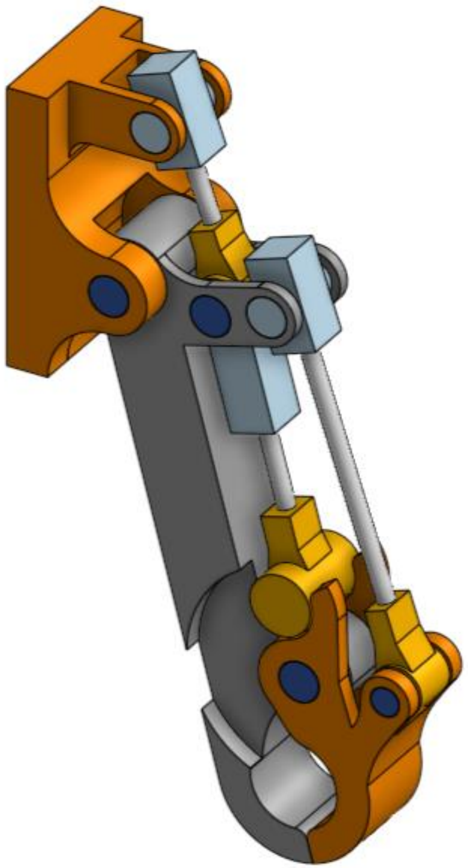
MAST: Modular Adaptive Separation Technology

Team Members:

- Jay Kim – *Undergraduate, Mechanical Engineering*
- Adelaide Yu – *Undergraduate, Electrical Engineering*
- Makoa Shope – *Undergraduate, Mechanical Engineering*
- Anthony Krebs – *Undergraduate, Mechanical Engineering*
- Chase Lampe – *Undergraduate, Mechanical Engineering*
- Ny'asia Crosley – *Undergraduate, Mechanical Engineering*
- Ashle Jantzen – *Undergraduate, Electrical Engineering*
- Christian Sekavec – *Undergraduate, Mechanical Engineering*
- Caleb Willman – *Undergraduate, Mechanical Engineering*

Technical Advisors:

- Jennifer Erickson – *Faculty Advisor*
- Janice Houston – *Technical Advisor*
- Jeff Budny – *Technical Advisor*
- Preston Lippert – *Technical Advisor*
- Alexander Lampe – *Technical Advisor*
- Angel Abbud-Madrid – *Technical Advisor*



Solution Overview

- ☐ Topic and Scope
- ☐ System Requirements
- ☐ Introducing MAST

Topic & Scope

The Problem: Cryogenic Boil-Off

- Excessive heat transfer causes propellant to vaporize
- Reduces available propellant for mission operations

Critical for Long Duration Missions

- Extended missions face greater propellant conservation challenges
- Thermal equilibrium becomes increasingly problematic over time

Our Approach

Developing innovative solutions that balance:

- Structural integrity
- Thermal isolation
- Mass increase
- Ease of implementation

Project Scope

1. Design compact mechanical system suitable for lander integration
2. Demonstrate measurable reduction in heat transfer
3. Validate load-bearing capacity under launch conditions
4. Ensure system reliability for crew safety

Requirements

Type	Level	Req	Requirement	Verification Method	Verification Rationale
High Level	**1**	**HL1**	The design shall be easily adaptable to NASA adoption.	Testing and Analysis	Concept TRL must be maximized for ease of adoption. The solution must also not interfere with boundary systems like tank skirt and fuselage.
High Level	**1**	**HL2**	The design shall survive in a space environment.	Testing and Analysis	The solution needs to survive extreme temperature gradients, micro gravity, vacuum, and radiation. This can be verified through component tests and thermal analysis.
High Level	**1**	**HL3**	The design shall be fieldable in 3 – 5 years (Artemis III).	Analysis	Material components need to come from verified existing technologies, and the proposed schedule needs to be accurate.
High Level	**1**	**HL4**	The design shall not pose additional risks to the crew.	Testing and Analysis	The design cannot include anything that imposes mission or life-threatening risks to the crew. A risk analysis table is used for verification.
High Level	**1**	**HL5**	The design shall survive launch and landing loads.	Testing and Analysis	The solution needs to withstand certain vibrations, aggressive landing forces, and varying challenges associated with launching the system. This will be done through Finite Element simulation.
High Level	**1**	**HL6**	The design shall survive a mission duration of multiple months.	Testing and Analysis	The design requires no maintenance and utilizes materials suited to last extended durations in a space environment.

Requirements

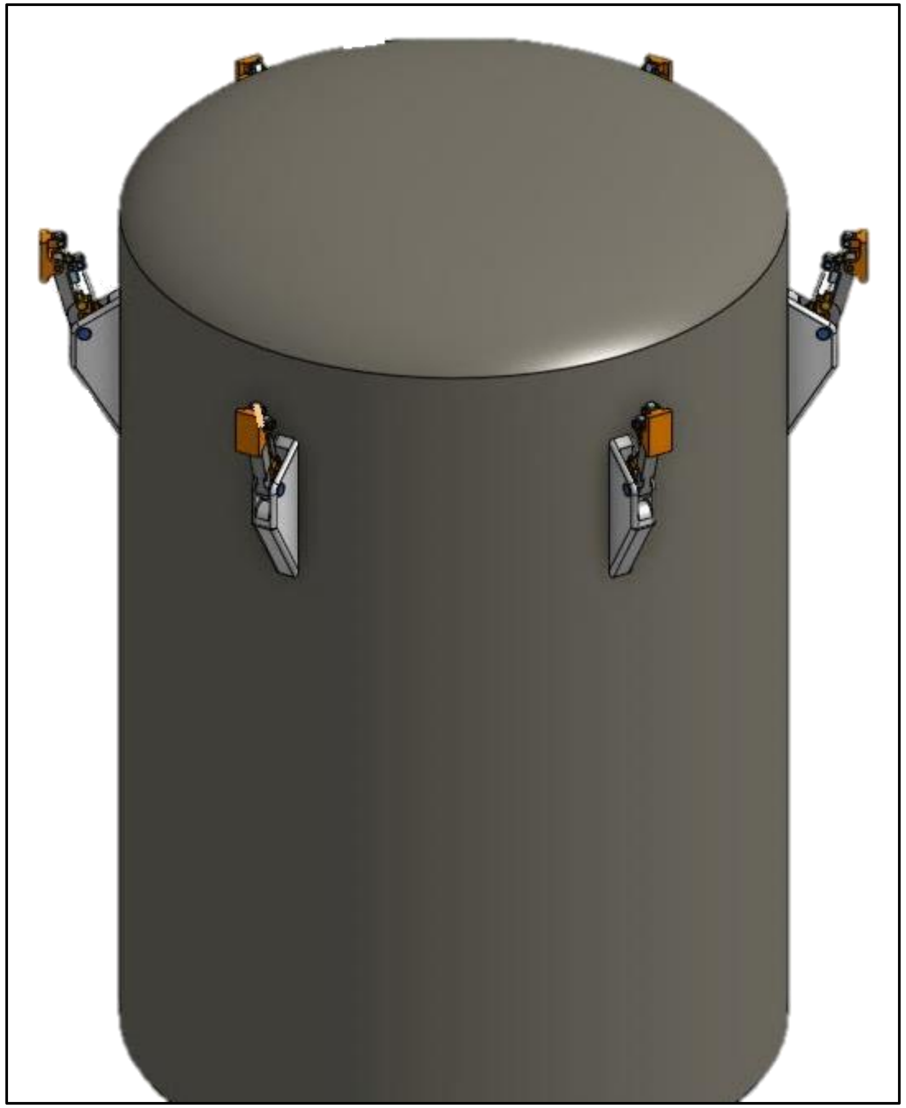
Type	Level	Req	Requirement	Verification Method	Verification Rationale	Parent
Interface	**2**	**IF1**	The structure shall meet regulatory standards for safety.	Analysis	The structure shall strive for certifications beyond regulatory standards and aim for exceptional safety features.	HL4
Interface	**2**	**IF2**	The solution shall use readily available technologies and mfg. processes.	Analysis	The design uses processes trusted and tested from aerospace manufacturing to reduce time to field readiness.	HL3
Performance	**1**	**PR1**	The design shall prevent a substantial order of kilowatts of heat from transferring into cryogenic tanks	Testing and Analysis	The design shall minimize heat transfer between the propellant tank and the vehicle. This will allow optimal thermal management of the tank's cooling system.	
Performance	**2**	**PR2**	The structure shall support fluid and tank mass during periods of high acceleration. (5+ G's)	Testing and Analysis	The structure shall be designed with materials that enhance durability and minimize overall mass. It will positively affect fuel and cost efficiency.	HL5
Performance	**2**	**PR3**	The structure shall survive vibrational loads induced by launch (3 G’s in each axial direction)	Testing and Analysis	The launch and landing processes provide large vibration quantities; thus, numbers are pulled from user's guides.	HL5
Performance	**2**	**PR4**	The structure shall maintain a coefficient of thermal expansion equal to the fuselage.	Testing and Analysis	Due to large temperature gradients in space, thermal expansion is a concern and must be limited.	HL2

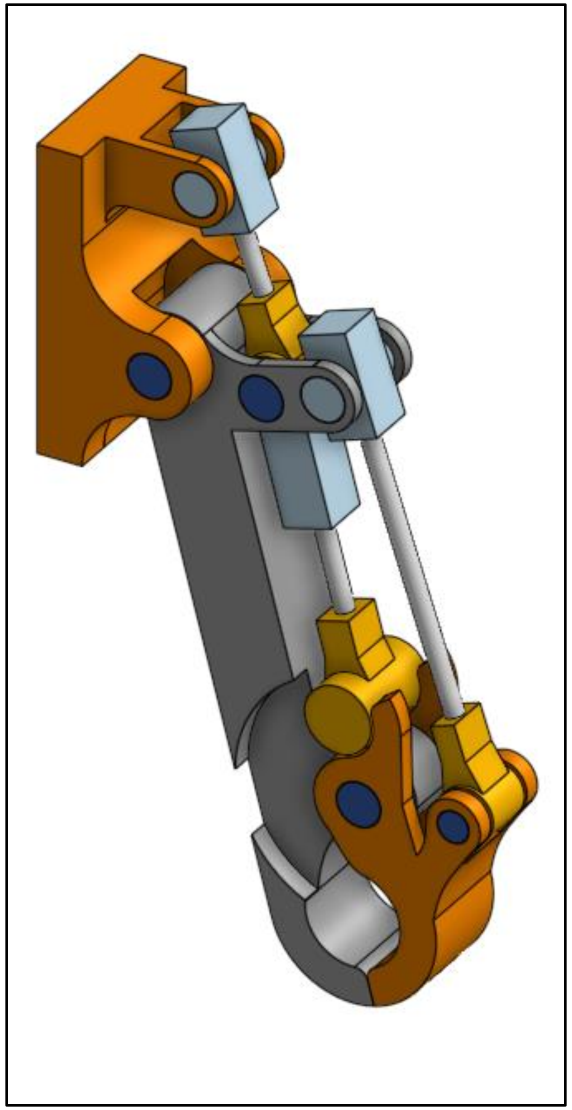
Requirements

Type	Level	Req	Requirement	Verification Method	Verification Rationale	Parent
Performance	**2**	**PR5**	The structure shall be operational without maintenance.	Demonstrate	Maintenance on such a small system is not feasible, so the system needs to survive its window without failure.	HL6
Performance	**2**	**PR6**	The support system shall support cryogenic propellant tanks carrying upwards of 275,000 kg.	Analysis	Based on given guidelines, the maximum tank dimensions are 7 meters in diameter and 10 meters in height. Oxygen is the heaviest of three considered propellants.	HL5
Structural	**3**	**ST1**	The structure shall fit within the space surrounding the tank skirt.	Analysis	The tank structure will optimize dimensions to fit within multiple tank systems.	IF2
Structural	**3**	**ST2**	The support shall not weigh more than 25 kg individually.	Analysis	A single support needs to be minimal in weight to reduce cost.	HL1
Structural	**3**	**ST3**	The mechanical Factor of Safety shall not be less than 1.5 anywhere.	Analysis	Using FEA, the FoS on any point of the support needs to meet industry standards.	HL5

Introducing MAST

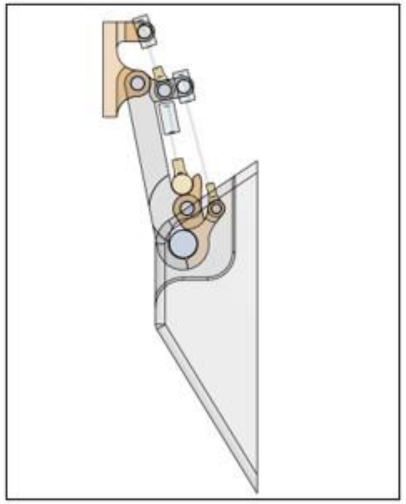
- Modular Adaptative Separation Technology
- Three actuator retractable design
- Welded to fuselage and tank skirt
- Jaws unclamp to remove conductive heat transfer
- Modular in design – for any tank of any size
- Titanium allow for strength and low conduction





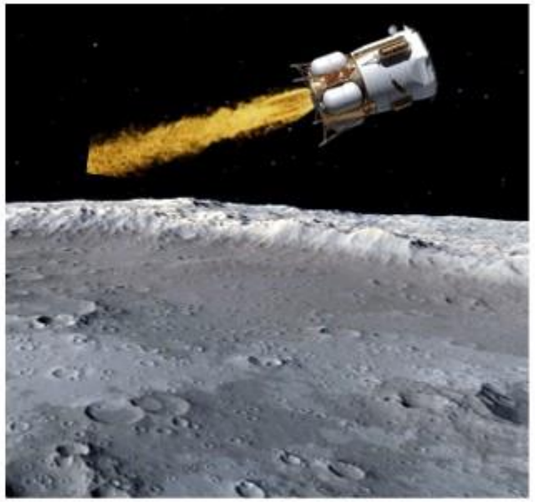
Operational Overview

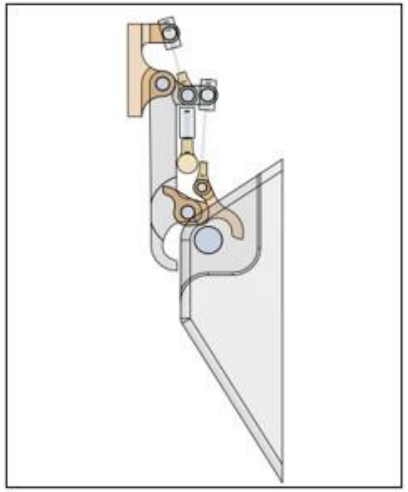
Modes of Operation



High Load Phase

- Support arm is engaged to provide stability during high structural load conditions
- Provides required structural load path





Low Load Phase

- Support arm is released to eliminate points of heat transfer across structural load path
- Support can change configuration repeatedly based on mission needs

Component Overview and Operation

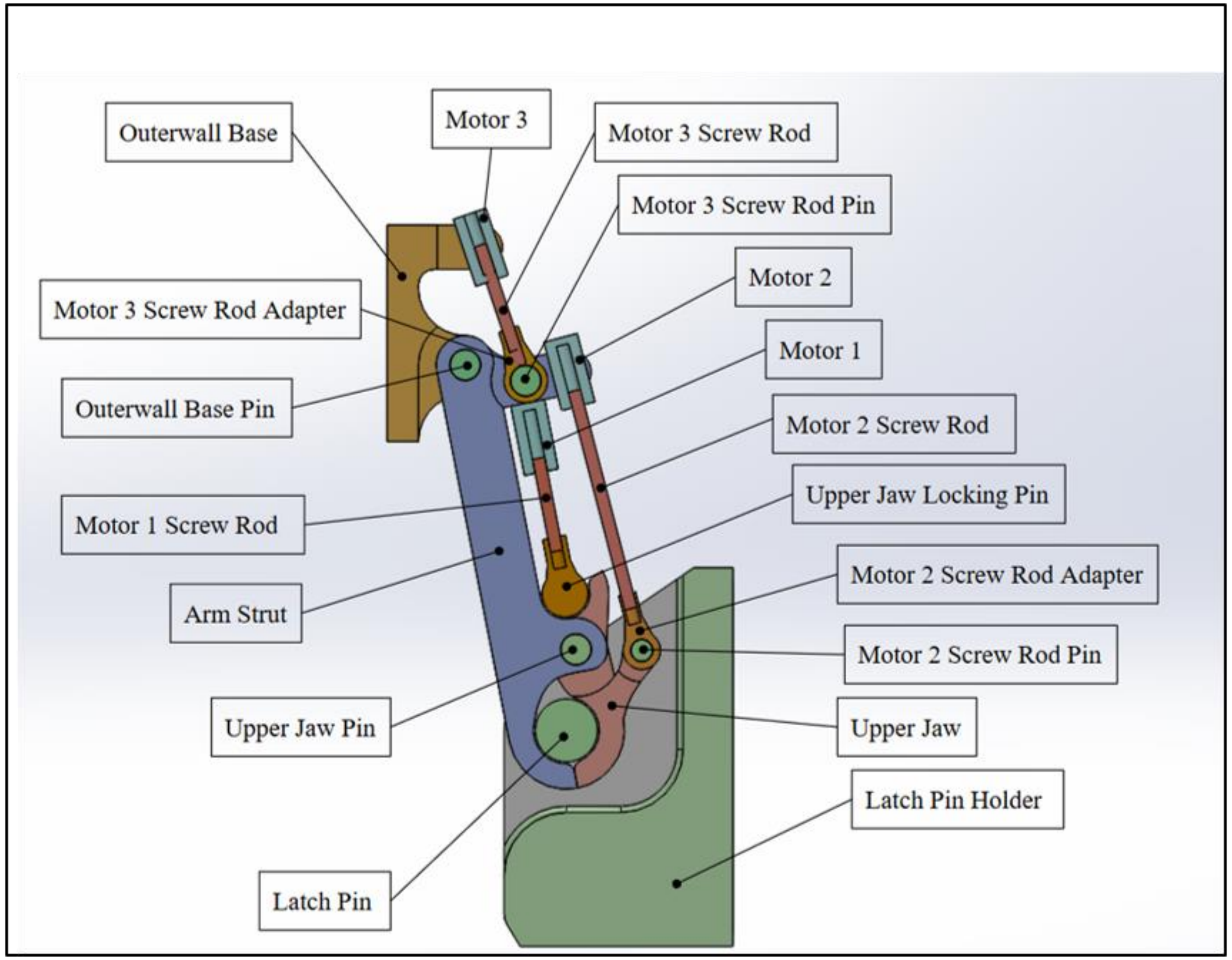
- Arm strut and upper jaw act as main structural components
- In contact with latch pin

Operation:

- Motor 1 retracts, allowing movement of upper jaw
- Motor 2 retracts, detaching upper jaw
- Motor 3 extends, detaching arm strut
- Small vacuum medium will remove heat transfer

Details:

- Designed for 12 supports
- ~23.8 kg
- 55.4 x 29.9 x 10 cm

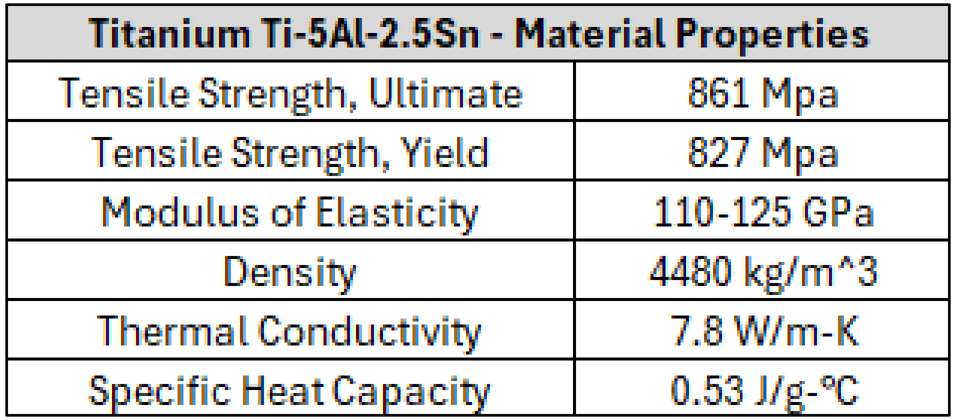


Engineering Analysis

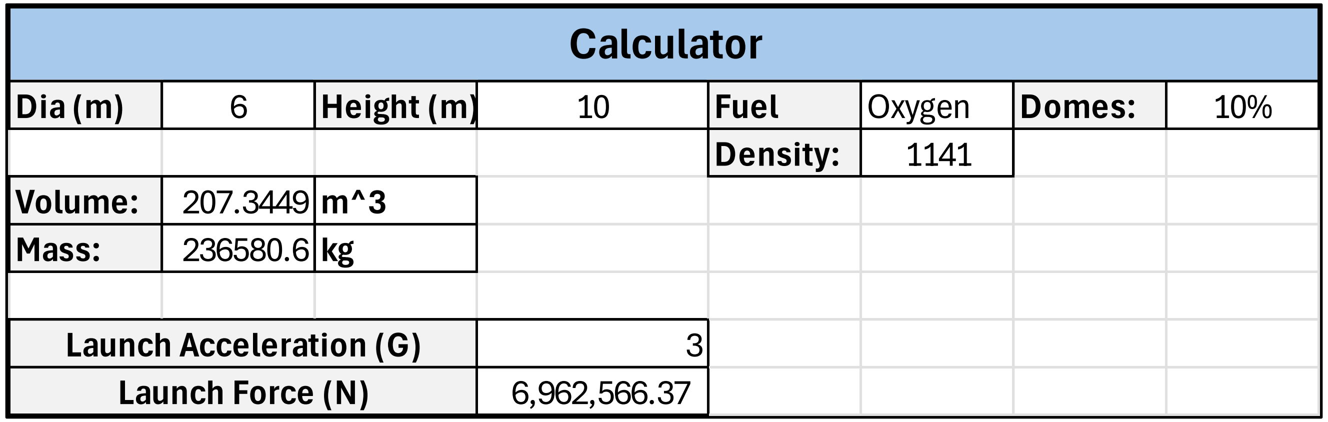
- ☐ Simulation Conditions
- ☐ Mechanical Analysis
- ☐ Thermal Analysis
- ☐ Discussion
- ☐ Limitations

Simulation Conditions

- Three test cases:
    - Launch
    - Landing
    - Thermal
- Finite element analysis (FEA) used in SolidWorks Simulator
- Ti-5Al-2.5Sn alloy
- Considered three fuels:
    - Oxygen
    - Hydrogen
    - Methane
- Minimum FoS 1.5



Titanium Ti-5Al-2.5Sn - Material Properties	
Tensile Strength, Ultimate	861 Mpa
Tensile Strength, Yield	827 Mpa
Modulus of Elasticity	110-125 GPa
Density	4480 kg/m^3
Thermal Conductivity	7.8 W/m-K
Specific Heat Capacity	0.53 J/g-°C



Calculator							
Dia (m)	6	**Height (m)**	10	**Fuel**	Oxygen	**Domes:**	10%
				Density:	1141		
Volume:	207.3449	**m^3**					
Mass:	236580.6	**kg**					
Launch Acceleration (G)			3				
Launch Force (N)			6,962,566.37				

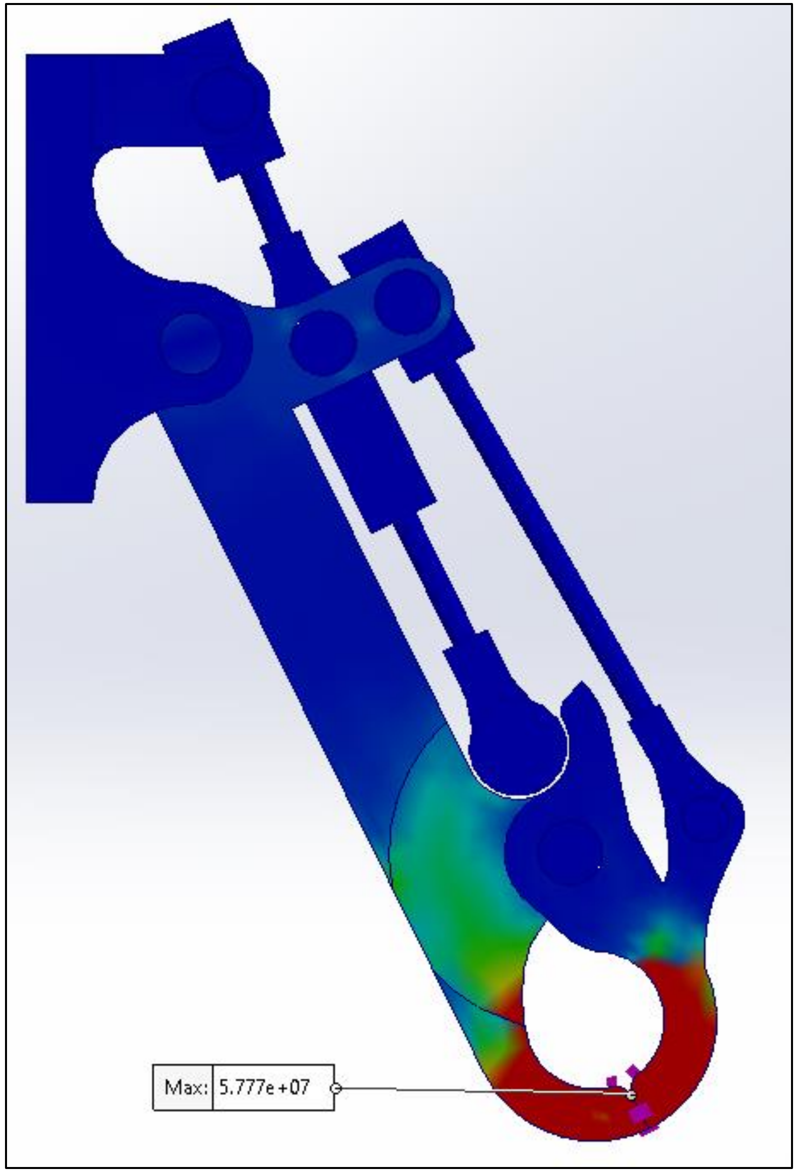
Mechanical Setup and Results

Launch:

- Mass Acceleration Curve utilized
- Vibration and thrust considerations
- 290 kN of downward thrust
- Minimum FOS = 14.31

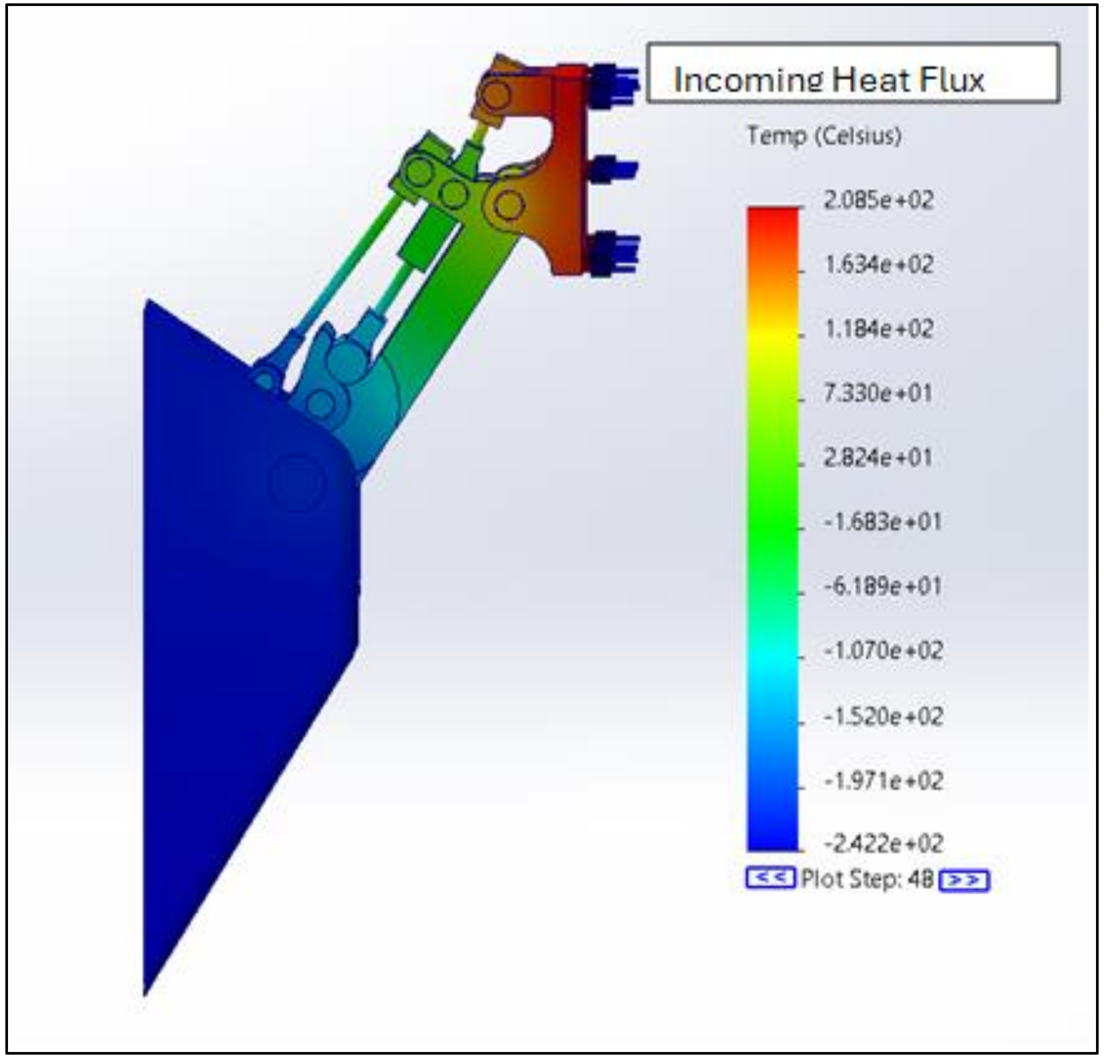
Lunar Landing:

- Used SWS Drop Test Sim
- Tested at 3.1 ft/s lunar landing w/ tank
- Minimum FOS = 10.3



Thermal Simulation Analysis and Results

- Solar radiation assumed for energy source
- Thermal Conductivity 7.8 W/(m*K)
- Incoming heat flux of 1410 W/m^2
- Initial Conditions:
- Arm strut: –150°C
- Latch pin holder: –253°C



Boil off Analysis and Results

- A Simplified 1-D analysis was conducted
  - Constant cross-section and material properties
  - Worst case heat differential
  - Estimated 28 Watts transfers per support

- Based on this we can calculate the boil off rate of a given propellant
  - Traditional Supports: 6.85 g/s
  - MAST High Load: 0.752 g/s
  - MAST Low Load: 0.188 g/s

- ~97% Reduction in heat transfer and boil off rate

Latent heat vaporization H2: 447 kJ/kg
Heat Transfer Rate: 28 W/support
Traditional Supports: 2500 W total

Simulation Discussion

Requirement	Simulation Result	Requirement Met
PR1 Prevents substantial order of kilowatts from entering tank.	Latch pin holder maintained steady state temperature of -242.2° C. Estimated around 28W transfers into the tank at the worst conditions.	YES
PR2 Support tank during high acceleration(3G).	Factor of safety for assumed acceleration of 3G downward into addition to vibrational acceleration of 1G for a total of 4G downward resulted in FoS of 14.	YES
PR3 Survive vibration loads (1G).	Stress analysis included the 1G loading in other two directions perpendicular to downward loading. FoS was 14	YES
PR4 CTE for fuselage and base roughly equivalent.	Aluminum 2024 –T4 CTE: 24.7μm/m-°C Ti-5Al-2.5Sn CTE: 9.5 μm/m-°C	YES
PR6 Support tank against 290 kN of downward force.	Simulation found FoS of 14 for the worst condition with the highest acceleration.	YES
ST2 Single support has mass less than 25kg.	Individual support met the 25kg limit at ~24kg.	YES
ST3 Mechanical FoS no less than 1.5 anywhere on support.	Simulation found FoS of 10 for the worst condition with the highest acceleration.	YES

Analysis Limitations

- Structural Scope
  - Includes only major structural supports
  - Secondary contacting hardware not considered (Valves, Sensors, Pumps)
- Thermal Assumptions
  - Conduction is the only mode of heat transfer
  - Radiation and convection neglected
  - No reflection of solar radiation
  - No eclipse times
- General Considerations
  - Simplified geometry assumed in hand calculations
  - Boundary condition assumed at the fuselage and inner tank

Implementation Considerations

- ❑ Implementation Timeline
- ❑ Cost of Implementation
- ❑ Risk Mitigation

Implementation Timeline

- Based on cube satellite manufacturing
- Fits within req HL3 for Artemis III
- Confidence of ±5 months

Phase	Major Elements	Estimated Time (Months)
Planning	Confirm Calculations, Drawings, Schedule, Cost)	4.5
Testing and Iteration	Test supports, iterate for scenarios and configurations	9.5
Manufacturing for Assembly	CNC, Ship Material, Wire	4
Assembly	Welding, Final Validation	3.5
Integration with Spacecraft	Integrate skirt supports with fuselage	3
Safety Checks	Check welds, strength, etc.	2
Total (Months)		26.5

Cost of Implementation

- Calculated through NASA's cost planning guide
- Flight and material
- Manufacturing and integration
- Implementation of 12 MAST structures
- Reduces needed quantity of propellant

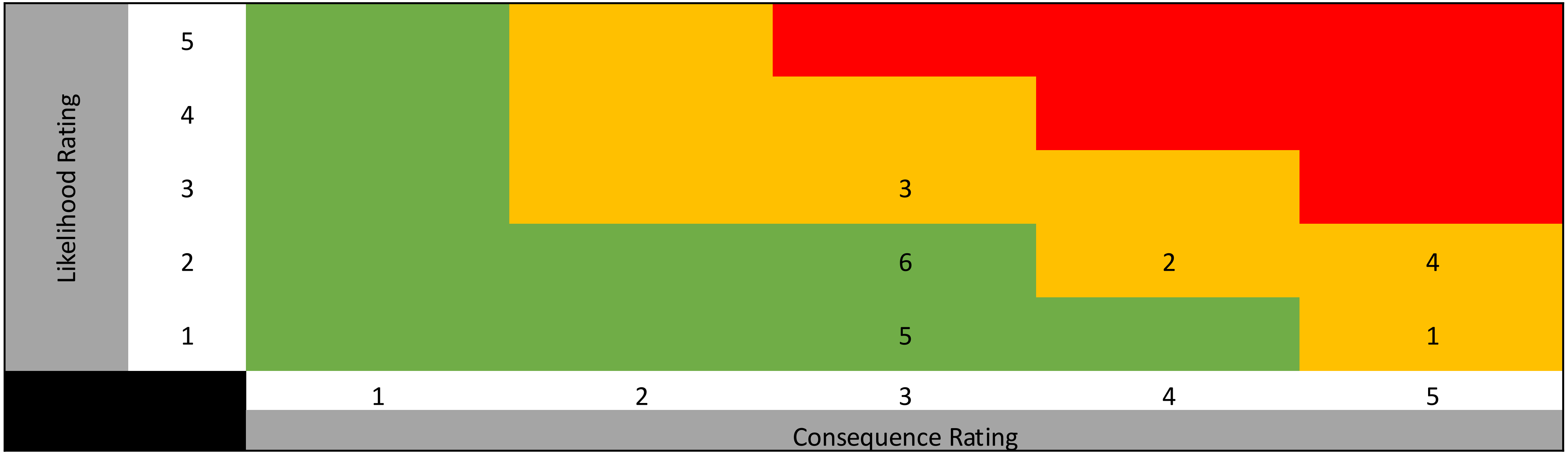
Items	**Lunar Landing Cost**	**Lunar (UC)**	**LEO Launch Cost**	**LEO (UC)**
Resource	Cost	Uncertainty Cost	Cost	Uncertainty Cost
Material	$216,672.00	$246,412.80	$216,672.00	$246,412.80
Manufacture	$53,000.00	$70,000.00	$53,000.00	$70,000.00
Integrate and Test	$2,430,000.00	$1,611,500.00	$810,000.00	$1,611,500.00
Launch	$285,600,000.00	$357,000,000.00	$856,800.00	$1,071,000.00
Total	**$288,299,672.00**	**$358,927,912.80**	**$1,936,472.00**	**$2,998,912.80**

Resource	**Cost Type**	**Amount**	**Cost Per Unit**	**Cost**	**Uncertainty**	**Cost UC**			
								# of Supports	Weight Per (kg)
Ti-5Al-2.5Sn	Per kg	571.2	$60.00	$34,272.00	0.15	$39,412.80		12	23.8
Stepper Motors	Per Unit	36	$5,000.00	$180,000.00	0.15	$207,000.00			
Circuitry	Per Unit	12	$200.00	$2,400.00	0.10	$2,640.00			
Manufacturing	Per Hour	160	$200.00	$32,000.00	0.40	$44,800.00			
Testing		1	$800,000.00	$800,000.00	1.00	$1,600,000.00			
Assembly	Per Hour	60	$350.00	$21,000.00	0.20	$25,200.00		Alternate launch cost to LEO	
Safety Checks	Per Check	2	$5,000.00	$10,000.00	0.15	$11,500.00	Per kg to Launch	$3,000.00	Uncertainty
Launch Cost (Lunar)	Per kg	285.6	$1,000,000.00	$285,600,000.00	0.25	$357,000,000.00	Launch Cost (LEO)	$856,800.00	$1,071,000.00
			Total	**$286,679,672.00**	**Total (UC)**	**$358,930,552.80**		$1,936,472.00	$3,001,552.80

Risk Mitigation

- A – Accept, W – Watch, M – Mitigate
- Retire low risks, mitigate high risks
- Most critical: 1, 2, 3, 4

	Likelihood	Cost	Schedule	Technical
1	1%-10%	<1% Program Budget	1 Week Delay	Minimal Impact
2	11%-30%	1 to 2.5% Budget	2 Week Delay	Minor Impact on performance or mission
3	31%-60%	2.5 to 5% Budget	Multi-week delay to delivery	Moderate impact to performace, low impact on mission
4	61%-80%	5 to 10% Budget	Month long delay to delivery	Large impact to performance, moderate impact to mission
5	81%-99%	>10% Budget	Multi-month long delay to delivery	Massive impact to performance, almost certain mission loss



Likelihood Rating						
	5	🟩	🟨	🟥	🟥	🟥
	4	🟩	🟨	🟨	🟥	🟥
	3	🟩	🟨	🟨 3	🟨	🟥
	2	🟩	🟩	🟩 6	🟨 2	🟨 4
	1	🟩	🟩	🟩 5	🟩	🟨 1
		1	2	3	4	5
		Consequence Rating				

Risk Mitigation

Risk	Risk Statement (if/then)	Cost Consequence Rating	Technical Consequence Rating	Schedule Consequence Rating	Likelihood Rating	Status	Mitigation Plan
1	If the structure is damaged during the mission, then it must be repaired.	5	5	3	1	M	Analyze and test the structure to minimum safety factor
2	If the spacing between the skirt and fuselage is too small, then the design will need to be altered.	3	1	4	2	M	Use NASA standard clearances as references and adapt to such.
3	If the design is too heavy, then it will not be approved for space travel and cost will increase.	2	1	3	3	W	Optimize support structure for mass.
4	If the structure cannot withstand launch forces, then an alternative solution must be used.	2	5	3	2	M	Use simulation tools and experiments to replicate practical launch environment.
5	If the structure allows a large amount of heat transfer, then heat will need to be removed from the cryogen tanks.	2	3	2	1	W	Multiple configurations of the design will be tested, to minimize heat transferred.
6	If the design is too expensive or complicated to manufacture, then the design will need to be changed.	3	2	3	2	A	Use a decision matrix balancing both structural complexity and strength.

Conclusion

- ❑ NASA Alignment
- ❑ Summary Chart

Alignment

HL1 –

- Based on NASA standards
- Justifies low TRL solution with high TRL components

HL2 –

- Electronic and mechanical components verified
- Titanium alloy prevents overheating

HL3 –

- Fieldable in just over two years
- Pairs with existing NASA technology

HL4 –

- Mechanically and thermally verified

HL5 –

- Verified using SolidWorks Simulator

HL6 –

- Non-load bearing during low load phase

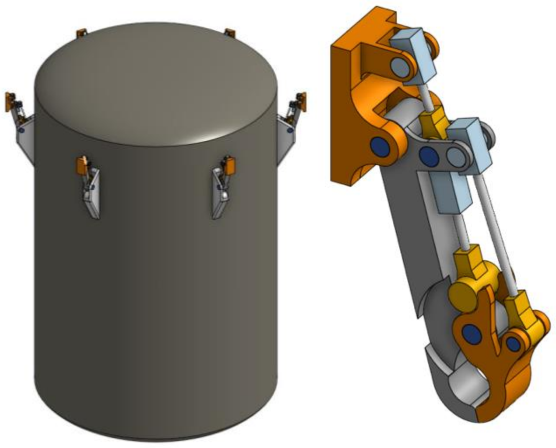
Type	Req	Requirement
High Level	HL1	The design shall be easily adaptable to NASA adoption.
High Level	HL2	The design shall survive in a space environment.
High Level	HL3	The design shall be fieldable in 3 – 5 years (Artemis III).
High Level	HL4	The design shall not pose additional risks to the crew.
High Level	HL5	The design shall survive launch and landing loads.
High Level	HL6	The design shall survive a mission duration of multiple months.

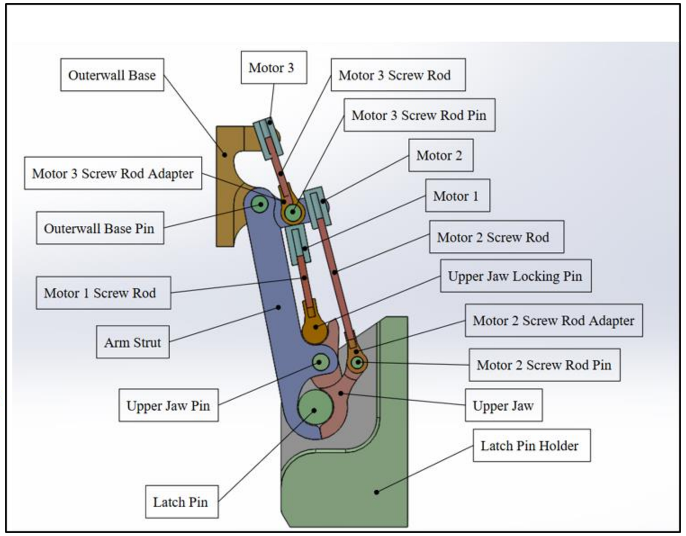
Colorado School of Mines – MAST (Modular Adaptive Separation Technology)

Theme Category, Major Objectives, & Technical Approach

- Advanced Structural Supports for Heat Reduction
- Goals
  - Minimize heat transfer
  - Adapt to low-load conditions
  - Withstand launch forces, vibrations, and lunar landing impulse
  - Work in cis-lunar and lunar environments
- Technical Approach
  - Utilize existing technologies where available
  - Verify design through SolidWorks Simulator
  - Using finite element, conduct static load and thermal analyses

Image/Graphic:





Key Design Details & Innovations of the Concept

Design Details

- Triple Actuator System
- Welds to fuselage and skirt
- Jaws unclamp to remove contact

Innovations

- Decoupling of conductive elements
- Modular in design
- Removes medium for heat transfer
- Reduces propellant boiloff

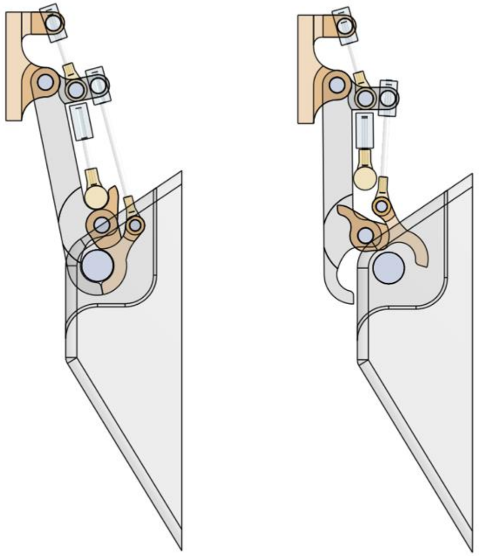


Figure: Jaws closed at launch (left), Jaws opened post launch (right)

Summary of Schedule & Costs

- Calculated Costs: Materials, Components, Manufacture and Assembly, Safety, Launch
- Uncertainty for upper bound estimates
- Lunar landing cost: $288,299,672
- With uncertainty: $358,927,912.80
- LEO launch: $1,936,472
- With uncertainty: $2,998,912.80

Phase	Estimated Time (Months)
Planning	4.5
Testing and Iteration	9.5
Manufacturing for Assembly	4
Assembly	3.5
Integration with Spacecraft	3
Safety Checks	2
Total (Months)	26.5

Q&A Period