Fresnel-Assisted Sintering Technology

Prudent Landers - Colorado School of Mines

June 25th, 2024

Introduction

Project Title: Fresnel Assisted Sintering Technology (FAST)

University: Colorado School of Mines

Faculty Advisor: Mark Florida

Introduction

Mechanical Engineers:

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Electrical Engineers:

Aiden Semet, Madeleine Nightengale-Luhan, Alex Fisher

Problem Statement & Background

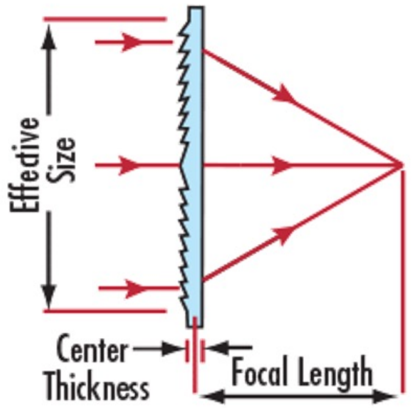
- During the three phases of the human lander, lunar ejecta can be lifted into the atmosphere. This lifted ejecta can orbit around the lunar surface, and cause damage to nearby equipment.
- As such, The Prudent Landers were tasked with reducing lunar erosion and ejecta during descent, ascent, and landing of the human lander

Design Overview

- The proposed solution uses an automated rotating Fresnel Lens capable of sintering lunar regolith into hexagonal tiles
- These tiles will be sintered into a hexagonal bed structure, which will enable the human lander to ascend, descend, and land without ejecting as much lunar particles
- The angling and position of the Fresnel lens and regolith bed are automated to ensure proper positioning of the focal point of the lens during the entire process

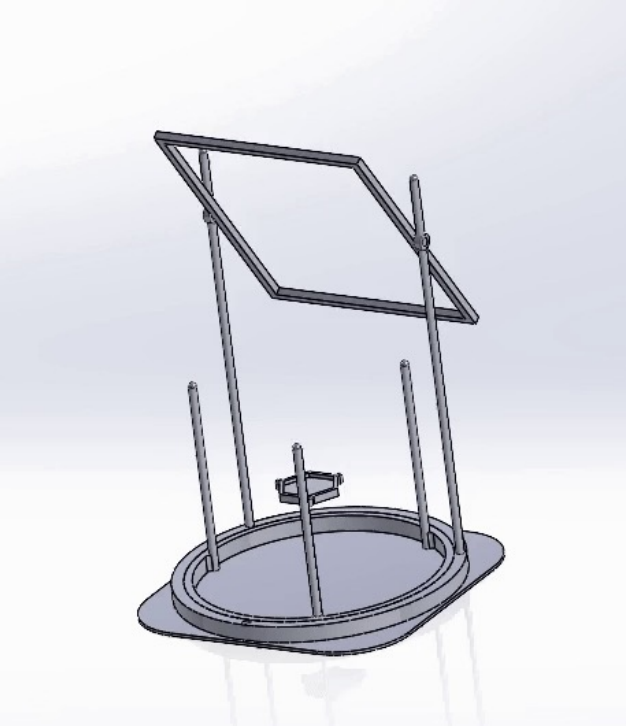
Innovative Technology

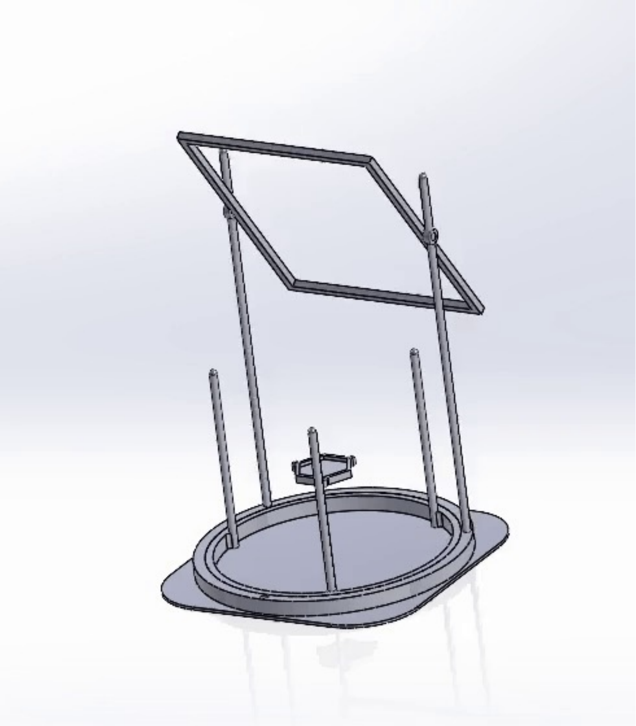
- Fresnel lens uses heat from focused sunlight
- Autonomous system of additive manufacturing
  - Layer by layer system of sintering
- Hexagonal tiles for landing pad
- Improved Fresnel Lens material and focal angle



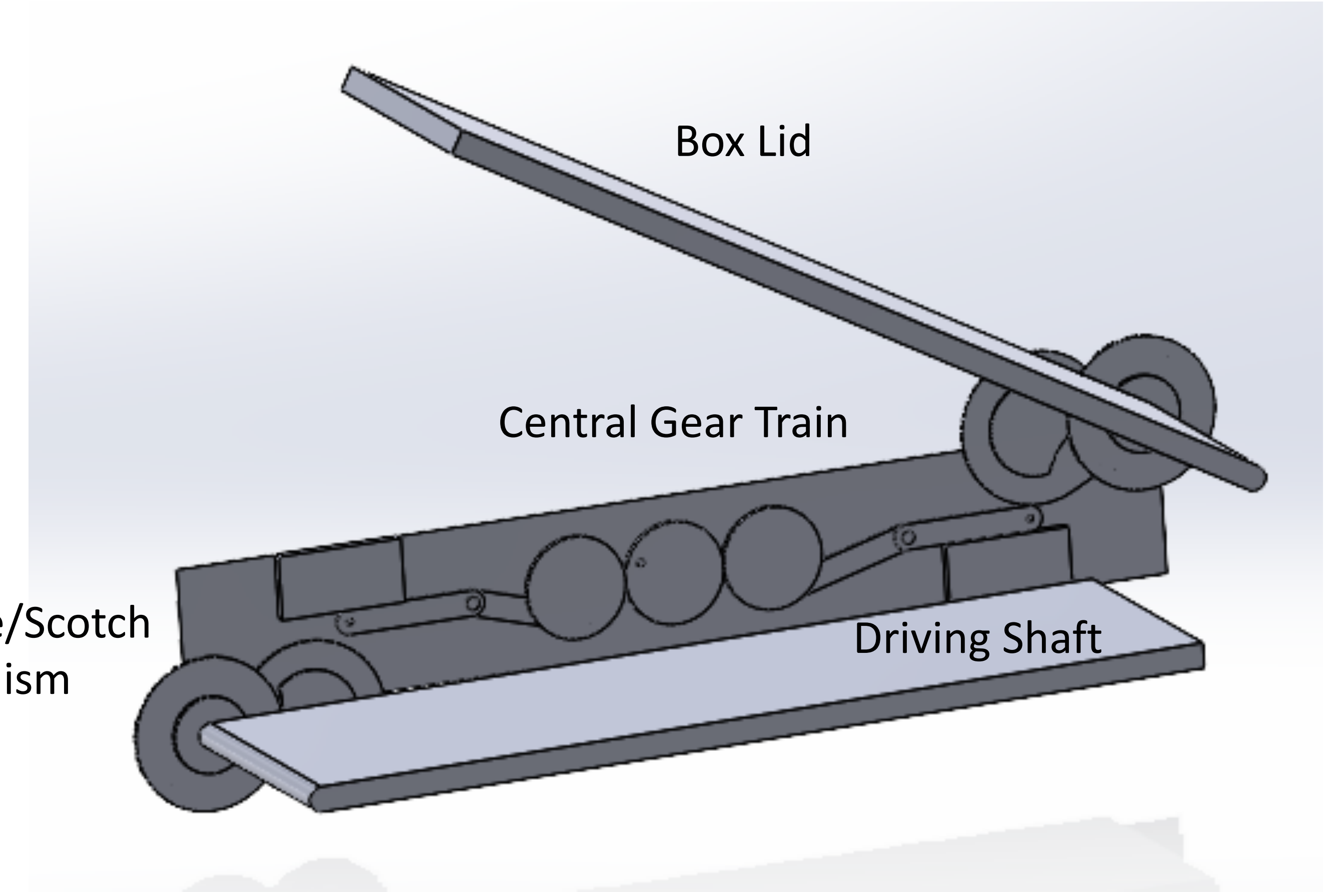
Model Overview

- Triaxial Sinter Bed Controls
- Motorized Lens Pins
- Motorized Base with 360 Rotation
- Motorized Sinter Bed



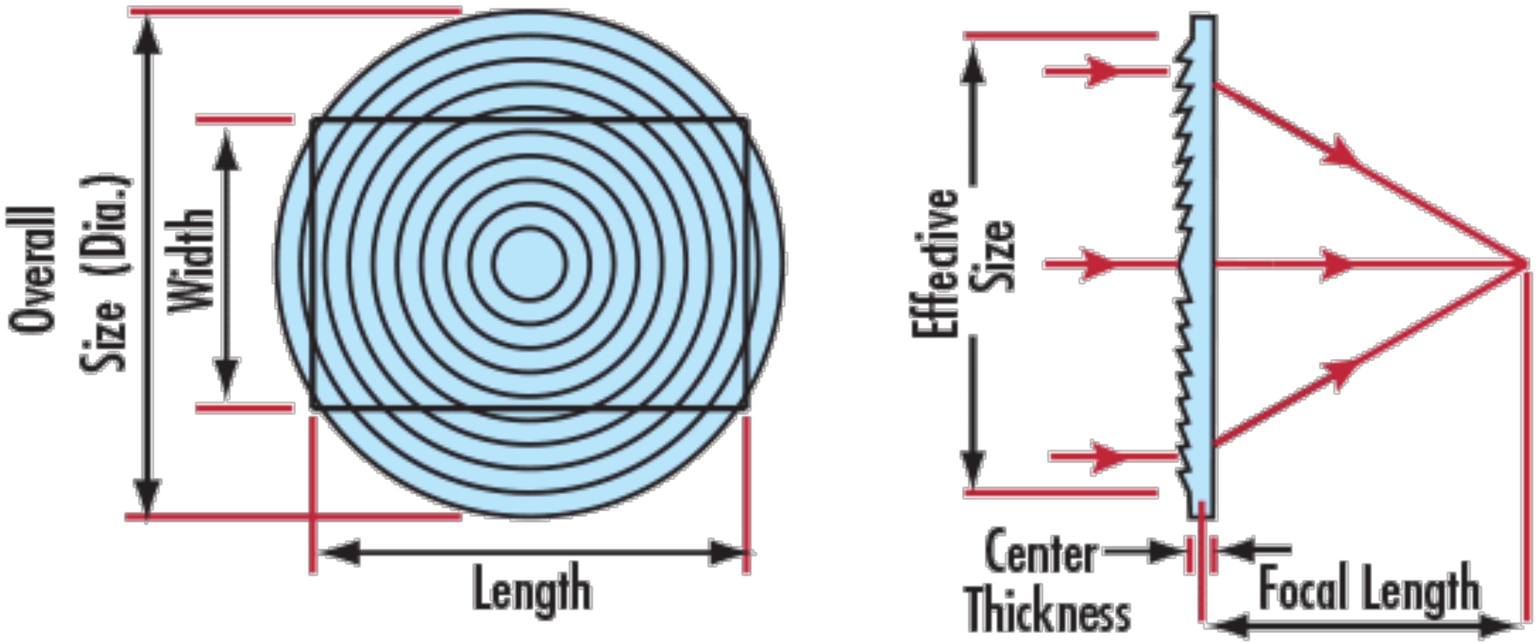


Mechanical Analysis (Sintering Bed)



Engineering Analysis (Fresnel Lens)

A Fresnel Lens has many concentric circles that direct light into a focal point.



Engineering Analysis (Fresnel Lens)

- Testing Goal: To prove sintering is possible
- Our testing:
  - Dimensions: 1.016m x 0.762m
  - Focal length: 1.267 cm high at 0.787 m length
  - Mass: 6.35 kg
  - Density: 1.18
  - Material: Acrylic
  - In ideal conditions, the focal point would get up to 1400K or "solar capture" of 1.084kW

Engineering Analysis (Heat Transfer)

- Surface temperature high enough to melt the regolith
- Used heat transfer analysis to see what depth the melting temperature could reach
- Assumed a semi-infinite solid and constant flux
- Modeled depths and times at various locations, regolith properties

$$T(d,t)=\left[\frac{2q_o''\sqrt{\frac{\alpha t}{\pi}}}{k}exp\left(-\frac{d^2}{4\alpha t}\right)\right]-\left[\frac{q_o''d}{k}erfc\left(\frac{d}{\sqrt{4\alpha t}}\right)\right]+T_i$$

Engineering Analysis (Heat Transfer)

$$T(d,t) = \left[\frac{2q_o'' \sqrt{\frac{\alpha t}{\pi}}}{k} exp\left(-\frac{d^2}{4\alpha t}\right) \right] - \left[\frac{q_o'' d}{k} erfc\left(\frac{d}{\sqrt{4\alpha t}}\right) \right] + T_i$$

$T_i = 286\ [K]$(~56°F), or previous second's T value at a given depth

$$q_o'' = 5.3266 * 10^4 \left[\frac{W}{m^2}\right]$$

Irradiation/Solar Flux (constant)

$$k = (1.281 * 10^{-2}) + (4.431 * 10^{-10})(T_i) \left[\frac{W}{m * K}\right]$$

Thermal Conductivity of Regolith

$$C_p = (-3.6125) + (2.7431)(T_i) + (2.3626 * 10^{-3})(T_i^2) - (1.234 * 10^5)(T_i^3) + (8.9093 * 10^{-9})(T_i^4) \left[\frac{J}{kg * K}\right]$$

Volumetric Heat Capacity of Regolith

$$\rho = 1500 \left[\frac{kg}{m^3}\right]$$

Density of Regolith (constant)

$$\alpha = \frac{k}{\rho * C_p} [No\ units]$$

Equation 7: Alpha Ratio

Electrical Subsystem

Estimated Total Power Consumption: **931.65W**

- 1 Fine Sun Sensor – Tracks the sun with <0.3 degrees of error
- 8 Space-Rated Stepper Motors – Orients the lens and bed for optimal sintering
- 1 Microcontroller – Automates the lens system
- 1 High-Power Laser – Sinters the placed tiles together via an automated rover.

Quantity	Component	Voltage	Amperes (A)	Individual Power Consumption (Watts)	Total Power Consumption (Watts)
1	Fine Sun Sensor	5	0.003	0.25	0.25
8	Space-Rated Motor	24	4.2	100.8	806.4
1	Microcontroller	5	5	25	25
1	High-Power Laser	110	90.9	100	100W

Verification & Validation

- Terrestrial Experiments
  - Testing matched heat transfer calculations for adequate temperatures and fluxes for production
  - Proving our equations through experimentation indicates that Fresnel Sintering is a feasible solution

Grout Solution

- Raised issue from the Hawaii PISCES Project
  - Gases from rocket exhaust becomes trapped under tiles and explodes the landing pad
- Solution involved sealing grout gaps utilizing sintered regolith
  - Will require a 100W sintering laser on rover
  - Rover will trail the grout between each tile and seal the landing pad gaps

Grout Solution

- Requirements
  - Transferable high power 100W laser
  - Navigation and positioning system for precise surface sintering
  - Continuous bond between each tile of regolith grout
  - Preparation of landing pad tiles prior to rover deployment
  - Testing and safety procedures ensured prior to launch
    - Conducted tests in simulated environment to ensure sintering process will bond properly on lunar surface
    - Ensures the landing of a rocket will be supported on lunar landing pad
  - Simulate impact from rocket exhaust

Grout Solution

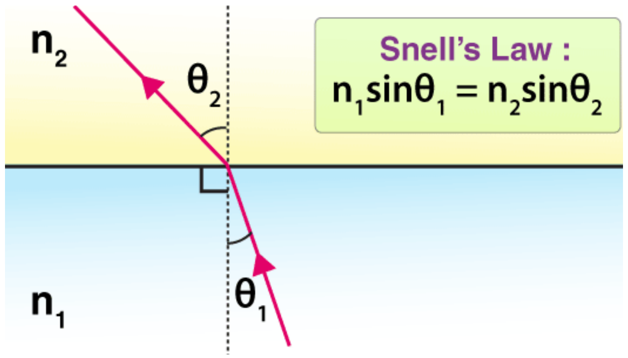
- Development
  - Phase 1 - Designing and prototyping the tiles, grout material, rover and laser system
  - Phase 2 - Conducting laboratory tests to optimize the sintering process and validate the strength of bonding
  - Phase 3 - Performing field tests in vacuum environment to ensure the system functions properly
  - Phase 4 - Implementation of design on lunar environment and monitoring of performance during rocket landings

Vacuum Environments

- In a vacuum environment, heat can only transfer through means of radiation
- With the current Fresnel lens set up, radiation mode heat will still sinter the regolith as desired but might overachieve results as the lack of heat loss to air via convection will influence the results
- Lower G could affect the material strength of the sintered lunar regolith, making the strength of the tiles weaker than originally intended

Solar Inclination Angle

- Solar inclination angle of Sun at the Lunar polar region is around 1.5°
- Using Snell's Law, output angle of energy is around 1.5° below the horizontal
- Light refracts upwards 0.14 inches through the lens
- Using the Fresnel equation, it was determined that transmissivity of energy would sit around 90%
- Angle of repose of regolith is around 58°, can stand test bed at 50°



$$t_s = \frac{2n_1 \cos\theta_1}{n_1 \cos\theta_1 + n_2 \cos\theta_2}$$

Variables:

- n_1 or n_2 = light going through medium 1 or 2
- θ_1 or θ_2 = angle of light going into or out of the lens
- t_s = transmissivity of energy

Fresnel Lens Material

- Acrylic doesn't have material properties built for space
- Needs to fit hot and cold temperature fluctuations on the moon
- Solution includes Polycarbonate
  - Refractive index of 1.5848
  - Higher density than acrylic (1.20 to 1.18)
  - Proven successful against high impact for landings & temperature needs

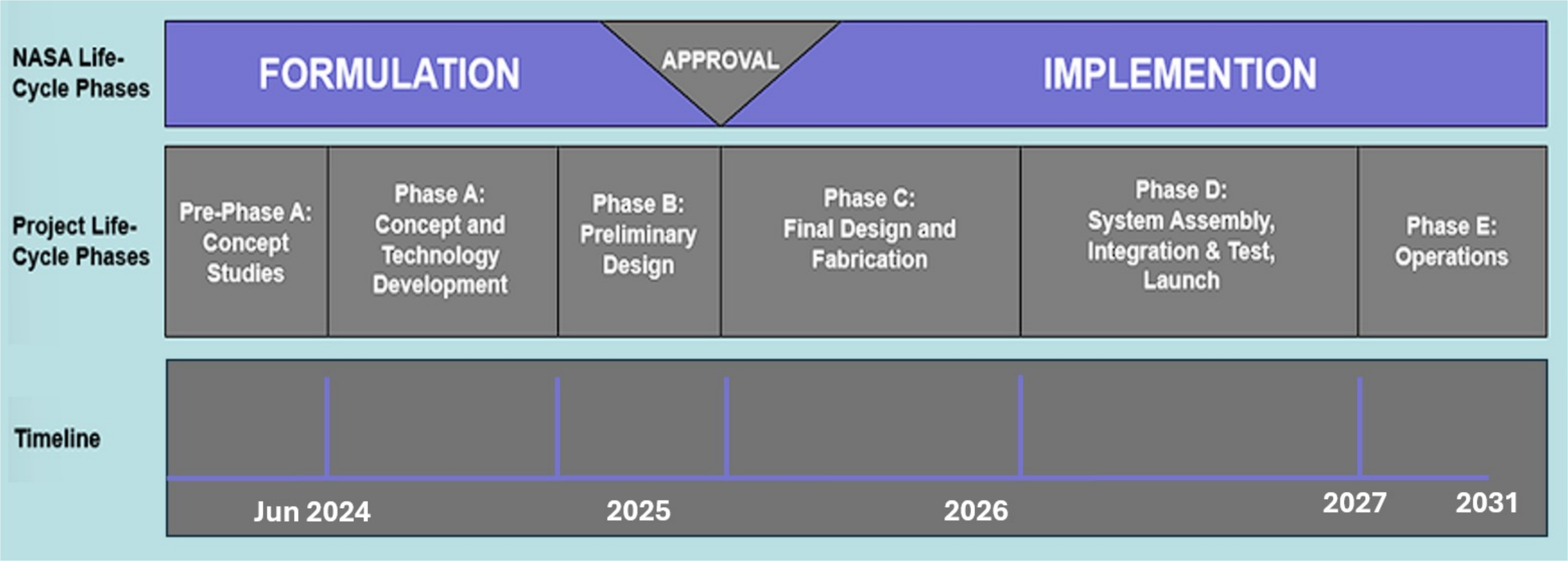
Lunar Operations

- To create an adequate pad size for the Blue Moon HLS landers, *FAST* should be launched and tested on Artemis 3
- Optimal placement of *FAST* would be near habitat solar array
- *FAST* should be used in coordination with the LTV
- Construction process is semi-automated

Credit: SpaceX

Path To Flight Timeline

- Most of the Pre-phase A already covered
- Technology development estimated to take around 7 months
  - Solar lens and 3-D printing technology widely documented
- Wide margins for Phases C and D
  - Will require significant engineering effort and precautions



Cost Estimation

- Over a 7-year period, 2024 to 2031, the cost of this project is estimated at $2.43 million.
- Most of the cost, around 64%, attributed to staff cost
- The rest may be spent on other expenses such as: Facility Prep and Support, Software, and Travel
- Estimated total FTE of 11.92

Life Cycle Cost Estimate		Activity Dataset: HuCL							Produced: 06/04/24					
Mission Start Year:	2024	Operations Start Year:		2027	Mission Complete Year:			2031	Inflation Rate		3.0%			
Estimated Staffing Level	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**Total**	**Pct.**
Management Staff FTE	0.25	0.25	0.25	0.50	0.50	0.50	0.50	0.50	0.00	0.00	0.00	0.00	3.25	27.3%
Administrative Support FTE	0.00	0.00	0.00	0.02	0.02	0.02	0.02	0.02	0.00	0.00	0.00	0.00	0.10	0.8%
Technical Coordination Staff FTE	0.00	0.00	0.00	0.75	0.75	0.75	0.75	0.75	0.00	0.00	0.00	0.00	3.75	31.5%
Development Staff FTE	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.3%
Technical / Science Staff FTE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0%
Operations Staff FTE	0.00	0.00	0.00	0.08	0.08	0.08	0.08	0.08	0.00	0.00	0.00	0.00	0.38	3.2%
Sustaining Engineering Staff FTE	0.00	0.00	0.00	0.06	0.06	0.06	0.06	0.06	0.00	0.00	0.00	0.00	0.28	2.3%
Engineering Support Staff FTE	0.00	0.00	0.00	0.83	0.83	0.83	0.83	0.83	0.00	0.00	0.00	0.00	4.13	34.6%
Estimated Total FTE	**0.26**	**0.26**	**0.26**	**2.23**	**2.23**	**2.23**	**2.23**	**2.23**	**0.00**	**0.00**	**0.00**	**0.00**	**11.92**	
Estimated Staff Costs, K$	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**Total**	**Pct.**
Management Staff Cost	38	39	40	82	84	87	90	92	0	0	0	0	551	35.5%
Administrative Support Staff Cost	0	0	0	1	1	1	1	1	0	0	0	0	7	0.4%
Technical Coordination Staff Cost	0	0	0	82	84	87	90	92	0	0	0	0	435	28.1%
Development Staff Cost	1	1	1	0	0	0	0	0	0	0	0	0	4	0.2%
Technical / Science Staff Cost	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0%
Operations Staff Cost	0	0	0	8	9	9	9	9	0	0	0	0	45	2.9%
Sustaining Engineering Staff Cost	0	0	0	6	6	6	7	7	0	0	0	0	32	2.1%
Engineering Support Staff Cost	0	0	0	90	93	96	99	101	0	0	0	0	479	30.9%
Total Estimated Staff Cost	**39**	**40**	**41**	**269**	**277**	**286**	**296**	**302**	**0**	**0**	**0**	**0**	**1,550**	**63.8%**
Other Non-Staff Costs	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**Total**	**Pct.**
System Purchase Cost	2	2	2	0	0	0	0	0	0	0	0	0	6	0.7%
COTS Software License Cost	7	7	7	3	3	3	3	3	0	0	0	0	36	4.1%
Facility Preparation and Support Cost	23	23	23	33	33	33	33	33	0	0	0	0	234	26.6%
System Maintenance Cost	0	0	0	4	4	4	4	4	0	0	0	0	20	2.3%
Network / Communications Cost	4	4	4	4	4	4	4	4	0	0	0	0	32	3.6%
General Supplies Cost	10	10	10	13	13	13	13	13	0	0	0	0	95	10.8%
Archive Media Cost	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0%
Distribution Media Cost	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0%
Travel Cost	25	25	25	25	25	25	25	25	0	0	0	0	200	22.7%
Training Cost	0	0	0	3	1	1	1	1	0	0	0	0	7	0.8%
Data Purchase Cost	0	0	0	25	25	25	25	25	0	0	0	0	125	14.2%
Computer Services Cost	0	0	0	25	25	25	25	25	0	0	0	0	125	14.2%
Total Estimated Non-Staff Costs, K$	**71**	**71**	**71**	**135**	**133**	**133**	**133**	**133**	**0**	**0**	**0**	**0**	**880**	**36.2%**
Total Estimated Cost, K$	**110**	**111**	**112**	**404**	**410**	**419**	**429**	**435**	**0**	**0**	**0**	**0**	**2,430**	

FTE Estimation

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Development Staff Cost	1	1	1	0	0	0	0	0	0	0	0	0	4	0.2%
Technical / Science Staff Cost	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0%
Operations Staff Cost	0	0	0	8	9	9	9	9	0	0	0	0	45	2.9%
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Engineering Support Staff Cost	0	0	0	90	93	96	99	101	0	0	0	0	479	30.9%
Total Estimated Staff Cost	**39**	**40**	**41**	**269**	**277**	**286**	**296**	**302**	**0**	**0**	**0**	**0**	**1,550**	**63.8%**

Non-Staff Cost Estimation

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System Maintenance Cost	0	0	0	4	4	4	4	4	0	0	0	0	20	2.3%
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Travel Cost	25	25	25	25	25	25	25	25	0	0	0	0	200	22.7%
Training Cost	0	0	0	3	1	1	1	1	0	0	0	0	7	0.8%
Data Purchase Cost	0	0	0	25	25	25	25	25	0	0	0	0	125	14.2%
Computer Services Cost	0	0	0	25	25	25	25	25	0	0	0	0	125	14.2%
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Total Project Cost Estimation

Total Estimated Cost, K$	**110**	**111**	**112**	**404**	**410**	**419**	**429**	**435**	**0**	**0**	**0**	**0**	**2,430**	

Conclusion

- Successfully found solution to mitigate Plume Surface Interaction
- Created autonomous design
- Tested prototype in Denver, Colorado
- Validated data with calculation for South Pole of Moon
- Low human interaction with lunar operations needing LTV transportation
- Fully ready for use by 2027