	15.1%
023-MCB-DF6-FC4	6	4	5.9	18.1%
019-MCB-DF6-FC0	6	0	3.2	13.0%
019-MCB-DF6-FC1	6	1	3.5	11.5%
019-MCB-DF6-FC2	6	2	3.8	9.4%
023-MCB-DF5-FC4	5	4	4.9	20.7%
026-MB-DF5-FC0	5	0	3.6	9.9%
023-MCB-DF4-FC0	4	0	2.9	25.5%
023-MCB-DF4-FC1	4	1	3.1	25.1%
023-MCB-DF4-FC2	4	2	3.4	24.7%
023-MCB-DF4-FC3	4	3	3.7	23.9%
023-MCB-DF4-FC4	4	4	3.9	22.8%
019-MCB-DF4-FC0	4	0	1.8	18.5%
019-MCB-DF4-FC1	4	1	2.1	17.7%
019-MCB-DF4-FC2	4	2	2.4	16.8%
019-MCB-DF4-FC3	4	3	2.6	14.9%
026-MB-DF4-FC0	4	0	2.9	14.7%
019-MCB-DF4-FC4	4	4	2.9	11.5%

THERMOS



Lookup table name			*Excel data range name*		*Rows lookup range:*	
Starship Version Lookup Table			**STARSHIPLOOKUP**		**STARSHIPLOOKUP_ROWS**	

Starship Version	**Model var name**	**Row No.**	**V1**	**V2**	**V3**	**Units**
Max payload mass to destination		2	0	100000	200000	kg
Tanker propellant load	**TNKPROPMASS**	3	1200000	1600000	2500000	kg
Depot propellant load	**DEPPROPMASS**	4	1200000	1600000	2500000	kg
HLS propellant load	**HLSPROPMASS**	5	1200000	1500000	2300000	kg
Ship height	**SHIPHEIGHT**	6	50.3	52.1	69.8	m
Tanker dry mass baseline, before tech	**TNKDRYMASS**	7	100000	103578	138767	kg
Depot dry mass baseline, before tech	**DEPDRYMASS**	8	100000	103578	138767	kg
HLS dry mass baseline, before tech	**HLSDRYMASS**	9	100000	103578	138767	kg
Booster prop load	**SHPROPMASS**	10	3300000	3650000	4050000	kg
External surface area of Starship	**SURFACEAREA**	11	1428	1479	1979	m2
Front surface area of Starship, projected	**FRONTAREAPROJ**	12	64	64	64	m2
Front surface area of Starship, conic	**FRONTAREACONE**	13	232	232	232	m2
Side surface area of Starship	**SIDEAREA**	14	1196	1247	1747	m2
Baffles Subsystem Mass	**STDBAFFLES**	15				kg


30%
25%
20%
15%
10%
5%
0%
-5%
-10%
Lunar Ascent Propellant Margin
(includes unusable residuals)
Robust Architectures
(Lunar Ascent Margin > 20%)
Feasible Architectures
(Lunar Ascent Margin 10 - 20%)
High-risk Architectures
(Lunar Ascent Margin < 10%)
Infeasible Architectures
(insufficient propellant for return from LSP)
25.5%
023-MCB
18.5%
019-MCB
14.7%
026-MB
10
11
12
13
14
15
16
Number of Tanker Flights Required for HLS, Artemis III
MARGIN V3-CC
MARGIN V2 & CC
MARGIN - NO CC

			HLS	DEP	TNK	
Starship Version			V3	V3	V3	
Passive Insulation solution - SS front			MLI60-A144	MLI60-A144	301STEEL	
Passive Insulation solution - SS sides			MLI60-A144	MLI60-A144	301STEEL	
Cryocooler technology			CREARE	CREARE	NONE	
Max thermal lift per cryocooler			150	150	0	
Number of Cryocoolers to use			7	8	0	
Custom Baffles for Prop Mixing			Regular	Regular	Regular	
Net heat flux into propellant tanks	**NETHEATFLUX**	LEO	6805	1139	82778	W
Net heat flux into propellant tanks	**NETHEATFLUX**	NRHO / HEO	1304	0		W
Net heat flux into propellant tanks	**NETHEATFLUX**	LSP	24698			W
	HVAPLOX	214000.00				W*s/kg
Boiloff rate LOX tank		LEO	0.01590	0.00266	0.19341	kg / s
Boiloff rate LOX tank		NRHO / HEO	0.00305	0.00000		kg / s
Boiloff rate LOX tank		LSP	0.05771			kg / s
	HVAPMETH	511000.00				W*s/kg
Boiloff rate LCH4 tank		LEO	0.00666	0.00111	0.08100	kg / s
Boiloff rate LCH4 tank		NRHO / HEO	0.00128	0.00000		kg / s
Boiloff rate LCH4 tank		LSP	0.02417			kg / s

Net Heat Flux Calculations

Projected area front	FRONTAREAPROJ		63.6	63.6	63.6	m2
Area side	SIDEAREA		1,747.4	1,747.4	1,747.4	m2
Orbit-average front area looking at Sun	OAFRONTSUN	LEO	59%	59%	59%	
Orbit-average side area looking at Sun	OASIDESUN	LEO	0%	0%	0%	
Orbit-average front area looking at Earth	OAFRONTEARTH	LEO	41%	41%	41%	
Orbit-average side area looking at Earth	OASIDEEARTH	LEO	29.5%	29.5%	29.5%	
Orbit-average front area looking at Sun	OAFRONTSUN	NRHO	100%	100%		
Orbit-average front area looking at Sun		LSP	0%	0%	0%	
Orbit-average side area looking at Sun		LSP	50%	50%	50%	
Orbit-average side area looking at Moon		LSP	50%	50%	50%	
Front absorptivity			0.0185	0.0046	0.25	
Front effective emissivity			0.0185	0.0046	0.58	
Side absorptivity			0.0185	0.0046	0.25	
Side effective emissivity			0.0185	0.0046	0.58	
Environmental heat flux reaching exterior tank	ENVHEATFLUX	LEO	7211	1803	77771	W th
Environmental heat flux reaching exterior tank	ENVHEATFLUX	NRHO	1610	403		W th
Environmental heat flux reaching exterior tank	ENVHEATFLUX	LSP	24029			W th
Environmental heat flux reaching tanks	ENVHEATFLUX	LEO	7211	1803	77771	W th
Environmental heat flux reaching tanks	ENVHEATFLUX	NRHO	1610	403		W th
Environmental heat flux reaching tanks	ENVHEATFLUX	LSP	24029			W th
Internal heat flux conducted to tanks	INTHEATFLUX		500	500	500	W th
Solar panel heat flux onto side of tanks	BACKPANELFLUX	LEO	144	36	4507	W th
Solar panel heat flux onto side of tanks	BACKPANELFLUX	NRHO	244	61		W th
Solar panel heat flux onto side of tanks	BACKPANELFLUX	LSP	1219			W th
Power-limited cooling capacity (in orbit)			6322	6322		
Power-limited cooling capacity (on lunar surface)			1260			
Heat flux removed by CC (in orbit)			-1050	-1200	0	W th
Heat flux removed by CC (on lunar surface)			-1050			W th

THERMOS

Surface Material Description	Lookup name	mass in kg / m2	Abs	Emm
	don't use this			
	BLACK	1	0.99	0.98
No coating, 301 steel	**301STEEL**	0	0.25	0.58
White Paint	**WHITE**	1	0.12	0.9
Magnesium Oxide in White paint	**MGOWHITE**	1	0.09	0.9
AZ Tech Inorganic Low Alpha White Paint	**AZTWHITE**	1	0.09	0.91
silver backed, used on skylab, space shuttle, and hubble	**QIOPTIQ**	1	0.06	0.83
SOLEC LO/MIT	**SOLEC**	1	0.23	0.17
MLI, 40 layers	**MLI40**	12	0.005	0.005
MLI, 20 layers	**MLI20**	8	0.006	0.006
MLI, 60 layers	**MLI60**	16	0.004	0.004
MLI60-A138, Johnson (2010)	**MLI60-A138**			
MLI40-A139, Johnson (2010)	**MLI40-A139**	6.43	0.0049	0.0049
MLI60-A140, Johnson (2010)	**MLI60-A140**	6.78	0.0042	0.0042
MLI60-A141, Johnson (2010)	**MLI60-A141**	6.67	0.0059	0.0059
MLI20-A142Q, Johnson (2010)	**MLI20-A142Q**	5.79	0.0071	0.0071
MLI60-A143, Johnson (2010)	**MLI60-A143**	6.66	0.0050	0.0050
MLI60-A144, Johnson (2010)	**MLI60-A144**	6.47	0.0046	0.0046

Type of Cryocooler	Model var name	Row No.	SPEC MASS	PWR RATIO
units			kg/W(th)	none
no cryocooler used	**NONE**	2	0	0
generic efficient cryocooler	**GENERIC**	3	2	20
heavy, inefficient cryocooler	**HEAVYGEN**	4	6	60
Petach pulse-tube cryocooler	**PETACH**	5	0.7	15
Creare 150W 90K	**CREARE**	6	0.4	8

THERMOS

MLI Outer Cover Material Lookup Table			MLIOUTERLOOKUP		MLIOUTERLOOKUP_ROWS	
Type of MLI Outer Layer	**Model var name**	**Row No.**	**SPEC MASS**	**Abs**	**Em**	**thickness**
units			kg/m2	none	none	m
beta cloth	**BETACLOTH**	2	0.237	0.45	0.8	0.00002
aluminized beta cloth	**ALBETACLOTH**	3	0.271	0.37	0.3	0.00002
thin backed teflon	**THINBTEFLON**	4	0.028	0.1	0.4	0.0000013
thick backed teflon	**THICKBTEFLON**	5	0.55	0.1	0.85	0.0000254
thin coated and backed teflon	**THINCBTEFLON**	6	0.11	0.14	0.6	0.000011
thick coated and backed teflon	**THICKCBTEFLON**	7	0.27	0.14	0.75	0.0000127
thin coated and backed kapton	**THINKAPTON**	8	0.019	0.41	0.5	0.0000013
thick coated and backed kapton	**THICKKAPTON**	9	0.19	0.54	0.81	0.0000127

Lookup table name			*Excel data range name*		*Rows lookup range:*	
MLI Reflector Material Lookup Table			**MLIREFLLOOKUP**		**MLIREFLLOOKUP_ROWS**	
Type of MLI Reflector Material	**Model var name**	**Row No.**	**SPEC MASS**	**Abs**	**Em**	**thickness**
units			kg/m2	none	none	m
thin aluminized kapton	**THINALKAPTON**	2	0.011	0.14	0.05	0.0000076
thick aluminized kapton	**THICKALKAPTON**	3	0.19	0.14	0.05	0.000127
thin goldized kapton	**GOLDKAPTON**	4	0.011	0.3	0.04	0.0000076
thick goldized kapton	**GOLDKAPTON**	5	0.19	0.3	0.04	0.000127
thin aluminized mylar	**ALMYLAR**	6	0.007	0.14	0.05	0.0000007
thick aluminized mylar	**ALMYLAR**	7	0.175	0.14	0.05	0.0175

Dashboard knobs- Performance goals / decisions	Excel cell name	Value			Units	Notes
Required Endurance at NRHO	**REQENDNRHO**	90			days	Artemis III requirement, capability to wait at NRHO for Orion; relax it to compare how a purely-commercial mission might perform
Required Endurance at LSP	**REQENDLSP**	30			days	Artemis III requirement, cannot be less than this due to choice of NRHO rendezvous & safety requirements if ascent launch windows missed
Starship HLS Payloads staying on Moon	**HLS1WAYPAYLOAD**	13,152			kg	*This can be traded with HLS ascent propellant margins. Includes all specialized exploration equipment, consumables, rovers, deployable solar arrays - anything that will stay on Moon*
Starship HLS Payloads returning to NRHO	**HLSPAYLOADMASS**	30,000			kg	*This can be traded with HLS ascent propellant margins. It includes all specialized habitation equipment installed on Starship HLS, the crew and any equipment they have to bring back.*
How much delta V from HEO to TLI?	**TLIMINUS**	900			m/s	Set it to 3200 for LEO departure orbit. The higher the HEO apogee, the lower this should be. Default is 700 m/s for v3 depot in the v5 model, 850 m/s for the v2 depot. Lower it further to raise HEO apogee in order to make a mission feasible and/or to increase HLS prop margins, at the cost of having to send maybe more tankers to refuel the depot that will travel to HEO. (Raising HEO apogee will improve HLS starship propellant margins at the expense of a few more tankers required. It is expected that for supporting refilling for lunar missions, the apogee of the (HEO) highly elliptical orbit will end up being in MEO (Medium Earth Orbit))
Dashboard knobs - Technology Choices	**Default Variable Names**	**Value**	**Value**	**Value**	**Propellant Margin LSP - NRHO**	**27.08%**
		For HLS	For Depot	For Tanker	**Total Number of Tankers**	**15**
		default name	***Suffix: _DEP***	***Suffix: _TNK***		
Starship Version	**STARSHIPV**	V3	V3	V3		*Changing this allows us to run the model with V1, V2 or V3 Starship and see how mission feasibility is affected. For Starship specs, see LOOKUP TABLES tab.*
Passive Insulation solution - SS front	**PASSINSULFRONT**	MLI60-...	MLI60-...	301ST...		This defines the passive insulation strategy for the front of starship (e.g. area above the solar panels) used for calculations.
Passive Insulation solution - SS sides	**PASSINSULSIDE**	MLI60-...	MLI60-...	301ST...		This defines the passive insulation strategy for the side of starship (e.g. area under the solar panels). If both MLI and cryocoolers are used, the mass of the MLI structural support system is subtracted
Radiator design - backside of solar panels	**PANELRADIATORS**	Sawtooth	Sawtooth	Regul...		"Sawtooth" is a design with a small mass penalty where the radiator panel's cross section is like a sawtooth profile, and the sides facing the tank have low emissivity, whereas the sides looking at space have high emissivity
MLI Number of Layers - front	**MLILAYERSFRONT**					
MLI Number of Layers - sides	**MLILAYERSSIDE**					
Insulating / reflective material	**MLIMAINMATERIAL**					
Non-conductive separating material	**MLISEPMATERIAL**					
Outer shield / aeroshell material	**MLIOUTERMATERIAL**					
Cryocooler technology	**CRYOCOOLERS**	CREARE	CREARE	NONE		this defines whether active cryocoolers are used to achieve ZBO or not. selecting cryocoolers adds mass to the system, increase power needs => in case of HLS, we have 50kWe spare in NRHO as the design loads for when crew is on board cannot exceed 50 of the 100kWe. If any cryocoolers are used, a fixed mass is added for the network of pipes and manifolds
Cryo Sizing: Max Thermal Power of Cryocoolers used, per Cryocooler Unit	**CRYOPOWER**	150	150	0	W(th)	watts of heat removed by cryocooler (cooling capacity)
Number of Cryocoolers to use	**NUMBERCRYOS**	7	8	0		the number of cryocoolers used. Together with the type of cryocooler, this determines total cooling capacity, total power demand and total additional mass
Dashboard knobs used for stress-testing the HLS mission						
MLI Degradation factor	**MLIDEGRADE**	4				This factor is multiplied with effective emissivity. It is modeled as an average across the entire passive insulation of the HLS system.
Number of failed cryocoolers	**FAILEDCRYOS**	0				Any failures are assumed to occur upon the first startup, and then they remain inactive for the entirety of the HLS mission.
Dashboard knobs - not used for HuLC						
Lunar Cargo Starship Payload	**CARGOPAYLOADMASS**	100,000			kg	This is used only for calculations of number of tankers required for cargo missions

THERMOS

Backup: NASA GEVS

https://standards.nasa.gov/standard/gsfc/gsfc-std-7000

General Environmental Verification Standard (GEVS) for GSFC Flight Programs and Projects

Goddard Space Flight Center
Greenbelt, MD 20771

GODDARD TECHNICAL STANDARD

GSFC-STD-7000B

Approved: 04-28-2021
Revalidation Date: 04-28-2026
Superseding GSFC-STD-7000A

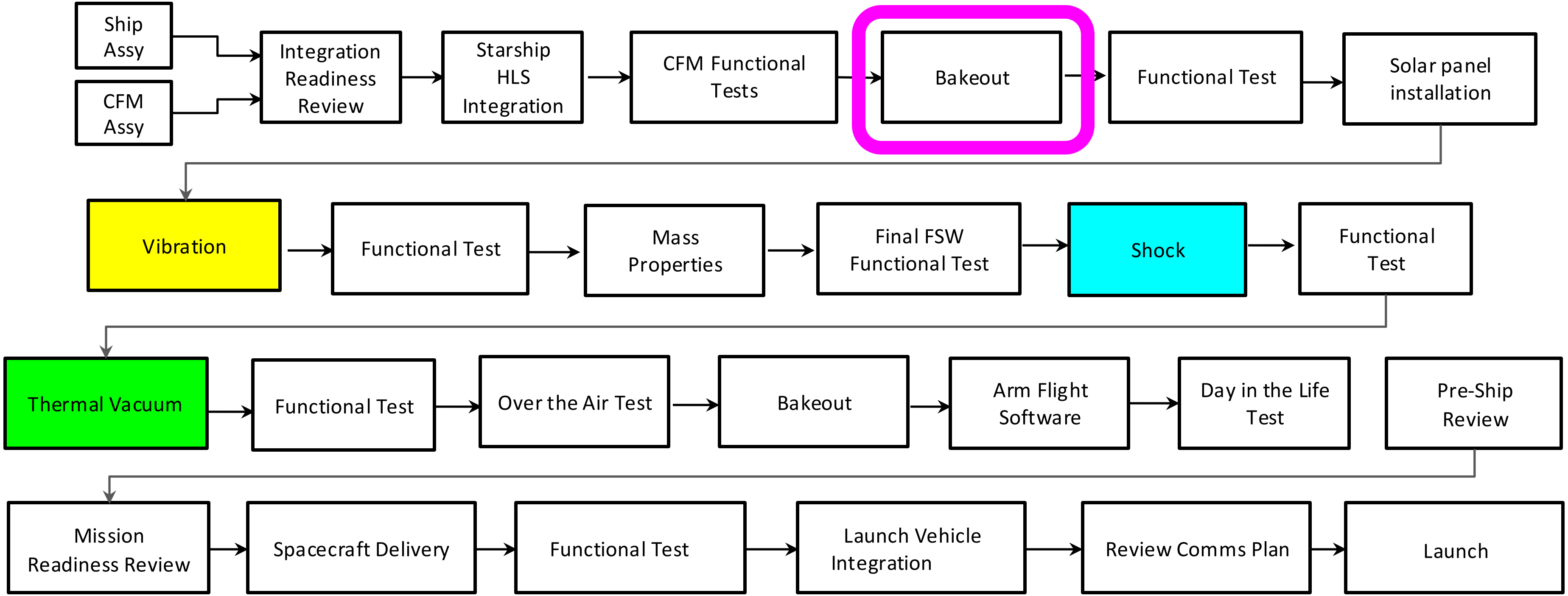
General Environmental Verification Standard (GEVS) for GSFC Flight Programs and Projects

THIS STANDARD HAS BEEN REVIEWED FOR EXPORT CONTROL RESTRICTIONS;
APPROVED FOR PUBLIC RELEASE
DISTRIBUTION IS UNLIMITED

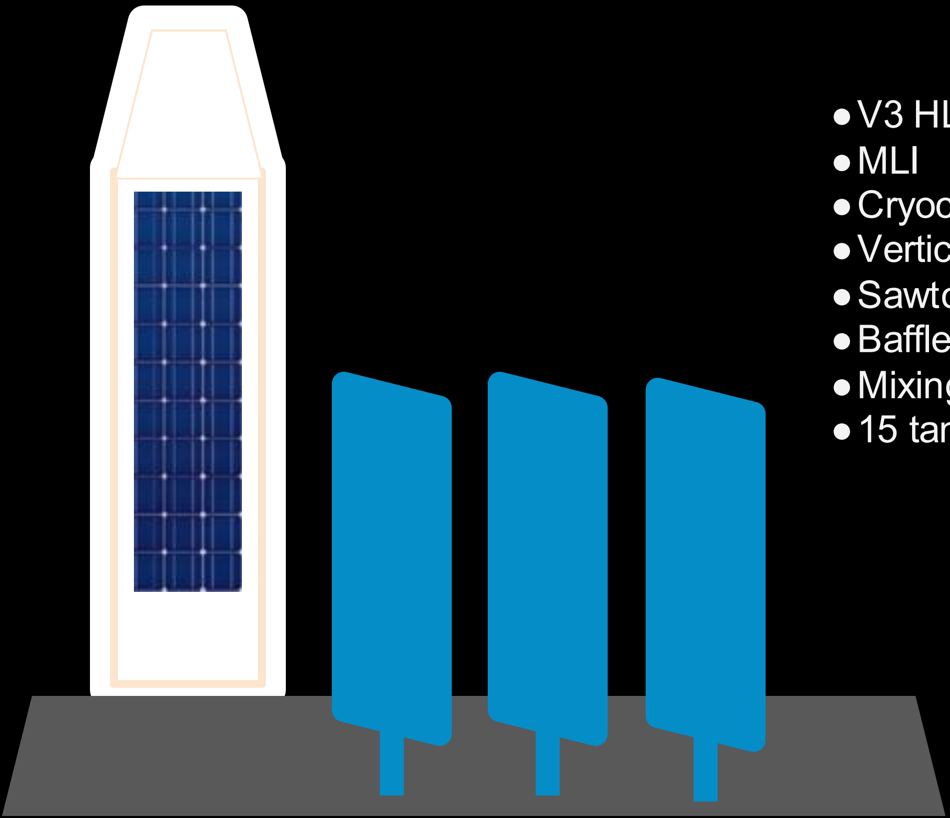
Replace with your point!! High Level Testing Flow

https://atos.net/wp-content/uploads/2020/10/Atos_Satellite_Testing_An_Introduction.pdf

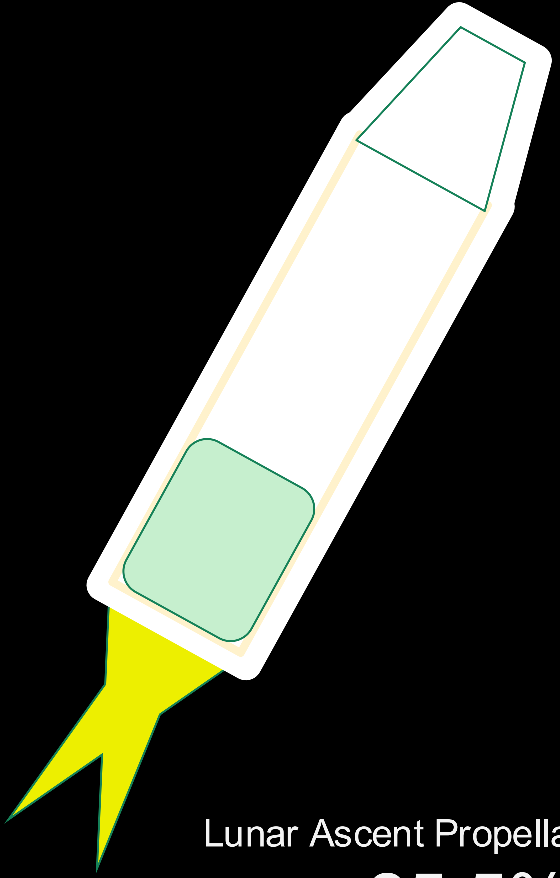
Replace with your point!! Notional SV Integration and Test Flow…

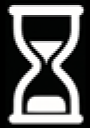


V3 Hybrid (Architecture 023-MCB)



- V3 HLS and Depot
- MLI
- Cryocoolers
- Vertical solar arrays
- Sawtooth radiators
- Baffles
- Mixing Pump
- 15 tanker flights

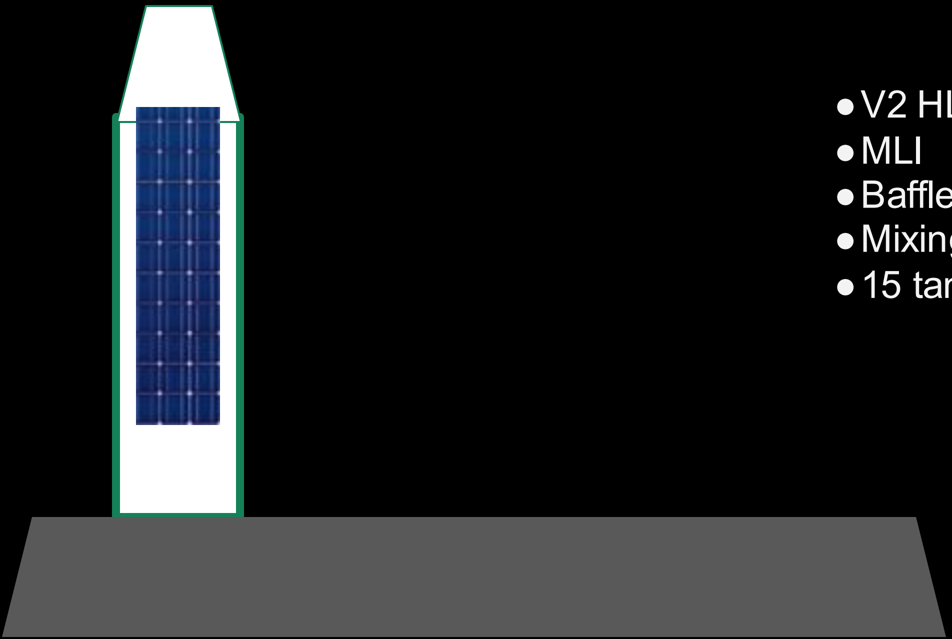




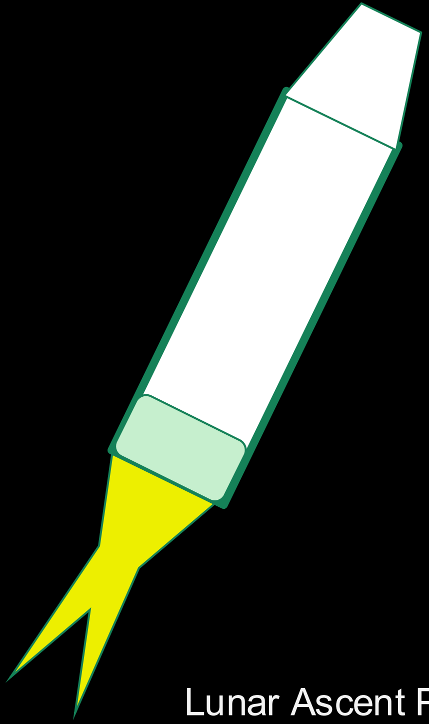
Lunar Ascent Propellant

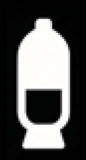
Margin: 25.5%

V2 Passive (Architecture 026-MB)



- V2 HLS and Depot
- MLI
- Baffles
- Mixing Pump
- 15 tanker flights

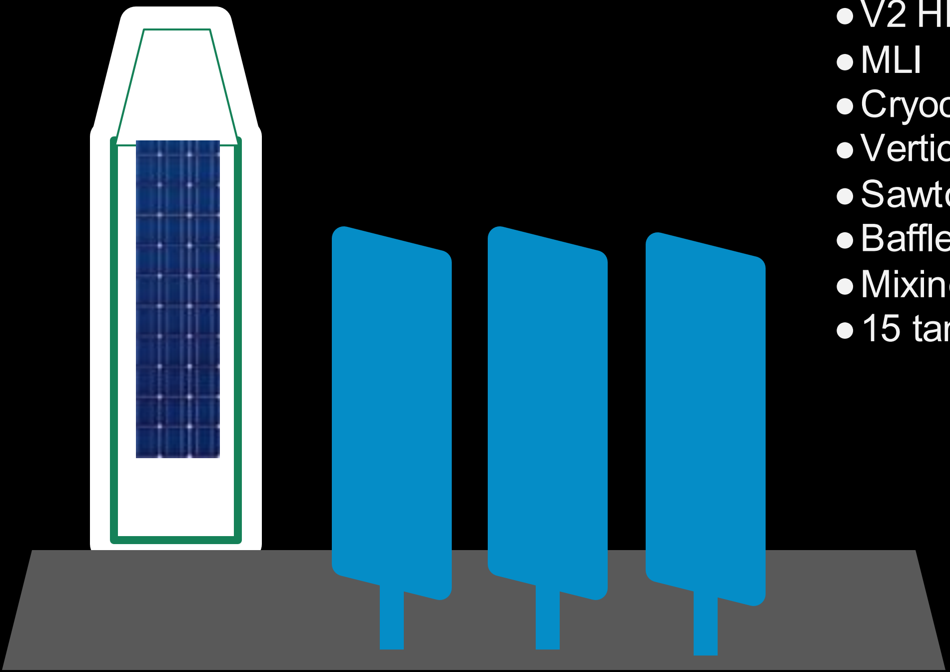




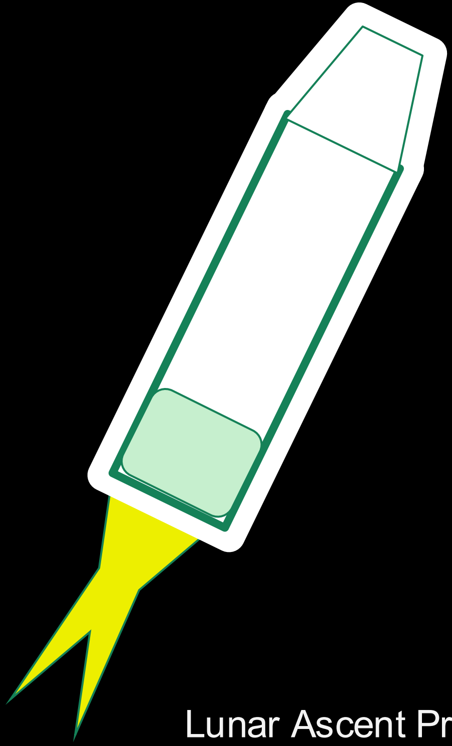
Lunar Ascent Propellant

Margin: 14.6%

V2 Hybrid (Architecture 019-MCB)

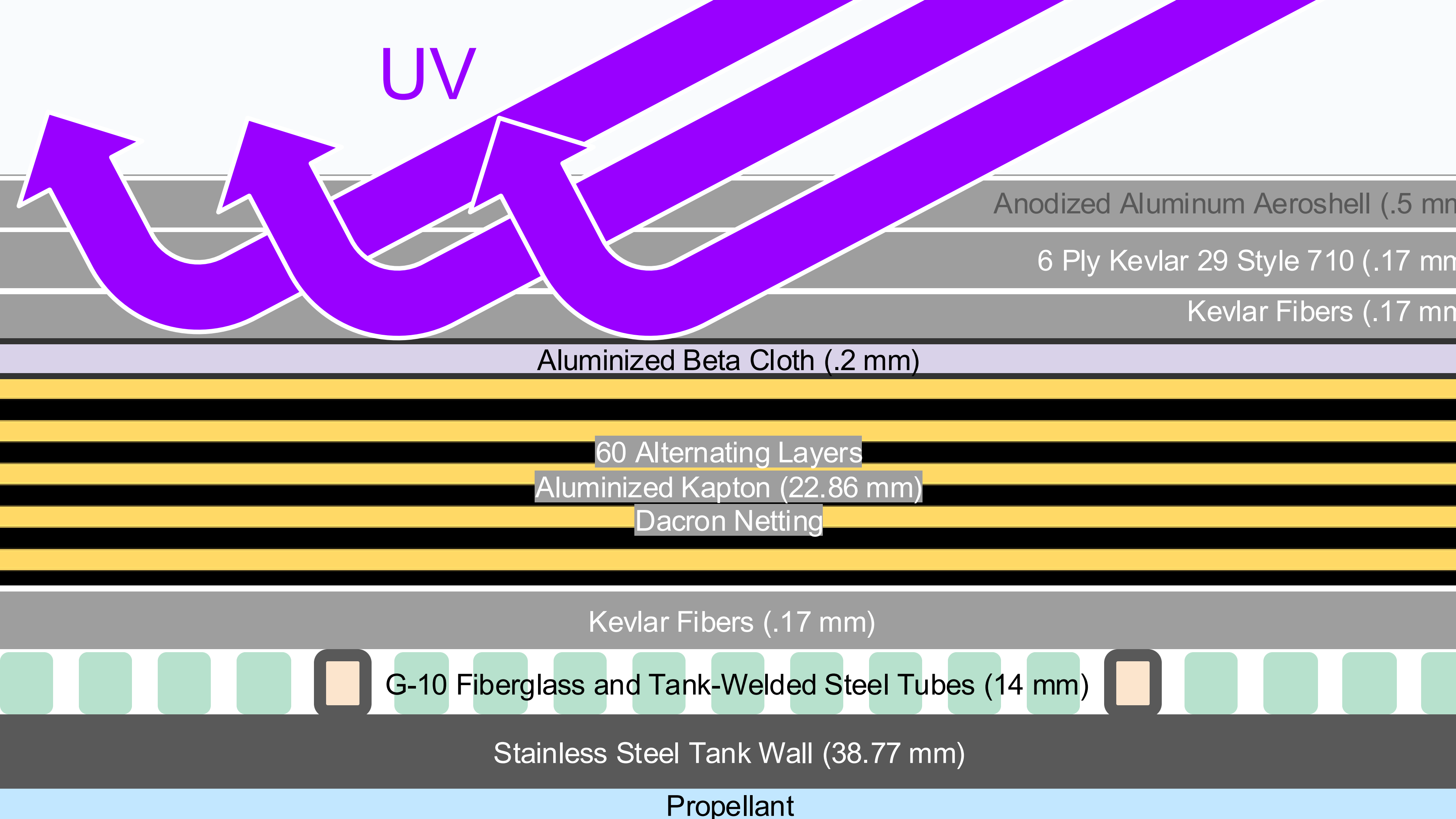


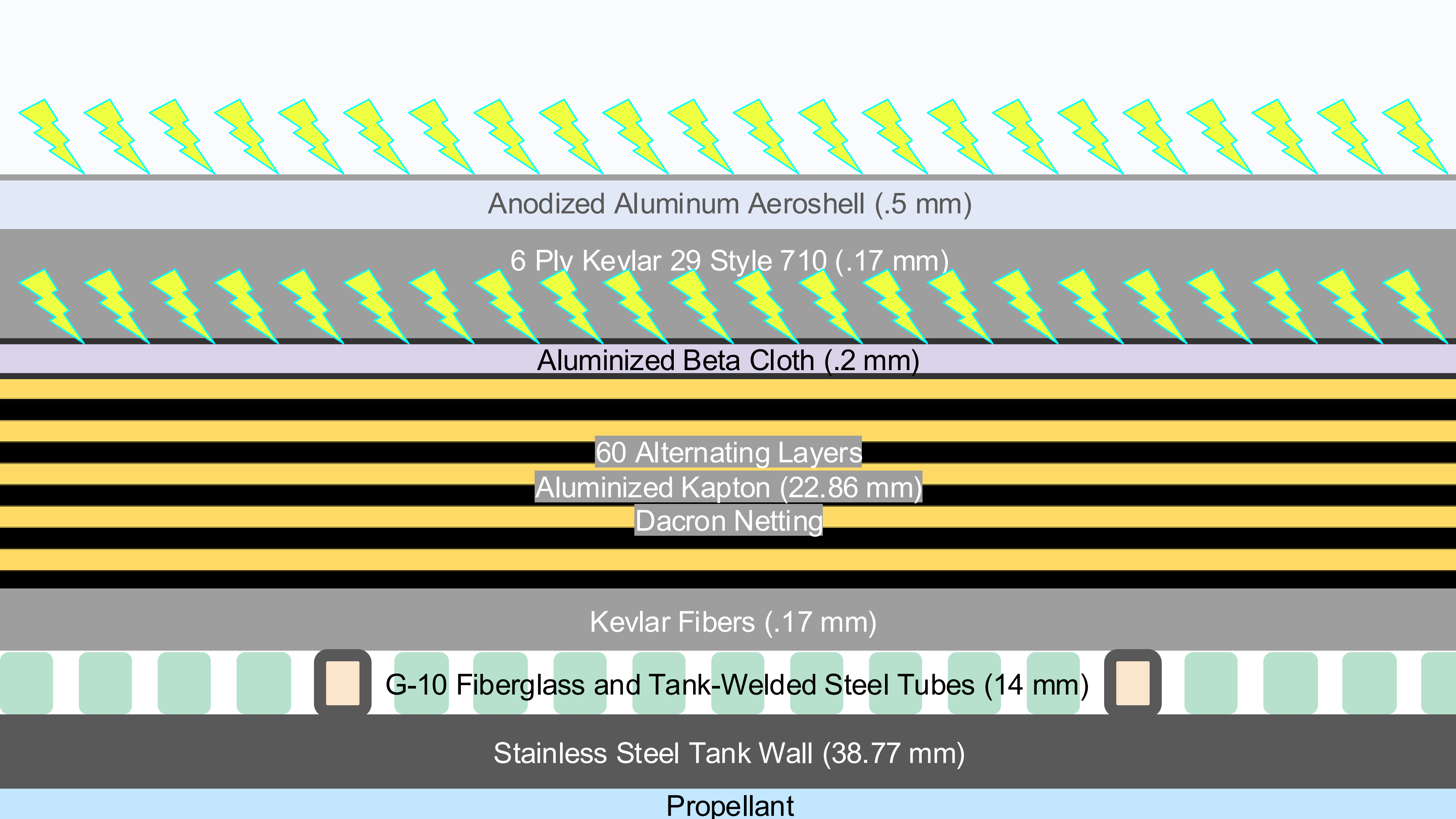
- V2 HLS and Depot
- MLI
- Cryocoolers
- Vertical solar arrays
- Sawtooth radiators
- Baffles
- Mixing Pump
- 15 tanker flights

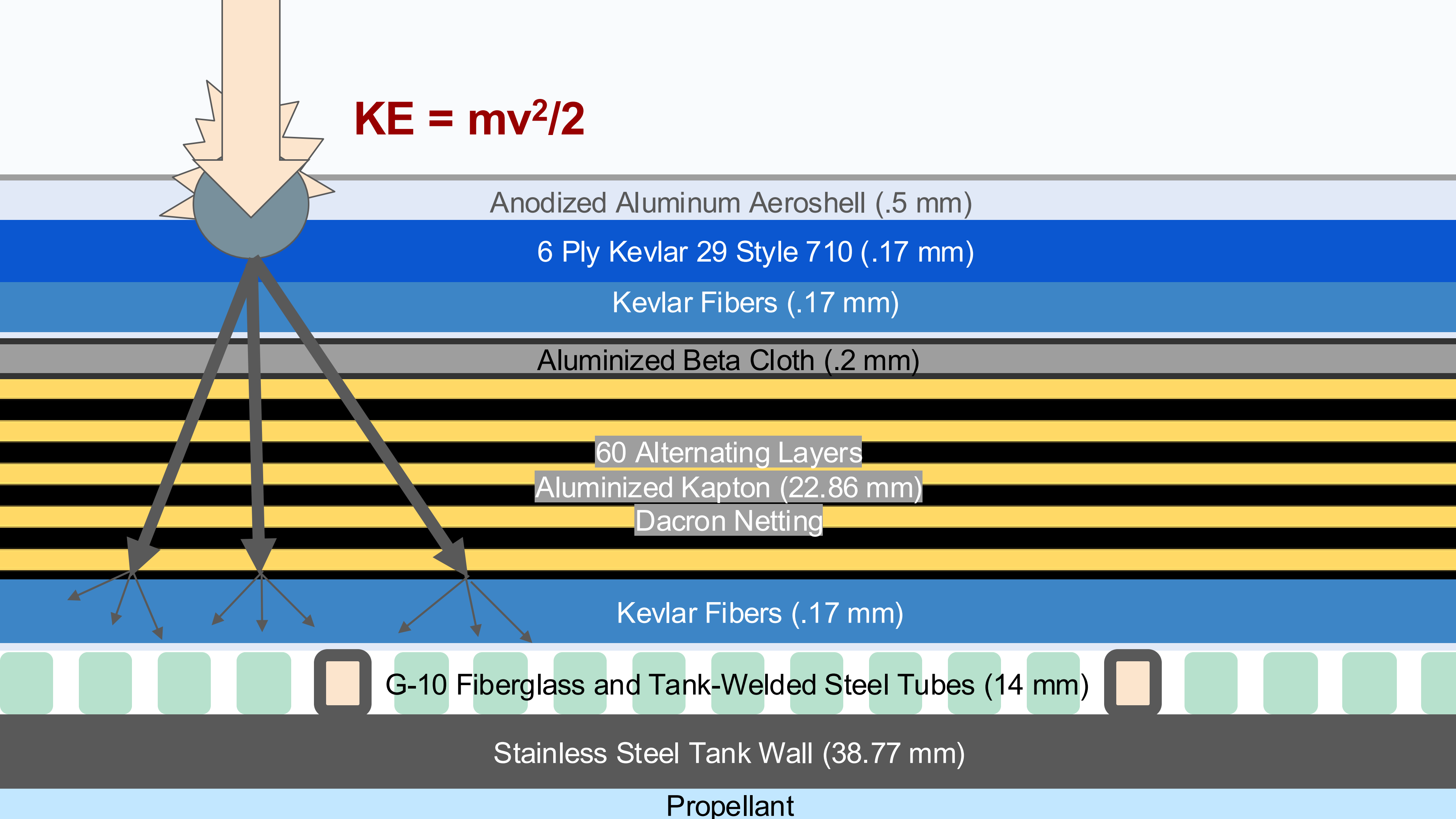


Lunar Ascent Propellant Margin: 16.2%

Qin
Qrefl
nodized Aluminum Aeroshell (.5 mm)
6 Ply Kevlar 29 Style 710 (.17 mm)
Kevlar Fibers (.17 mm)
QMLI
Aluminized Beta Cloth (.2 mm)
60 Alternating Layers
Aluminized Kapton (22.86 mm)
Dacron Netting
Qtubes
Kevlar Fibers (.17 mm)
G-10 Fiberglass and Tank-Welded Steel Tubes (14 mm)
Qthru
Stainless Steel Tank Wall (38.77 mm)
Propellant


UV
Anodized Aluminum Aeroshell (.5 mm
6 Ply Kevlar 29 Style 710 (.17 mm
Kevlar Fibers (.17 mm
Aluminized Beta Cloth (.2 mm)
60 Alternating Layers
Aluminized Kapton (22.86 mm)
Dacron Netting
Kevlar Fibers (.17 mm)
G-10 Fiberglass and Tank-Welded Steel Tubes (14 mm)
Stainless Steel Tank Wall (38.77 mm)
Propellant


Anodized Aluminum Aeroshell (.5 mm)
6 Ply Kevlar 29 Style 710 (.17 mm)
Aluminized Beta Cloth (.2 mm)
60 Alternating Layers
Aluminized Kapton (22.86 mm)
Dacron Netting
Kevlar Fibers (.17 mm)
G-10 Fiberglass and Tank-Welded Steel Tubes (14 mm)
Stainless Steel Tank Wall (38.77 mm)
Propellant



KE = mv²/2
Anodized Aluminum Aeroshell (.5 mm)
6 Ply Kevlar 29 Style 710 (.17 mm)
Kevlar Fibers (.17 mm)
Aluminized Beta Cloth (.2 mm)
60 Alternating Layers
Aluminized Kapton (22.86 mm)
Dacron Netting
Kevlar Fibers (.17 mm)
G-10 Fiberglass and Tank-Welded Steel Tubes (14 mm)
Stainless Steel Tank Wall (38.77 mm)
Propellant