

A Data-Derived Scaling Approach for Plume-Surface Interaction Crater Formation

Daniel C. Stubbs* and Manish Mehta†

NASA Marshall Space Flight Center, Huntsville, Alabama, 35812

This work presents a methodology for scaling test-scale plume-surface interaction (PSI) crater formation data to flight-scale. Methods for scaling both crater erosion rate and crater geometry (width and depth) were derived from scaling relationships proposed by previous PSI studies. Two methods for predicting crater width were investigated - one using an empirical scaling law for the crater aspect ratio and another informed by surface shear stress profiles from computational fluid dynamics (CFD). Data from three independent studies were then used to assess the performance of the developed scaling methodology. Results show that data from all three sources agree well with the crater erosion rate scaling methodology, with the caveat that limited data exist in regimes truly relevant to landing on the Moon. The performance of the geometry scaling methodology was more nuanced. The empirical scaling for crater aspect ratio performed well against PSI data obtained under Earth-atmospheric ambient pressure, but did a poor job of predicting the aspect ratio of craters formed from highly underexpanded plumes under vacuum conditions. Data from the Human Landing System (HLS) program's Plume Surface Interaction Ground Test will be used to further improve the performance of the scaling methodology and to provide flight-scale predictions for PSI effects caused by HLS landers.

I. Introduction

WHEN rocket engines are used to slow the descent of a spacecraft during landing or to ascend from the surface, the exhaust plume(s) from its engine(s) interact with the surface via the plume-surface interaction (PSI) phenomena, as depicted in Fig. 1. During PSI, the impinging plume flow causes surface erosion, which results in crater formation and ejecta blowing. The significance of PSI increases when landing on an unprepared planetary surface made of loose granular material known as regolith, like on the Moon and Mars.

The risks to spacecraft from PSI are significant. Even at altitudes of 50 m or more, PSI results in dust blowing on the surface, which forms a cloud of ejecta in the vicinity of the lander, and obscures the environment [1]. This dust cloud can degrade measurements from navigation sensors including radar, lidar, and camera systems that are used to navigate in close vicinity to the surface. At lower altitudes, the resulting surface erosion may cause crater formation, creating an uneven surface that could cause the lander to tip over upon landing. For example, during Apollo 15, the lander landed on the edge of a crater, which caused the lander to tip significantly [2]. While this crater was already on the surface and not a result of PSI, it still demonstrates the potential impacts of landing in a crater formed via PSI.

As the lander descends, the plume flow is redirected by the surface and ejecta become entrained within the plume flow. Payloads on the surface in the vicinity of the landing site will be exposed to these high velocity ejecta particles and could sustain significant damage if they are not designed to survive the environment [3]. This type of damage was observed during the Apollo 12 mission where the Surveyor III lander was sandblasted by the ejecta created

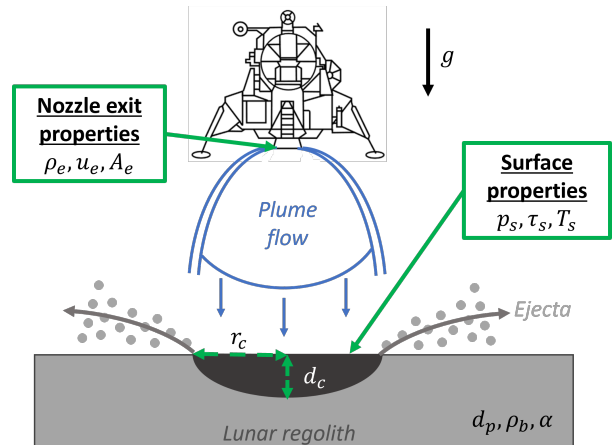


Fig. 1 Schematic of the PSI process.

*Aerospace Engineer, Aerosciences Branch, daniel.c.stubbs@nasa.gov, Member AIAA.

†Subject Matter Expert (SME), Aerosciences Branch, Senior Member AIAA.

by the Lunar Module (LM), which landed approximately 155 m away from the Surveyor site [4]. Farther away from the landing site, ejecta may no longer possess enough energy to directly cause damage, but falling ejecta can accumulate on solar panels, reducing performance, or form an abrasive layer on seals shortening their lifetime. Additionally, ejecta falling and accumulating on the surface away from the landing site alters the original surface state, and therefore could negatively impact science objectives.

If the surface erosion is significant enough to result in crater formation, then the impinging plume flow is redirected by the crater cavity and propagates toward the base region of the lander. This recirculating flow can induce large asymmetrical heating and pressure loads on the base of the vehicle. Furthermore, the ejecta entrained in this recirculating plume can cause increased ablation of the base heat shield. [4].

The human-class landers planned for use in the Artemis program have significantly higher thrust than the Apollo landers and are therefore expected to produce more significant PSI effects than were observed during the Apollo missions because the amount of surface material eroded by the plume roughly scales with the thrust of the lander [5]. For these reasons, PSI modeling tools to predict crater formation and ejecta blowing caused by the landing of high thrust, human-class landers on the surface of the Moon and Mars are critical to the success of future planned missions as part of the Artemis program and beyond.

Modeling PSI is a challenging problem. The plume flow is commonly traveling at hypersonic velocities, is chemically reacting, and may contain regions of both continuum and rarefied flow. This complex plume flow then impinges on the granular surface where fluid-particle interactions and sub-surface diffusion flows must be considered. The development of tools to predict PSI can broadly be separated into two approaches: fully-computational tools that aim to solve the equations governing the plume flow and its interaction with the granular surface, and data-derived, empirical modeling scaling laws that scale experimental data to flight-scale.

A number of fully-computational tools are in development such as the gas-granular flow solver (Loci/GGFS) [6], the Descent Interpolated Gas Granular Erosion Model (DIGGEM) [7], and the hyperbolic granular model by Balakrishnan and Bellan [8]. Development work on these models is still ongoing [6, 9], which is challenging due to a lack of data to validate against under flight-relevant conditions. While these tools offer the ability to generate high fidelity predictions for PSI, they are computationally expensive. Therefore, the need remains for empirical, data-derived models which can quickly provide lower fidelity predictions for flight-scale PSI over a range of possible flight trajectories. Results from both approaches can then be compared to gain insight into the potential range of PSI effects and define bounding environments given the lack of flight-scale data to validate against.

To address this need, the present work develops a data-derived methodology for scaling test-scale PSI crater formation data to provide predictions for flight-scale PSI effects. To accomplish this, previous PSI studies in the literature were surveyed to identify scaling relationships supported by data for crater erosion rate and crater aspect ratio. An alternative approach for predicting crater width based on computational fluid dynamics (CFD)-predicted surface impingement shear stress distributions was also investigated as an alternative to the aspect ratio scaling law. These scaling relationships were then used to develop a methodology for scaling test-scale, experimental data to flight-scale. Finally, PSI crater formation data from multiple sources were used to assess the performance of the developed methodology. In the future this methodology will be used to generate flight-scale predictions of PSI environments for NASA's Human Landing System (HLS) program with data from the HLS program's PSI Ground Test (GT).

II. Background

Plume-surface interactions have been the focus of numerous studies dating back to the 1950s due to the relevance of PSI to the Moon landings as part of the Apollo program [10]. Since then, PSI has continued to be the focus of multiple studies due to its relevance to the Mars probe landings [11] and the planned landings as part of the Artemis program [12].

From previous PSI studies, a number of mechanisms have been defined to phenomenologically describe the overall behavior of PSI crater formation depending on the dominant physical mechanisms at play. These mechanisms include *viscous shear erosion* and *deep cratering mechanisms*. Viscous shear erosion occurs when the shear stress from the plume flow along the surface exceeds the shear strength of the surface material, and typically results in relatively shallow and wide craters. Deep cratering mechanisms occur in more extreme cases where the plume flow results in an impingement pressure strong enough to induce significant diffusion flows below the surface, and include bearing capacity failure [13], diffusion driven shearing [14], and diffused gas explosive erosion [11]. These deep cratering mechanisms typically result in deeper, narrower craters that form rapidly compared to craters formed primarily via viscous erosion. Which mechanism will be dominant for a given PSI crater formation event depends on the impingement

pressure and shear forces imparted on the surface by the plume and the properties of the surface such as shear strength, bearing capacity, and permeability. The impingement forces from the plume are influenced by factors such as the rocket engine thrust, ambient pressure, and nozzle altitude, while the surface properties are influenced by factors such as regolith particle size, shape, and cohesion.

Multiple studies have focused on developing engineering model scaling laws for PSI crater formation. Early work by Roberts [15] developed a theory for surface erosion around the concept that the erosion rate is determined by the “excess shear stress” in the gas [16]. Later work by Rajaratnam and Beltaos developed a scaling relationship for the final asymptotic state of the crater, which they referred to as the “erosion parameter” [17]. Subsequently, Haehnel et al. expanded the erosion parameter to include the impact of permeability of the bed material [18]. Metzger et al. proposed a logarithmic fit for the crater depth over time [14], which has since been extended to predict volumetric erosion rate [5, 19, 20]. LaMarche and Curtis proposed an arctangent fit for the crater depth evolution, which is better at predicting the asymptotic crater depth than the logarithmic fit proposed by Metzger et al. [21]. Gorman et al. conducted a scaling analysis of crater formation observed for multiple lunar- and Martian-relevant environments to develop a relationship between the kinetic energy gained by the particles eroded from the surface to the power of the impinging jet [22]. Sonar and Katsuragi conducted a study of craters formed in granular beds by subsonic impinging jets and determined a scaling relationship to predict the resulting asymptotic crater morphology [23].

The present work builds upon the scaling relationships developed by Metzger et al. [5] and by Sonar and Katsuragi [23] to develop a methodology for scaling experimental PSI crater formation to flight scale.

III. Methodology

The methodology for scaling experimental PSI crater formation data to provide predictions at flight-scale can be broken into two components. The first component scales experimental measurements of crater erosion rate to an equivalent flight-scale crater erosion rate, which can be integrated over time to obtain a prediction for the flight-scale crater volume. The second component includes additional steps to obtain predictions for flight-scale crater width and depth from the predicted volume. Two approaches were investigated for accomplishing the second component. The first approach leverages a scaling relationship for the crater aspect ratio - the ratio of the crater width to depth - from Sonar and Katsuragi [23]. The second approach leverages CFD predictions for the shear stress resulting from the plume impinging onto a flat surface.

A. Erosion rate scaling

The first component of the scaling methodology builds upon foundational works conducted by Metzger et al. [5, 14, 24]. Metzger et al. conducted experiments studying crater formation resulting from subsonic jets impinging onto granular beds and noted that the crater depth growth was logarithmic with time as

$$d_c(t) = a \ln(bt + 1), \quad (1)$$

where d_c is the crater depth, t is time, and a and b are fitting coefficients. By fitting this equation to the depth evolution of craters formed across a range of nozzle heights, plume exit velocities, plume gas densities, granular particle sizes, and gravity conditions, Metzger et al. were able to determine how the fitting coefficients a and b changed as a function of those parameters. Metzger et al. found that

$$a \propto h d_p^{1/3} \quad (2)$$

$$b \propto \frac{\rho_e u_e^2 A_e}{h^3 d_p^2}, \quad (3)$$

where h is nozzle height, d_p is granular particle diameter, ρ_e and u_e are the plume gas density and velocity at the nozzle exit, respectively, and A_e is the nozzle exit area. Metzger et al. [19] combined this into an equation, which essentially states that the erosion rate is proportional to the square of the densimetric Froude number as

$$\dot{V}_c \propto a^3 b \propto \frac{\rho_e u_e^2 A_e}{\rho_b g d_p}, \quad (4)$$

where $\dot{V}_c$ is the volumetric erosion rate of the crater, ρ_b is the bulk density of the granular media, and g is gravity. This equation for volumetric erosion rate scaling has recently been updated by Metzger et al. [5, 20] to include the effects of

particle cohesion based on results from Metzger et al. [24] as

$$\dot{V}_c \propto \frac{\rho_e u_e^2 A_e}{\rho_b g \beta d_p + \alpha}, \quad (5)$$

where β represents the cosine of the crater wall angle relative to the horizontal surface, and α represents the cohesive energy of the granular particles. Dotson et al. have since conducted experiments with simulants of various bulk densities, particle diameters, and cohesion and found good agreement with the denominator of Eq. (5) [25].

The erosion rate scaling relationship developed by Metzger et al. (Eq. (5)) is integrated into the overall scaling methodology by first multiplying the volumetric erosion rate by the bulk density of the granular material and noting that the engine mass flow rate is $\dot{m}_e = \rho_e u_e A_e$. This converts Eq. (5) into

$$\dot{m}_c = \rho_b \dot{V}_c = C_1 \frac{\dot{m}_e u_e}{g \beta d_p + \frac{\alpha}{\rho_b}}, \quad (6)$$

where $\dot{m}_c$ is the mass erosion rate of the crater and C_1 is introduced as a proportionality constant with units of velocity. Second, Eq. (6) is normalized by the engine mass flow rate to yield the normalized crater erosion rate η as,

$$\eta = \frac{\dot{m}_c}{\dot{m}_e} = C_1 \frac{u_e}{g \beta d_p + \frac{\alpha}{\rho_b}}. \quad (7)$$

The ratio of the normalized erosion rate at flight-scale (η_f) to test-scale (η_t) is then,

$$\frac{\eta_f}{\eta_t} = \left(\frac{u_{e,f}}{u_{e,t}} \right) \frac{g_t \beta_t d_{p,t} + \frac{\alpha_t}{\rho_{b,t}}}{g_f \beta_f d_{p,f} + \frac{\alpha_f}{\rho_{b,f}}}, \quad (8)$$

where subscripts t and f are introduced to represent quantities at test- and flight-scale, respectively.

Equation (8) can easily be rearranged to yield normalized erosion rate at flight scale as a function of known quantities. The normalized erosion rate at test-scale is determined directly from experimental measurements of crater erosion rate resulting from a known engine mass flow rate. The engine nozzle exit velocity, acceleration due to gravity, and surface soil properties of particle size, cohesion, and bulk density are known for both test- and flight-scale.

Therefore, the normalized erosion rate at flight-scale can be predicted from the measured normalized erosion rate at test-scale and other known quantities as

$$\eta_f = \eta_t \left(\frac{u_{e,f}}{u_{e,t}} \right) \frac{g_t \beta_t d_{p,t} + \frac{\alpha_t}{\rho_{b,t}}}{g_f \beta_f d_{p,f} + \frac{\alpha_f}{\rho_{b,f}}}. \quad (9)$$

Finally, the crater erosion rate at flight-scale can be predicted from the normalized erosion rate at flight-scale provided by Eq. (9) and engine mass flow rate at flight-scale as

$$\dot{m}_{c,f} = \eta_f \dot{m}_{e,f}. \quad (10)$$

Equation (10) provides the crater erosion rate, which by integrating over time, can be used to determine the crater volume as a function of time as

$$M_{c,f}(t) = \int_0^t \dot{m}_{c,f}(t) dt, \quad (11)$$

where $M_{c,f}(t)$ is the total mass eroded at flight-scale as a function of time. The crater mass erosion rate term in Eq. (11) is written as a function of time. As the lander moves along its trajectory, the erosion rate is expected to change over time as a result of changes in altitude, engine thrust, engine gimbal angle, etc. However, the experimental data will only be available at discrete, constant operating conditions, e.g., constant altitude and thrust. Therefore, a table of erosion rates at flight-scale conditions corresponding to the test-scale data will be calculated from the test-scale crater mass erosion rate using Eq. (10). Then, flight-scale erosion rate as a function of time will be calculated by interpolating across values in the table based on how the lander trajectory changes over time.

Note that the scaling methodology presented in this section leverages scaling relationships which were developed using crater formation data obtained in the viscous erosion regime. Therefore, predictions made using this approach

are expected to decrease in accuracy as the significance of deep cratering mechanisms increases. However, limited experimental data are available from craters formed via deep cratering mechanisms, so the ability of this approach to predict cratering in this regime remains unknown. The concept identified by Metzger [5] that crater erosion rate is driven by an energy balance between the plume and the surface may still apply, even in the case of deep cratering, but the specifics of the energy balance are likely much more complicated due to complex phenomena unique to deep cratering such as sub-surface diffusion flows.

The normalized erosion rate scaling provided by Eq. (8) and used by Eqs. (9) and (10) only provides a way to scale across different engine mass flow rates, nozzle exit velocities, gravity conditions, and soil properties. The flight-scale normalized erosion rate given by Eq. (9) is itself a function of other parameters not captured in the equation such as ambient pressure and nozzle altitude. Therefore, this scaling methodology requires that the test-scale data used to calculate η_t be obtained under flight-relevant conditions matching parameters not captured by Eq. (9) as much as possible.

B. Crater geometry scaling

Once the crater volume has been obtained using the approach provided in the previous section, the crater depth and width may be obtained using one of the two approaches in this section. The first approach leverages a scaling relationship developed by Sonar and Katsuragi [23] for the crater aspect ratio. The second approach uses CFD predictions for surface shear stress values along with a threshold shear stress required to cause erosion to predict a region of the surface within which erosion will occur. The diameter of this region is used to predict the crater width and an assumption about the general crater geometry is used to solve for crater depth. Alternatively, using the second approach, the assumption of the crater geometry may be relaxed and instead the crater depth is assumed to be proportional to the local shear stress.

1. Aspect ratio-based scaling

The first approach for obtaining predictions of crater depth and width from a known crater volume leverages the aspect ratio scaling obtained by Sonar and Katsuragi [23]. Crater aspect ratio, R_c , was defined as the ratio of the crater width to depth as

$$R_c = \frac{2r_c}{d_c}. \quad (12)$$

Sonar and Katsuragi conducted experiments of subsonic plumes impinging onto various different types of granular surfaces at multiple nozzle heights with multiple nozzle diameters to develop a scaling relationship for crater aspect ratio as

$$R_c \propto \begin{cases} (M_e G_e \nu^{-1/2})^{-1} & \text{if } h > h_T \\ (\nu \delta)^{1/2} & \text{if } h < h_T \end{cases}, \quad (13)$$

where $G_e = D_e/h$, $\nu = \rho_p/\rho_e$, $\delta = D_e/d_p$, and $h_T = 10M_e\delta^{1/2}D_e$. Here, h_T is the threshold height, M_e is the nozzle exit Mach number, D_e is the nozzle exit diameter, h is the height of the nozzle above the surface, ρ_p is the mineral density of the surface particles, and ρ_e is the density of the plume flow at the nozzle exit [23].

Equation (13) provides a scaling relationship for the crater aspect ratio. Taking the ratio of Eq. (13) at flight-scale to test-scale, a relationship can be developed to predict the crater aspect ratio at flight-scale from a measured aspect ratio at test-scale and other known parameters as

$$R_{c,f} = R_{c,t} \left(\frac{\nu_f \delta_f}{\nu_t \delta_t} \right)^{1/2}, \quad (14)$$

where $R_{c,t}$ is measured from the test and the remaining parameters are known from the operating conditions at both test- and flight-scale. Note that Eq. (14) assumes that both the test- and flight-scale nozzle height are less than the threshold height defined by Sonar and Katsuragi, which is the case for the HLS PSI GT and HLS landers on the Moon.

With the crater volume obtained using the methods described in Sec. III.A and the aspect ratio obtained using Eq. (14), the remaining unknowns are crater depth and crater radius. These two unknowns can be solved from the known crater volume and aspect ratio by solving the system of equations formed by Eq. (12) plus a geometry constraint equation relating the crater volume to the depth and radius. For example, assuming the crater is a paraboloid,

$$V_{c,f} \propto \frac{1}{2} \pi r_{c,f}^2 d_{c,f}. \quad (15)$$

2. Local shear stress-based scaling

The second approach for obtaining predictions of crater depth and width uses predictions for surface shear stress combined with an estimate for the threshold shear stress required to cause surface erosion. When viscous shear erosion is the dominant mechanism driving crater formation, the local erosion rate can generally be correlated with the local shear stress as shown in Fig. 2. With this approach, the crater width is predicted based on the maximum radial location where the surface shear stress falls below the threshold value as shown in Fig. 3.

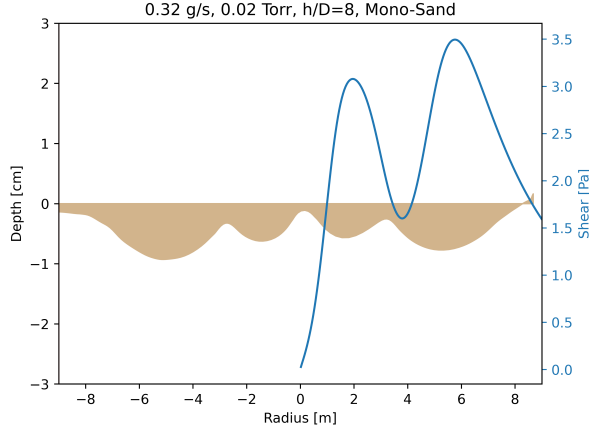


Fig. 2 Example crater profile from the Physics Focused Ground Test (PFGT) run 25 with CFD-predicted surface shear stress overlaid.

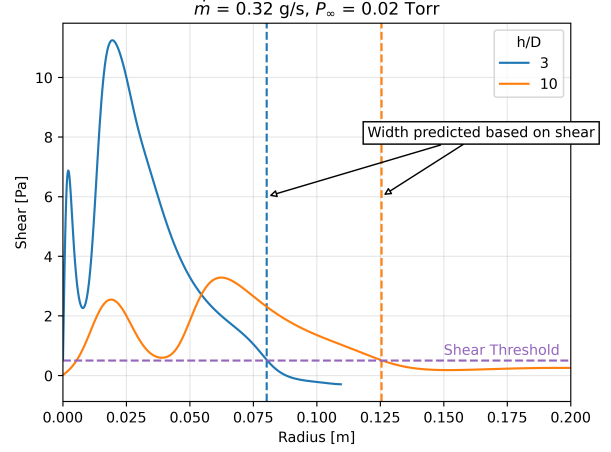


Fig. 3 CFD-predicted surfaced shear stresses for $h/D=3$ and 10 with annotations highlighting predicted crater width based on a threshold shear value.

To investigate the viability of this shear-stress based technique for predicting crater width, data from NASA’s Physics Focused Ground Test (PFGT) campaign were used. Predictions for surface shear stress from PFGT were obtained using CFD simulations with Loci/CHEM [26]. These cases were run as axisymmetric plumes impinging onto a flat plate since the objective was to obtain an estimate for the surface shear stress. Three configurations of the turbulence model were investigated to determine the sensitivity of the results to the turbulence model used. The three configurations tested were laminar (i.e., no turbulence model), Menter’s baseline model (BSL) [27] without compressibility correction, and BSL with the Wilcox compressibility correction [28]. Ultimately, the BSL turbulence model without compressibility correction was used. Flow through the nozzle was introduced via an isentropic inflow boundary condition of nitrogen with stagnation pressure and temperature set to match the steady-state values of the plenum conditions measured in the PFGT experiments. The ambient pressure of the simulations was set to match the measured ambient pressure midway through the ten-second test duration (since the pressure increased during testing). The impingement plate was represented using a viscous wall boundary condition with a constant temperature of 298.15 K.

The threshold shear stress required to result in surface erosion is unique to each material and is a function of material properties such as compaction. Therefore, the threshold shear stress must be experimentally measured for each material (or an appropriate analog in the case of lunar regolith).

While not used in this work, the CFD-predicted surface shear stress distribution could be used to inform the overall geometric profile of the crater rather than just the crater width. This would remove the need to assume something about the crater geometry (e.g., parabolic). If it is assumed that the local erosion rate is proportional to the local shear stress then,

$$\dot{v}(r) = C_2 \tau(r), \quad (16)$$

where $\dot{v}(r)$ is the local erosion rate as a function of radial location (still assuming axisymmetric), C_2 is a proportionality constant, and $\tau(r)$ is the local shear stress. Performing axisymmetric integration of the local erosion rate would then yield the overall erosion rate of the crater as,

$$\dot{V} = 2\pi \int_0^r r \dot{v}(r) dr. \quad (17)$$

When viscous shear erosion is the dominant mechanism, it is assumed that Eq. (16) holds, therefore by substituting

Table 1 Summary of regolith simulants for PFGT erosion rate experiments [12].

Simulant	Material	Specification
Mono-Disperse Glass Beads	Soda Lime	Nominal diameter 125-177 μm
Mono-Disperse Sand	Silica	Nominal diameter 125-177 μm
Bi-Disperse Sand	Silica	Product 1: Nominal diameter 45-53 μm Product 2: Nominal diameter 125-177 μm Equal mix by volume
Tri-Disperse Mixture	Silica + BP-1	Equal mix by volume of bi-disperse sand particle sizes and BP-1
Irregular Mixture	Sieved BP-1	Nominal diameter 212-350 μm
Full-Range Lunar	BP-1	Particle size distribution varies; Lunar mechanical simulant

Eq. (16) into Eq. (17), the volumetric erosion rate of the crater can be written in terms of the local shear stress as,

$$\dot{V} = 2\pi C_2 \int_0^r r \dot{\tau}(r) dr. \quad (18)$$

If $\tau(r)$ is known from CFD and $\dot{V}$ is known from the methods described in Sec. III.A, then the proportionality constant C_2 can be solved for enabling the calculation of local erosion rate based on local shear stress using Eq. (16). The result can then be integrated over time to calculate the depth of the crater as a function of radius.

C. Physics Focused Ground Test

Data from NASA's PFGT campaign were used to assess the performance of the scaling methodology with experimental PSI data obtained using highly underexpanded plumes under vacuum conditions. For a more comprehensive overview of the PFGT test campaign the reader is directed to Refs. [12, 29, 30]. A brief description of the PFGT test campaign is included here to provide context needed to understand the PFGT data discussed in Sec. IV. The PFGT test campaign was an experimental campaign conducted at Marshall Space Flight center in 2021 and 2022 to study PSI crater formation and ejecta dynamics under lunar- and Martian-relevant conditions. Both erosion rate and impingement plate experiments were conducted. Erosion rate testing utilized a half-domain style of experiment wherein the plume flow was bisected by a transparent splitter plate that enabled optical access to a cross-sectional view of the crater evolution [12]. The PFGT experiments were conducted at nozzle heights ranging from 3 to 13 diameters above the surface, ambient pressures from 0.02 to 4.5 Torr, nozzle mass flow rates from 0.32 to 8.6 g/s, and with multiple simulants as shown in Table 1. Data from the mono-disperse sand (MDS) and irregular (IRR) simulants will be used in this study as discussed in Sec. IV.

A high-speed camera was used to record the crater evolution through the view provided by the splitter plate. An image processing algorithm using the adaptive contour method was used to track the evolving crater contour through the images. The tracked crater contours were then further processed to calculate the crater depth, width, and volume evolution over time. The crater depth was defined as 99th percentile of the depth of all points identified along the crater contour. Crater width was defined as the distance between the left-most and right-most points on the crater contour. For calculating crater width, only points at least 2 mm below the surface were considered to obtain a reliable definition of the crater region and avoid erroneously detecting small variations in the initial surface as part of the crater. Finally, the crater volume was calculated by revolving the right half of the crater contour about its center axis and assuming it is axisymmetric

$$V = 2\pi \int_0^r r d(r) dr, \quad (19)$$

where V is the crater volume and r is the radial location along the crater contour. In practice, this integration was performed numerically using the trapezoidal technique.

D. Reduced gravity data from Metzger

The reduced gravity data published by Metzger [31] were used to assess the performance of the scaling methodology across different gravity conditions with both a low cohesion regolith simulant (sand) and a high cohesion simulant (JCS-Mars-1A). Specifically, these data were used to check the predictions provided by the denominator of Eq. (5).

These data include crater formation measurements with sand and JSC-Mars-1A at lunar gravity (1.67 m/s^2), Martian gravity (3.73 m/s^2), Earth gravity (9.81 m/s^2), and hyper gravity (17.66 m/s^2). The sand simulant used included particle diameters ranging from $250 \mu\text{m}$ to $300 \mu\text{m}$. The JSC-Mars-1A simulant had a median particle diameter of $320 \mu\text{m}$. All cratering measurements were taken with a 0.95 cm constant diameter pipe positioned 7.62 cm above the surface with a plume velocity at the pipe exit of 30 m/s . All the reduced gravity experiments conducted by Metzger were with an ambient pressure of 101 kPa .

For the tests conducted with sand, the data files available at [31] included crater depth, width, and volume as a function of time. Data from multiple tests at each gravity condition were available for tests conducted with sand. Data from two tests at hyper gravity, five tests at Earth gravity, four tests at Martian gravity, and nine tests at lunar gravity were used.

For the tests conducted with JSC-Mars-1A simulant, the data files available did not include crater volume data. Therefore, the original images were downloaded and processed to extract the crater volume. Initially, automated image processing techniques were investigated for detecting the crater profile in the images, but the low contrast of the crater profile in the images made this unsuccessful. As such, custom MATLAB program was used to manually trace the crater profile at multiple times throughout the crater evolution as shown in Fig. 4. While this manual process yielded lower temporal resolution compared to the data available with the sand simulant, which were obtained using automated processing techniques, the technique was sufficient for obtaining an estimate of average erosion rate. Crater volume was calculated from each traced crater contour using Eq. (19) as described in Sec. III.C.

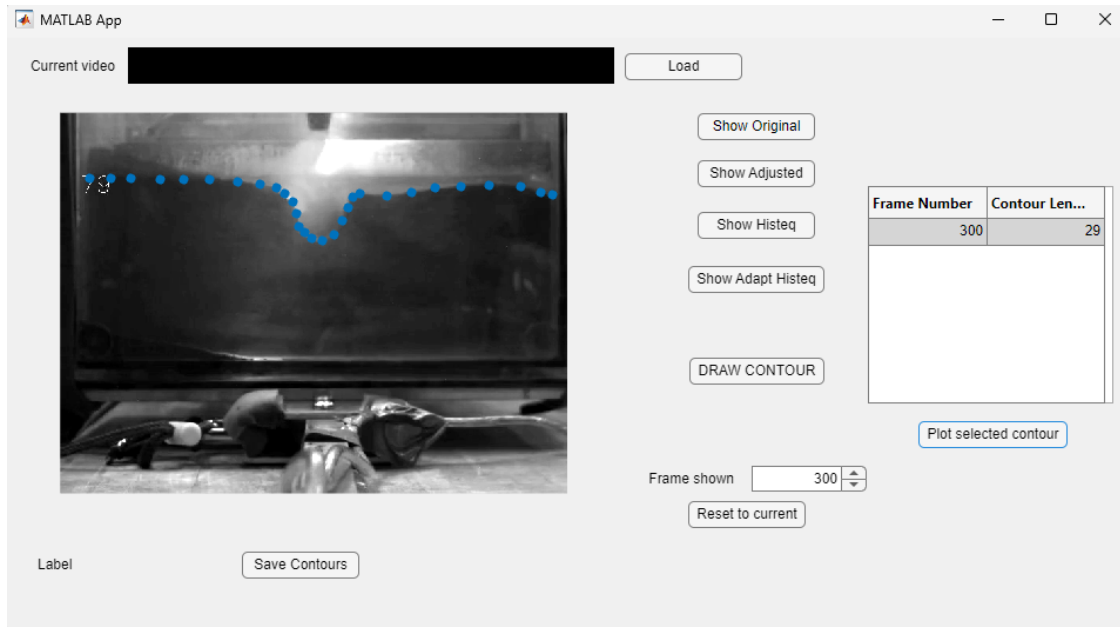


Fig. 4 Screenshot of MATLAB app developed to enable manual tracing of the crater contours.

The data from Metzger were post-processed to calculate erosion rate as follows. First, the data were offset so that the depth evolution started at $t = 0s$ for each of the tests. Then, a linear fit was applied to the data from each case with volume and time as the dependent and independent variables, respectively. The slope of each linear fit was taken to be the mean erosion rate for each test. Finally, the erosion rate data were grouped based on gravity level and the mean and standard deviation were calculated for each group.

IV. Results

A. Erosion rate scaling

Crater formation data available in the literature were used to assess the performance of the developed scaling. First, data from Metzger et al. were used to provide data from subsonic jets impinging onto granular surfaces comprising sand and JSC-Mars-1A Martian regolith simulant under both Earth-gravity and reduced gravity conditions [31].

Second, data from Stubbs [32] were used to provide Earth-gravity data with sonic jets impinging onto sand at multiple nozzle heights and plume mass flow rates. Lastly, data from NASA's PFGT were used to provide Earth-gravity data of highly underexpanded, supersonic plumes impinging onto a sand surface under lunar-relevant ambient pressure conditions [12, 29, 30, 33]. Data from PFGT are of particular interest since the scaling relationships used were developed using experiments conducted at Earth atmospheric ambient pressure with subsonic or moderately underexpanded plumes, which do not really represent the highly underexpanded plumes of a rocket engine operating in space. Furthermore, studies have shown that the cratering process may be significantly affected by changes in atmospheric pressure [34], so it was desirable to investigate the performance of the scaling methodology with a dataset obtained using highly underexpanded plumes under vacuum conditions.

The reduced gravity data provided by Metzger [31] were processed to extract the mean erosion rate for each gravity condition described in Sec. III.D. The resulting mean erosion rates are shown in Figs. 5 and 6 for sand and JSC-Mars-1A simulants, respectively. The error bars in Fig. 5 represent the standard deviation of erosion rate across multiple tests at the same gravity condition. Error bars are not shown in Fig. 6 because data were only used from a single test at each condition. The dashed black line in both figures represents a fit of $1/g$ to the erosion rate data. The data were obtained with constant nozzle exit properties ($\rho_e u_e^2 A_e = \text{const}$) and constant simulant properties ($\rho_b d_p = \text{const}$). For the sand simulant data, $\alpha = 0$, and Eq. (5) simplifies to

$$\dot{V} \propto \frac{1}{\beta g}. \quad (20)$$

The R^2 value of the $1/g$ fit to the sand data was 0.96, indicating that the data follow the gravity scaling predicted by Eq. (20) well.

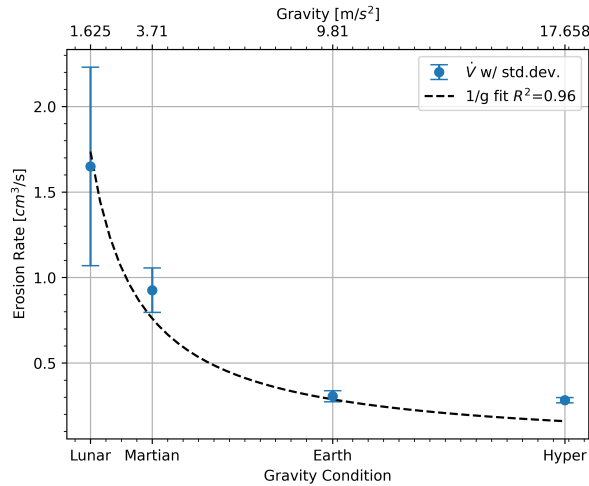


Fig. 5 Mean erosion rate of sand data from Metzger [31] at different gravity levels.

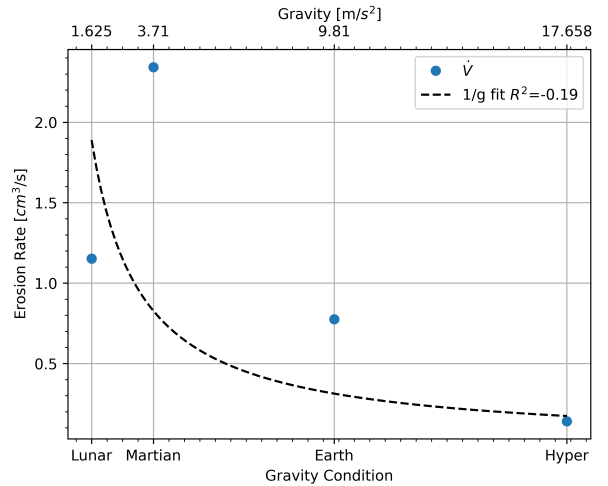


Fig. 6 Mean erosion rate of JSC-Mars-1A data from Metzger [31] at different gravity levels.

The JSC-Mars-1A data shown in Fig. 6 do not follow the $1/g$ scaling well, which indicates the increasing significance of cohesion as gravity decreases. This is because the relative importance of the $\rho_b g \beta d_p$ term in the denominator of Eq. (5) decreases as g decreases, while the cohesion remains the same. For example, the cohesive energy at Earth gravity contributes 2% to 8% of the denominator, whereas at lunar gravity, its contribution is 12% to 34%.

The data from Stubbs [32] were used as a completely independent dataset from the Metzger et al. data, which were originally used in the development of Eq. (5). The Stubbs data were obtained in a full-domain experiment using a non-intrusive measurement methodology with a 4.93 mm sonic nozzle impinging onto a bed of 600 μm to 850 μm sand under Earth-atmospheric ambient pressure. The data were taken across three nozzle mass flow rates of 5.2, 7.0, and 8.5 g/s, with nozzle altitudes ranging from 25 to 80 diameters above the surface. The nozzle heights and mass flow rates tested were significantly higher than those tested by Metzger et al. Since all the data were obtained with the same simulant, at Earth gravity and with a constant nozzle exit velocity, $\rho_b g \beta d_p + \alpha = \text{const}$, $u_e = \text{const}$, and Eq. (5) simplifies to

$$\dot{V} \propto \rho_e u_e^2 A_e = \dot{m}_e u_e \propto \dot{m}_e. \quad (21)$$

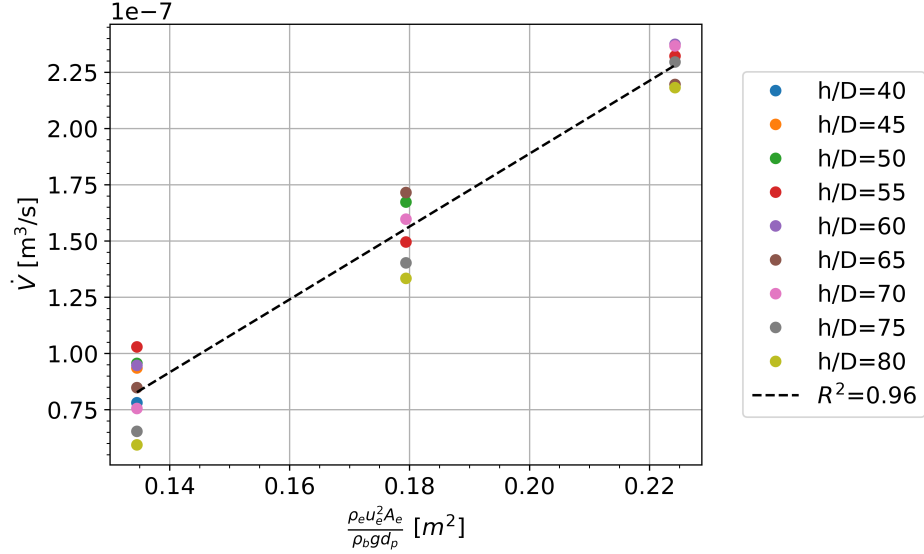


Fig. 7 Mean erosion rate data from Stubbs [32].

Stubbs applied the logarithmic fit for crater depth proposed by Metzger [14] shown in Eq. (1) to the crater depth evolution data and found good agreement [32] for $h/D_e > 13$. To verify the scaling predicted by Eq. (5), crater volume evolution data from Stubbs were processed to extract the mean volumetric erosion rate for each test and plotted versus Eq. (5) with $\alpha = 0$ as shown in Fig. 7. The dashed black line represents a linear fit through the data with an R^2 value of 0.96, suggesting that the data are well characterized by the predicted scaling. Additionally, the data show no significant change in erosion rate across the range of nozzle heights tested by Stubbs, which is in agreement with the scaling relationship in Eq. (5).

The data presented so far from Metzger et al. and Stubbs have shown good agreement with the scaling methodology, but were obtained from experiments using subsonic jets under Earth atmospheric ambient pressure. Therefore, it is important to investigate if the scaling relationships still perform acceptably with a PSI experiment more representative of the environments encountered during a lunar landing. To support this investigation, data from PFGT were used to assess the performance of the scaling methodology with data obtained using highly underexpanded plumes under vacuum conditions. According to the scaling for erosion rate determined by Metzger et al. and shown in Eq. (5), the volumetric erosion rate of the crater should not be a function of nozzle height. A subset of the PFGT data were used to investigate this as shown in Tables 2 and 3.

Table 2 List of PFGT runs shown in Fig. 8

Run	P_∞ (Torr)	h/D	Simulant	$\dot{m}$ (g/s)
R12a	0.02	10	MDS	0.32
R14	0.02	10	MDS	8.6
R18a	0.02	13	MDS	0.32
R23a	0.02	5	MDS	0.32
R24	0.02	6	MDS	0.32
R25	0.02	8	MDS	0.32
R26	0.02	10	MDS	0.32
R28	0.02	5	MDS	0.32
R9	0.02	3	MDS	8.6

Table 3 List of PFGT runs shown in Fig. 10

Run	P_∞ (Torr)	h/D	Simulant	$\dot{m}$ (g/s)
R11	2.0	3	MDS	8.6
R15	2.0	10	MDS	0.32
R16	2.0	10	MDS	8.6
R21	2.0	13	MDS	0.32
R27	2.0	13	MDS	0.32
R5	2.0	4	MDS	8.6
R7	2.0	3	MDS	0.32

Figure 8 shows the volumetric erosion rate as a function of nozzle height for craters formed using MDS simulant at

an ambient pressure of 0.02 Torr and two different nozzle mass flow rates of 0.32 and 8.6 g/s. The data from 0.32 g/s at an ambient pressure of 0.02 Torr do not exhibit any significant change in erosion rate across nozzle heights from $h/D = 5$ to 13, which is in agreement with the scaling determined by Metzger et al. For a nozzle mass flow rate of 8.6 g/s and an ambient pressure of 0.02 Torr, only data from nozzle heights of $h/D = 3$ and 10 were available. The erosion rate decreased from approximately 350 cm^3/s at $h/D = 3$ to 100 cm^3/s at $h/D = 10$. This decrease is likely due to a change from the deep cratering regime to the viscous shear erosion regime as nozzle height was increased indicating that the scaling relationships presented in Sec. III.A are likely only valid when viscous shear erosion is the dominant mechanism. The craters formed with a nozzle mass flow rate of 0.32 g/s likely remained in the viscous shear erosion regime even at lower nozzle heights due to the significantly lower surface impingement pressures resulting from the lower mass flow rate plume.

Figure 9 helps to further investigate this by showing a montage of crater images throughout the 10 s test duration for a few of the different conditions shown in Fig. 8. Crater images shown in the top two rows are from tests where the nozzle mass flow rate was 8.6 g/s at nozzle heights of $h/D = 3$ and $h/D = 10$, respectively. Crater images shown in the bottom two rows are from tests where the nozzle mass flow rate was 0.32 g/s at nozzle heights of $h/D = 5$ and $h/D = 10$, respectively. The crater formation observed for R9 as shown in the top row of Fig. 9 was significantly more rapid and energetic compared to the crater formation observed for R14, R28, and R26. The crater formation observed from R9 resulted in a significantly deeper and wider crater than the other runs shown. Additionally, the formation process was notably more chaotic with sudden rapid increases in crater depth and dynamic collapse events compared to the other runs, which exhibited slower but consistent erosion of the surface layer. This difference in behavior is indicative of deep cratering mechanisms being present for R9 but viscous shear erosion being dominant for the other runs. Lastly, the runs at lower nozzle heights were observed to result in craters having a parabolic shape while runs at higher nozzle heights resulted in annular craters.

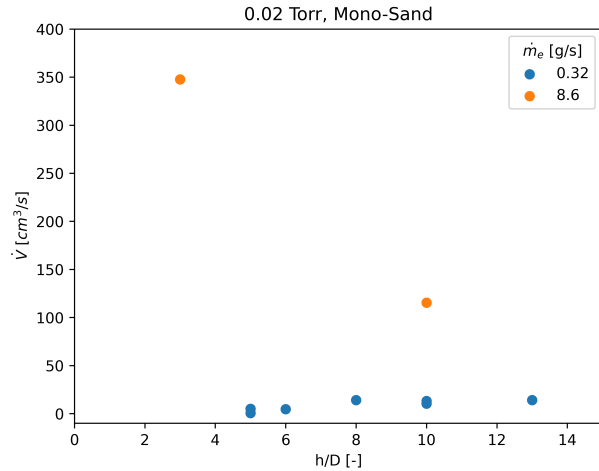


Fig. 8 Volumetric crater erosion rate across a range of nozzle heights for two different mass flow rates at an ambient pressure of 0.02 Torr.

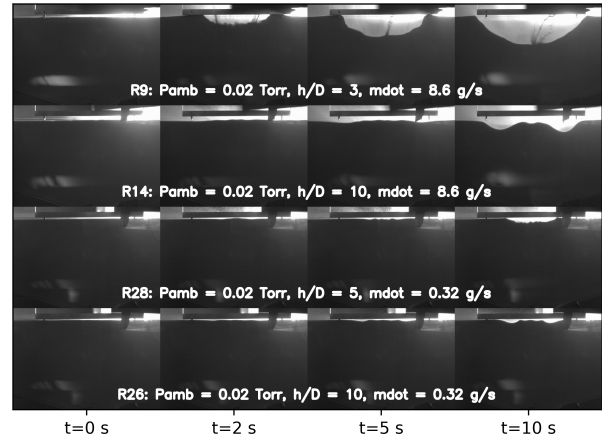


Fig. 9 Montage of crater images for a subset of PFGT cases plotted in Fig. 8.

Data from runs with an ambient pressure of 2 Torr were also used to investigate the scaling of erosion rate with nozzle height as shown in Fig. 10. Like with the runs at an ambient pressure of 0.02 Torr, the runs from 0.32 g/s at 2 Torr did not show significant change in erosion rate with nozzle height, agreeing with the scaling methods discussed in Sec. III.A. Differently from the runs at 0.02 Torr, however, the runs from 8.6 g/s at 2 Torr did not show the same increase in erosion rate with decreasing nozzle height that was seen from the 8.6 g/s runs at 0.02 Torr (Fig. 8). Instead, the erosion rate remained nominally constant across the range of nozzle heights tested at 8.6 g/s and 2 Torr. If it is true that the increase in erosion rate for the runs at 0.02 Torr and 8.6 g/s is due to a shift from viscous shear erosion to deep cratering, then it follows that all three of the 8.6 g/s runs at 2 Torr must be in the same cratering regime since no distinct change in erosion rate is observed. Since the increase in ambient pressure collimates the plume, concentrating the plume onto a smaller region of the surface, it seems likely that all of the 8.6 g/s runs at 2 Torr shown in Fig. 10 are in the deep cratering regime. This can be further investigated via Fig. 11, which shows a montage of crater images from a

subset of the runs shown in Fig. 10. The montage of crater images from runs at 2 Torr shows that craters formed with a nozzle mass flow rate of 8.6 g/s (R11 and R16) were much larger than craters formed with a nozzle mass flow rate of 0.32 g/s (R7 and R15). Furthermore, the craters formed at 2 Torr and 8.6 g/s at both $h/D = 3$ and $h/D = 10$ exhibited the same type of dynamic collapse events followed by rapid growth as was observed for the $h/D = 3$, 8.6 g/s case at 0.02 Torr. As such, it was concluded that all of the 8.6 g/s runs at 2 Torr shown in Fig. 10 were experiencing deep cratering mechanisms. The reason why deep cratering mechanisms were seen for all nozzle heights at 8.6 g/s and 2 Torr but only for $h/D = 3$ at 8.6 g/s and 0.02 Torr is likely due to the more collimated plume at 2 Torr creating a smaller region of higher surface impingement pressure when compared to the plume at 0.02 Torr. These high impingement pressures lead to deep cratering even at higher nozzle heights. This collimated nature of the plume is also evidenced by the narrower craters formed at 2 Torr compared to 0.02 Torr.

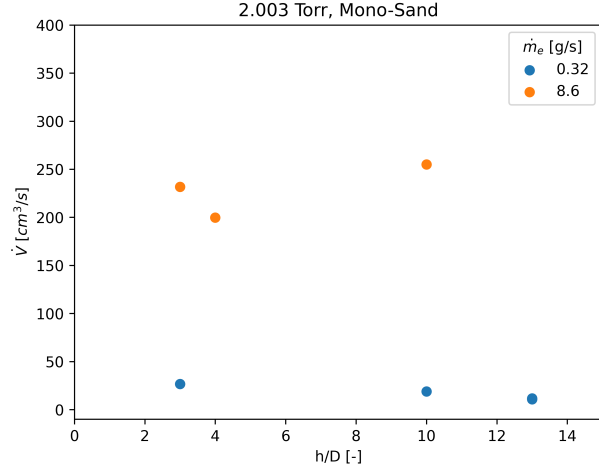


Fig. 10 Volumetric crater erosion rate across a range of nozzle heights for two different mass flow rates at an ambient pressure of 2 Torr.

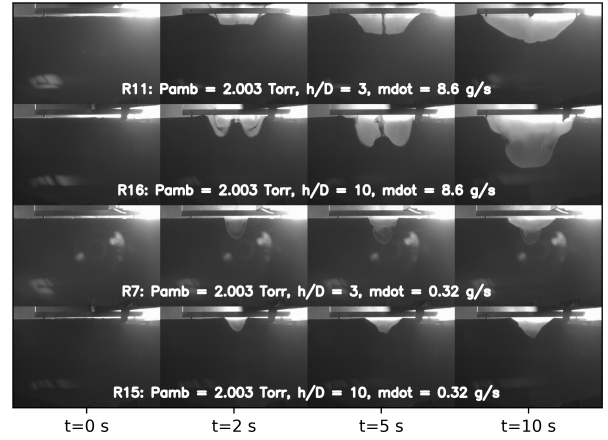


Fig. 11 Montage of crater images for a subset of PFGT cases plotted in Fig. 10.

In addition to verifying that no change in erosion rate was observed with nozzle height, the PFGT data were also used to investigate crater erosion rate scaling with nozzle mass flow rate. To accomplish this, a subset of PFGT data shown in Table 4 were used where nozzle mass flow rates of 0.32, 0.64, and 1.28 g/s were tested at $h/D = 8$ and an ambient pressure of 0.02 Torr. The volumetric crater erosion rate from these cases is shown in Fig. 12 where a linear trend in crater erosion rate with nozzle mass flow rate can be seen ($R^2 = 0.89$), which is in agreement with the scaling methodology presented in Sec. III.A.

B. Aspect ratio scaling

In addition to checking the performance of the erosion rate scaling presented in Sec. III.A, the performance of the crater geometry scaling discussed in Sec. III.B was also investigated. To do this, data from Metzger [31], Stubbs [32], and PFGT were processed to calculate the same scaling parameters as described by Sonar and Katsuragi [23]. The resulting aspect ratio scaling parameters are shown in Fig. 13 as points of various colors overlaid onto the data from Sonar and Katsuragi, which is represented as a gray shaded region. The expected regime of $M_e G_e \delta^{1/2}$ to be covered in the upcoming HLS program PSI GT is represented by a shaded brown region. The data from Metzger and Stubbs show moderately good agreement, but the data from PFGT do not fit the trends predicted by Sonar and Katsuragi. Sonar and Katsuragi predicted that for low nozzle heights, the crater aspect ratio would cease to be a function of nozzle height and become only a function of ν and δ (recall $\nu = \rho_p / \rho_e$ and $\delta = D_e / d_p$). Therefore, the value of $R_c / (\nu \delta)^{1/2}$ was found to asymptote for low nozzle heights (large values of $M_e G_e \delta^{1/2}$). The PFGT data do not follow this trend, instead values of $R_c / (\nu \delta)^{1/2}$ calculated from PFGT data deviate significantly from the trends established by Sonar and Katsuragi. This is not entirely unexpected as the operating conditions of the PFGT experiment were with highly underexpanded supersonic plumes under vacuum conditions - significantly different from the subsonic atmospheric experiments conducted by Sonar and Katsuragi.

Since the agreement between the aspect ratio scaling proposed by Sonar and Katsuragi and the PFGT data was

Table 4 List of PFGT runs shown in Fig.

Run	P_∞ (Torr)	h/D	Simulant	$\dot{m}$ (g/s)
R25	0.02	8	MDS	0.32
R29a	0.02	8	MDS	0.64
R30	0.02	8	MDS	1.28

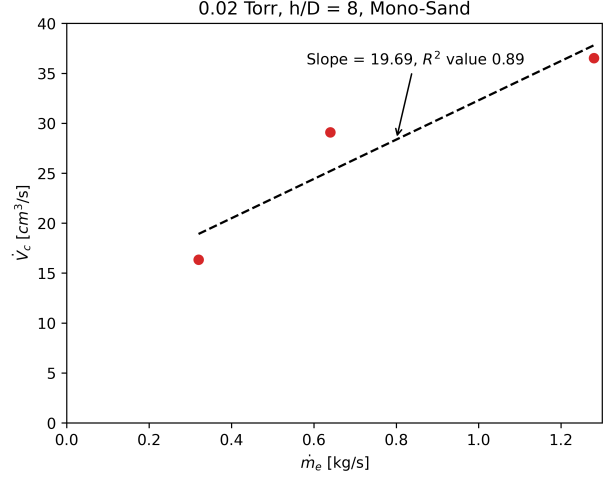


Fig. 12 Crater erosion rate for multiple nozzle mass flow rates from runs at 0.02 Torr with Mono-Sand simulant.

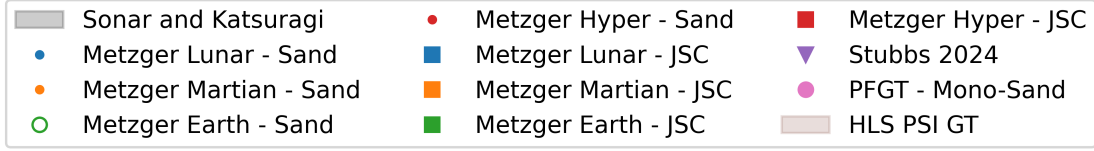


Fig. 13 Aspect ratio scaling showing data from Sonar and Katsuragi [23], Metzger [31], and Stubbs [32].

poor, an alternative method for predicting the crater width based on predicted surface shear stress profiles from CFD as discussed in Sec. III.B.2 was investigated. To investigate the validity of this approach for predicting crater width, data from PFGT were used [12]. Specifically, data obtained using the MDS and IRR simulants with a nozzle mass flow rate of 0.32 g/s and an ambient pressure of 0.02 Torr were used. For these conditions, the crater width was extracted for each nozzle height of 5, 6, 8, 10, and 13 nozzle diameters above the surface. Then, the shear stress values predicted by the CFD simulations at these locations was investigated. Figure 14 shows this comparison indicating that as the crater width

increases with nozzle height, the CFD-predicted shear stress at the edge of the crater remains relatively constant with an average value of $\tau_c = 0.25$ Pa and $\tau_c = 0.47$ Pa for the MDS and IRR simulants, respectively. Using these average

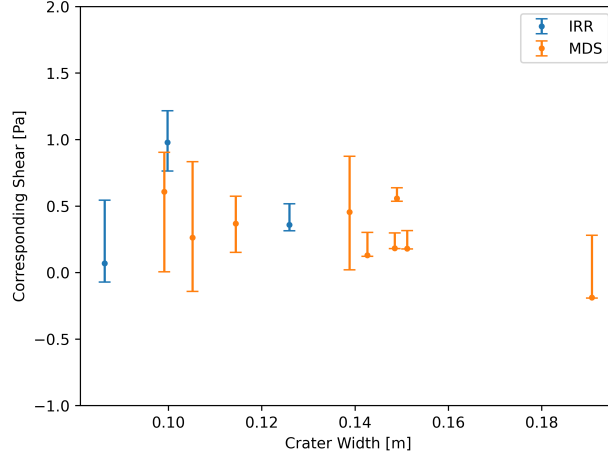


Fig. 14 Comparison of surface shear stress values from CFD extracted at the edge of the crater.

values for threshold shear stress, the crater width was predicted using the surface shear stress values obtained from CFD and compared with the actual crater width measured from the experiments. These comparisons are shown in Fig 15 (a) and (b), respectively, and generally indicate good agreement when predicting the crater width in this way.

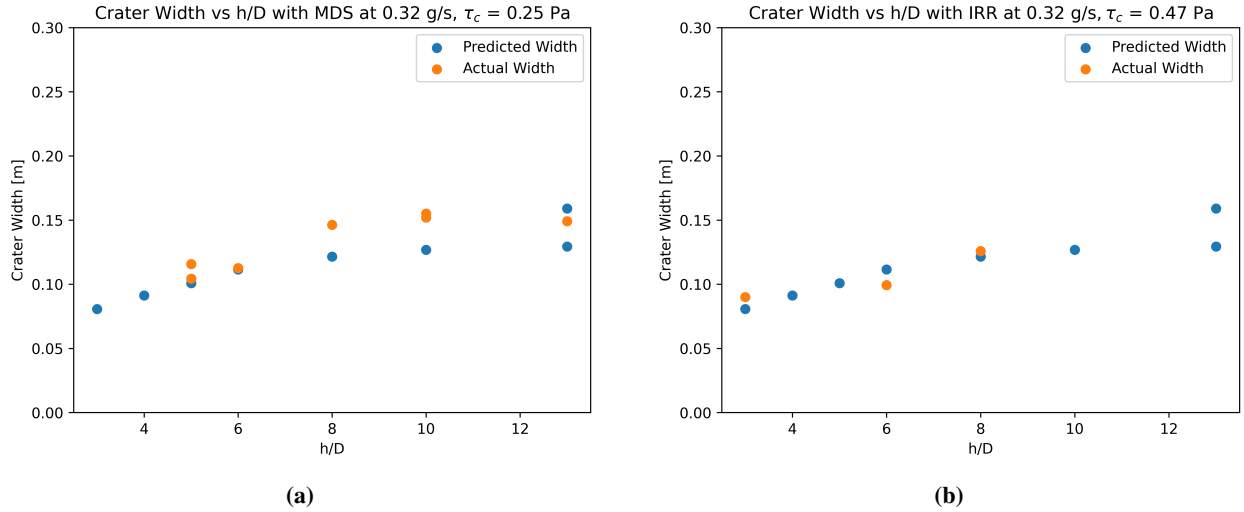


Fig. 15 Predicted versus actual crater widths using empirically determined threshold shear value for (a) MDS and (b) IRR simulant cases with a nozzle mass flow rate of 0.32 g/s, and ambient pressure of 0.02 Torr, and a range of nozzle heights.

More data of PSI crater formation with supersonic plumes at low ambient pressure conditions are needed to fully investigate the capabilities of both approaches for predicting crater geometry. It is hoped that data from the upcoming HLS program PSI GT will aid in this investigation.

V. Conclusions

A methodology for scaling test-scale PSI crater formation data to flight-scale was developed for the purposes of providing flight-scale predictions to NASA's HLS program. Methods for predicting both the crater erosion rate and crater geometry were developed. Two different methods for predicting crater geometry were investigated. One method

for predicting crater geometry utilizes empirical aspect ratio scaling relationships while the other utilizes surface shear stress predictions obtained with CFD. Together, these techniques can be used to provide predictions for final crater volume, depth, and width.

Data from Metzger [31], Stubbs [32], and NASA's PFGT campaign [12] were then used to investigate the performance of the developed scaling methodology. The reduced gravity data from Metzger enabled investigating the scaling across multiple gravity levels and highlighted the importance of the cohesion term at low gravity levels. The data from Stubbs served as a set of independent data that were not involved in the initial development of the Metzger scaling equations and included data at higher nozzle mass flow rates and nozzle heights than the data from Metzger. Lastly, data from PFGT enabled an investigation of the scaling methodology under lunar-relevant conditions with supersonic, highly underexpanded plumes in a vacuum.

Data from PFGT were also used to investigate performance of the two methods for predicting crater geometry. Based on these results, PFGT data were found to have poor agreement with the aspect ratio scaling proposed by Sonar and Katsuragi [23]. Prediction of crater width using the surface shear stress distributions from CFD showed promising results with the PFGT data, but more work is needed to verify the performance of this technique with more data.

Ultimately, the scaling methodology proposed in this work performed well against the data available for assessing its performance. It should be noted that the parameter space covered by the data used in this study is still significantly different from conditions relevant to the landers that will be used for the HLS program. This is most evident when looking at Fig. 16, which shows the maximum surface impingement pressure created by the plumes used in the PFGT campaign compared to the impingement pressures seen during the Apollo missions and expected from the HLS landers to be used in the Artemis missions.

The upcoming HLS PSI GT is expected to address some of these concerns. The HLS PSI GT will be conducted in a 60-ft vacuum sphere at NASA's Langley Research Center (LaRC). Tests will be conducted with both a non-combusting, heated ethane gas plume and a hybrid rocket motor plume. The hybrid rocket motor plume will be used to investigate the sensitivity of PSI to more representative thermal velocities which can only be achieved with a reacting flow plume. With both propellant systems, tests will be conducted at nozzle heights ranging from 4 to 32 nozzle exit diameters above the surface and at chamber pressures ranging from 2.5 to 12 MPa. Both impingement plate and erosion experiments will be conducted as part of the HLS PSI GT. Impingement plate experiments will be conducted with the plume impinging onto a flat plate instrumented with pressure transducers, thermocouples, shear sensors, and heat flux sensors. Impingement plate experiments will only be conducted for the ethane system as the high temperatures of the hybrid rocket motor plume would damage the impingement plate. For erosion experiments, the plume will be directed downwards onto a bed of BP-1 lunar regolith simulant.

Surface erosion measurements will be obtained using the Stereo Cameras for Lunar Plume Surface Studies Ground Test (SCALPSS-GT) instrument [35]. The SCALPSS camera system was recently used successfully to measure the post-landing terrain from Firefly Aerospace's Blue Ghost Mission 1 (BGM1) [36–40]. A dust concentration monitor (DCM) [41] and millimeter wave Doppler radar (MWDR) [42] will be used to measure regolith particles ejected from the surface. Flow visualization of plume impingement will be obtained using a Rayleigh scattering technique for the ethane plume and using planar laser-induced fluorescence of the OH radical for the hybrid rocket plume. Initial results demonstrating the standoff shock height above the impingement plate for the ethane plume are discussed in Rodrigues et al. [43]. Impingement pressures in HLS PSI GT will have similar magnitude to those of HLS landers on the lunar surface, as shown in Fig. 16. Flow visualization and impingement plate data from HLS PSI GT will be used to validate computational fluid dynamics simulations of the plumes. Erosion rate and ejecta data will be used to validate the scaling methodology and to provide flight-scale predictions for PSI effects caused by HLS landers.

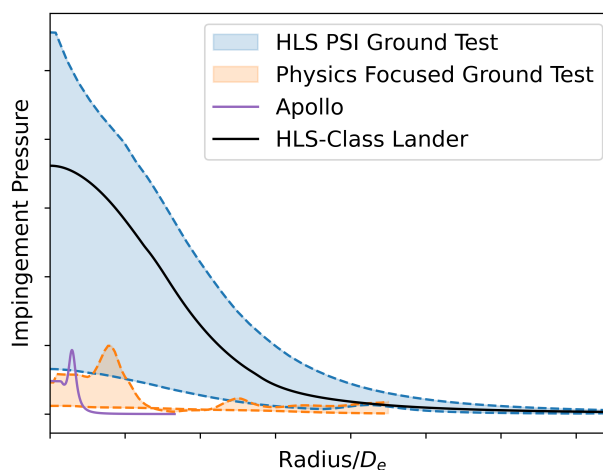


Fig. 16 Comparison of impingement pressure magnitudes between the Apollo LM, HLS-class landers, PFGT campaign, and HLS PSI GT campaign.

Acknowledgments

The authors would like to thank Christopher Morris, Wesley Chambers, and Michael Manginelli from NASA Marshall Space Flight Center, Ashley Korzun from NASA Langley Research Center, and Gregory Schallcross from the NASA Jet Propulsion Laboratory for their support and feedback. The authors would like to thank Jonathan Boustani from NASA Marshall Space Flight Center for his support in running CFD simulations to inform the model development efforts. Resources supporting this work were provided by the NASA High-End Computing (HEC) Program through the NASA Advanced Supercomputing (NAS) Division at Ames Research Center.

References

- [1] Metzger, P. T., Smith, J., and Lane, J. E., “Phenomenology of soil erosion due to rocket exhaust on the Moon and the Mauna Kea lunar test site,” *Journal of Geophysical Research*, Vol. 116, No. E6, 2011. <https://doi.org/10.1029/2010JE003745>.
- [2] Metzger, P. T., Lane, J. E., Immer, C. D., and Clements, S., “Cratering and Blowing Soil by Rocket Engines During Lunar Landings,” *International Conference on Case Histories in Geotechnical Engineering*, 2008.
- [3] Batcheldor, D., and Mantovani, J., “Mapping Lunar Lander Plume Ejecta Trajectories to Lunar Surface Elevations,” *Earth and Space 2022*, American Society of Civil Engineers, Denver, Colorado, 2023, pp. 17–26. <https://doi.org/10.1061/9780784484470.002>.
- [4] Watkins, R. N., Metzger, P. T., Mehta, M., Han, D., Prem, P., Sibille, L., Dove, A., Jolliff, B., Moriarty III, D. P., Barker, D. C., Patrick, E., Kuhns, M., and Laine, M., “Understanding and Mitigating Plume Effects During Powered Descents on the Moon and Mars,” , Feb. 2021. URL <http://arxiv.org/abs/2102.12312>.
- [5] Metzger, P. T., “Erosion rate of lunar soil under a landing rocket, part 1: Identifying the rate-limiting physics,” *Icarus*, Vol. 417, 2024. <https://doi.org/10.1016/j.icarus.2024.116136>.
- [6] West, J., Howison, J. C., Liever, P., Dawson, T., Shurtz, T., and Weaver, A. B., “Initial Validation of a Gas-Granular Flow Solver Using a Subscale, Reduced Pressure Plume Surface Interaction Ground Test,” *AIAA SCITECH 2025 Forum*, 2025. <https://doi.org/10.2514/6.2025-2571>.
- [7] Weaver, A., Shurtz, T., Liever, P., Dawson, T., Howison, J., and West, J., “A Hybrid CFD/Engineering Model Tool for Lunar Lander Surface Erosion Prediction,” *Earth and Space 2024*, American Society of Civil Engineers, Miami, Florida, 2024, pp. 137–144. <https://doi.org/10.1061/9780784485736.013>.
- [8] Balakrishnan, K., and Bellan, J., “Hyperbolic high-fidelity simulations of cratering on a particle bed induced by a turbulent supersonic plume,” *International Journal of Multiphase Flow*, Vol. 179, 2024. <https://doi.org/10.1016/j.ijmultiphaseflow.2024.104902>.
- [9] Weaver, A. B., Shurtz, T., Liever, P., and West, J., “Validation Assessment of Loci/GGFS Gas Granular Flow Solver Predictions of Ejecta from Physics Focused Ground Test,” *AIAA SCITECH 2025 Forum*, 2025. <https://doi.org/10.2514/6.2025-2570>.
- [10] Land, N. S., and Clark, L. V., “Experimental investigation of jet impingement on surfaces of fine particles in a vacuum environment,” Tech. rep., NASA, 1965.
- [11] Mehta, M., Renno, N. O., Marshall, J., Rob Grover, M., Sengupta, A., Rusche, N. A., Kok, J. F., Arvidson, R. E., Markiewicz, W. J., Lemmon, M. T., and Smith, P. H., “Explosive erosion during the Phoenix landing exposes subsurface water on Mars,” *Icarus*, Vol. 211, No. 1, 2011, pp. 172–194. <https://doi.org/10.1016/j.icarus.2010.10.003>.
- [12] Korzun, A. M., Eberhart, C. J., West, J., Liever, P., Weaver, A., Mantovani, J., Langton, A., Kemmerer, B., and Atkins, A., “Design of a Subscale, Inert Gas Test for Plume-Surface Interactions in a Reduced Pressure Environment,” *AIAA SCITECH 2022 Forum*, 2022. <https://doi.org/10.2514/6.2022-1808>.
- [13] Scott, R. F., and Ko, H.-Y., “Transient rocket-engine gas flow in soil,” *AIAA Journal*, Vol. 6, No. 2, 1968, pp. 258–264. <https://doi.org/10.2514/3.4487>.
- [14] Metzger, P. T., Immer, C. D., Donahue, C. M., Vu, B. T., Latta, R. C., and Deyo-Svendsen, M., “Jet-Induced Cratering of a Granular Surface with Application to Lunar Spaceports,” *Journal of Aerospace Engineering*, Vol. 22, No. 1, 2009, pp. 24–32. [https://doi.org/10.1061/\(ASCE\)0893-1321\(2009\)22:1\(24\)](https://doi.org/10.1061/(ASCE)0893-1321(2009)22:1(24)).
- [15] Roberts, L., “The action of a hypersonic jet on a dust layer,” *Institute of Aerospace Sciences 31st Annual Meeting*, 1963.

- [16] Metzger, P. T., Lane, J. E., and Immer, C. D., "Modification of Roberts' Theory for Rocket Exhaust Plumes Eroding Lunar Soil," *Earth & Space 2008*, American Society of Civil Engineers, Long Beach, California, United States, 2008, pp. 1–8. [https://doi.org/10.1061/40988\(323\)4](https://doi.org/10.1061/40988(323)4).
- [17] Rajaratnam, N., and Beltaos, S., "Erosion by Impinging Circular Turbulent Jets," *Journal of the Hydraulics Division*, Vol. 103, No. 10, 1977, pp. 1191–1205. <https://doi.org/10.1061/JYCEAJ.0004852>.
- [18] Haehnel, R. B., Dade, W. B., and Cushman-Roisin, B., "Crater Evolution Due to a Jet Impinging on a Bed of Loose Particles," *Earth & Space 2008*, American Society of Civil Engineers, Long Beach, California, United States, 2008, pp. 1–10. [https://doi.org/10.1061/40988\(323\)2](https://doi.org/10.1061/40988(323)2).
- [19] Metzger, P. T., Lane, J. E., Immer, C. D., Gamsky, J. N., Hauslein, W., Li, X., Latta, R. C., Iii, and Donaue, C. M., "Scaling of Erosion Rate in Subsonic Jet Experiments and Apollo Lunar Module Landings," *Earth and Space 2010*, American Society of Civil Engineers, Honolulu, Hawaii, United States, 2010, pp. 191–207. [https://doi.org/10.1061/41096\(366\)21](https://doi.org/10.1061/41096(366)21).
- [20] Metzger, P. T., "Erosion rate of lunar soil under a landing rocket, part 2: Benchmarking and predictions," *Icarus*, Vol. 417, 2024. <https://doi.org/10.1016/j.icarus.2024.116135>.
- [21] LaMarche, C. Q., and Curtis, J. S., "Cratering of a particle bed by a subsonic turbulent jet: Effect of particle shape, size and density," *Chemical Engineering Science*, Vol. 138, 2015, pp. 432–445. <https://doi.org/10.1016/j.ces.2015.08.030>.
- [22] Gorman, M. T., Rubio, J. S., Diaz-Lopez, M. X., Chambers, W. A., Korzun, A. M., Rabinovitch, J., and Ni, R., "Scaling laws of plume-induced granular cratering," *PNAS Nexus*, Vol. 2, No. 9, 2023, p. pgad300. <https://doi.org/10.1093/pnasnexus/pgad300>, URL <https://academic.oup.com/pnasnexus/article/doi/10.1093/pnasnexus/pgad300/7279083>.
- [23] Sonar, P., and Katsuragi, H., "Air jet impact craters on granular surfaces: a universal scaling," , Sep. 2024. URL <http://arxiv.org/abs/2409.04988>.
- [24] Metzger, P. T., Latta III, R. C., Schuler, J. M., and Immer, C. D., "Craters Formed in Granular Beds by Impinging Jets of Gas," *AIP Conference Proceedings*, 2009, pp. 767–770. <https://doi.org/10.1063/1.3180041>.
- [25] Dotson, B., St John, A., Hall, R., Sapkota, D., Britt, D., and Metzger, P., "Understanding the effects of geotechnical properties on viscous erosion rate from plume surface interactions," *Planetary and Space Science*, Vol. 261, 2025. <https://doi.org/10.1016/j.pss.2025.106117>.
- [26] Luke, E. A., *A rule-based specification system for computational fluid dynamics*, Mississippi State University, 1999.
- [27] Menter, F. R., "Two-equation eddy-viscosity turbulence models for engineering applications," *AIAA Journal*, Vol. 32, No. 8, 1994, pp. 1598–1605. <https://doi.org/10.2514/3.12149>.
- [28] Samimy, M., and Elliott, G. S., "Effects of compressibility on the characteristics of free shear layers," *AIAA Journal*, Vol. 28, No. 3, 1990, pp. 439–445. <https://doi.org/10.2514/3.10412>.
- [29] Rubio, J. S., Gorman, M., Diaz-Lopez, M. X., and Ni, R., "Plume-Surface Interaction Physics Focused Ground Test 1: Setup and Preliminary Results," *AIAA SCITECH 2022 Forum*, 2022. <https://doi.org/10.2514/6.2022-1809>.
- [30] Diaz-Lopez, M. X., Gorman, M., Rubio, J. S., and Ni, R., "Plume-surface Interaction Physics Focused Ground Test 1: Diagnostics and Preliminary Results," *AIAA SCITECH 2022 Forum*, 2022. <https://doi.org/10.2514/6.2022-1810>.
- [31] Metzger, P., "Reduced Gravity Experiment Data for Scour Hole Formation Including Raw Videos," , Feb. 2024. <https://doi.org/10.5281/zenodo.10611667>.
- [32] Stubbs, D. C., "An experimental investigation of crater formation physics during plume-surface interactions using non-intrusive measurement techniques," Ph.D. thesis, Auburn University, Aug. 2024. URL <https://etd.auburn.edu/handle/10415/9325>.
- [33] Eberhart, C. J., West, J., and Korzun, A. M., "Overview of Plume-Surface Interaction Data from Subscale Inert Gas Testing at NASA MSFC Test Stand 300 Vacuum Facilities," *AIAA SCITECH 2022 Forum*, 2022. <https://doi.org/10.2514/6.2022-1811>.
- [34] Stubbs, D. C., Silwal, L., Bhargav, V. N., Thurow, B. S., Raghav, V., and Scarborough, D. E., "The Effect of Reduced Ambient Pressure on Plume-Surface Interaction Cratering Dynamics," *AIAA Journal*, Vol. 63, No. 3, 2025, pp. 1062–1077. <https://doi.org/10.2514/1.J064431>.
- [35] Tyrrell, O. K., Weisberger, J. M., Fahringer, T. W., Danehy, P. M., and Hutchins, W. D., "Investigating Photogrammetric Accuracy of a Lunar-lander-induced Crater Measurement System," *AIAA SCITECH 2023 Forum*, American Institute of Aeronautics and Astronautics, 2023. <https://doi.org/10.2514/6.2023-2475>.

- [36] Danehy, P. M., Tyrrell, O. K., Weisberger, J. M., Fahringer, T. W., and Chambers, W. A., “Firefly Blue Ghost Mission 1: SCALPSS 1.1 Short Focal Length Camera Descent Imaging,” *AIAA SciTech 2026 Forum*, American Institute of Aeronautics and Astronautics, 2026.
- [37] Fahringer, T. W., Weisberger, J. M., Tyrrell, O. K., Danehy, P. M., Manginelli, M. S., Witherow, W. K., and Liddle, D. A., “Firefly Blue Ghost Mission 1: SCALPSS 1.1 Camera Calibration,” *AIAA SciTech 2026 Forum*, American Institute of Aeronautics and Astronautics, 2026.
- [38] Maddock, R. W., Munk, M. M., Danehy, P. M., Tyrrell, O. K., Weisberger, J. M., Fahringer, T. W., Lueg, R. T., Wilson, C. J., Scammell, A. D., Martin, K. J., Shabat, A. B., Foyer, S. E., Coleman, M., Johnson, K. C., Lehotay, J. D., Nguyen, C.-D. P., Rodgers, M. R., Vitullo, N. A., Rawls, J. R., McPherson, C. M., Manginelli, M. S., Witherow, W. K., Chambers, W. A., and Banks, M. E., “Firefly Blue Ghost Mission 1: SCALPSS 1.1 Payload and Mission Overview,” *AIAA SciTech 2026 Forum*, American Institute of Aeronautics and Astronautics, 2026.
- [39] Tyrrell, O. K., Weisberger, J. M., Fahringer, T. W., and Danehy, P. M., “Firefly Blue Ghost Mission 1: SCALPSS 1.1 Post-Landing Terrain Measurements,” *AIAA SciTech 2026 Forum*, American Institute of Aeronautics and Astronautics, 2026.
- [40] Weisberger, J. M., Tyrrell, O. K., Fahringer, T. W., and Danehy, P. M., “Firefly Blue Ghost Mission 1: SCALPSS 1.1 Long Focal Length Camera Descent Imaging,” *AIAA SciTech 2026 Forum*, American Institute of Aeronautics and Astronautics, 2026.
- [41] Kemmerer, B. W., Lane, J. E., Wang, J. J., III, J. R. P., Johansen, M. R., Buhler, C. R., and Calle, C. I., “Electrostatic precipitator dust density measurements in a Mars-like atmosphere,” *Particulate Science and Technology*, Vol. 39, No. 3, 2021, pp. 271–284. <https://doi.org/10.1080/02726351.2019.1697978>.
- [42] Kemmerer, B. W., Langton, A. G., Mantovani, J. G., Atkins, A. R., Batchelder, D. P., and Bastin, G. L., “Development of the Dust Ejecta Radar Technology (DERT) to Determine Plume-Surface Interaction Ejecta Velocities on Planetary Surfaces,” *2023 IEEE International Radar Conference (RADAR)*, 2023, pp. 1–6. <https://doi.org/10.1109/RADAR54928.2023.10371018>.
- [43] Rodrigues, N. S., Korzun, A. M., Broslawski, C. J., Schwartz, T., Nemie, E. J., Chambers, W. A., Wagner, R. L., Danehy, P. M., Lueg, R. T., Wilson, M., Shafner, J., Tucker, D., Kuster, L., Crider, J., Lehotay, J. D., Braun, A. M., and Diaz-Lopez, M. X., “Initial Measurements of Plume Impingement in the NASA Langley 60-foot Vacuum Sphere,” *AIAA SciTech 2026 Forum*, 2026.