

Comparison of Ejecta Distributions from Normal Incident Hypervelocity Impact on Lunar Regolith Simulant

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ABSTRACT

The National Aeronautics and Space Administration (NASA) is progressing toward long-term lunar habitation. Critical to the design of a lunar habitat is an understanding of the lunar surface environment; of specific importance is the primary meteoroid and subsequent ejecta environment. The document, NASA SP-8013, was developed for the Apollo program and is the latest definition of the ejecta environment. There is concern that NASA SP-8013 may over-estimate the lunar ejecta environment. NASA's Meteoroid Environment Office (MEO) has initiated several tasks to improve the accuracy of our understanding of the lunar surface ejecta environment.

This paper reports the results of experiments on projectile impact into powdered pumice and unconsolidated JSC-1A Lunar Mare Regolith simulant (JSC-1A) targets. The Ames Vertical Gun Range (AVGR) was used to accelerate projectiles to velocities in excess of 5 km/s and impact the targets at normal incidence. The ejected particles were detected by thin aluminum foil targets placed around the impact site and angular distributions were determined for ejecta. Comparison of ejecta angular distribution with previous works will be presented. A simplistic technique to characterize the ejected particles was formulated and improvements to this technique will be discussed for implementation in future tests.

Key Words: lunar, regolith, meteoroid impact, ejecta distribution, impact testing

1. INTRODUCTION

The series of tests discussed in this paper grew out of two focus areas, related to exploration of the lunar surface. The primary goal of this series of tests was to calibrate ground-based cameras utilized to observe and record meteoroid impacts on the lunar surface. The other focus was the need to increase our understanding of the ejecta environment on the lunar surface. NASA's Meteoroid Environment Office (MEO) offered the opportunity to gather ejecta distribution data during a series of test shots using the Ames Vertical Gun Range (AVGR).

The AVGR is a 0.30 caliber light gas gun that can launch projectiles to velocities ranging from 0.5 km/s to nearly 7 km/s. A very unique feature of the AVGR is the ability to vary the gun's angle of elevation with respect to the target. The angle of elevation of the gun can be varied in 15-degree increments from 0 to 90 degrees, thus permitting oblique angles of impact. Impact events can be recorded with a variety of high-speed imaging options¹.

NASA SP-8013 describes the ejecta environment subsequent to meteoroid impact². The graph shown in Figure 1 indicates approximately a 4 order of magnitude increase in the number of ejecta particles of mass, m , from the baseline primary meteoroid impact flux of mass, m , as defined by the Grün model³. The design of a long-term habitation structure to survive the ejecta environment described in NASA SP-8013 would require excessive mass, making it difficult and potentially cost prohibitive to launch and deliver the structure to the lunar surface. A better understanding of the lunar ejecta environment is required to optimize the lunar habitat design.

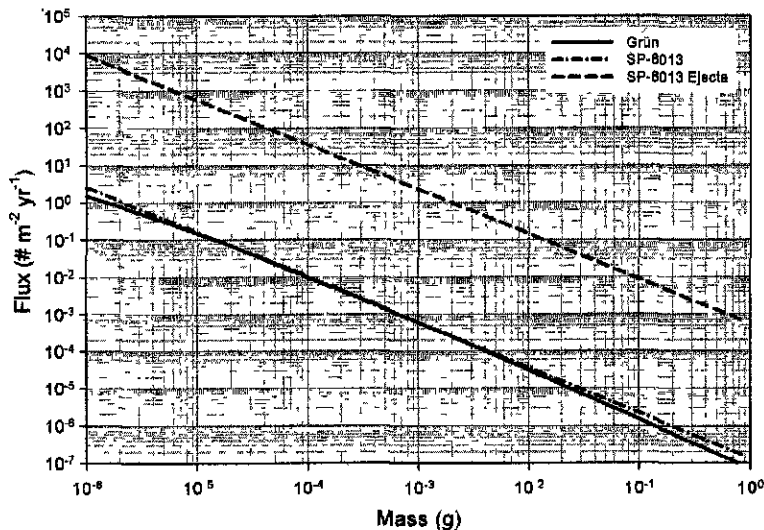


Figure 1. Estimation of the lunar ejecta flux compared to the prediction of primary impact flux from the Grün model.

2. EXPERIMENT

The purpose of this series of experiments was to collect information enabling the characterization of the ejecta angular distribution resulting from a hypervelocity impact into simulated regolith. These ejecta characterization experiments were secondary experiments in the AVGR, and as such were dependent upon the test parameters required by the primary experiment: the calibration of video cameras from the primary impact flash. Therefore one of the constraints of the ejecta characterization experiment was that the ejecta experiment could not influence, bias, perturb, or otherwise contaminate the calibration of the video camera.

The experiment set-up, shown in Figure 2, consisted of placing sheets of aluminum foil in two specific locations, identified as position “D” and position ‘B” around the periphery of the AVGR vacuum chamber. The 0.17 mm thick foils were positioned such that the ejecta would impact the foils at near-normal incident angles. In each case, the projectile was fired vertically (90°) into each powered regolith simulant. The projectile in each case was 6.35 mm diameter, 0.29 g Pyrex sphere. The incident projectile velocities ranged from 2.5 km/s to 5.18 km/s.

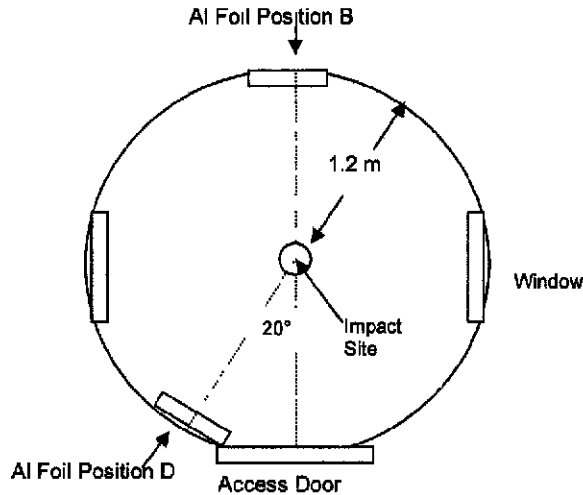


Figure 2. Top view schematic of the test chamber – specifically indicating the positions of the aluminum foil detectors D and B.

3.0 RESULTS

As shown in figure 3, the foil targets were divided into 1° wide horizontal bands after the impact test was performed and the number of penetrations in each band was counted. The 1° band was approximately 1 inch (2.54 cm). The number of penetrations was documented as penetrations / unit area. The unit area is the area defined by the 1° band and 12 inches (30.48 cm), which is approximately 12 in² (77.42 cm²).

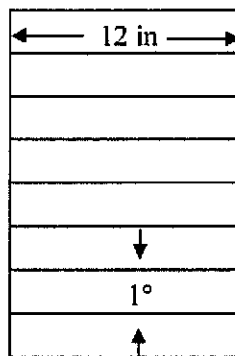


Figure 3. Schematic showing how the foils were divided into 1° bands, 12 inches wide.

The JSC1-a targets produced more ejecta penetrations than the pumice target given equivalent incident projectile mass, composition, and velocity. The impact test using powdered pumice performed at 2.5 km/s did not produce ejecta that penetrated the foil detectors. The impact test using JSC1-a produced a significant number of ejecta penetrations. Projectile impact velocities of 3.78 and 5.18 km/s produced primary ejecta that penetrated the foil targets. The results from counting penetration in foils are shown in Figures 3 and 4 and indicate a preferred ejecta angle ranging between 30° to 43° with respect to the horizontal.

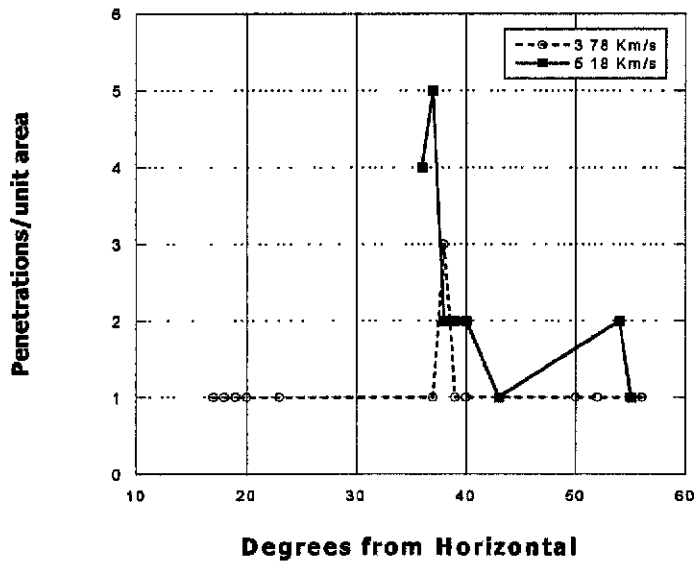


Figure 3. Angular distributions of pumice ejecta with sufficient velocity to penetrate the aluminum foil detectors.

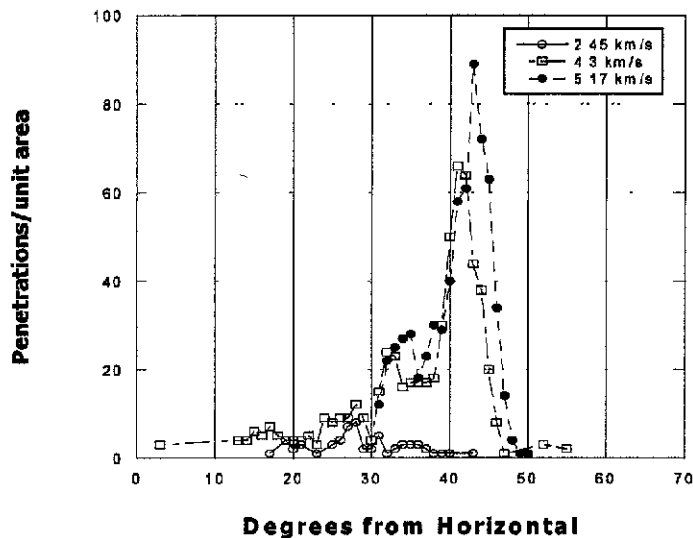


Figure 4. Angular distributions of JSC1-a ejecta with sufficient velocity to penetrate the aluminum foil detectors.

4. SUMMARY AND DISCUSSION

The Ames Vertical Gun Range (AVGR) was used to accelerate spherical Pyrex projectiles of 0.29 g to velocities ranging between 2.5 km/s and 5.18 km/s. Impact on the powered pumice target occurred at normal incidence.

The ejected particles were detected by thin aluminum foil targets placed around the powered targets in a vacuum chamber maintained at a vacuum level of 0.5 Torr during the impact test. The pumice was fine grain, 60 μm diameter particles and the JSC1-a was a larger grain powered target with average grain size of _____. The results presented in this paper indicate that a peak ejection angle for penetrating ejecta is approximately 38° off the horizontal for pumice and 41° to 43° for the JSC1-a. Previous work by Yamamoto resulted in a peak ejection angle of approximately 30° (Yamamoto, 2002, p.92). Yamamoto et al used a “staple-shaped” copper projectile with impact velocities ranging from 243 m/s to 272 m/s and impacted a target consisting of soda-lime particles with a nominal diameter of 220 μm . Cintala et al. performed a series of impact tests using spherical aluminum particles accelerated to velocities ranging from 0.8 to 1.92 km/s (Cintala, 1999). The incident projectiles had a nominal diameter of 4.76 mm and impacted coarse-grained sand with grain sizes ranging from 1-3 mm.

Cintala provides extensive detail for characterizing the ejecta angular and size distributions and recorded ejecta angles ranging between 38° and 55°. Cintala, Yamamoto, and this work used varying techniques to determine ejecta distributions, with Cintala and Yamamoto also providing ejecta velocities.

This experiment made no attempt to measure ejection velocities. Speculation on anticipated ejecta velocities was aided by referencing Yamamoto's work, which states "In the case of the vertical impact of the projectile, most ejecta have velocities lower than 24% of the projectile speed." (Yamamoto, 2002, p.87) If Yamamoto's 24% prediction can serve as a guide for the higher velocities in this experiment, then using 24% of the incident projectile speeds of 2.5, 3.78, and 5.18 km/s provides upper threshold ejecta speeds of approximately 600 m/s, 907 m/s, and 1243 m/s, respectively. Using the penetration equation given in NASA SP-8013 (page 7) describing threshold penetrations of "single thin ductile metal plates", we get a penetration threshold velocity for the aluminum foil of approximately 988 m/s. This equation is:

$$t = K_1 \rho^{-1/6} m^{0.352} V^{0.875} \quad (1)$$

where t is the thickness of the foil penetrated, K_1 is a constant, ρ is the mass density of the ejecta (1.3 gm/cm³ for pumice), m is the mass of the ejecta particle, and V is the ejecta velocity. This calculation assumes all ejecta particles are 60 μ m diameter pumice. If Yamamoto's 24% prediction holds true for this body of work, then there is an explanation of why the impact in pumice at 2.5 km/s did not produce ejecta that penetrated the aluminum foil and why the 3.78 and 5.18 km/s impacts did produce foil penetrating ejecta. This explanation needs to be confirmed by a future experiment.

The lunar meteoroid ejecta environment needs to be better characterized. This work, integrated with other activities being initiated by NASA's Constellation program, can lead to a more accurate understanding of the ejecta environment. To build on this existing database, additional tests at the AVGR are scheduled. These tests will include varying the regolith target to begin to understand the differences in mare and highland regolith by using foil detectors of various thicknesses to gain information on ejecta velocity distributions. Detectors will also be placed at various distances from the impact site to better characterize the ejecta dispersions.

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3. Cooke, W. Unpublished presentation of lunar Impact ejecta analysis, 2007

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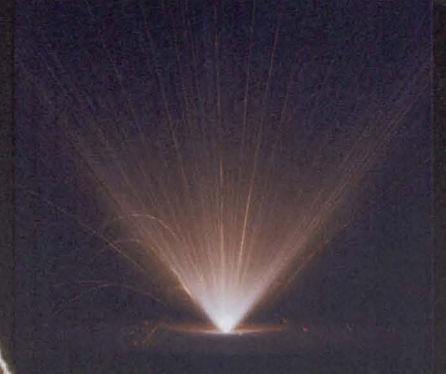
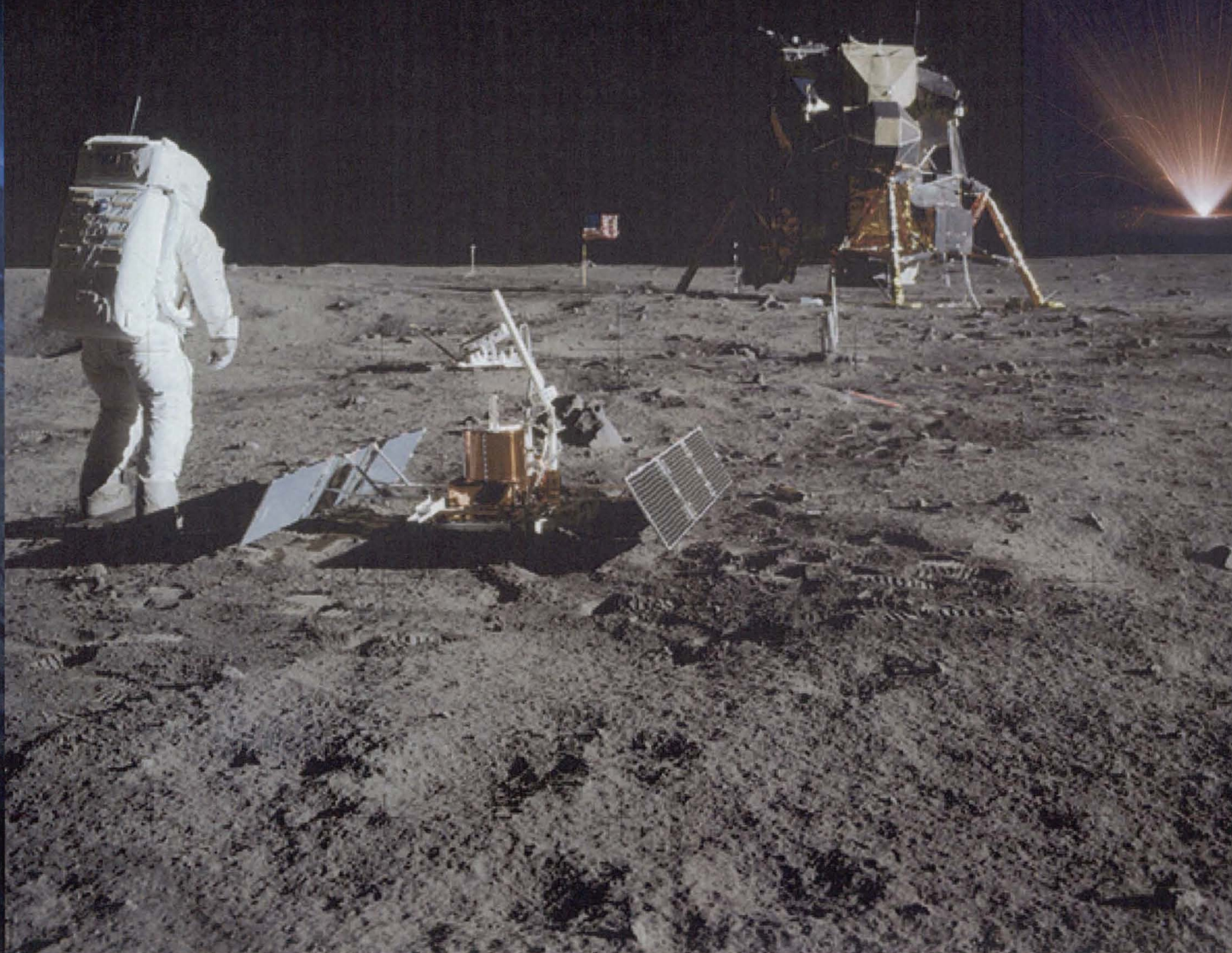


Outline



Comparison of Ejecta Distributions from Normal Incident Hypervelocity Impact on Lunar Regolith Simulant

- **Background**
- **Discussion of the Problem**
- **Overview of the AVGR Test System**
- **Description of the Experiment(s)**
- **Results**
- **Summary**



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Automated Lunar and Meteor Observatory



Remotely operated from control building

Recording Devices

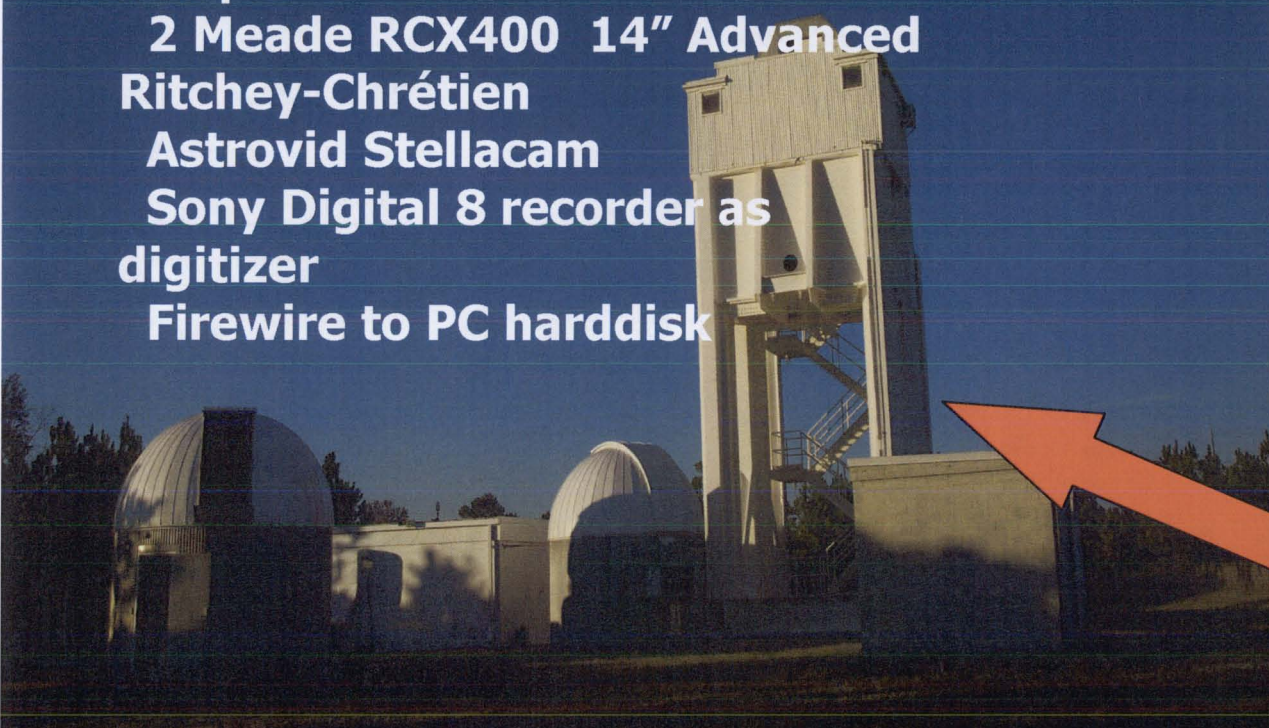
Telescopes

2 Meade RCX400 14" Advanced Ritchey-Chrétien

Astrovid Stellacam

Sony Digital 8 recorder as digitizer

Firewire to PC harddisk



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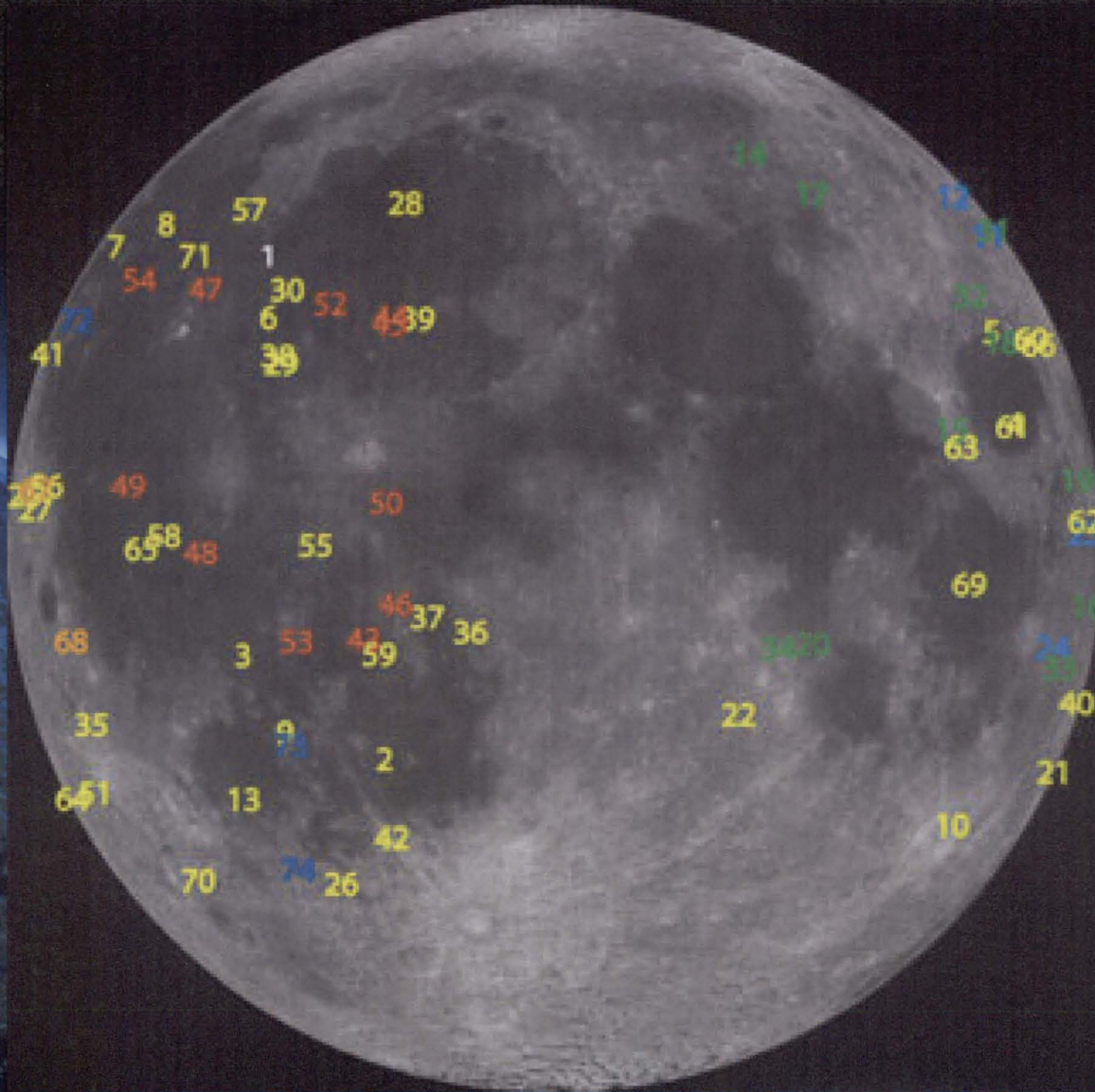
Observing the Moon



- Dark (not sunlit) side only
 - Earthshine illuminates lunar features
- Crescent and quarter phases – 0.1 to 0.5 solar illumination
 - 5 nights waxing (evening)
 - 5 nights waning (morning)
- 4-6 nights of data a month, weather dependent
- Observing procedure
 - Aim scopes at Moon
 - Record video with WinDV
 - CCD camera → Digital 8 recorder → hard drive
 - Adjust tracking occasionally



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#2 equivalent
to 4 tons of TNT

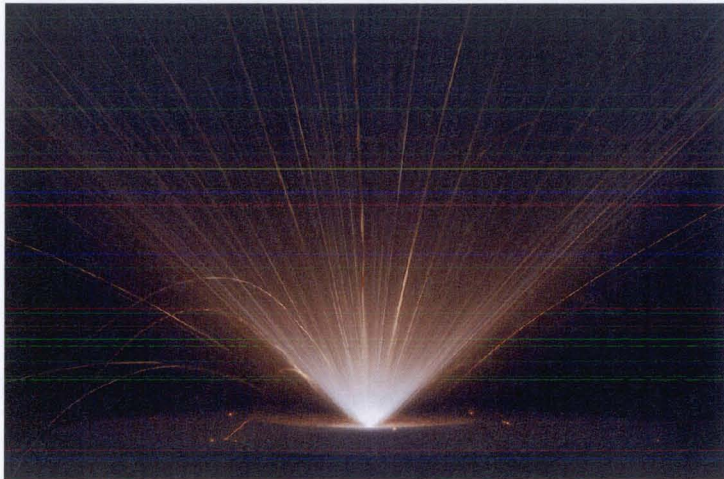
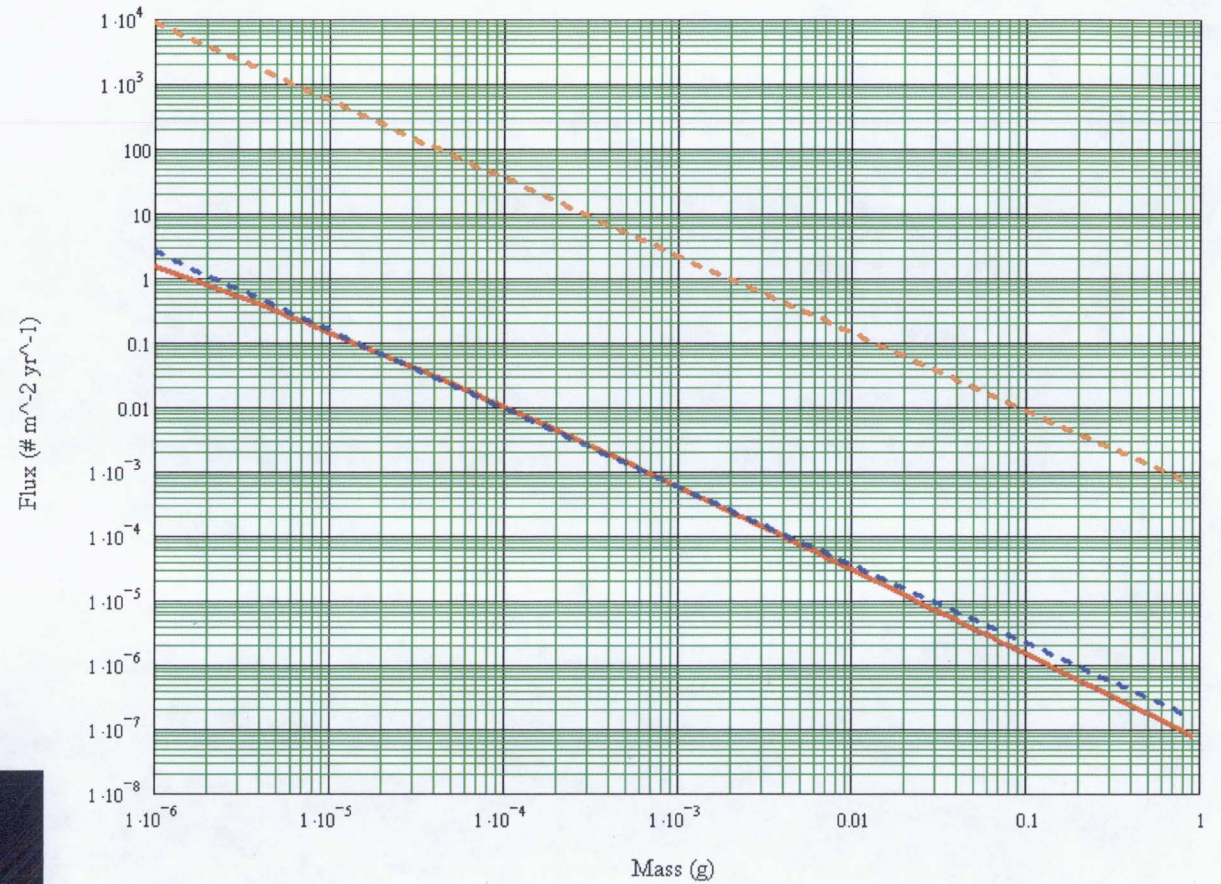
65, 66, 67 confirmed
by WCO

Yellow are sporadic background meteoroids

Red is likely Taurid, green Geminids, blue Leonids, orange Orionids

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The Problem



Ames Vertical Gun Range (AVGR)

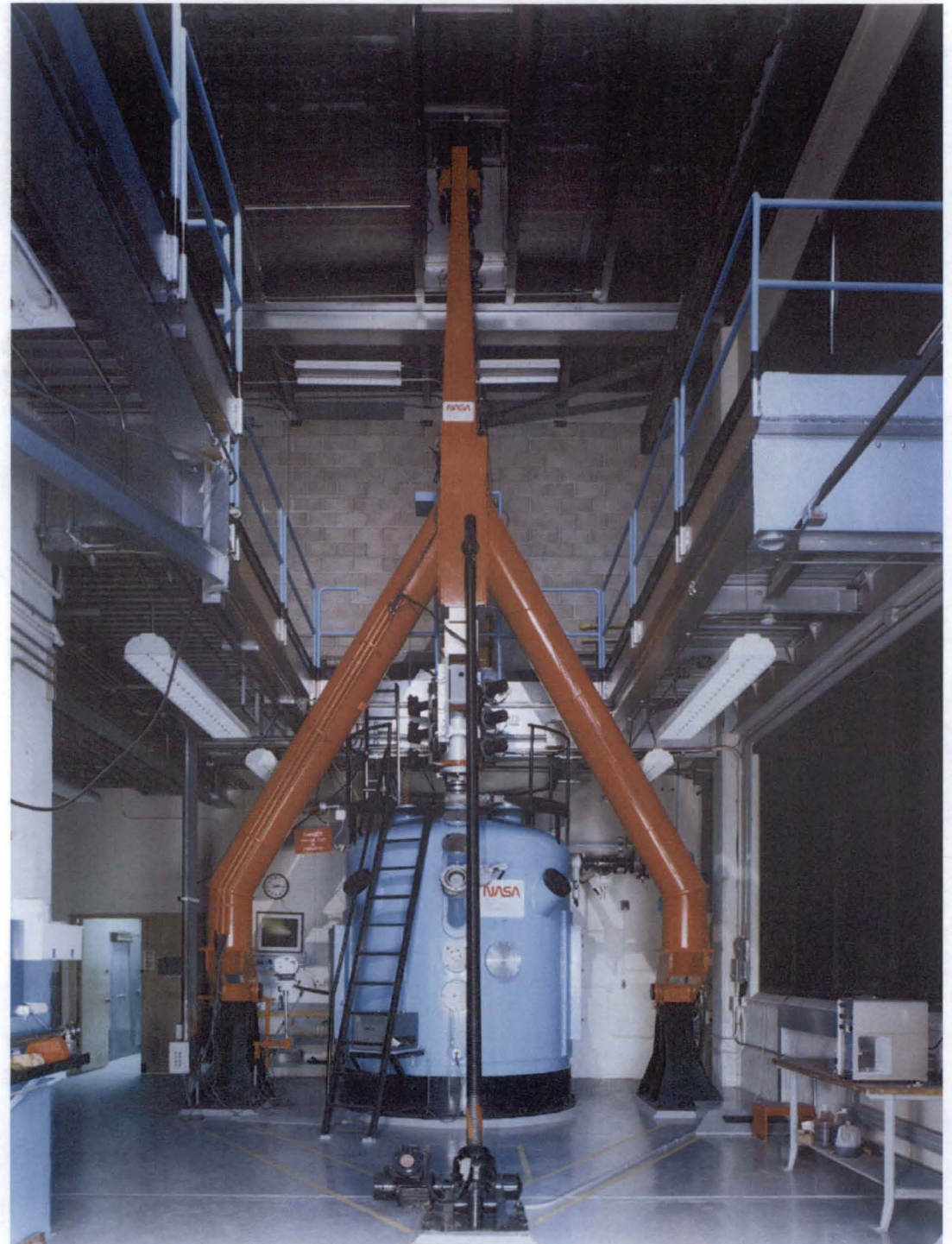
0.30 Caliber Light Gas Gun

Projectile velocity range 0.5 to 7 km/s

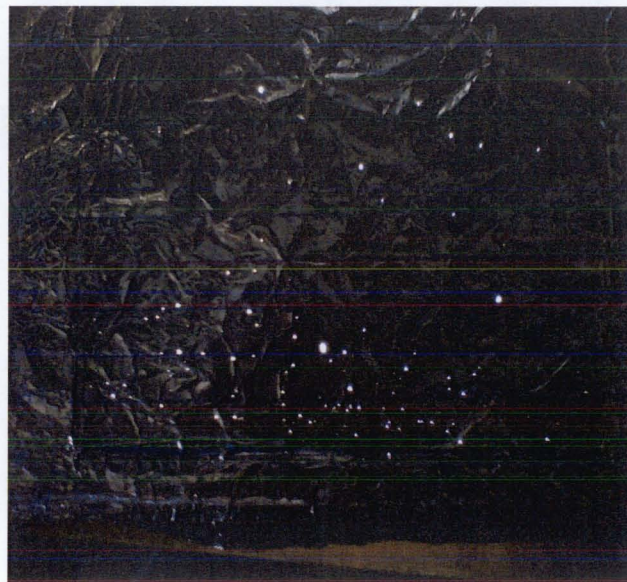
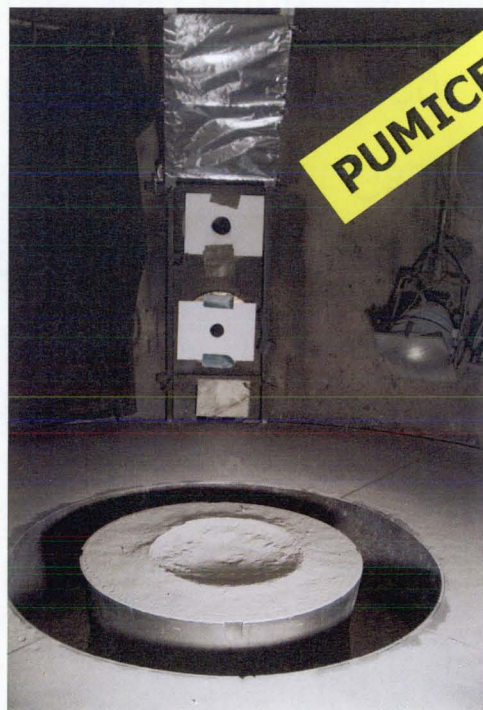
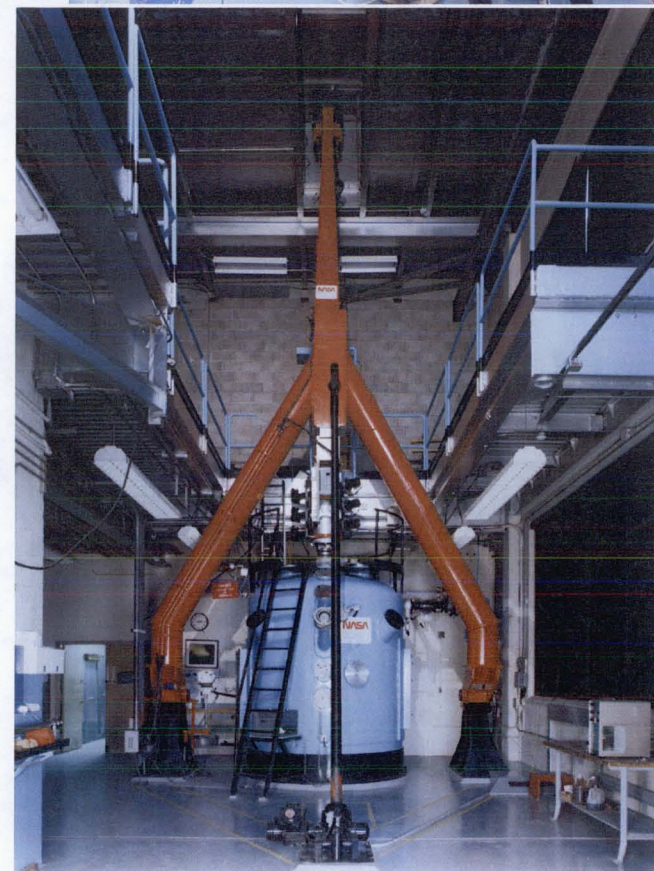
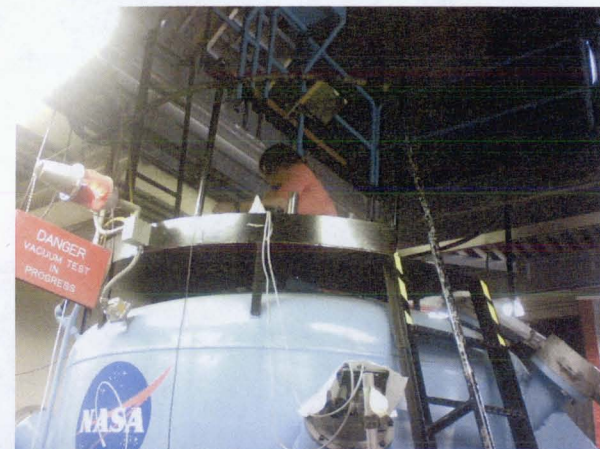
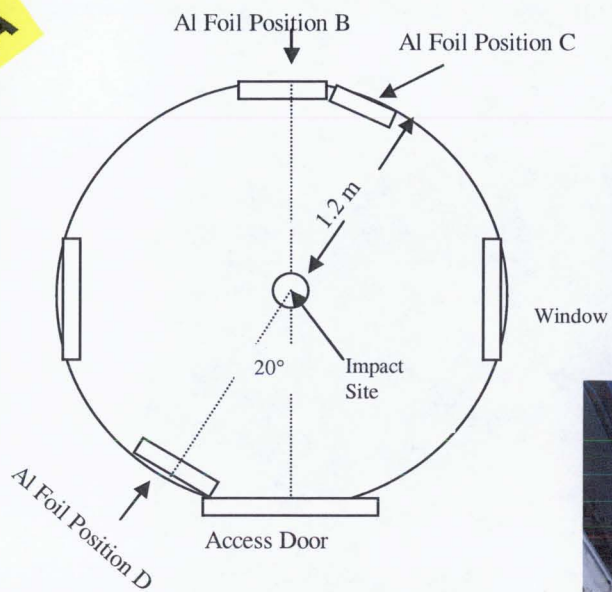
Adjustable Impact Angle

30°, 45°, 60°, 90°

0.5 Torr vacuum in Chamber

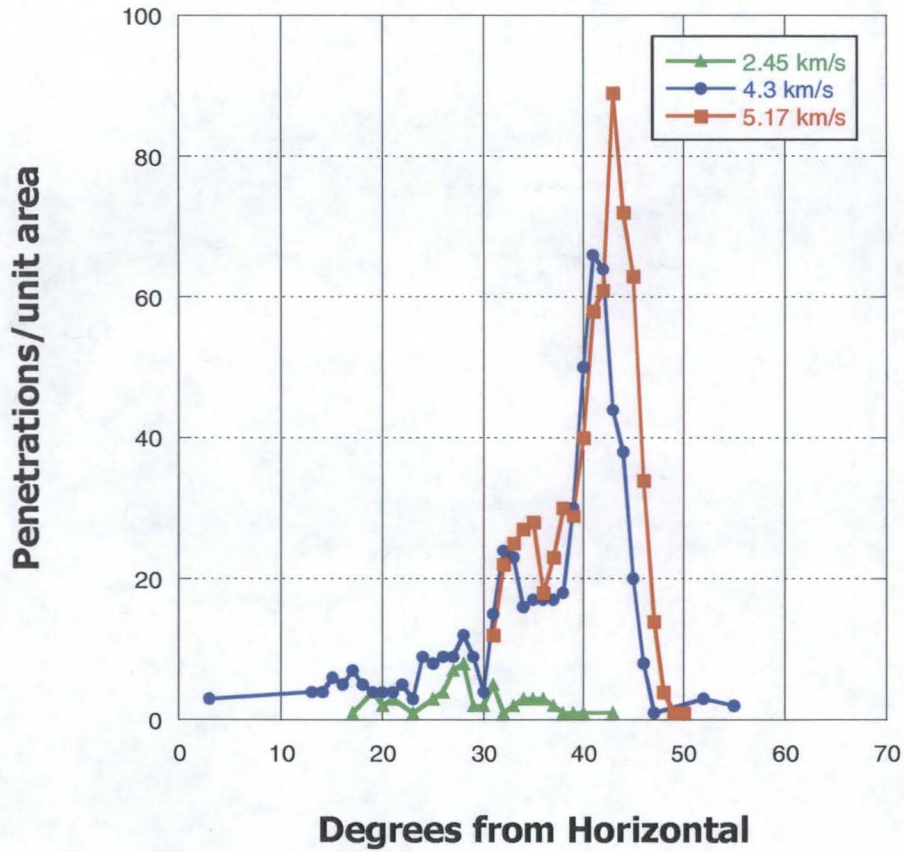


Al Foil Detector positions D & B for Pumice Test shots AL Foil Detector position C for JSC1-A Test shots

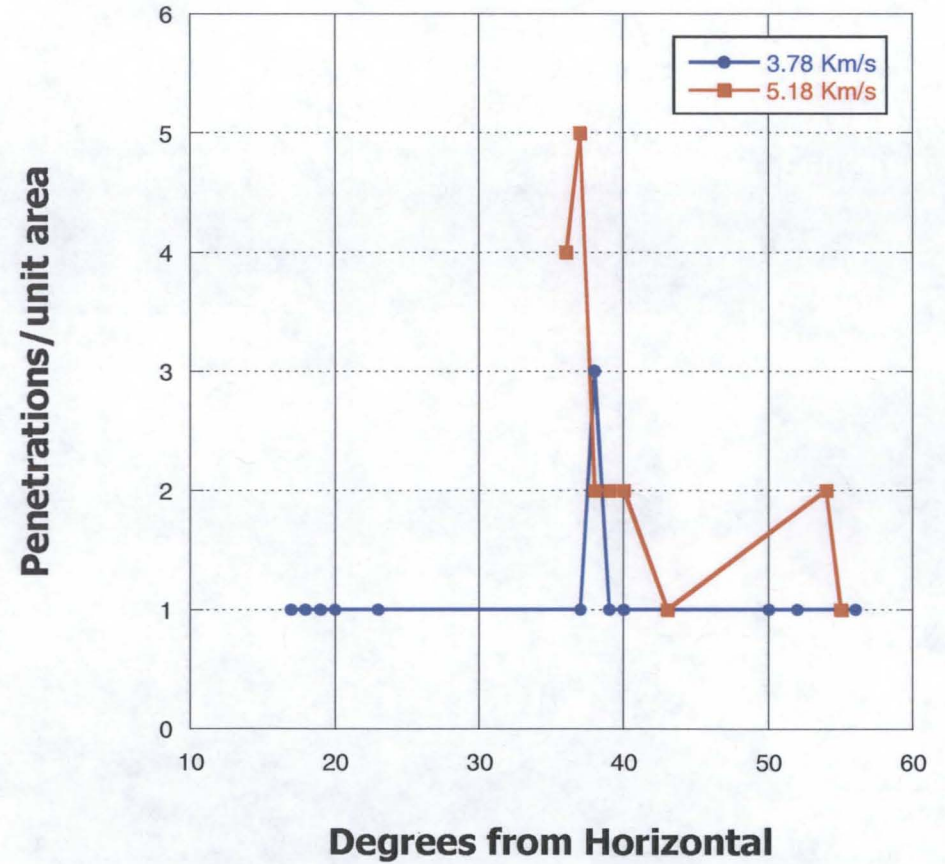


The Results

JSC-1A



Pumice





Estimation of Velocity Constraints



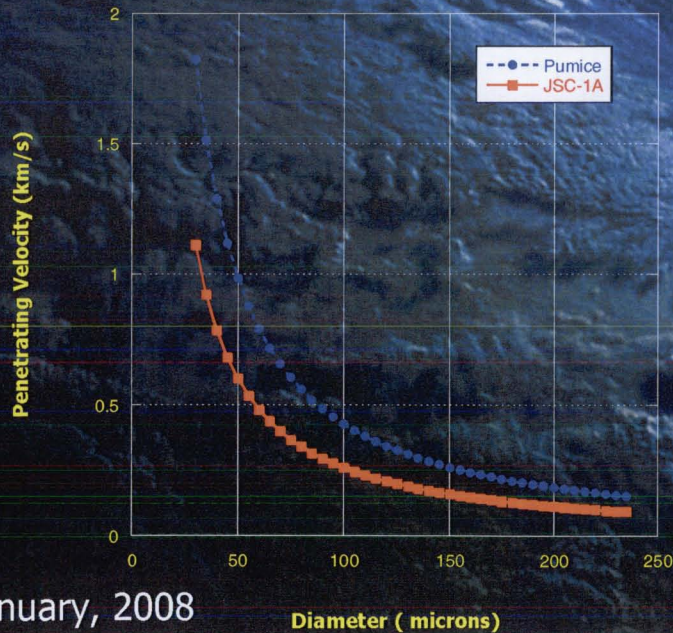
K_1 is a constant (0.54)

$$t = K_1 \rho^{1/6} m^{0.352} V^{0.875}$$

ρ is the mass density of the ejecta
(1.3 g/cm³ for pumice: 2.9 g/cm³ for JSC-1A)

M is the mass of the ejecta particle

V is the ejecta velocity required to penetrate the aluminum foil of thickness t



Target	Incident Projectile Velocity (km/s)	Peak Ejecta Velocity (m/s)	Mean Regolith Particle Diameter (microns)	Penetration Threshold velocity (m/s)
Pumice	2.5	600	60	988
Pumice	3.78	907	60	988
Pumice	5.18	1243	60	988
JSC-1A	2.45	588	188	127
JSC-1A	4.3	1032	188	127
JSC-1A	5.17	1240	188	127

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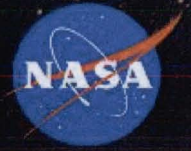
Diameter (microns)

Summary



- **AVGR used to impact 0.29g Pyrex spheres with Regolith simulant targets**
 - **Pumice, JSC-1A**
- **Impact Velocities ranged from 2.45 to 5.18 km/s**
- **Peak ejecta angles varied with target material:**
 - **Pumice - 38°**
 - **JSC-1A - 28 ° and 42° to 43°**
- **Previous work by Cintala and Yamamoto found:**
 - **Cintala found peak ejection angle ranging from 38° to 55°**
 - **0.8 – 1.92 km/s spherical Al impacting coarse-grained sand**
 - **Yamamoto found peak ejection angle of 30°**
 - **Staple-shaped Cu projectile**
 - **243 to 272 m/s**
 - **soda-lime target**
- **Penetration equations indicate**
 - **Pumice ejecta penetration threshold is 988 m/s**
 - **JSC1-A ejecta penetration threshold is 127 m/s**
- **Experiment to measure ejecta velocity is needed**

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Back up slides

January, 2008



Cintala

Spherical Al particles
0.8 to 1.92 km/s
4.76 mm diameter
Coarse-grained sand
1-3 mm diameter
Peak ejection angle between
38° and 55°

Yamamoto

Staple-shaped Cu projectile
243 to 272 m/s
Soda-lime target
220 μm diameter
Peak ejection angle 30°