Preliminary Surface Stabilization to Mitigate Lunar Plume Surface Interaction

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Plume Surface Interaction (PSI)

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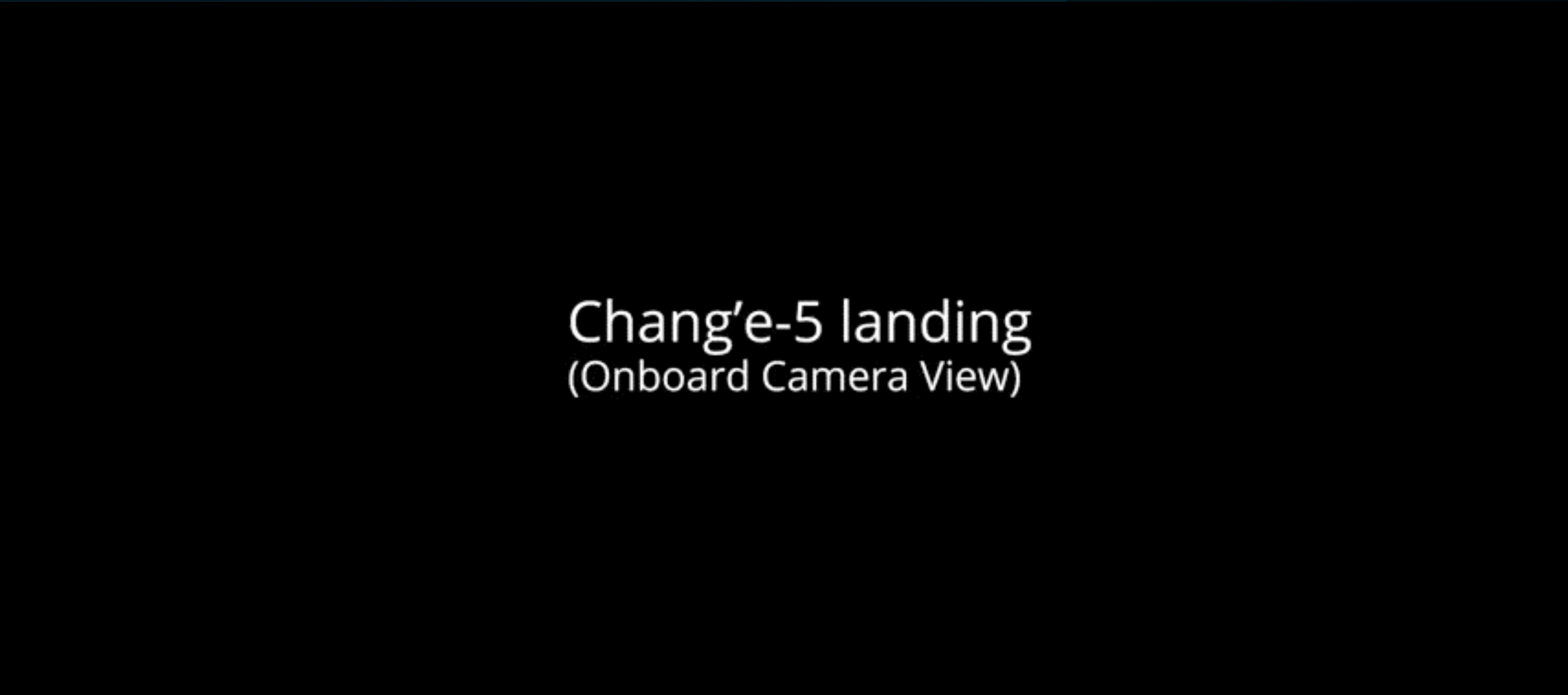
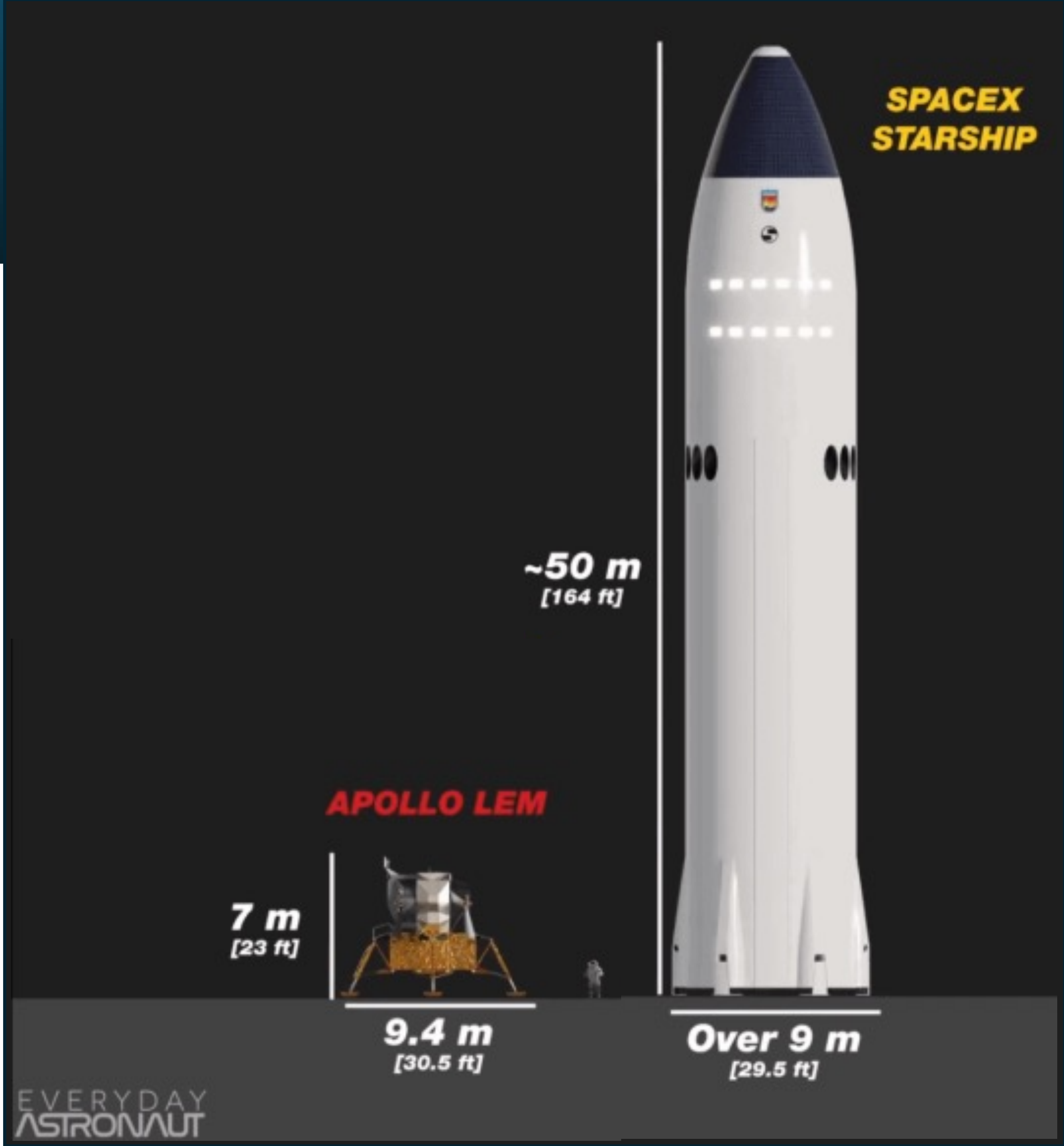


The Problem

- Plume-Surface Interaction (PSI) dates back to Apollo, this issue must be solved for Artemis and beyond.
- PSI is an erosional phenomenon, it is a multi-faceted issue with wide ranging consequences on crewed missions to the Moon.

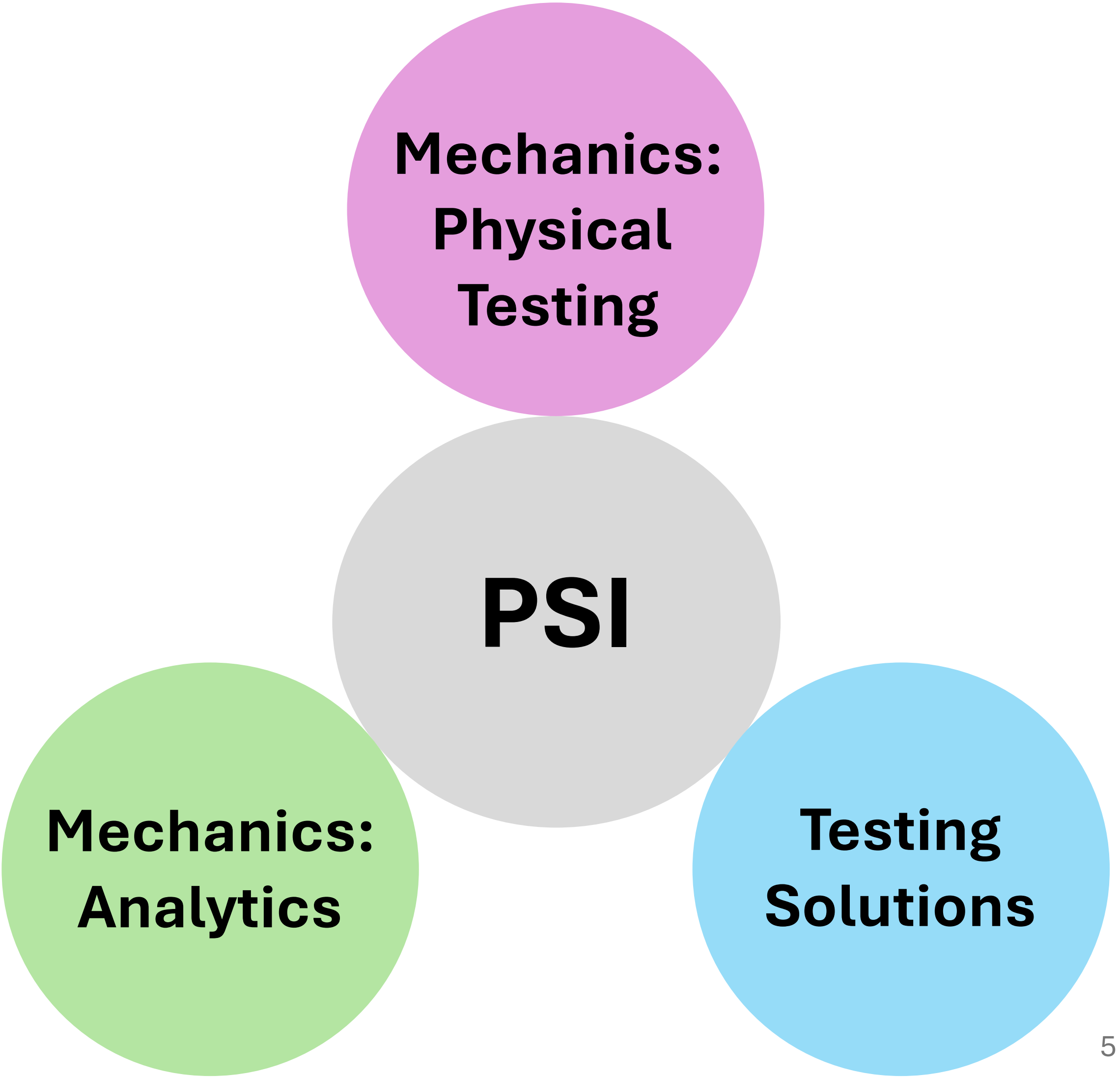


A Coordinated Approach

The team recognized the importance of understanding the mechanisms of PSI as well as mitigating its negative effects.

The Maroon Moon team took a 3-prong approach :

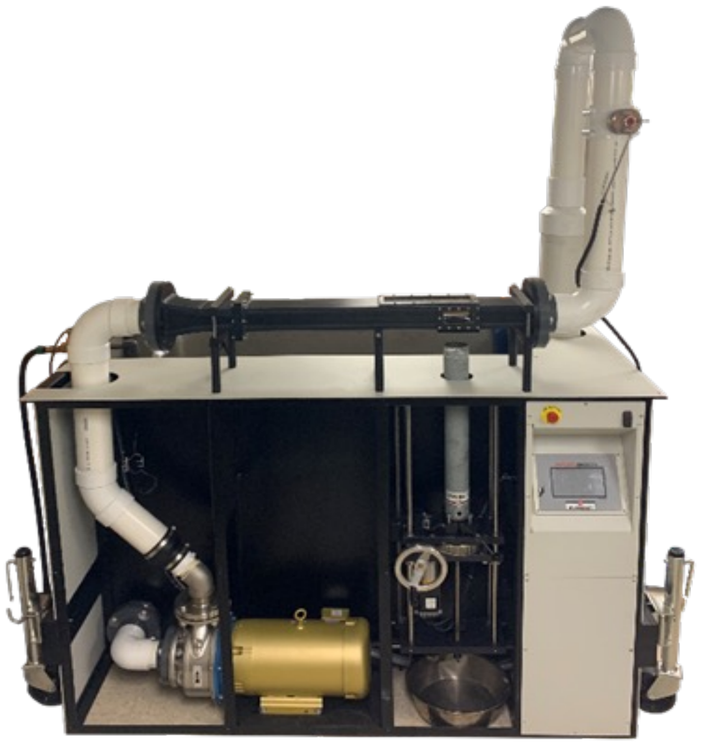
1. Testing/understanding the mechanics of PSI
   - Erosion Function Apparatus
2. Analysis/further understanding the mechanics:
   - Analytical Transformation between Water and Air Mediums
   - Gas flow CFD
   - CFD-DEM Cohesive Effects
3. Zeroing in on solutions:
   - Development of Gas-Granular Erosion Apparatus
   - Proposed CLPS flight experiment

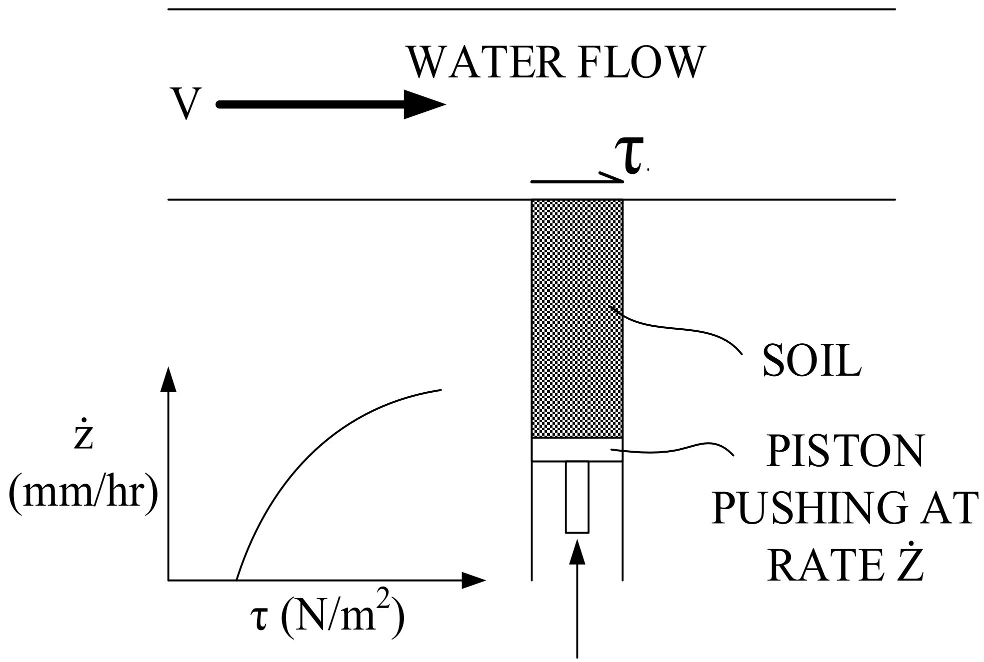


EFA Testing

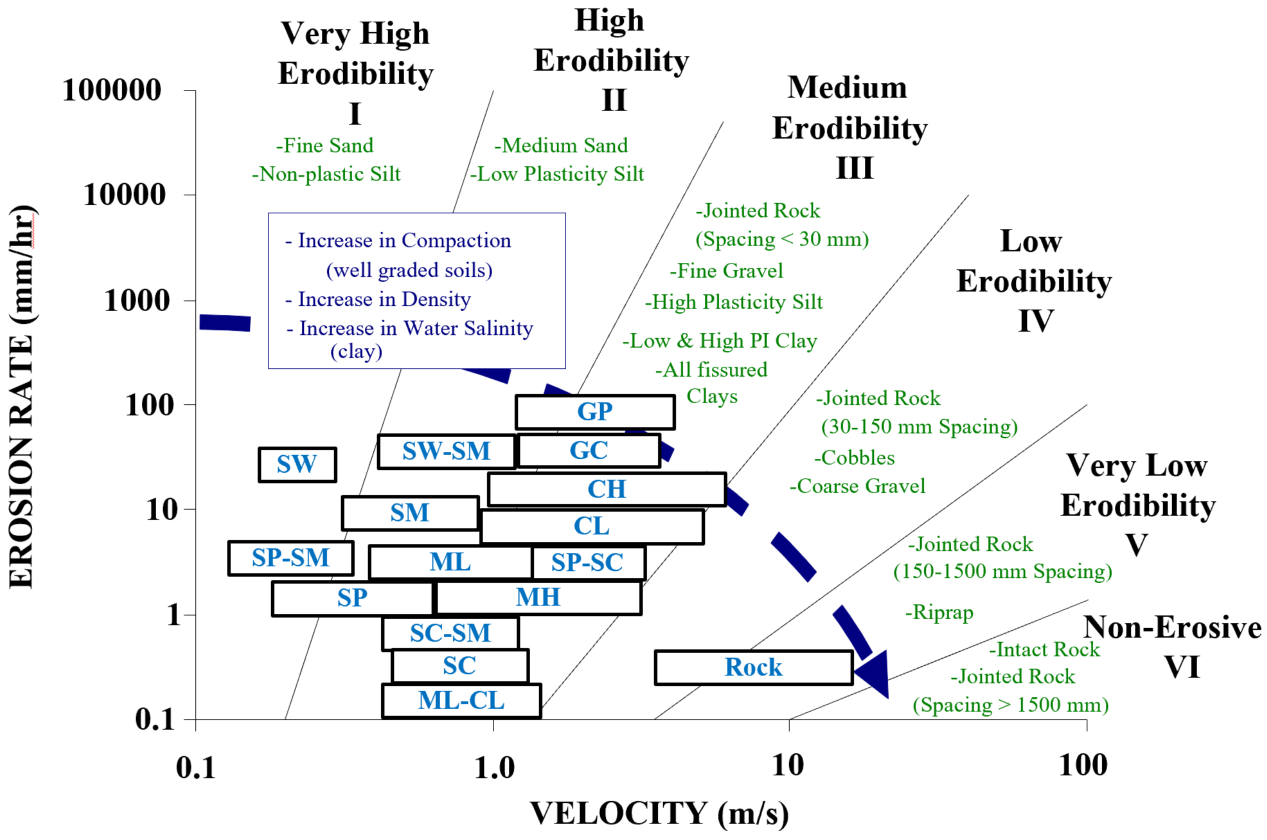
Erosion Function Apparatus (EFA)

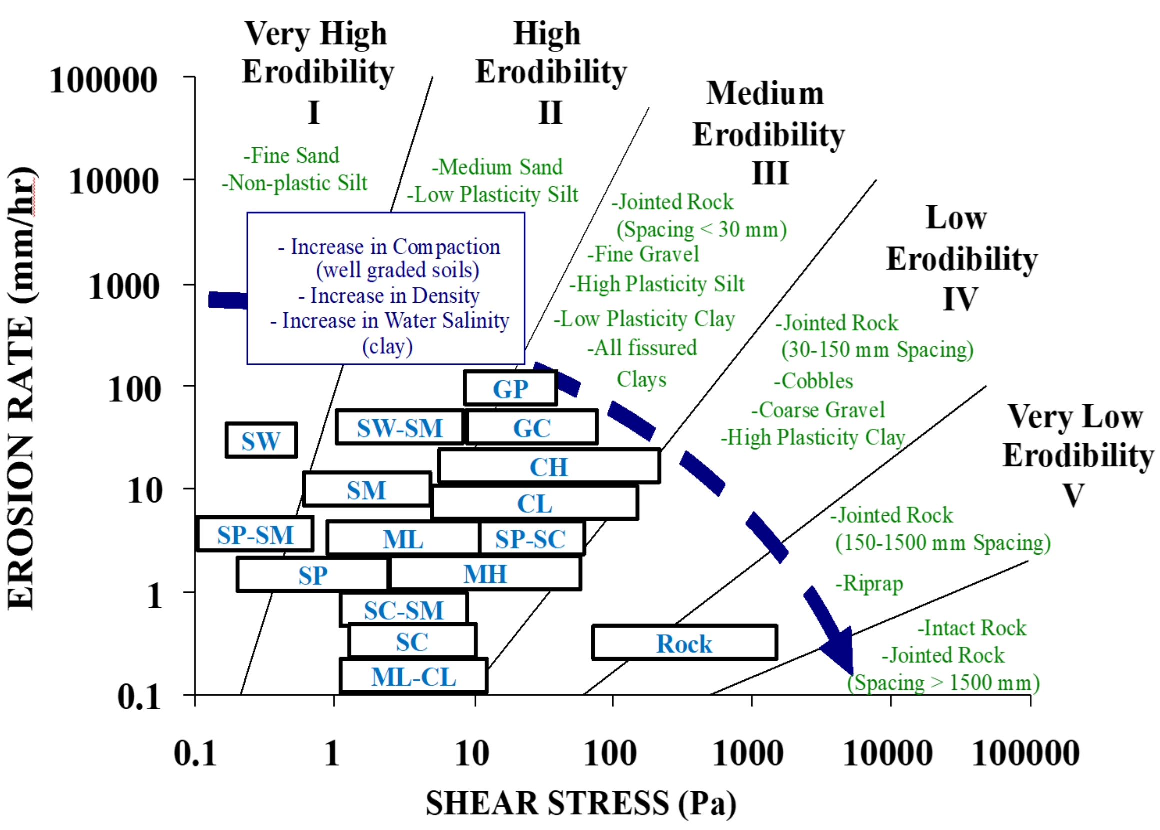
- Erosion Function Apparatus is a water-based channel that records and measures the erodibility of soils.
- Similar behavior between erosion on Earth and PSI on the Moon.





Erosion Charts





Lunar Simulant: BP-1

- BP-1 was used to simulate lunar soil in the EFA.
- BP-1 falls within one standard deviation range of lunar regolith particle size distribution.
- Rough and angular particle shapes add to regolith-like cohesive effects.
- Correction from technical paper, not using JSC-1

Surface Stabilization Trade Study

Proposal	Advantages	Disadvantages
Deflector	• Simple	• Massive • Heavy and difficult to transport
Epoxy/Resin Binder	• Mass-efficient	• Degrades with UV radiation
Geomembrane	• Limits gas interaction with the surface below	• Requires large amount of water
Sintering	• No additives to regolith	• Requires high amount of energy
Tackifiers and Soil Stabilizers	• Easy application	• Lower shear strength

Deflector

- Info: Physical object blocking flow
- Advantage: Simplicity
- Disadvantages: High transportation and mass costs

Epoxy Resin Binder

- Info: Sealant covering surface
- Advantage: Mass Efficient
- Disadvantage: Degrades with UV Radiation

Geomembrane

- Info: Fabric made of layers of plastic
- Advantage: Limits gas interaction with surface below
- Disadvantage: Requires high amount of water

Sintering

- Info: Binding upper level of regolith by heat
- Advantage: No additives to regolith
- Disadvantage: Requires high amount of energy

Tackifiers and Soil Stabilizers

- Info: Solution applied to bind soil
- Advantage: Easy to Apply
- Disadvantage: Low Shear Strength

Solution Selection

From these three mitigation techniques, more specific solutions were analyzed.

	Light CA glue	Medium CA glue	Epoxy Resin	Polyacrylamide Tackifier
Advantages	Easy to Apply	Easy to Apply	Strong bond	Liquid application and meant to stop erosion
Disadvantages	Boils at 150 °C Heavy	Boils at 150 °C Heavy	Higher Viscosity Degrades in UV radiation	Required to be diluted with water
Cure Time	Seconds	2 minutes	15 min to 1 hour	N/A
Thermoplastic or Thermoset	Thermoplastic	Thermoplastic	Thermoset	Thermoplastic

Solution Selection

From these three mitigation techniques, more specific solutions were analyzed.

	Sodium Polyacrylate	Liquid acrylic Polymer	(Polylactic Acid) PLA Plastic	Sintering
Advantages	Powdered form Easy to pack	Used in concrete Can handle high shear loads	Lightweight Solid, Easy to transport	No additives to regolith
Disadvantages	Must be mixed with water Gel substance	Required to be mixed with tougher materials	Melts, shrinks	Requires high energy input
Cure Time	10 seconds	Less than 7 days	15 minutes	2 hours
Thermoplastic or Thermoset	Thermoplastic	Thermoplastic	Thermoplastic	N/A

Cyanoacrylate

This solution:

- Easily Applicable if diluted with Acetone.
- Can withstand up to 120 °C.

However:

- Needs moisture to start curing.
- Can be heavy depending on area being covered.

15m^2 area requires 7 kg of CA and 52 kg of acetone.

Thermoplastic

This is:

- Lightweight
- Easy to transport

However:

- Deforms at 70 °C

15m^2 area requires 10 kg.

Sintering

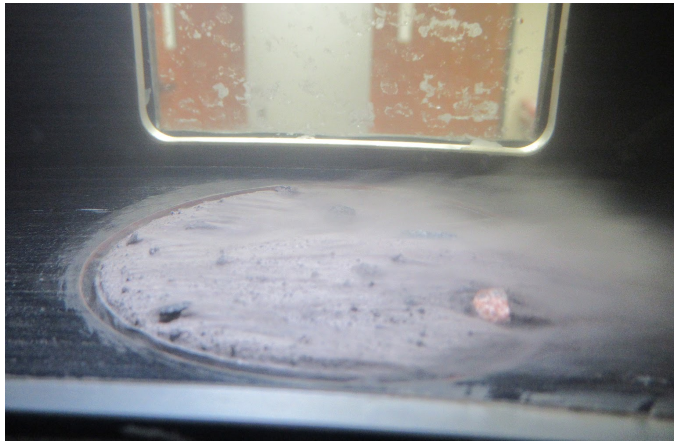
This is:

- Can withstand high surface temperatures.
- No additional weight from surface covering materials.

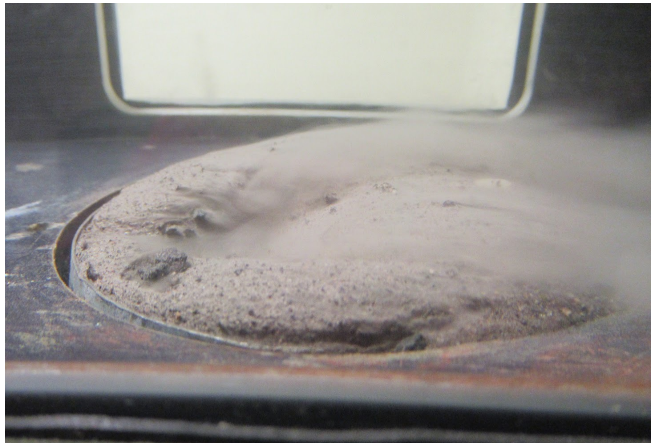
However:

- Requires high energy consumption from a rover vehicle.

Loose and Compacted Regolith Testing



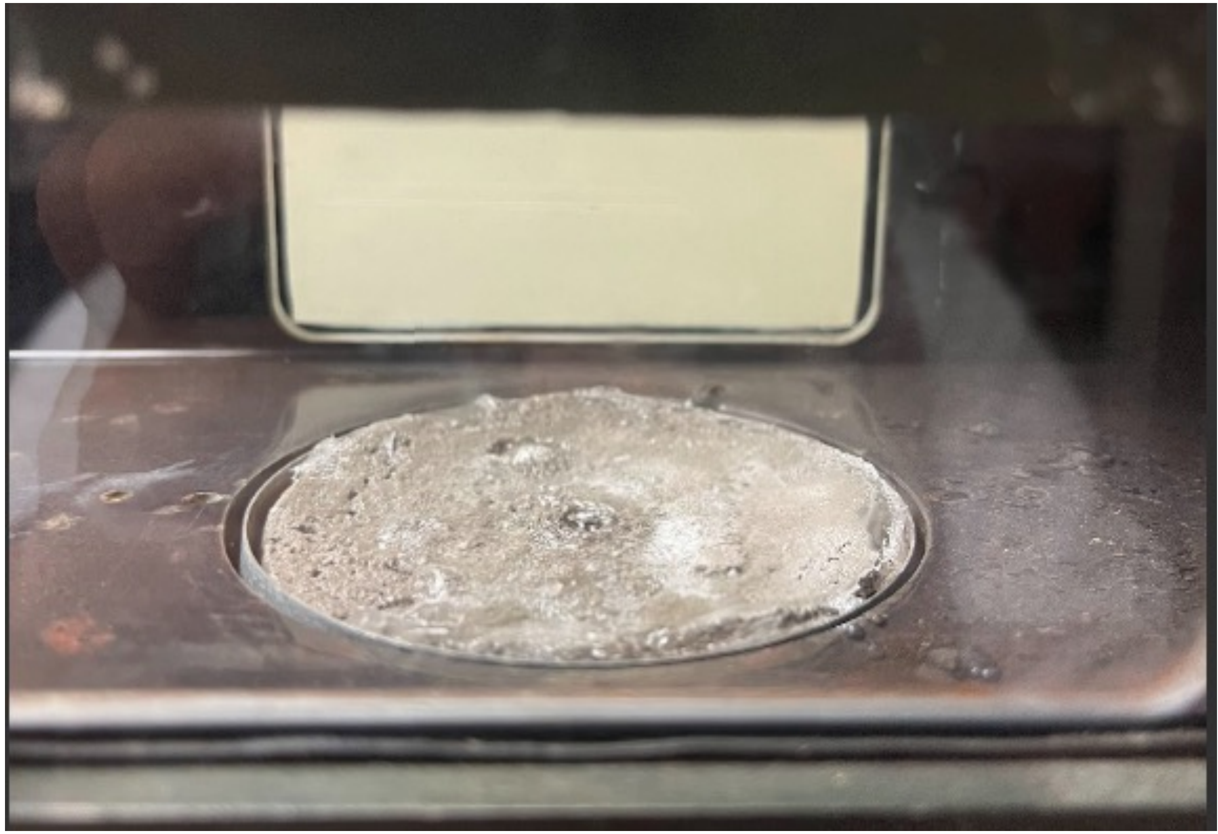
- Loose regolith had a relative density of 72%.
- Compacted regolith had a relative density of 98%.



Cyanoacrylate Testing

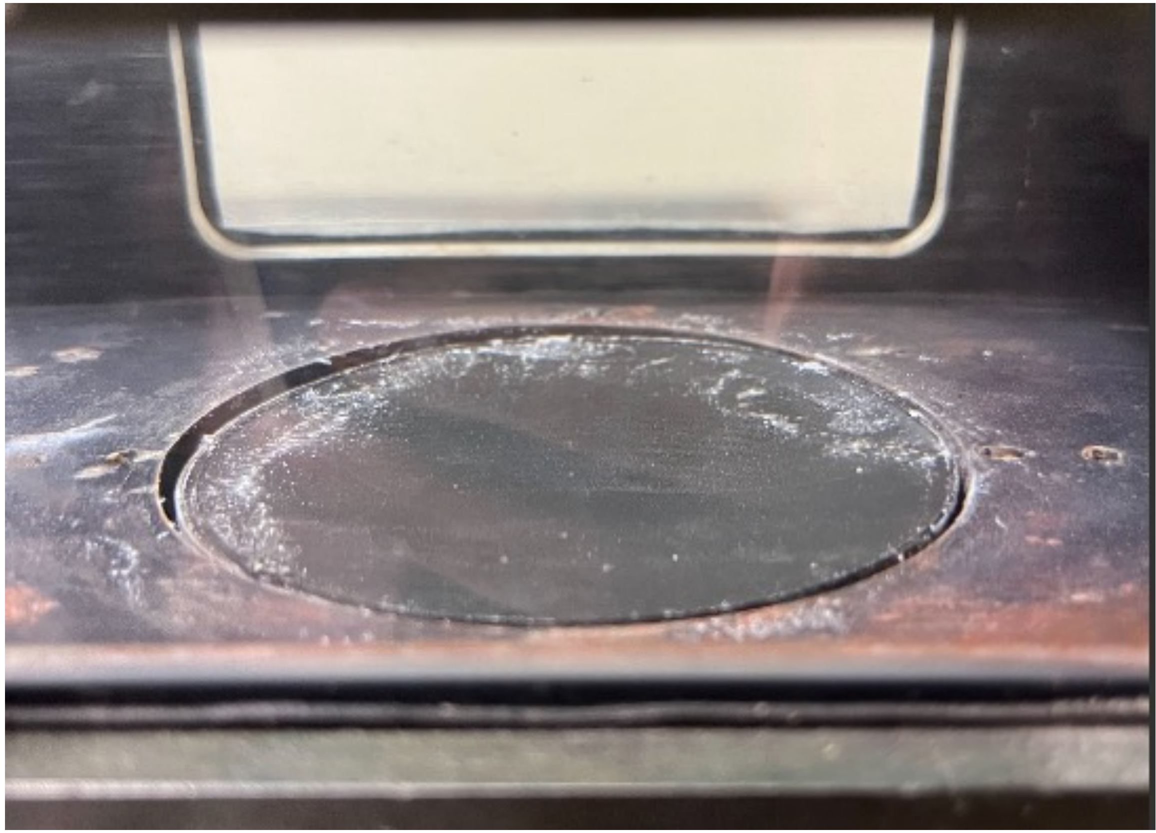
- Two solutions of 2 mL light and medium cyanoacrylate and 20 mL anhydrous acetone were poured on loose regolith and allowed to cure overnight.

- Neither cyanoacrylate experienced any erosion to the max velocity (6.5 m/s).



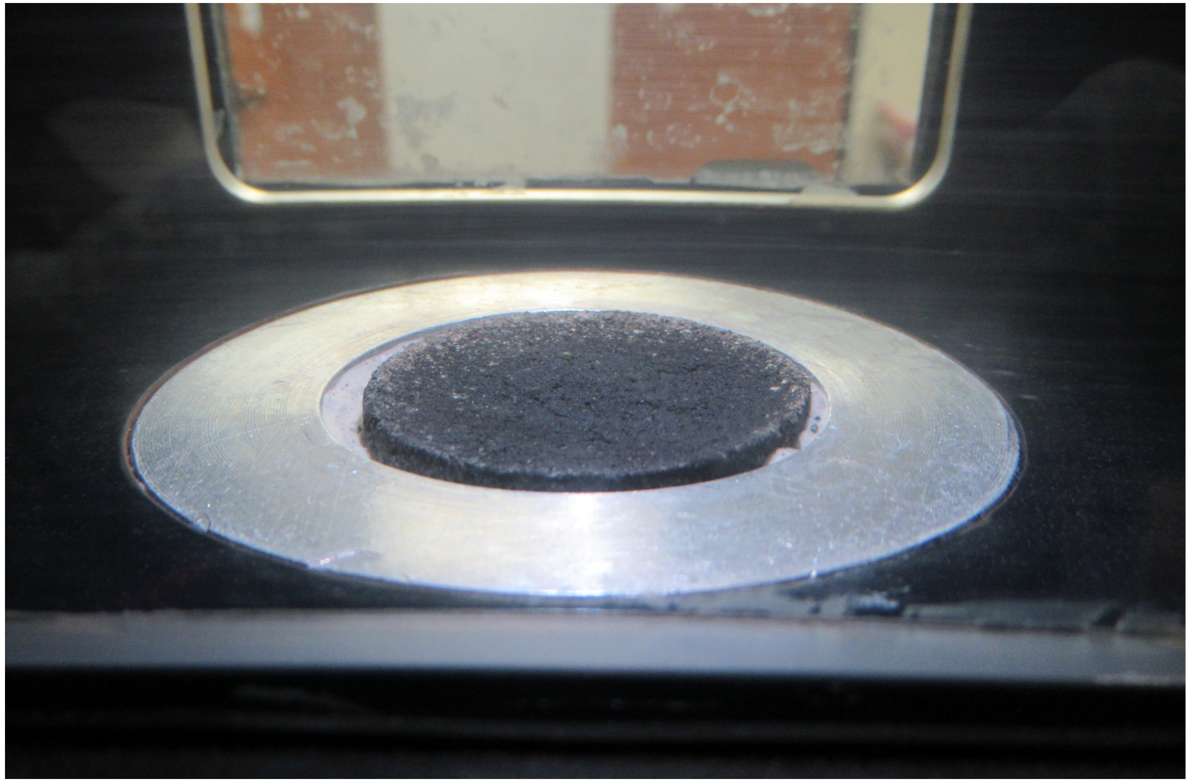
Thermoplastic Testing

- A 0.5 mm sheet of PLA was used.
- Melting of the PLA sheet caused holes and shrinkage.
- The PLA sheet did not experience any erosion to the max velocity (6.5 m/s).



Sintered Regolith Testing

- 6 samples were sintered for one hour; 3 at 1100 °C and 3 at 1200 °C.
- 4 of the 6 samples broke upon removal from furnace.
- Both 1100 and 1200 °C samples did not experience erosion to the max velocity (6.5 m/s).

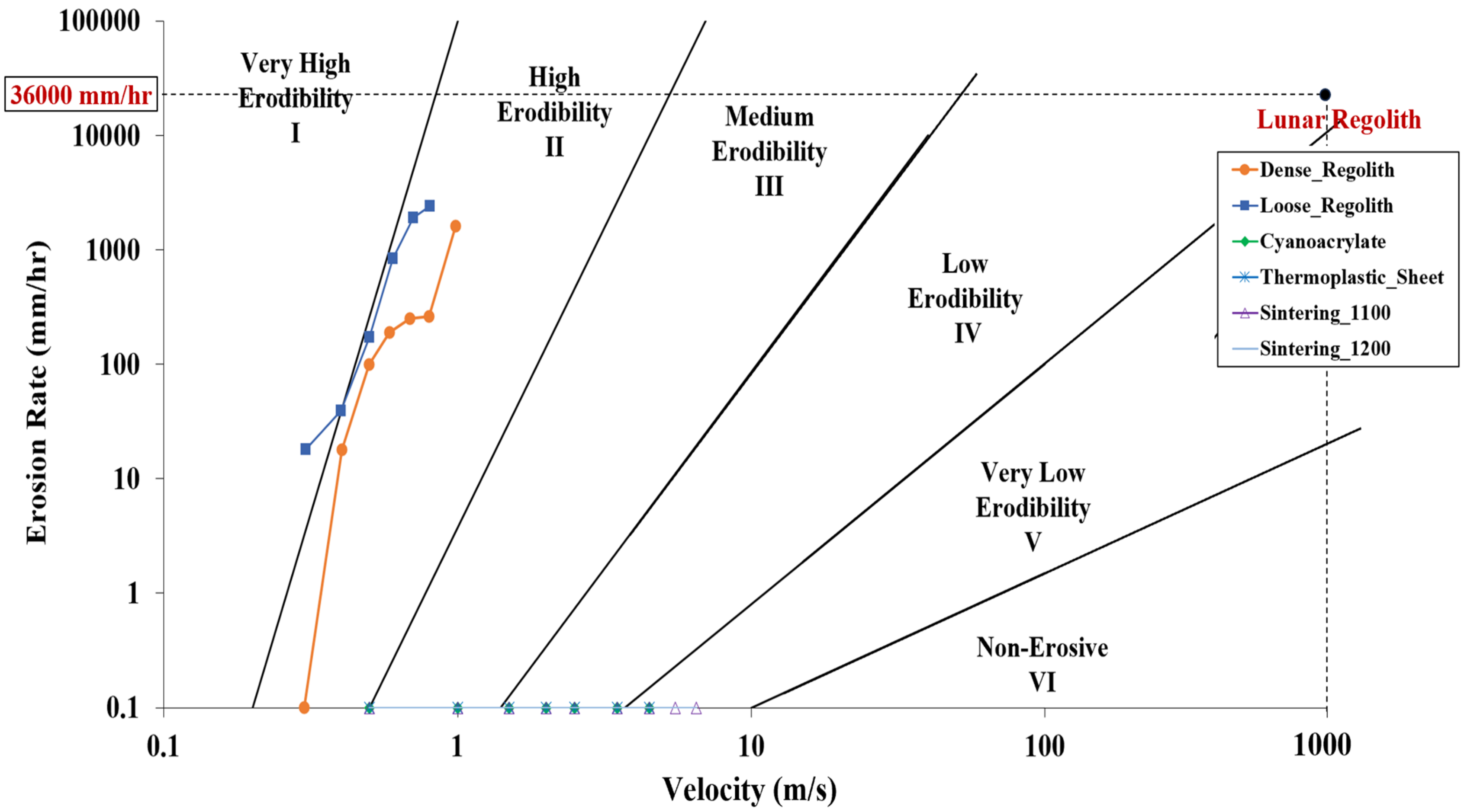


Erosion Rate for Crater

- Velocity → Erosion Rate → Crater Depth = Erosion Rate × Time of application
- Nominal Velocity Along Surface = 1000 m/s
- Time of application = 10 sec
- Allowable crater depth = 0.1 m
- Therefore, Erosion Rate = Crater depth/Time of application = 0.1/10 = 0.01 m/s
- 0.01 m/s = 36000 mm/hr.

Results

- Base lunar simulant has high erodibility.
- Solutions applied resulted in no erosion up to 6.5 m/s.
- Higher velocity testing is needed to see the limits of the applied solutions.



Analytical Transformation of Mediums

Mathematical Transformation - Shear Stress Equivalency

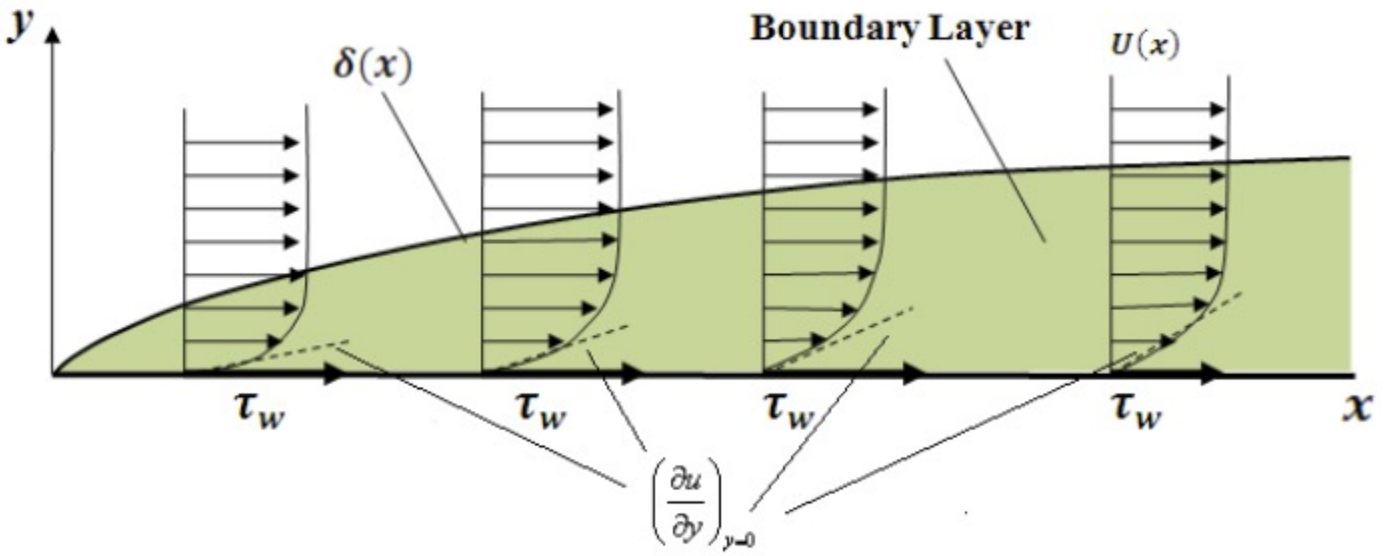
- A shear stress equivalency would be an ideal simple transformation method, however given the viscosity and velocity properties of the two flows this is not possible with our current water testing capabilities.

$$\tau = \mu \frac{du}{dy} \quad \Rightarrow$$

$$\tau = \mu_w u_w = \mu_{eg} u_{eg}$$

$$\tau = \mu_w u_w = \mu_{eg} u_{eg} \Rightarrow u_w = \frac{0.0000350\ Pa \cdot s * 3500\ m/s}{0.00853\ Pa \cdot s} = 143.61\ m/s$$

- However, there are other ways we can seek to find an equivalency between flows based on the boundary layer which greatly affects the erosion process.



Mathematical Transformation – Boundary Layer Thickness

- Since the erosion process is a boundary layer phenomena, we can formulate a treatment to compare the two vastly different flows based on this boundary layer thickness rather than the shear stress equivalency approach.

$$\delta_L \approx \frac{5.0}{\sqrt{Re_x}} x, \ (Blasius\ solution)$$

$$\delta_T \approx \frac{0.37}{Re_x^{1/5}} x$$

$$Re_x = \frac{\rho u L}{\mu}$$

$$\Rightarrow$$

$$\delta_L \approx 5x\left(\frac{\mu}{\rho u L}\right)^{1/2}$$

$$\delta_T \approx 0.37x\left(\frac{\mu}{\rho u L}\right)^{1/5}$$

$$\Rightarrow$$

$$Laminar\ Ratio = \left(\frac{\mu_w}{\rho_w u_w} / \frac{\mu_{eg}}{\rho_{eg} u_{eg}}\right)^{1/2} = 0.302$$

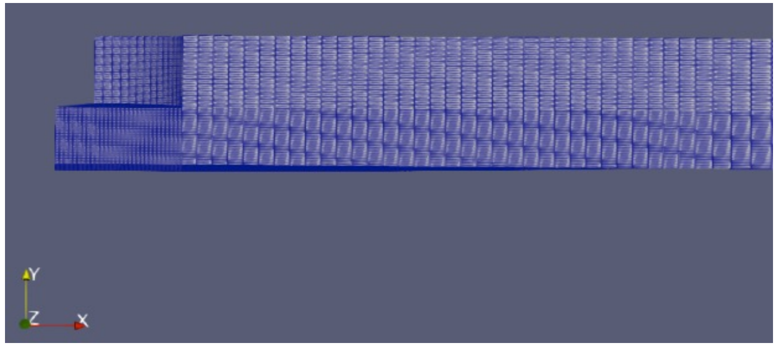
$$Turbulent\ Ratio = \left(\frac{\mu_w}{\rho_w u_w} / \frac{\mu_{eg}}{\rho_{eg} u_{eg}}\right)^{1/5} = 0.619$$

- Due to the distance traveled by the exhaust flow to the surface and the interactions with the lunar regolith, a turbulent flow is a reasonable approximation of the expected flow.
- The boundary layer is a good parameter for comparing the erosion behavior to EFA results

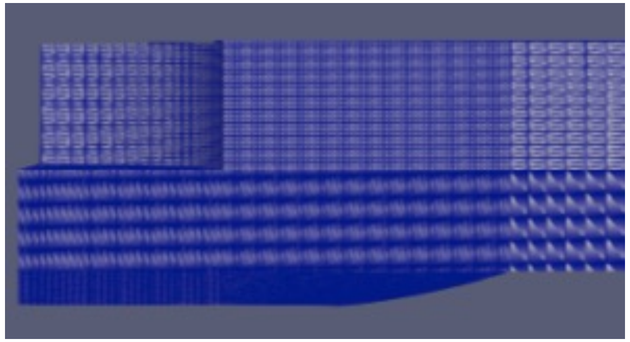
Computational Fluid Dynamics (CFD) Analysis

- For the flow properties of the slow moving boundary layer, we will design a CFD simulation to analyze surface along certain points relative to the exhaust jet.

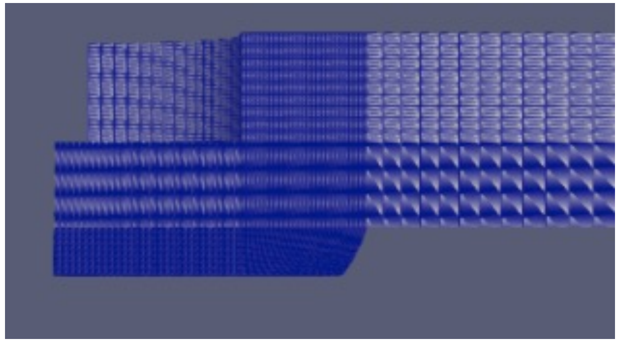
- The exact erosion mechanisms driving the formation of craters is not entirely known, especially when considering the formation of exhaust plume craters at the lunar south pole (Artemis landing site) vs closer to the equator where Apollo sites were located.



Apollo Crater
Bottom Radius = 100 cm
Top Radius = 350 cm
Depth = 4 cm



Median Case Crater
Bottom Radius = 120 cm
Top Radius = 180 cm
Depth = 12 cm



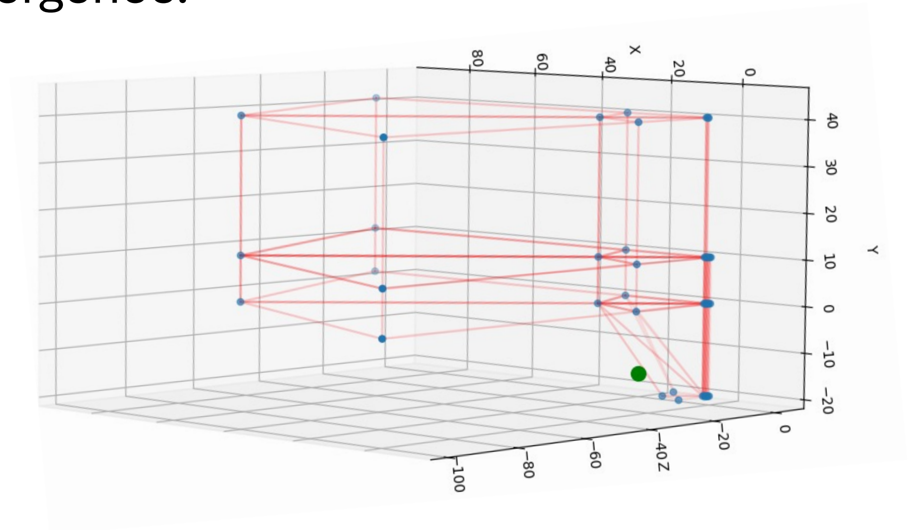
South Pole Crater
Bottom Radius = 115 cm
Top Radius = 125 cm
Depth = 20 cm

Varying depth-to-diameter ratios explored

CFD Analysis

- Distance of 35 cm from nozzle exit to surface used as a conservative estimate based on the Apollo lander, and this is a reasonable minimum expected separation distance. An example mesh is below.

- Note that exact cell distributions are changed from mesh to mesh to achieve an acceptable mesh quality without extreme skewness for ensuring proper convergence.

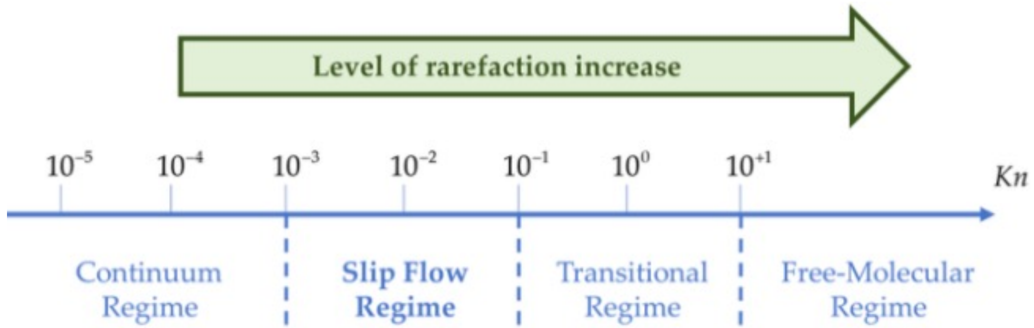



```
/*--------------------------------*- C++ -*----------------------------------*\
| =========                 |                                                 |
| \\      /  F ield         | OpenFOAM: The Open Source CFD Toolbox           |
|  \\    /   O peration     | Version:  v1706                                 |
|   \\  /    A nd           | Web:      www.OpenFOAM.com                      |
|    \\/     M anipulation  |                                                 |
\*---------------------------------------------------------------------------*/
FoamFile
{
    version     2.0;
    format      ascii;
    class       dictionary;
    object      blockMeshDict;
}
// * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * //

convertToMeters 0.01; // rest of file in cm

craterDepth -20; // default: -20
outerEdgeRadius 1000; // default: 100
maxHeight 80; // default: 40
halfHeight 35; // halfway to maxHeight from bottom of crater,  // default: 10
nozzleRadius 75; // default: 1.35
craterBottomRadius 115;  // default: 11
craterTopRadius 125; // default: 24
outerEdgeRadiusMaxCells 100; // default: 100, changes mesh skewness
MaxCellTuner 50; // default: 50

nozzleBoxLength #calc "0.35355339*$nozzleRadius";  // default: 0.4772970773 (based on 1.35 nozzleRadius)

outerEdgeRadiusNegative #calc "-1*$outerEdgeRadius";
outerEdgeRadiusMid #calc "0.7071067812*$outerEdgeRadius";
outerEdgeRadiusMidNegative #calc "-1*$outerEdgeRadiusMid";
outerEdgeRadius38 #calc "0.3826834324*$outerEdgeRadius";
outerEdgeRadius38Negative #calc "-1*$outerEdgeRadius38";
outerEdgeRadius92 #calc "0.9238795325*$outerEdgeRadius";
outerEdgeRadius92Negative #calc "-1*$outerEdgeRadius92";
```

CFD Analysis

- Since the exhaust flow is expanding into a vacuum, the pressure is rapidly diffusing into the surrounding environment and therefore the continuum flow may not necessarily be assumed. The continuum flow is only valid near the immediate exhaust jet impingement point.

$$Kn = \frac{\lambda}{L} = \frac{\mu_{eg}}{\rho_{eg}}\sqrt{\frac{\pi m_{eg}}{2k_B T_{eg}}} = \frac{3.507e{-5}}{0.005349}\sqrt{\frac{\pi \cdot 5.3654e{-26}}{2 \cdot 1.380649e{-23} \cdot 600}} = 2.09125 \times 10^{-5}$$



- A direct simulation Monte Carlo method will instead be used for this simulation approach, specifically dsmcFoam+ which is a specialized branch off of OpenFOAM primarily developed for rarefied gases in hypersonic flows, which features improvements for low pressure environments compared to the legacy dsmcFoam solver for OpenFOAM.

CFD Analysis

- The number density of the exhaust flow at the nozzle exit plane was calculated and the number of equivalent particles in the simulation was adjusted to account for both this and a reasonable convergence given the hardware limitations.

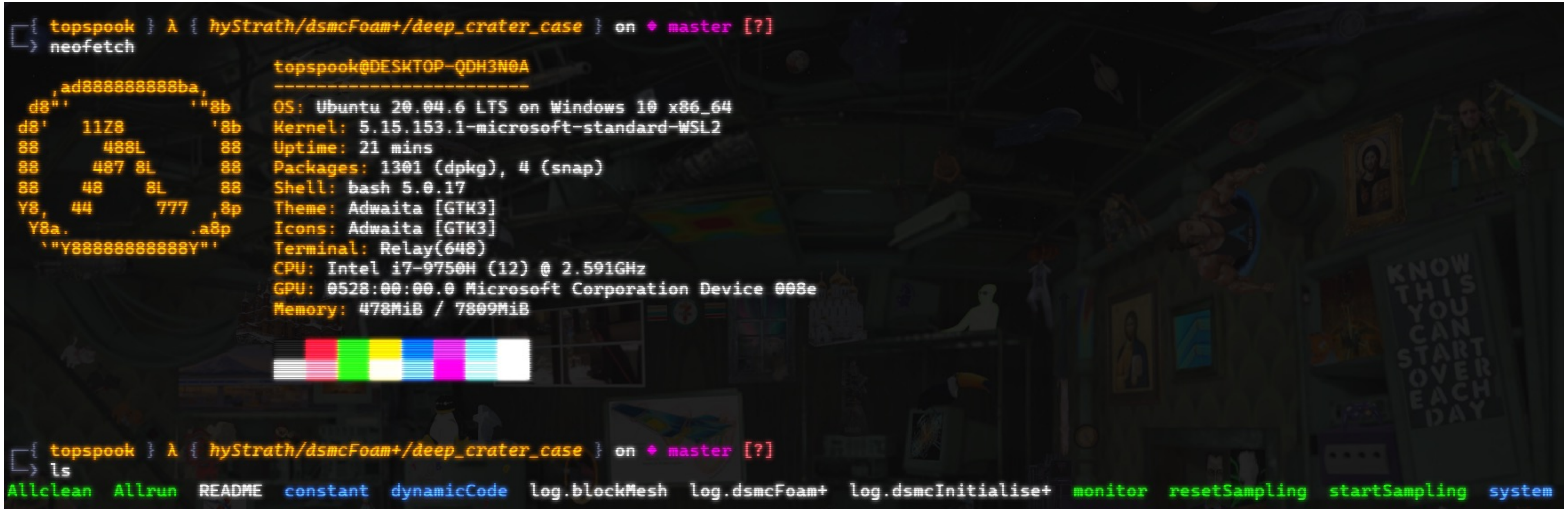
- Unfortunately, convergence was not achievable for a lower nEquivalentParticles number,
  which displayed a strange behavior of causing no particle injections into the simulation.

```
dsmcGeneralBoundaries
(
    boundary
    {
        generalBoundaryProperties
        {
            patchName               inlet;
        }

        boundaryModel   dsmcFreeStreamInflowPatch;

        dsmcFreeStreamInflowPatchProperties
        {
                typeIds                               (CO2 H2O);
                numberDensities
                {
                        CO2         0.55*9.97e23;
                        H2O         0.45*9.97e23;
                }

                velocity                          (0 -3500 0);
                translationalTemperature               600;
        }
    }

);
```

```
// General Properties
// ~~~~~~~~~~~~~~~~~~

nEquivalentParticles            5e17;


// Binary Collision Model
// ~~~~~~~~~~~~~~~~~~~~~~

BinaryCollisionModel            LarsenBorgnakkeVariableHardSphere;

LarsenBorgnakkeVariableHardSphereCoeffs
{
    rotationalRelaxationCollisionNumber     5.0;
}
```

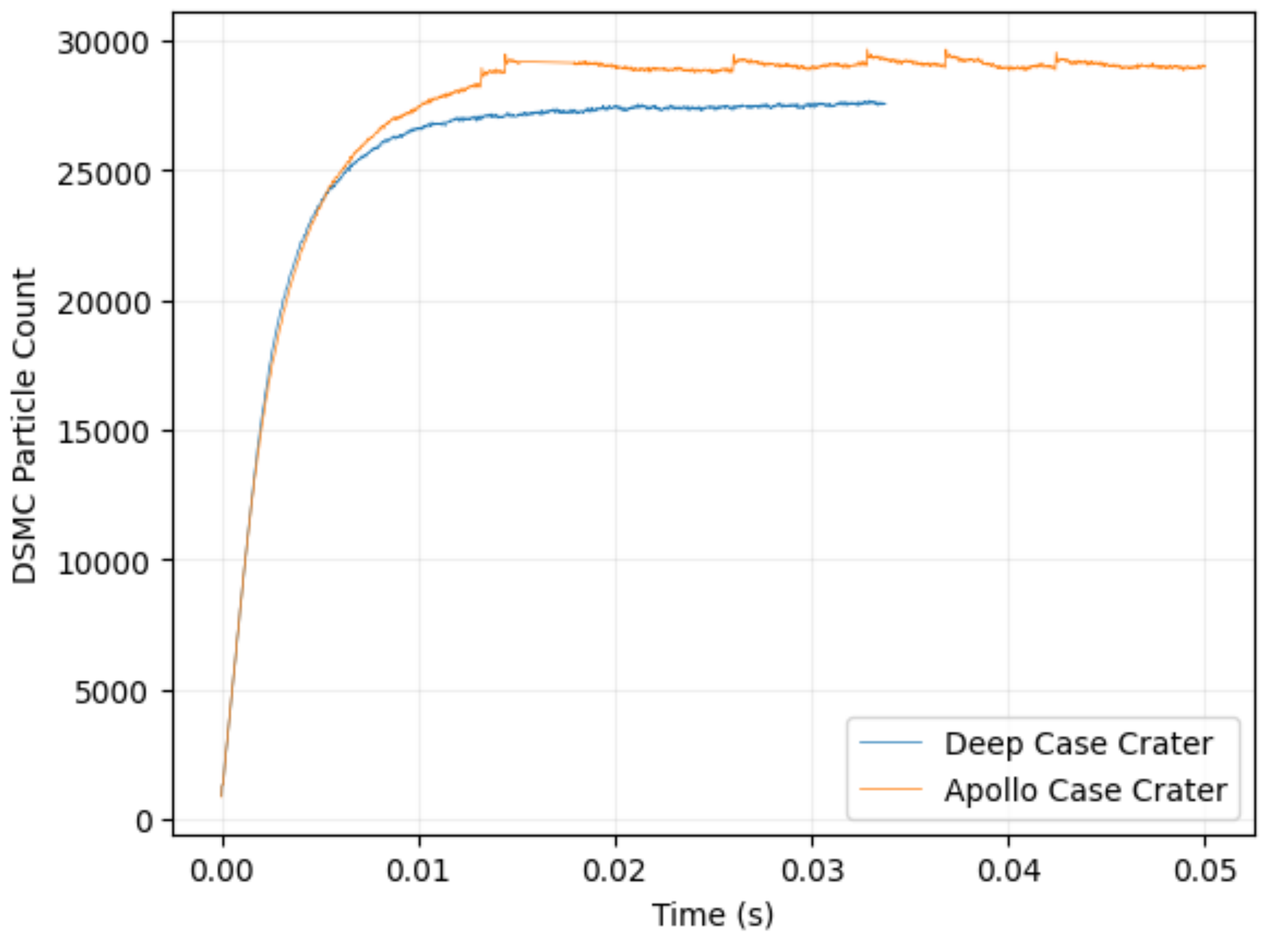
CFD Analysis

- The remaining setup files are mostly already setup from following a similar design to the supersonic flow and mixed species tutorial example folders that come with the dsmcFoam+ software. The folder structure is slightly different to the base openFoam dsmcFoam legacy solver, but most of the files are essentially the same including the subdomain breakdown between CPUs being handled automatically.

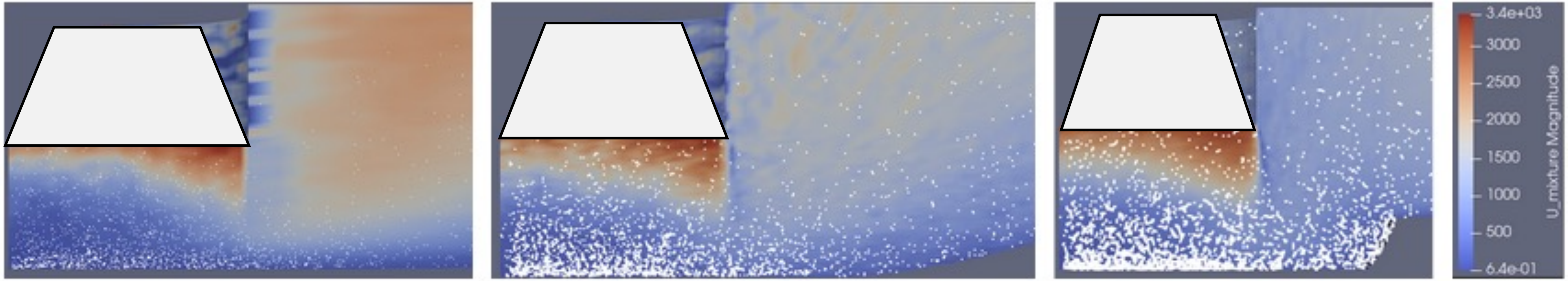


CFD Analysis - Convergence

- The convergence for a given simulation run is determined by the plateauing of the number of dsmc particles in the simulation, indicating that the number of particles being injected and leaving the simulation boundaries
  are equal and as such an equilibrium has been reached.



CFD Analysis – Velocity Results

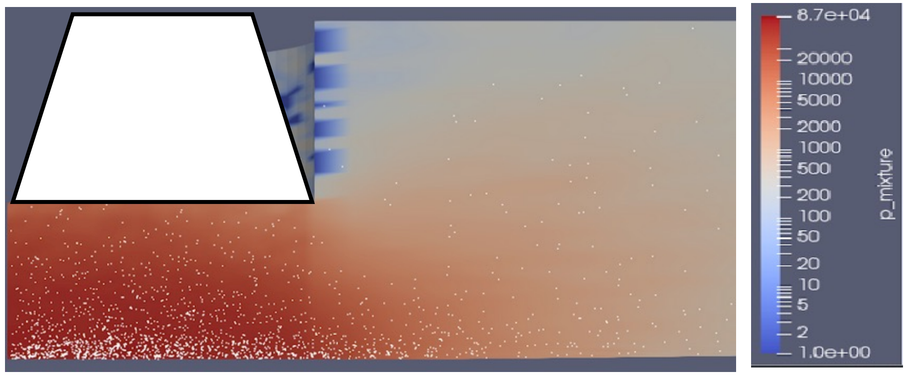


Apollo Crater
Median Case
Weaker South Pole Soil

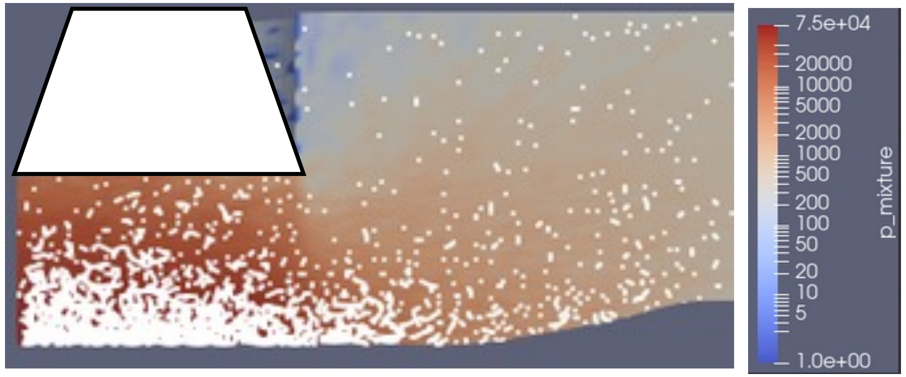
We see that for the shallower crater geometries there is less buildup near the crater edge and a more distinct boundary layer visible. The boundary layer being formed also shows an attenuated surface flow velocity of around 500m/s even with the conservative estimate of only a 35cm separation distance.

Boundary layer is less distinct for higher depth-to-diameter ratios.

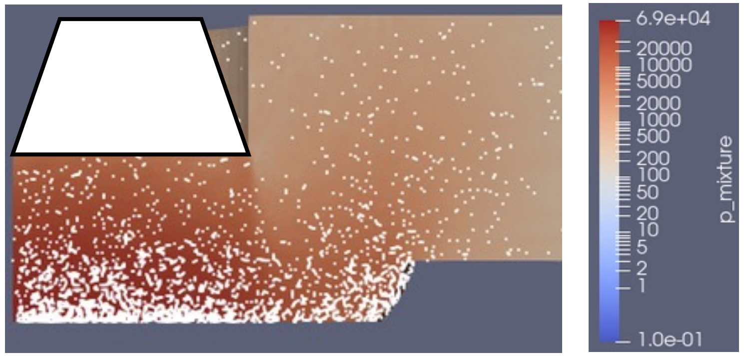
CFD Analysis – Pressure Results



Apollo Crater



Median Case

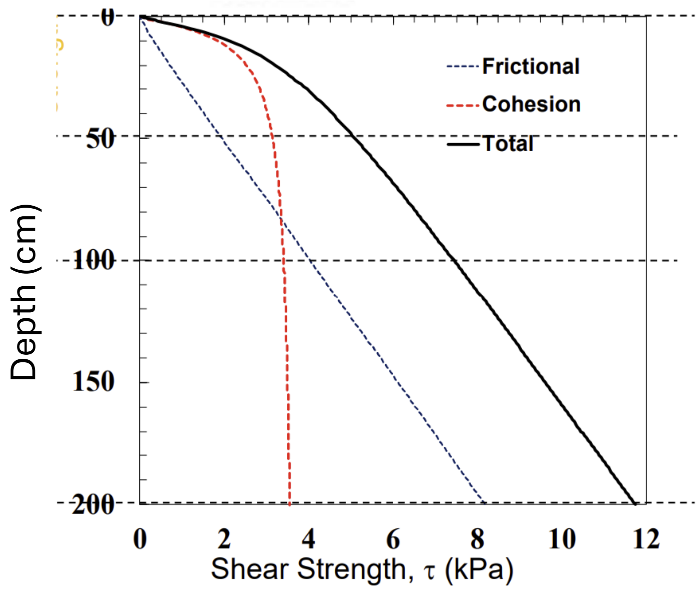


Weaker South Pole Soil

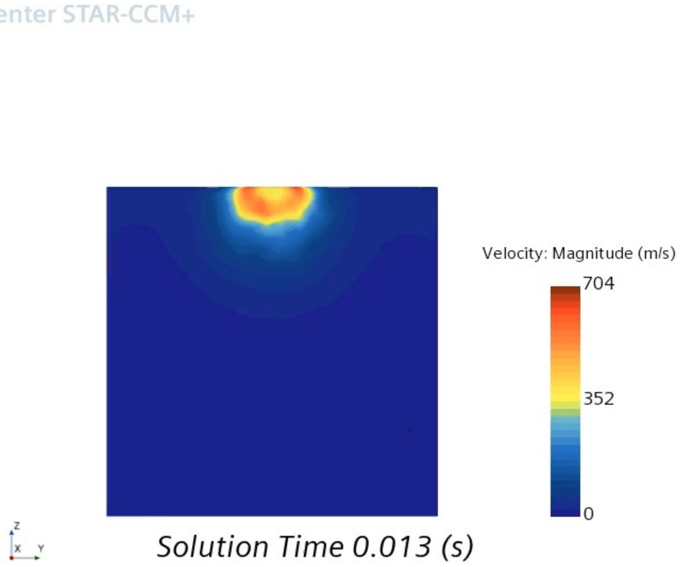
The maximum pressure can be seen to decrease for the deeper crater geometries, and there is a sharp drop off in pressure as the exhaust plume expands out from the impingement point at the surface. Note the log scale.

CFD-DEM – Effect of Cohesion

STAR-CCM+ → Linear Cohesion Model → $c' = w/2R$
Particle Diameter = 10 mm
Simulation Domain = 600 mm cube.
Gas Flow Velocity = 500 m/s



Regolith density and shear strength plotted vs depth for intercrater areas



Cohesion = 0 kPa

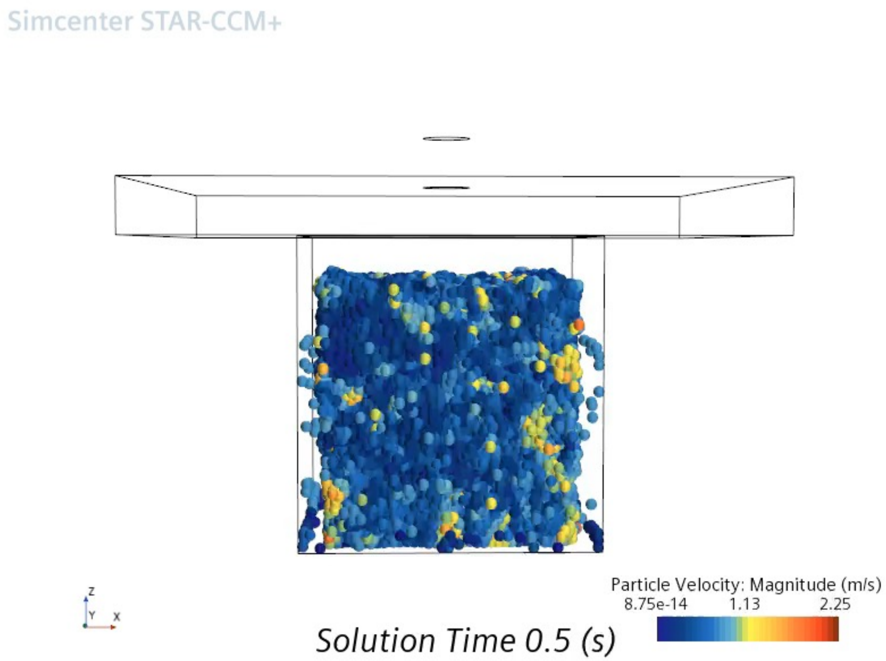
CFD-DEM – Effect of Cohesion

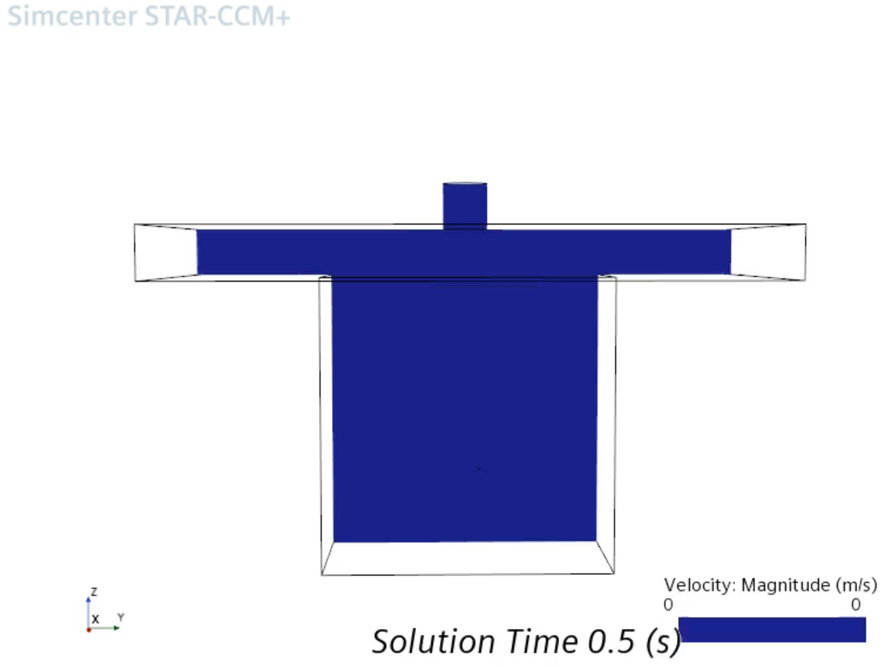
STAR-CCM+ → Linear Cohesion Model → $c' = w/2R$

Particle Diameter = 10 mm

Simulation Domain = 600 mm cube.

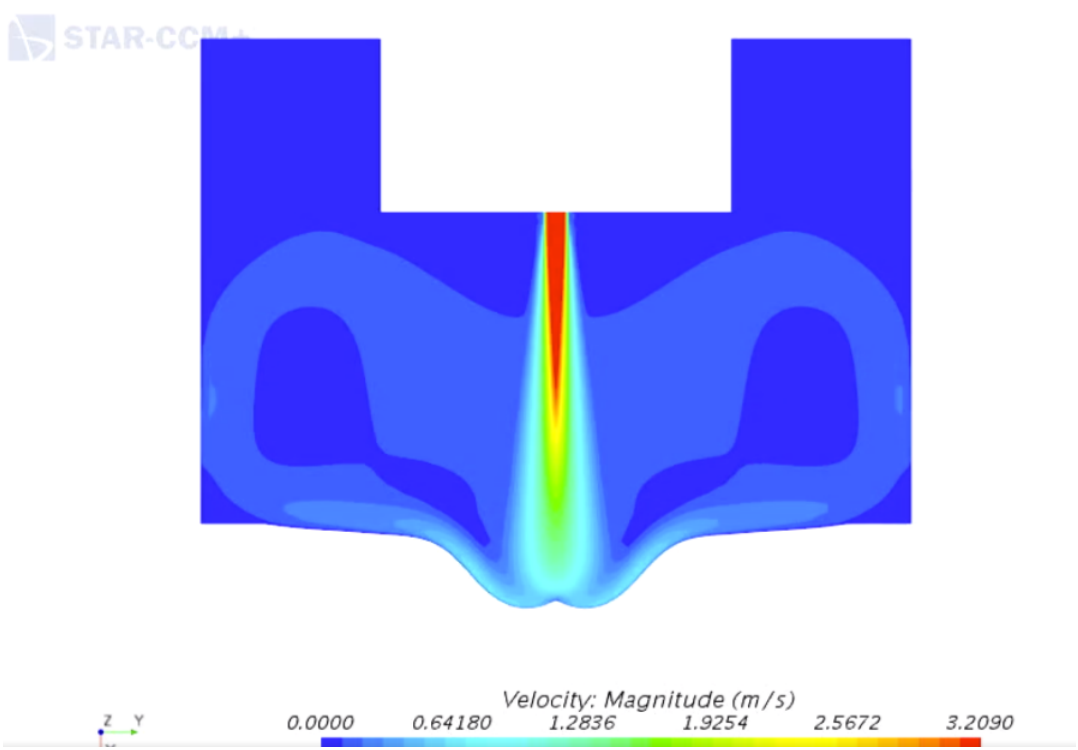
Gas Flow Velocity = 500 m/s

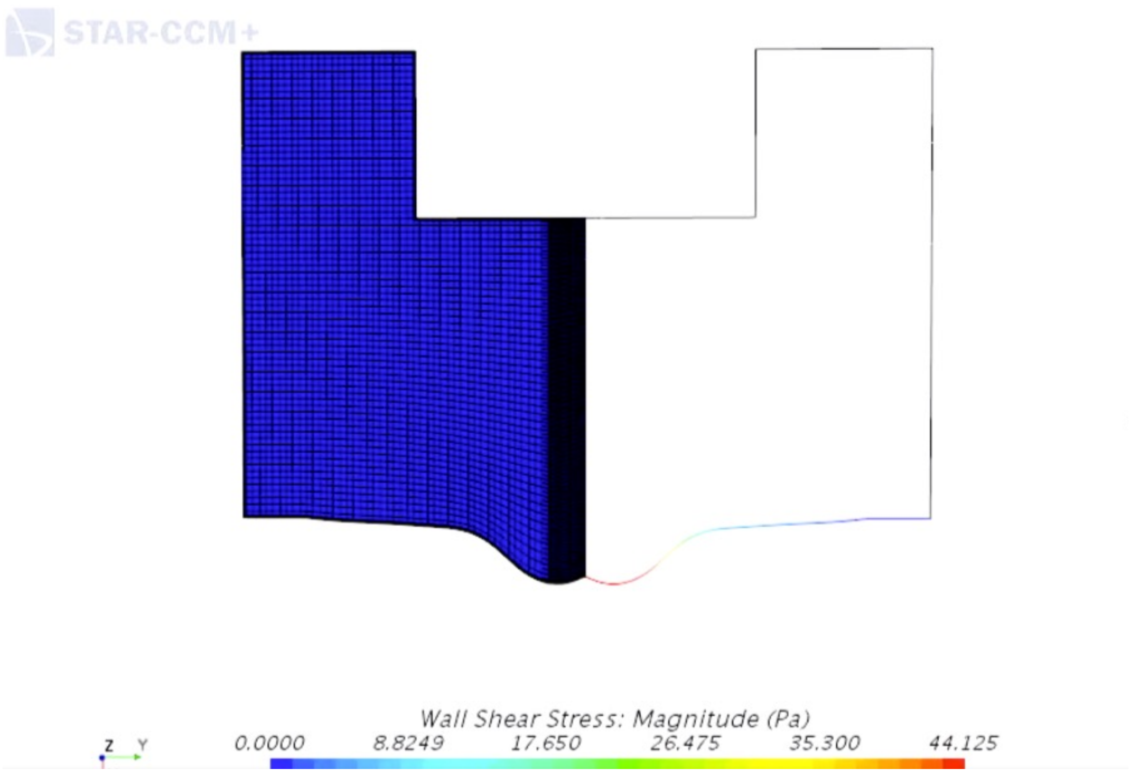




Cohesion = 100 kPa

CFD with Mesh Morphing – Jet Simulations





Gas-Granular Erosion Apparatus (GGEA)

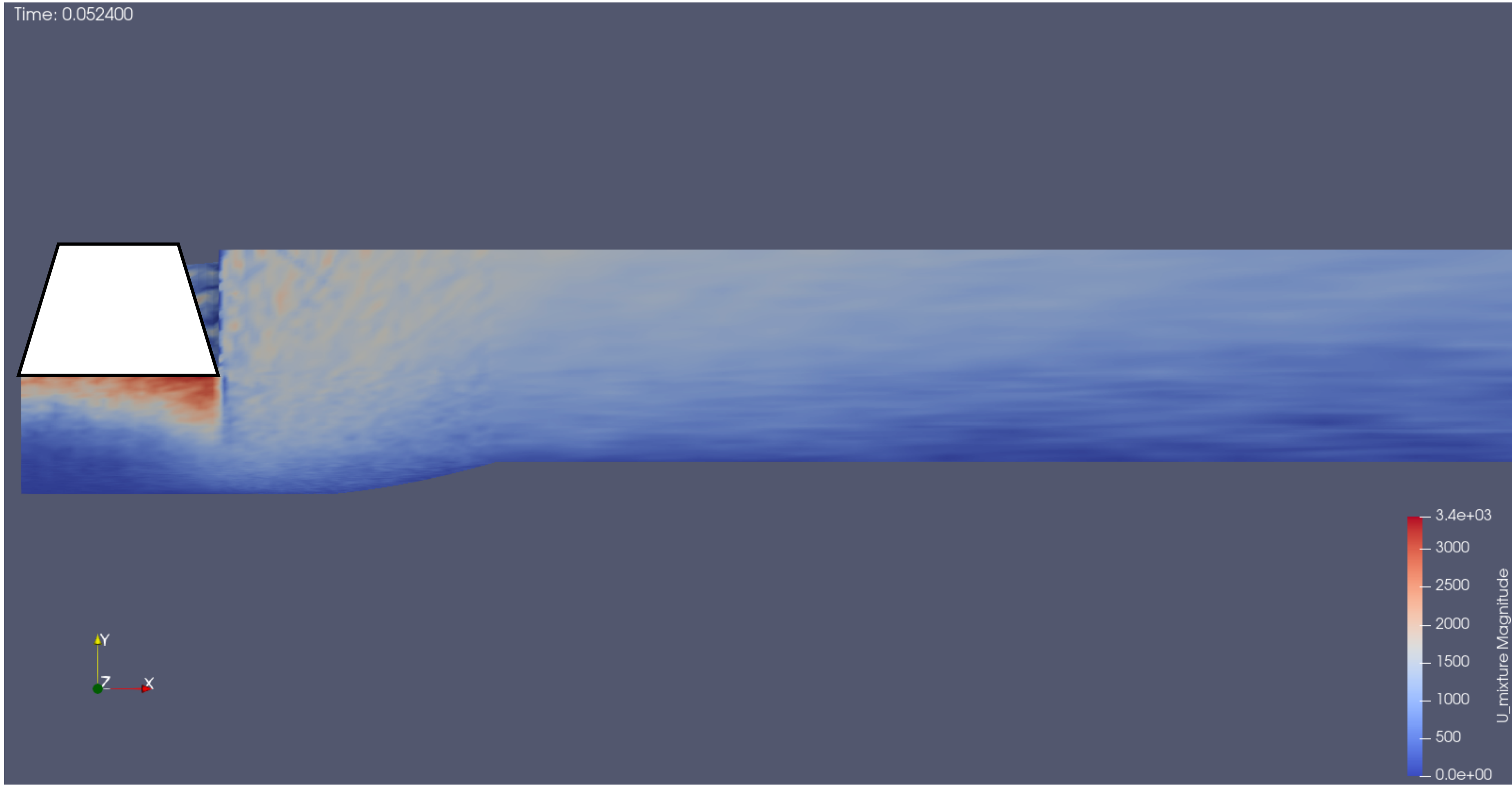
Gas-Granular Erosion Apparatus (GGEA)

- The EFA already existed and was readily available for initial testing.
- The EFA served as a starting point to develop a gas device, the GGEA.

GGEA: Initial Concepts

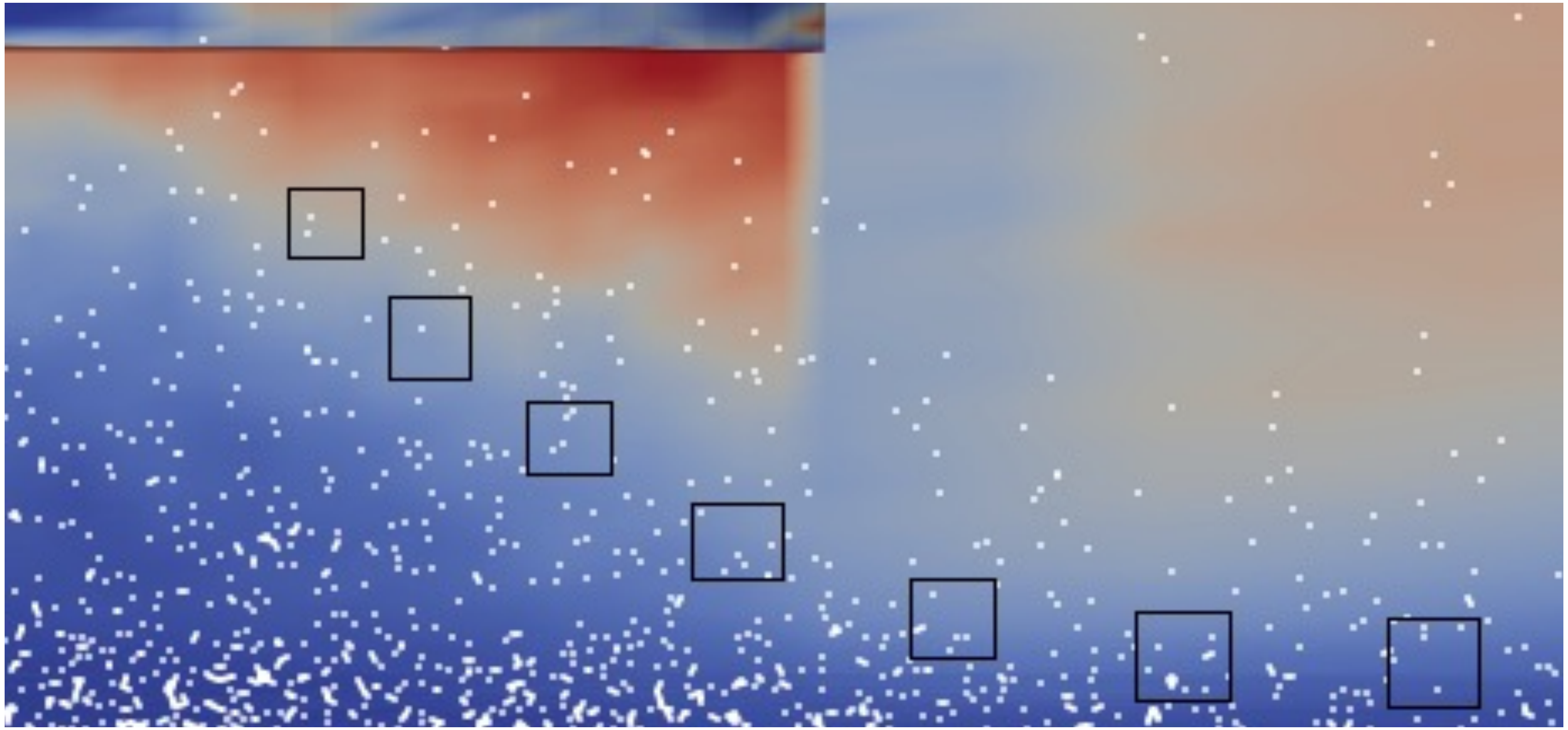
- Initially it was suspected that both a subsonic and supersonic form of the GGEA would be necessary.

- Through CFD analysis, our team determined that flow along the surface reaches speeds close to 500 m/s.



GGEA: Development

- The GGEA builds upon the design of the EFA which models viscous erosion.
- A second configuration of the GGEA was developed to simulate the stagnation impingement upon the surface.
- Discretely modeling various points throughout the flow in separate tests in the GGEA will form a more comprehensive idea of the PSI.

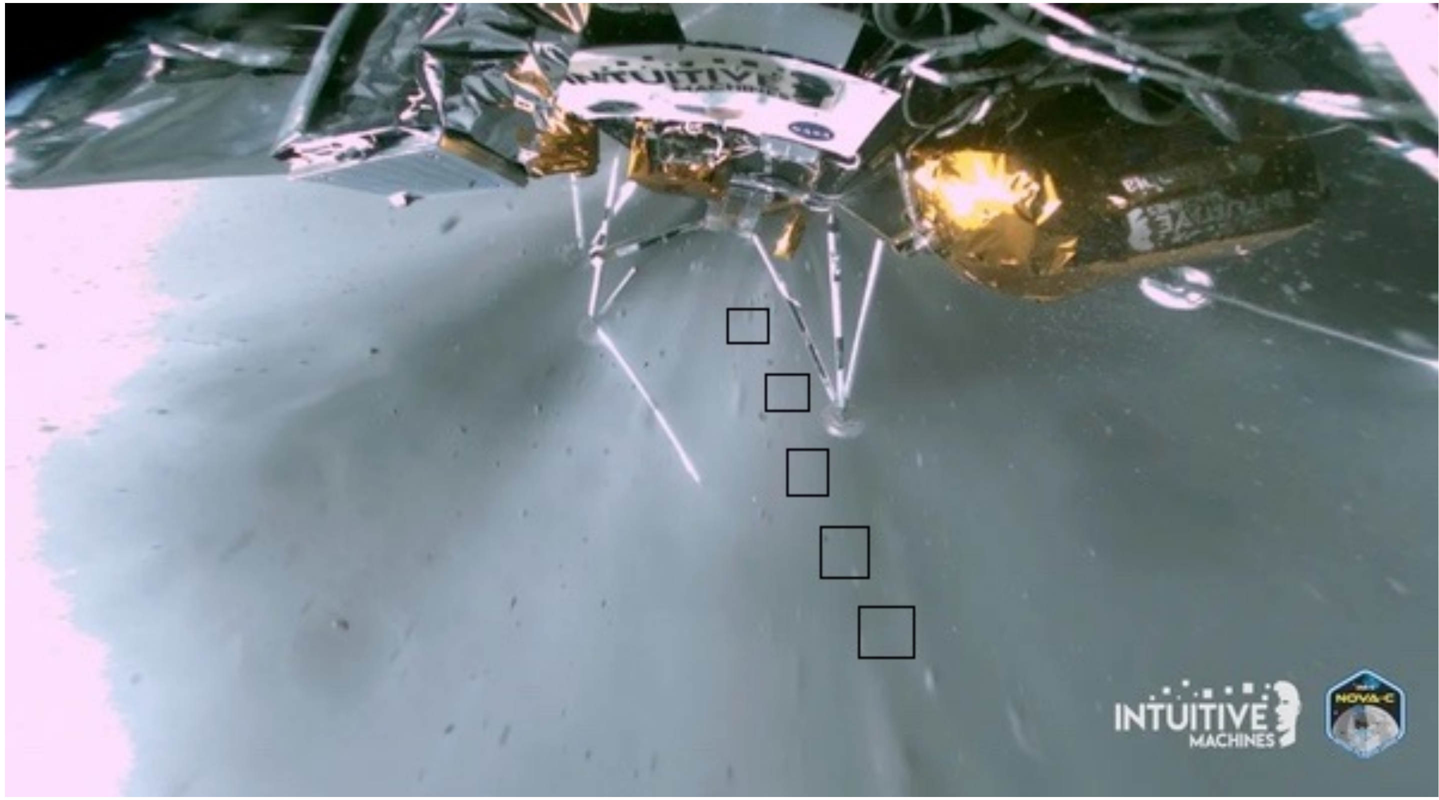


Strengths and Potential Obstacles of GGEA Testing

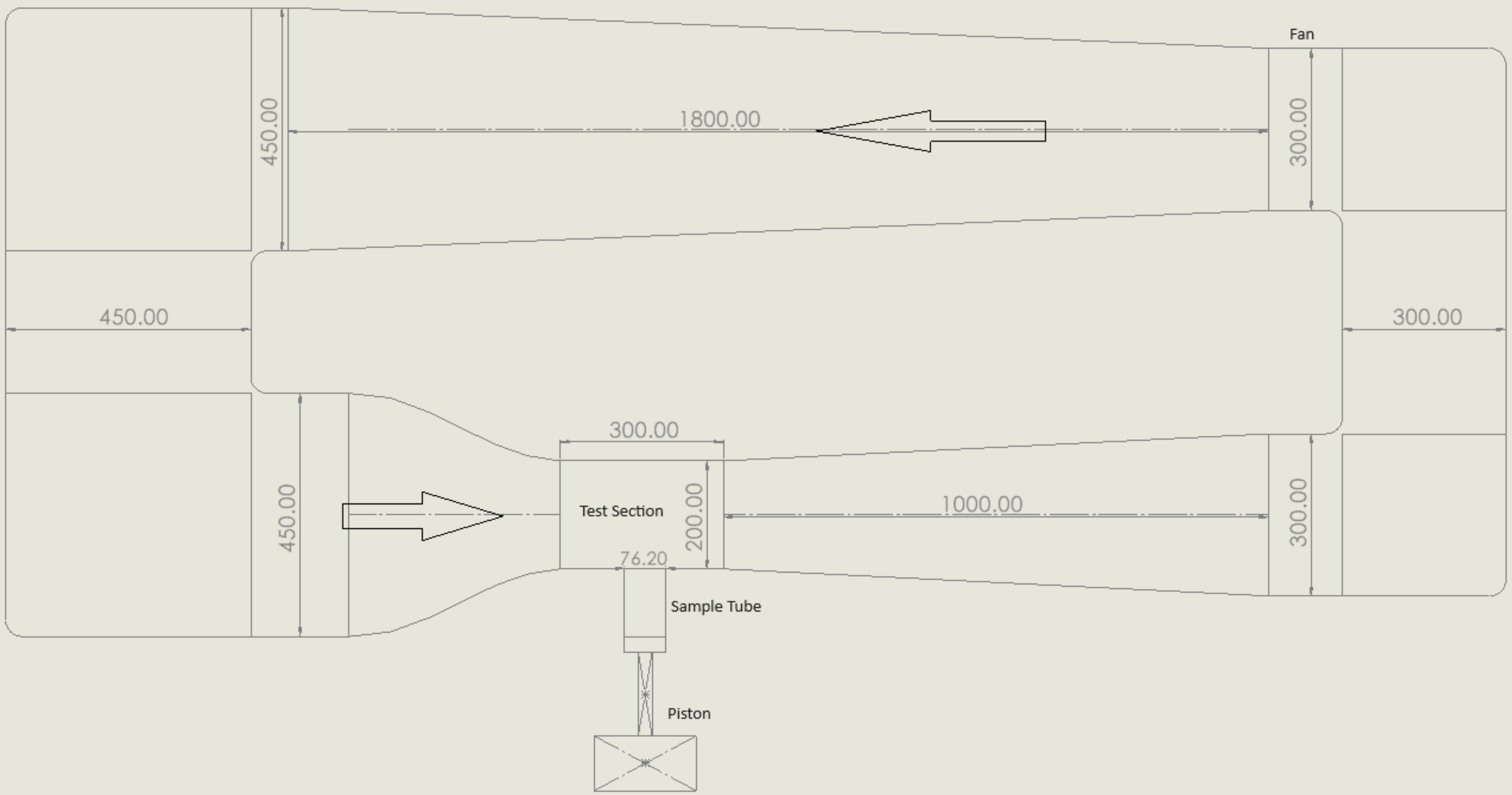
- The greatest strength of the EFA, which will only be improved in the GGEA, lies in the ability to <u>compare the effectiveness of different stabilizers.</u>

- One point of concern regarding the GGEA was the difficulty of simulating the vacuum conditions encountered on the Moon.

- Another possibility of improving the GGEA in the future would be to implement a cyclonic separator and filter lunar regolith that becomes entrained in the flow.



GGEA 1.1: Viscous Shear Testing Configuration



<u>Test Section:</u>

- Area: 200mm x 200mm ($0.04\ m^2$)
- Velocity: 270 m/s (M = ~0.8)

<u>Fan Section:</u>

- Area: 300mm x 300mm ($0.09\ m^2$)
- Velocity: 120 m/s

GGEA 2.1: Stagnation Impingement Testing Configuration

<u>Test Section:</u>

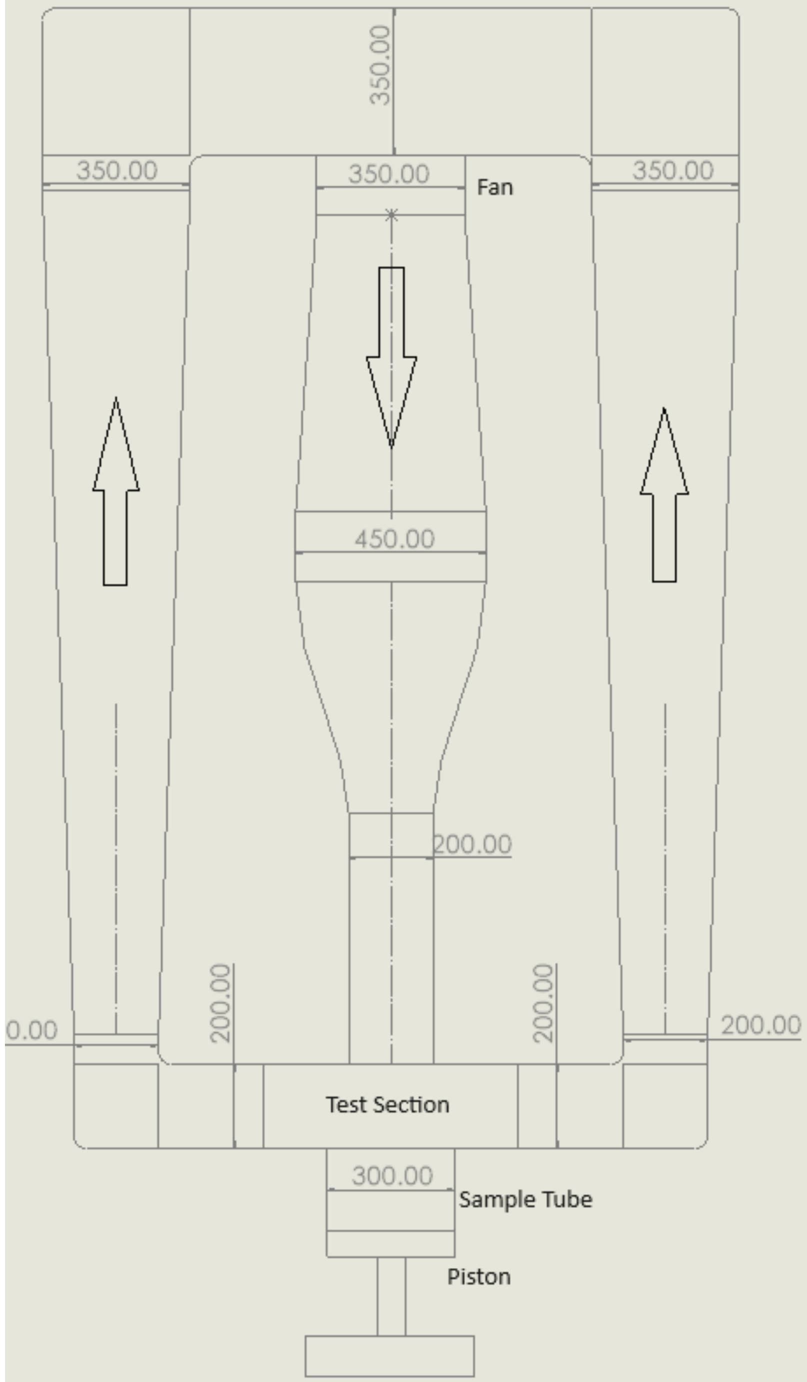
- Area: 200mm x 200mm ($0.04\ m^2$)
- Velocity: 270 m/s ($M = \sim 0.8$)

<u>Fan Section:</u>

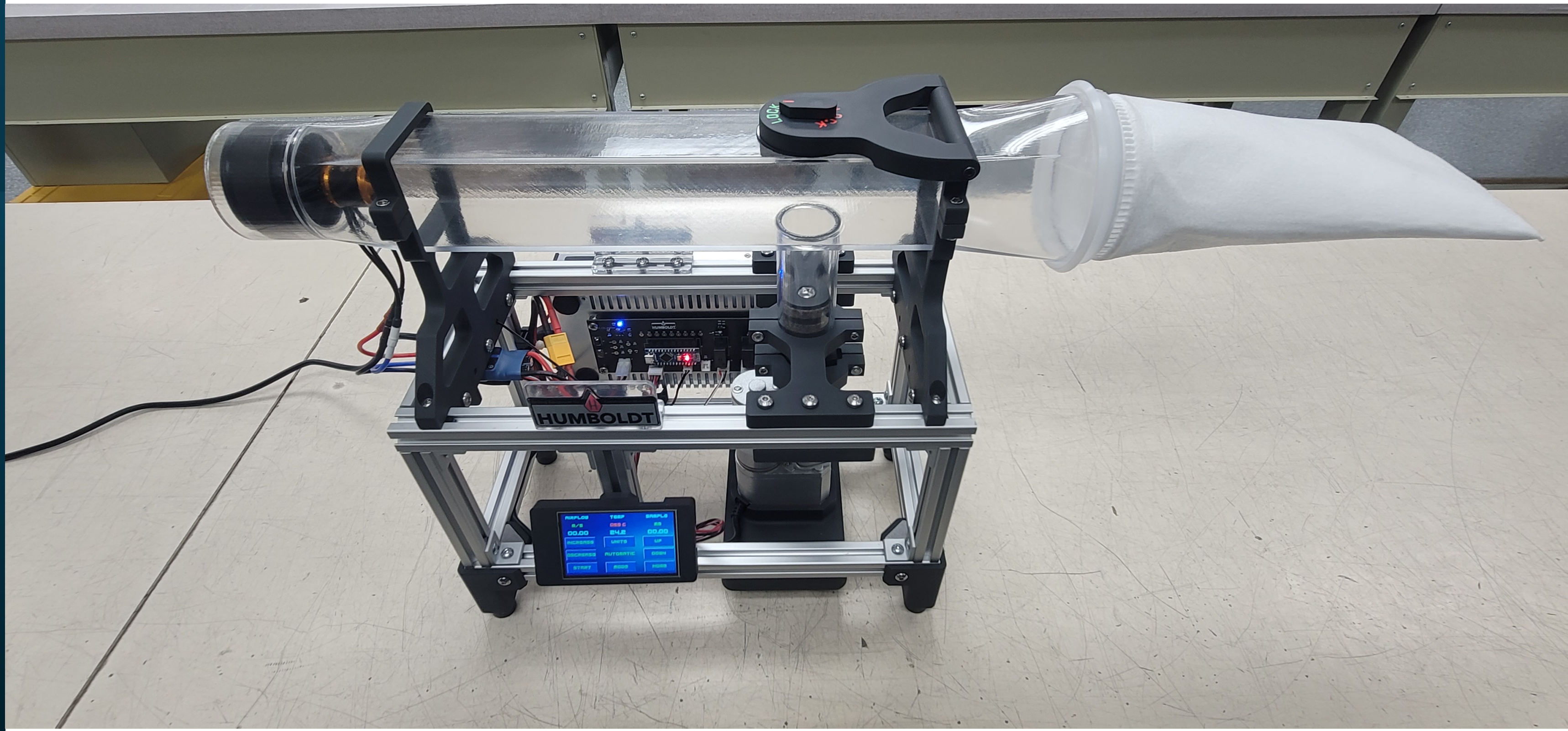
- Area: 350mm x 350mm ($0.1225\ m^2$)
- Velocity: 88.16 m/s

Note:

- Fan section in the GGEA 2.1 is slightly larger.
- GGEA 2.1 sample diameter is significantly larger.



Mini-GGEA: Gas Testing Prototype by Humboldt Mfg. Co.

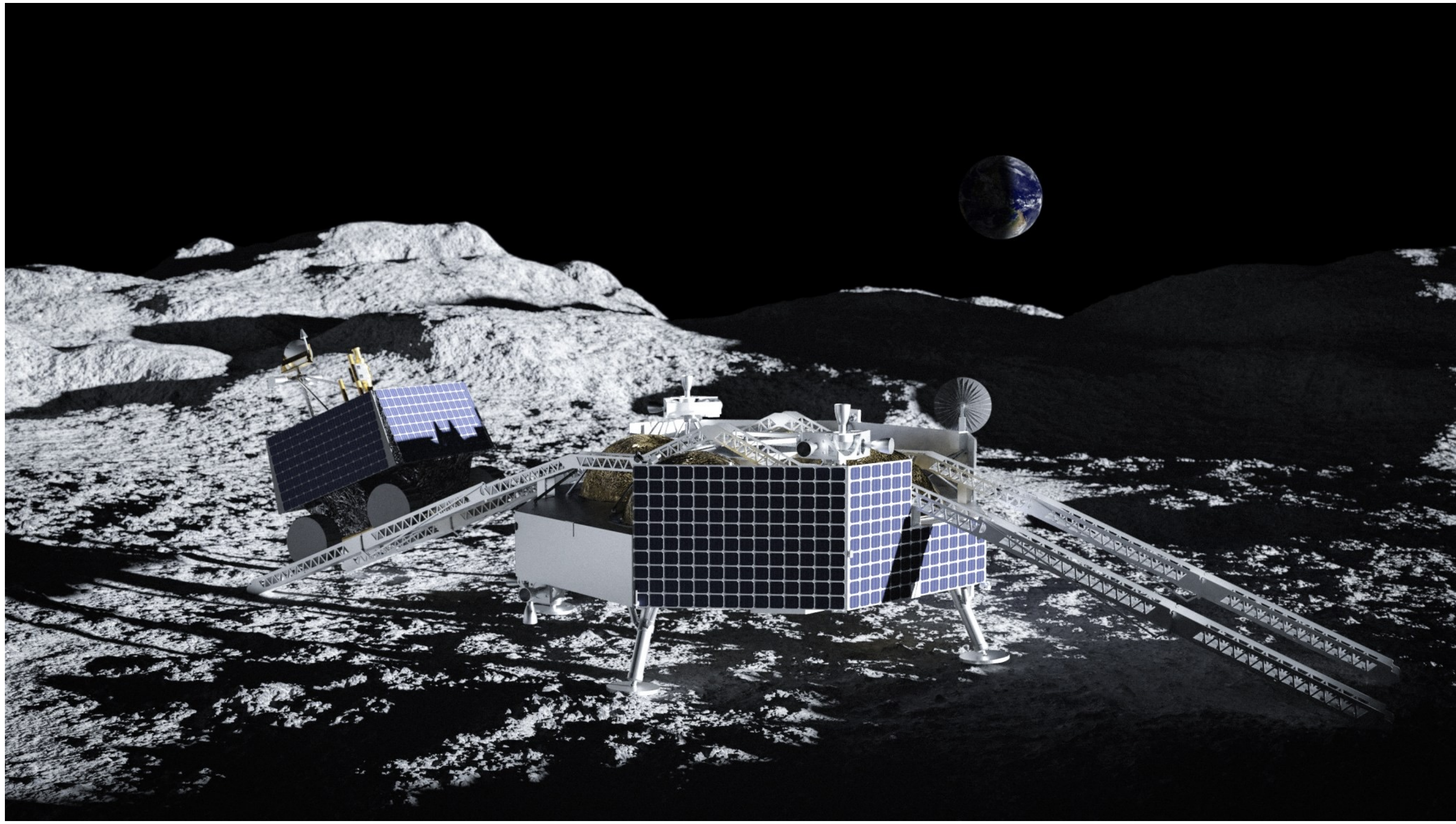


Surface Stabilizer Thermal Vacuum Testing

To test that the application on the lunar surface will function as expected, a thermal vacuum chamber will test the stabilizer itself against vacuum, temperature cycling and high energy UV radiation.

Surface Stabilization Flight Experiment

- An initial technology demonstrator relies upon a small lander, such as a Commercial Lunar Payload Service (CLPS) lander.
- The lander will blast away the top fluffy layer of regolith before the rover autonomously applies the stabilizer.
- The goal of the flight experiment is to increase the Technology Readiness Level (TRL) of this technique for use in future human missions.



Application To Lunar Surface: Cyanoacrylate

- So far in our initial tests using the EFA, CA has proven to be the most effective, lightweight stabilizer.
- CA is susceptible to degradation, so the less time that this initial stabilization is exposed to the UV and temperature fluctuations the better.
- CA can withstand 105 °C to -40 °C

Funnel Acetone CA Mixture → Apply external water mist → Curing Process

Permanent Landing Site Preparation

- There are two possible application methods for crewed missions to The Moon.
- A large rover can autonomously apply a stabilizer, in a method similar to that of the flight experiment.
- In crewed missions to The Moon, there will be astronauts on the surface who can implement a stabilizer that require a more involved application process.

Testing and Flight Experiment Milestones and Schedule

4 years in total

2 Year Testing Period

- EFA Testing
- GGEA Design and Construction
- Verifications of analytical transformations

2 Year Development Period

- Validation of EFA Testing in GGEA and further GGEA testing
- CLPS Surface Stabilization Flight Experiment Development
- Vacuum Thermal Testing
- Launch Preparations

Milestones and Schedule

Cost

The following budget was acquired from modeling the solution in NASA's Cost Estimation Toolkit (CET)

- 2024: $981,000 ; 2025: $1,009,000 ; 2026: $2,373,000 ; 2027: $3,095,000

These values take into account the

- cost of materials
- technology maturation
- software
- system development
- production
- labor for management, administrative, technical, and operational services

Estimated Staffing Level	2024	2025
Management Staff FTE	0.36	0.36
Administrative Support FTE	0.14	0.14
Technical Coordination Staff FTE	0.00	0.00
Development Staff FTE	6.64	6.64
Technical / Science Staff FTE	0.00	0.00
Operations Staff FTE	0.00	0.00
Sustaining Engineering Staff FTE	0.00	0.00
Engineering Support Staff FTE	0.00	0.00
Estimated Total FTE	**7.14**	**7.14**
Estimated Staff Costs, K$	**2024**	**2025**
Management Staff Cost	18	19
Administrative Support Staff Cost	7	7
Technical Coordination Staff Cost	0	0
Development Staff Cost	664	691
Technical / Science Staff Cost	0	0
Operations Staff Cost	0	0
Sustaining Engineering Staff Cost	0	0
Engineering Support Staff Cost	0	0
Total Estimated Staff Cost	**689**	**717**
Other Non-Staff Costs	**2024**	**2025**
System Purchase Cost	2	2
COTS Software License Cost	58	58
Facility Preparation and Support Cost	174	174
System Maintenance Cost	0	0
Network / Communications Cost	4	4
General Supplies Cost	21	21
Archive Media Cost	0	0
Distribution Media Cost	0	0
Travel Cost	25	25
Training Cost	8	8
Data Purchase Cost	0	0
Computer Services Cost	0	0
Total Estimated Non-Staff Costs, K$	**292**	**292**
Total Estimated Cost, K$	**981**	**1,009**

Thank You!

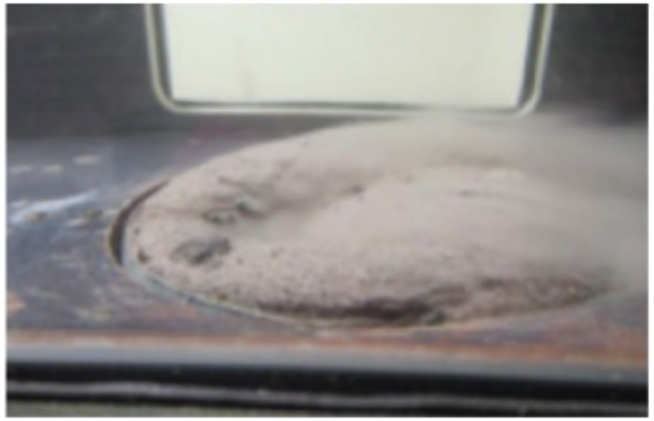
Texas A&M University Maroon Moon Team
Preliminary Surface Stabilization to Mitigate Lunar Plume Surface Interaction

HuLC
HUMAN LANDER CHALLENGE

Major Objectives & Technical Approach

- Experiment with different soil sealants that prevent erosion of lunar regolith simulant
- Experiment was performed with water tunnel erosion device (EFA)
- Analytically compared water and air mediums by using boundary layer thickness ratios
- Preliminary design of two Gas-Granular Flow Apparatus (GGEA) flow tunnels to specifically model PSI through the measurement of erosion in a high velocity gas flow

Image/Graphic:



Key Design Details & Innovations of the Concept

- Applying geotechnical erosion prevention techniques used on Earth to the lunar environment
- Using erosion function apparatus (EFA) to model PSI effects on lunar simulant
- Developing two unique gas-granular erosion apparatuses (GGEAs) that are designed to use high velocity exhaust gasses to accurately model PSI through erosion mechanisms

Summary of Schedule & Costs for the Proposed Solution's Path to Adoption

- 2 year Development period
  - Testing sealant solutions with EFA and beginning construction on the GGEA
  - Validating transformations between air and water mediums
- 2 year Operation period
  - Testing chosen sealant solutions in the GGEA
  - Construction of the CLPS Rover
  - Testing rover application in a vacuum chamber
- Costs are from NASA Cost Estimation Toolkit (CET)
  - 2024: $981,000, 2025: $1,009,000
    2026: $2,373,000, 2027: $3,095,000

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