Ground-Truthing Regolith Composition of the Lunar South Pole Using Small Penetrators

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Abstract. Penetrators allow access to the regolith subsurface that is largely unaltered by recent surface effects, while avoiding the need for complex and expensive landing and excavation equipment. Primary mission objectives for exploring the Lunar South Pole in this manner are to confirm the presence of water, particularly the permanently shadowed craters in that region, and perform an elemental analysis of the host rock or regolith of the Lunar South Polar Aitken basin. Secondary objectives include determination of the density, thermal properties, and RF attenuation of the local regolith, which are important for future lunar missions, particularly more mobile and complex rover missions. Penetrators must survive the large shock loading on impact; up to hundreds of thousands of times the force of gravity. Extensive testing is underway, as this is currently the only way to reduce the technical risk of the penetrator method of in-situ planetary exploration, particularly at the intended impact velocities where robust models of impact dynamics are not available. A small penetrator system is under development, weighing less than one kilogram, with ongoing tests performed using rapid turn-around and low-cost apparatus to refine penetrator geometry, screen electronics and develop the necessary sensors.

INTRODUCTION

Even before the dawn of spaceflight, it was hypothesized that the Lunar poles may possess water and other ices (Urey, 1952). The Clementine (Nozette et al., 1996) and Lunar Prospector (Feldman et al., 1998) spacecraft made tentative detections of hydrogen in the lunar regolith during the 1990s. However, radar analyses by ground-based facilities (Stacy, 1997; Campbell 2003) have not detected prominent signs of water ice, as they have in the polar regions of Mercury (Slade et al., 1992).

The heavy shadowing in both polar regions obscures both photography and passive spectral measurements, especially for the floors of basins and craters (Byrne , 2003). In-situ measurements are required to confirm the inferred regolith constituents arising from remote sensing data, at and below the surface.

Missions to ground-truth the regolith composition at the South Pole of the moon have been proposed multiple times since the first experimental results were interpreted as indicating the presence of water. Most of the planned missions involve landing a rover (Duke, 2002; Deans, 1997; Stooke, 2003) equipped with digging or drilling equipment to scout for water. An alternative method to carry the requisite instrumentation to provide ground-truth analysis of this type is to use penetrators, as has been considered in some detail by Russian researchers (Galminov et al., 2001).

Penetrator instruments offer an economical and powerful means of surveying the elemental composition of the Lunar South Pole Aitken Basin and other difficult to reach areas of the moon. Once firmly implanted and coupled to the host rock or subsurface regolith, an elemental analysis may be conducted via, as will be examined, evolved gas analysis and solid-state XRF spectroscopy using a radioactive source. Issues of this technique are discussed here.
Penetrators can serve two functions in planetary exploration; penetrometry and instrument emplacement. Penetrometry is the measurement of force, deceleration, velocity and/or depth during penetration to derive mechanical and/or structural information concerning the target. Historically, these measurements can be opportunistic, and have been common on both soft and hard lander missions including Surveyor, Luna, Apollo, Venera, Vega and Huygens (Ball and Lorenz, 2001).

Penetrators used as carriers for instrument emplacement serve to deliver payloads to the surface or subsurface of solid bodies. For in-situ measurements on the sub-surface of solid bodies throughout the solar system, penetrators provide unique advantages. Emplacement of instruments by penetrators provides strong mechanical coupling to rock, isolation from noise (mechanical and EM), and insulation from diurnal temperature variations (Meyer et al., 1996). Despite the recognised advantages and much interest in penetrators for planetary exploration, the lack of successful demonstration missions hampers their widespread use. Missions, past and future, using penetrators for payload delivery for sub-surface material analysis include Mars96, DeepSpace-2, Rosetta Lander, MUPUS PEN and Lunar-A (Ball and Lorenz, 2001).

While the two functions of penetrators are not mutually dependent, they can often overlap. The approach reported here is to develop a payload delivery penetrator which includes a penetrometer among its instruments. The driving force for penetration is free-fall impact, resulting in a simplified hard-lander for the exploration of planets, asteroids and comets. The penetrometer instrument is also used during testing to determine impact forces for optimizing the penetrator structural design.

**LUNAR ICE**

**Spatial Distribution**

Lunar ice can exist within permanently shadowed regions, predominantly crater interiors, as the Moon's obliquity of 1.5º, stable for the last two billion years (Ward, 1975), shelters them from direct solar heating near the poles (Watson, 1961; Arnold, 1979). Some argue that even within the so-called cold traps, impact bombardment, scattered sunlight, sputtering by ions (Lanzerotti et al., 1981), local interstellar Lyman A radiation (Morgan and Shemansky, 1991), and thermal emission would accelerate the evaporation of hydrogen or water ice at the surface, but models of cold trap conditions imply temperatures permanently below the stability point of water or even other ices (Watson, 1961; Vasavada, 1999; Ingersoll, 1992; Crider, 2003). A steady state between losses and new hydrogen implantation is implied by several workers. Estimates of the area effectively sheltered total between 18500 and tens of thousands of square kilometres (Margo, 1999).

**Stratigraphy**

The constituent form of the hydrogen in the regolith is unclear, though water's low vapour pressure (Estermann, 1955) and the returned radar profile makes it a likely bearer (Nozette et al., 1996). Three structures - grains with solar wind-implanted hydrogen (Starukhina and Shkuratov, 2000), hydrous minerals (Cocks et al., 2002), and interbedded thin sheets of ice (Campbell et al., 2003) - imply different depositional histories. Hydrogen is delivered to the poles via ballistic migration (Butler, 1997) or directly by meteoroids. Adsorbed hydrogen could reflect implantation of solar wind particles, outgassing and sputtering (Arnold, 1979), while hydrous minerals would be the result of slow reactions with anhydrous minerals in the regolith (Cocks et al., 2002). More coherent bodies of ice may reflect a cometary impact. Regolith gardening, which may have produced a "sealing" mechanism via diffusion (Crider and Vondark, 2003), would produce a distribution somewhat between the grain and layer scenarios.

The findings of (Feldman et al., 2001) imply that excess hydrogen - relative to a typical surface solar wind-implanted reservoir of 146 wppm (Haskin and Warren, 1991) - is present, buried beneath a regolith layer of indeterminate depth (Feldman et al., 1998). Assuming that regolith in the South Pole-Aitken Basin region is similar to that sampled elsewhere, a number of factors would control the minimum depth of excess
hydrogen (or ice): the thermal conductivity of the local regolith, diffusion of hydrogen, and heat flow from the Lunar core, among others. Estimates taken from considerations of these factors vary, but a hydrogen excess seems likely within the upper half-metre. (Crider and Vondrak, 2003) observe the saturation mass of water ice in regolith at 3.7%.

REGOLITH PROPERTIES

Composition

Lunar regolith is a heterogenous and locally varying mixture of five particle types: "mineral fragments, pristine crystalline rock fragments, breccia fragments, glasses of various kinds, and the unique lunar constructional particles called agglutinates" (McKay et al., 1991). Nearly all of these constituents measure less than 250 microns in size, with an average ~70 microns. Few rock fragments larger than 250 microns were found in most sampled regolith. The first two centimetres of regolith represent a finer fraction with very low thermal conductivity - 1.5 x 10-5 W/cm2 - while both density and thermal conductivity increase in the first half-metre, up to 1.05 x 10-4 W/cm2. Regolith can vary with topography and age, but its properties in a cold trap, where temperatures below 110 K would permit ice to remain stable for a billion years or more (Vasavada et al., 1999), are poorly constrained. The structure of agglutinates, the most dominant particle type in many regolith samples, is elongated, and most concomitant regolith properties vary laterally. We conjecture that any possible ice abundance is likely to reflect this heterogeneity.

One of the key in situ measurements in relation to delivery of water by comets is the maturity of the regolith. As regolith would serve to protect ice from desorption, sputtering, impact loss and evaporation, the properties of any shielding layer is a key parameter in determining the ice's age and possible longevity. The resurfacing rate from gardening has been variously estimated between 10 and 50 cm per 500 million years (Killen, 1997; Langevin, 1977; Gault, 1974). The age of regolith can be assessed in several ways, but two reasonably reliable indicators are the abundances of zinc and single-domain iron (McKay, 1991). As the impact velocity and resultant large temperature increase are expected to liberate hydrogen, thus strongly reducing FeO in the regolith, a simple iron abundance measurement may be an unreliable indicator. A low abundance of zinc, however, caused by its volatilization and escape in geologic time, can be correlated with age (McKay, 1991).

PREVIOUS PENETRATOR MISSIONS

To date two planetary exploration missions have flown payload carrier penetrators using free-fall impact, though neither was successful. Both missions were intended for Mars impact following considerable deceleration in the Martian atmosphere to below 300 m/s.

DeepSpace-2 consisted of two penetrators which were to impact at up to 300m/s, each about 100mm long and 40mm diameter. Designed to impact with the penetrator (the fore-body), a larger surface component did not penetrate (the aft-body), but remained attached to the penetrator by an umbilical and housed the communication system and meteorological sensors (See Figure 1). Since the fore-body decelerates over some depth of penetration its deceleration rate is lower, up to 300,000m/s² compared to up to 800,000m/s² for the aft-body. The penetrator carried sensors to measure acceleration, temperature and to detect water, and was designed to penetrate to a depth of 300 to 2000mm (Smrekar and Gavit, 1998). Unfortunately no signal was received from either of the two DeepSpace-2 penetrators after their deployment from the carrier spacecraft, prior to Mars atmospheric entry, and the failure analysis was inconclusive.
The Mars 96 mission carried two larger penetrators with a mass of 45kg each, similarly with a penetrator section and a surface component (Figure 2). Fore-body dimensions approximately 400mm long and 80mm in diameter allowed it to carry far more instruments than DeepSpace-2, including an Alpha/Proton Spectrometer, an X-Ray Spectrometer, a Neutron Spectrometer, seismometers, an accelerometer and temperature sensors. The aft-body was designed to partially penetrate the soil, submerging a Gamma Ray Spectrometer and additional temperature sensors. At an impact velocity of 80m/s, the deceleration rates are over 5,000m/s² for the fore-body section. Unfortunately the Mars 96 mission suffered a launch vehicle failure before achieving Earth orbit. (Surkov, 2001)
Currently in the cruise phase of its missions, the Rosetta lander carries a harpoon to secure it to the surface of the target comet. The harpoon is not a free-fall penetrator, but will be shot from a gas cylinder to impact the cometary surface at 40 to 60m/s, and penetrate to a depth of between 0.1 and 2.5m. It is equipped with a temperature sensor and accelerometer, and used for penetrometry and heat flow measurements (Kömle et al., 1997).

Under development for some years, the “Lunar-A” mission to the moon will carry two or three penetrators. These penetrators have a mass of about 13kg, not including components detached before impact such as a deceleration motor to slow the penetrator to below 300m/s at impact, and an attitude control system to maintain the correct orientation at impact (Mizutani, 1995). No aft-body is required for lunar penetrators as the lunar regolith is relatively transparent to radio waves (Carrier et al., 1991). The impact deceleration will be around 100,000m/s². The primary goal of the Lunar A penetrators is to create a seismic network and to make heat flow measurements.

**MISSION ANALYSIS**

*Mission Options*

Penetrator mission target bodies can be broken down into three categories: small bodies (e.g. asteroids and comets), large bodies with atmospheres (e.g. Mars), and large bodies without atmospheres (e.g. Earth’s Moon). The three different targets require different approaches to penetrator design.

Small bodies with low gravity present a range of possible impact velocities, depending on the deployment methods. Low impact velocities will result if the penetrator is deployed from a rendezvous spacecraft, whereas deployment from a spacecraft on a flyby trajectory could cause prohibitively fast impacts up to tens of kilometres per second. For large bodies with atmospheres, the penetrator can be slowed by air resistance to an impact velocity of a few tens to a few hundreds of meters per second. For large, airless bodies such as the moon the penetrator must carry deceleration rockets, as with the Lunar-A mission, or else have the ability to survive impact at velocities over 1,000m/s.

With many lunar orbiter missions planned in the next decade, ahead of lander and rover missions, there are potential piggy-back opportunities for small, simple penetrators. A related mission is already under development, carried on the Chandrayaan-1 spacecraft, however the Chandrayaan impactor will not carry instruments to survive the impact and will return little data on the composition or impact dynamics of lunar regolith.

*Baseline Mission*

A penetrator deployed from a lunar orbiter in a 100km circular orbit requires less than 30m/s velocity change to intersect the lunar surface. This could be produced without thrusters by the deployment system from the carrier spacecraft, allowing for a much simplified penetrator design. Impact would occur at approximately 1750 m/s and a very low angle of incidence (See Figure 3). Despite the apparent difficulties involved in implementing such a mission the simplicity, available opportunities and potential scientific return warrant a detailed investigation. The three primary challenges are identified as impact forces, impact angle, and regolith alteration at impact.
Figure 3. Piggy-back Lunar Impactor Trajectory

Impact Force Analysis

Although the baseline mission defines the impact velocity requirement, the acceleration rate requirement is more difficult to calculate. Below 1000 m/s it is acceptable to treat the penetrator as a rigid body in impact dynamics calculations, while above 3000 m/s the impact can be treated as a fluid interaction. In the intervening range the effect of the penetrator strength and the magnitude of projectile deformations introduce considerable complexities in modelling (Backman and Goldsmith, 1978). There is reason to believe, however, that penetrators will survive impacts at these velocities. Experiments done with cylindrical steel impactors and limestone targets at velocities up to 1700 m/s show penetration depths between 0.5 and 1.5 meters depending on impactor size (diameters between 7 and 25mm) (Frew et al., 2001). The impactors in these tests had a length to diameter ratio (L/D) of ten, and while most impactors survived intact, significant bending was observed when impact velocities exceeded 1700 m/s. It is expected that penetrators with lower L/D will survive intact, and testing will be required in this regard.

In order to proceed with the analysis it is necessary to make assumptions regarding the impact behaviour, which can later be tested at the required impact velocities in lunar soil stimulant and/or terrestrial analogues. A calculation of the impact acceleration was performed using rigid body impact equations, with necessary assumptions about the mechanical properties of lunar soil and the geometry of the penetrator. The penetrator geometry assumes an ogive nose cone and an L/D of ten, while soil properties are assumed to be the same as limestone, as described in (Frew et al. 2001). Although worst case assumptions are made throughout, this analysis should be interpreted as a starting point to guide the design until testing can be done to verify the impact force.

Experiments performed with cylindrical steel impactors and concrete and limestone targets at impact velocities up to 800 m/s exhibited near-constant deceleration rates, to within 50%, though higher velocity impacts show greater non-constant deceleration than low velocity impacts (Frew, 2001; Forrestal, 1994). The deceleration force can be calculated using equations (1) and (2) (Forestal, 1994):

\[ F = \pi a^2 (R + N \rho V^2) \]  
\[ N = \frac{8\psi - 1}{24\psi^2} \]

where \(2a\) = projectile diameter; \(\psi\) = calibre-radius-head, such that \(\psi = s / 2a\), where \(s\) = ogive radius; \(\rho\) = target density; \(R\) = target resistance parameter; and \(V\) = strike velocity.
The similarity to aerodynamic drag is apparent. The target resistance parameter can only be determined experimentally for each target, based on measurements of the final penetration depth. The target resistance for this geometry is:

\[ R = K + k \frac{2a_0}{2a} \]  

(3)

where \( 2a_0 \) is 25.4mm, the diameter of the reference impactor used in deriving these equations, and \( K = 607\text{MPa} \) and \( k = 86\text{MPa} \) were found from test to fit the data for impacts in limestone (Frew et al., 2001).

For lower velocity impacts (a few hundreds of m/s) the target resistance term of equation (1) dominates the penetration process (Forrestal et al., 2003), and thus this method of determining the deceleration rate is only useful once penetrometry data is available. For high velocity impacts over 1000m/s the velocity term of equation (1) dominates. Although the target resistance of unconsolidated lunar regolith is expected to be lower than that of limestone, the velocity term is independent of target strength.

To arrive at a worst case situation the smallest foreseeable penetrator diameter was used, with \( 2a = 30\text{mm} \), giving a target resistance of 680MPa. Although spherical, parabolic and blunt nose geometries are being considered, a short ogive shape was used to match the penetration model, and a 45mm ogive was chosen for these calculations (\( \psi = 1.5 \)). Preliminary penetrator design calls for 50% steel alloy and 50% glass-epoxy matrix (electronics packaging), giving a mass of 1.0kg. Best estimates of bulk density of lunar regolith indicate increasing density from around 1400 kg/m\(^3\) in the top 15 cm to around 1800 kg/m\(^3\) below 100cm, (Carrier et al., 1991) compared to around 2300 kg/m\(^3\) for the limestone (Frew et al., 2001). The higher value from lunar regolith was used. The calculated deceleration force is shown in Table 1, resulting in an impact acceleration rate of \( 4 \times 10^6 \text{ m/s}^2 \).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
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<tbody>
<tr>
<td>Shank Diameter</td>
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</tr>
<tr>
<td>Ogive Radius</td>
<td>m</td>
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</tr>
<tr>
<td>Penetrator Length</td>
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</tr>
<tr>
<td>Steel Mass</td>
<td>kg</td>
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<tr>
<td>Epoxy Mass</td>
<td>kg</td>
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</tr>
<tr>
<td>Target Resistance</td>
<td>MPa</td>
<td>680</td>
</tr>
<tr>
<td>Target Density</td>
<td>kg/m(^3)</td>
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</tr>
<tr>
<td>Impact Velocity</td>
<td>m/s</td>
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</tr>
<tr>
<td>Impact Force</td>
<td>N</td>
<td>4018325</td>
</tr>
<tr>
<td>Acceleration Requirement</td>
<td>m/s(^2)</td>
<td>4014310</td>
</tr>
</tbody>
</table>

**Impact Geometry**

Impact incidence angles less than 30 degrees are expected due to the likely impact orbit trajectory. Depending on the deployment mechanism from the carrier spacecraft the attack angle may also be considerable. Impact experiments conducted for the Lunar-A development indicate that “both the oblique incidence and a finite attack-angle will affect the penetration dynamics significantly because rotational torque will be applied to the penetrator at impact and during the course of penetration” (Gold et al., 1977).

Although impact accelerations were not recorded in the testing for the Lunar-A mission, no significant difference in penetration path length was observed between normal and oblique impacts at impact incidence angles down to 45 degrees and velocities between 80 and 200m/s. From this it appears likely that
deceleration forces are not affected significantly by the impact incidence angle; however this will need to be verified at higher impact velocities and lower incidence angles.

Testing for the DeepSpace-2 mission with ogive nose geometries caused significant deflections in the penetration path, resulting in the penetrator exiting the side of the penetration target at a low incidence angle (Lorenz and Shandera, 2001). With low initial incidence angle there is the possibility of skipping on the surface or re-emerging from the regolith. While this would be an interesting mechanism to study, and may lead to hard new landing techniques (so-called “litho-braking”), it is undesirable for the penetrator where the aim is to become imbedded in the regolith. Two possible solutions to this are non-symmetrical nose geometry or an angle of attack offset to direct the penetrator down into the regolith, though neither technique has been tested as yet. Similar asymmetric stabilizers have been suggested for vertically impacting penetrators to achieve a horizontal deflection and avoid penetration to too great a depth (Galimov et al., 2001).

Another finding of the Lunar-A testing was that the penetration path length becomes shorter with increasing attack angle, with a reduction of around 50% at an attack angle of 10-degrees (Shiraishi et al., 2000). It appears, therefore, that the penetration path length is dependent on the flight path cross-section of the penetrator, which is around double at 10 degrees attack angle based for a cylindrical penetrator with L/D of 7. It follows that the attack angle of the penetrator should be kept to a minimum by either the carrier spacecraft deployment mechanism or an attitude control system that acts during the ballistic descent phase. A lower L/D will also reduce this effect, at the cost of decreasing the ballistic coefficient. Further tests of the effect of attack angle and L/D are planned for the higher impact velocities that are required for our mission.

The low incidence angle is also likely to place the penetrators in the leading edge of hills or crater walls, which may not be the ideal location to look for water ice. More detailed mission analysis is required to determine the optimum landing sites corresponding to the lowest delta-V requirement (thus the lowest incidence angle) that allows access to a permanently shadowed crater floor.

Communications

Based on tests of the permittivity of various Apollo lunar soil samples at 450MHz, it was concluded that “radio waves would generally penetrate more than 30 wavelengths before being attenuated by 8.6 dB (1/e in voltage), and even in the case of the most absorbent soils found in some mare regions (Apollo 11 site) the attenuation length would be 10-15 wavelengths” (Gold et al., 1977). As a result, radio communications on the lunar surface need not be by direct line-of-sight (Carrier et al., 1991), making it unnecessary to have an aft-body section for the penetrator antenna, provided that the regolith attenuation is included in the link calculation and penetration is less than 10 wavelengths, which for the expected UHF system is around 5 meters. The presence of water and possible differences in composition of the south polar regolith may significantly increase this attenuation, and a large link margin, around of 20dB, is desirable for all penetrators on the first mission.

Regolith Alteration at Impact

Temperature

Kinetic energy from the impact event is transformed by various means into thermal energy, raising the temperature of both the penetrator and the surrounding regolith. Small amounts of energy may also be absorbed in the excavation of a crater, and the in vaporization of regolith volatiles.

A treatment of temperature changes induced in the penetrator body at velocities of a few hundred meters per second is given in Lorenz and Shandera (Lorenz and Shandera, 2002), indicating that the heating pulse accounts for 25 to 50% or the kinetic energy. If the same proportion of heat transfers to the penetrator at the impact velocity of 1750m/s there is the potential for the entire steel penetrator, with a thermal capacity
of 450 J/Kg/K, to reach temperatures above the melting point (1650K)! The survival of penetrators at similar test velocities (Frew et al., 2001) indicate that this does not occur.

At these high velocities it is likely that more energy will be dissipated through shock and acoustic wave propagation and ablation than is the case at lower impact velocities. When it comes to rest, the high temperature areas of the penetrator will be a jacket of ablated material and regolith, expected to be at around the melting temperature, and the deformation region at the nose of the penetrator. The impact tests into limestone that were previously discussed showed a mass loss due to erosion (ablation) of the tip of the penetrator of up to 10% at impacts around 1700m/s (Frew et al., 2001).

It is possible that the potting material will insulate the electronics for some time while heat is conducted away through the surrounding material, though alternatives to lead-tin solder may be required if the temperature exceeds the low melting point to this eutectic. Analysis results shown in Table 2 indicate that conversion of only 10% of the impact energy to heat in the penetrator will cause the bulk penetrator temperature to rise by over 300 Kelvin. This is an important issue to resolve, and is a high priority in the immediate test series.

### Table 2. Impactor Heating

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact Velocity</td>
<td>m/s</td>
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</tr>
<tr>
<td>Impactor Mass:</td>
<td>kg</td>
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</tr>
<tr>
<td>Impact Energy</td>
<td>J</td>
<td>1531250</td>
</tr>
<tr>
<td>Energy to heat</td>
<td></td>
<td>10%</td>
</tr>
<tr>
<td>Mass of steel</td>
<td>g</td>
<td>0.785</td>
</tr>
<tr>
<td>Mass of Epoxy</td>
<td>g</td>
<td>0.216</td>
</tr>
<tr>
<td>Thermal capacity - steel</td>
<td>J/kg/K</td>
<td>420</td>
</tr>
<tr>
<td>Thermal capacity - Epoxy</td>
<td>J/kg/K</td>
<td>800</td>
</tr>
<tr>
<td>Total heat capacity</td>
<td>J/K</td>
<td>502</td>
</tr>
<tr>
<td>Temperature change</td>
<td>K</td>
<td>305</td>
</tr>
</tbody>
</table>

**Liberation of Atomic Hydrogen**

Solar wind hydrogen is also released at impact, and will chemically reduce the local FeO to produce water and native iron (McKay, 1991). Although the abundance of solar wind hydrogen is expected to be lower in the permanently shadowed craters, the relocation of regolith during meteorite impacts may produce levels of solar wind hydrogen comparable to the levels as seen in the Apollo samples, 146 wppm (Haskin and Warren, 1991), at least in local areas. Positive detection of water must therefore be in excess of the upper limit expected to be produced in this process, which is difficult to achieve using the proposed evolved gas analyzer (see below) as it does not provide accurate quantitative readings due to the lack of consistence sample collection and containment. The heat of impact is expected to release all the contained volatiles, producing a dramatically higher reading than dry areas of the moon that is discernable with the proposed instruments. The deployment of multiple penetrators becomes important now in validating this data, by providing comparative readings from areas that are in sunlight, directly exposed to the solar wind but unlikely to contain water.
INSTRUMENTS

Evolved Gas Analyser

Detection of water is proposed using an evolved gas analyser, incorporating an absorption spectrometer, making use of the heat of impact to vaporize the water contained in the local regolith. A similar instrument was implemented on DeepSpace-2 for detecting water on Mars (Blue, 1999). The detection spectrum will be centered on 1.37um, the absorption line for water, using a solid-state detector and either multiple discrete frequency diodes or a tuneable diode laser. Additional absorption bands may be targeted for detection of other volatiles, particularly hydrocarbons.

The water vapour must be brought into the detection chamber free of particulate matter so as not to block the light path. During impact it is possible that external openings will be closed by the impact forces or blocked with debris (both crushed regolith and ablated penetrator material). This possibility is reduced by having rear-facing, internal apertures and short, narrow channels or porous material leading to a small detection chamber. The geometry of one aperture is illustrated in Figure 4, though a number of apertures will be used, to provide redundancy. The front section of the penetrator is likely to deform at impact, and the apertures must be behind the deformation zone. A more complex containment mechanism was implemented on DeepSpace-2 (Blue, 1999), involving collection of a sample with a drill and sealing with a pyrotechnic device, however the higher impact velocity in our scenario makes this unfeasible.

As the proposed containment system is un-sealed, it is necessary to take measurements immediately following impact as the water vapour may dissipate rapidly. This is alleviated somewhat by the sample collection geometry, which causes hard-packed regolith to create a seal in the main cavity entrance. The integrity of this seal is unknown, however, and it may be impossible to simulate due to our current ignorance of the south pole regolith properties and the current lack of lunar regolith simulate with accurate mechanical properties.

![Figure 4. Sample collection and volatile containment concept (not to scale)](image)

X-Ray Fluorescence

Physical Mechanism of XRF
X-ray fluorescence spectroscopy (XRF) is universally recognized as a very accurate method of measuring the atomic composition of a material by irradiating a sample with high energy photons such as x-rays or gamma rays and observing the resulting x-ray fluorescence emitted by the sample. The technique is only applicable to qualitative identification of elements having atomic numbers greater than oxygen (> 8). The process begins by exposing the sample in question to a source of x-rays or gamma rays. When a primary x-ray from a radioactive source strikes a sample the x-ray is either absorbed by the atom or scattered through the material. If absorbed by the atom, the x-ray energy is transferred to an inner electron via the Photoelectric Effect. If the primary x-ray had sufficient energy, electrons are ejected from the inner shells (typically K, L) creating vacancies; these vacancies yield an unstable condition for the atom. The atom returns to a ground state electronic configuration by transferring electrons from the outer shells (M, N, etc) to the inner shells and, in this process, gives off a characteristic x-ray whose energy is the difference between the two binding energies of the corresponding shells (Skoog, 1997).

Since each element has a unique set of energy levels, each element produces x-rays at a unique set of energies. This allows a non-destructive measure of the elemental composition of a sample using appropriate solid-state hardware such as a CCD-type detector.

**Applicability**

Particular focus of XRF technology has turned to mining and mineral characterization activities. Fluorescence can be produced by primary excitation sources like alpha particles, protons, or high energy electron beams. Laboratory-based instruments such as the Phillips PW2404 produce XRF via x-ray tubes with accelerating voltages of 60 kV at 50 mA. This is impractical when applied to penetrating instruments, which are planned to be on the order of several inches in size.

Portable handheld XRF spectrometers have become widely available in recent years. These devices are typically several inches in size and offer field geologists and mining engineers’ in-situ analyses of rock and soil samples. These instruments utilize radioactive sources as the method of excitation. Several isotopes can be used for portable XRF applications including $^{109}\text{Cd}$, $^{57}\text{Co}$, $^{55}\text{Fe}$, $^{241}\text{Am}$ and $^{153}\text{Gd}$. The isotope or combination of isotopes used for any application is selected based on the ability of the selected isotope(s) to induce fluorescence of the element being measured. A great deal of literature is available on this subject. The technology has now evolved to the point where Pb, Cd, Fe, Ni, Cu, Zn, Mn, Co, Ti, V, Cr, Ag, and Sn are routinely detected using portable, handheld devices (of course this list is not exhaustive). Since the method is fast and non-destructive to the sample it is the choice-method for field applications and industrial monitoring of controlled materials. Some commercial handheld x-ray fluorescence spectrometers are listed in Table 3.

<table>
<thead>
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**Detectors**

Most modern laboratory XRF spectrometers depend on scintillation crystals with collimating lenses. Scintillation crystals respond to radiation by emitting a flash of light proportional to the energy of the photon that is stopped in the crystal. CsI and NaI are the most common compounds used in this application. Scintillation crystals can be very efficient due to the size of crystals that can be grown, yet their resolution is relatively poor. Photomultiplier tubes are used to convert the light emitted by these detectors into
electrical pulses which can then be processed. Temperature drift, size, and power requirements are the main obstacles to overcome in designing systems that use these detectors, which are not feasible for penetrator-type instruments. Large semiconductor crystals may also be prone to shattering at the impact velocities encountered during emplacement of the penetrator.

**Potential (Energy Dispersive) Solid-State Detectors for Penetrators**

Energy dispersive solid state detectors offer the best option for penetrator instrument detectors since they are widely used and very robust. These detectors convert incident photons directly to electrical pulses. Solid state detectors are fabricated from a variety of materials including germanium, silicon, cadmium telluride, mercuric iodide, and cadmium zinc telluride. The best detector for a given application depends on several factors. For instance, germanium detectors have the best resolution, but require liquid nitrogen cooling which makes them impractical for portable penetrator applications. Silicon, on the other hand, needs no cooling, but is inefficient in detecting photons with energies greater than a few tens of keV. In the last few years, detectors fabricated from high Z semiconductor materials have gained acceptance due to their ability to operate at room temperature and their inherently high quantum efficiencies. Detectors made from cadmium telluride, mercuric iodide, and cadmium zinc telluride are also routinely used.

Cadmium Zinc Telluride (CZT) is a wide band gap semiconductor that is fabricated into detectors that provide two key advantages for use in portable instrumentation: (1) the high density of the crystal provides excellent stopping power over a wide range of energies and (2) the ability to operate at room temperatures without the need for liquid nitrogen cooling allows the construction of compact devices. The resolution of CZT is intermediate between scintillators and germanium devices. Recent advances in the understanding of crystal growth and detector fabrication using CZT hold the promise of providing low cost high resolution detectors for small penetrating instruments. CZT detectors can be fabricated into a variety of shapes and sizes making it possible to produce detectors capable of meeting the requirements of a wide assortment of possible conditions encountered during coupling the penetrator to the subsurface soil upon impact. Similar studies on the effects of impacting electronic components at high-velocity are currently underway by Heliocentric Technologies Inc.

**A Proposed Concept**

Figure 5 shows the typical construction of an energy dispersive x-ray fluorescence spectrometer using a radioactive source. Although this design is mainly found in larger laboratory-based instruments, use of an energy dispersive solid-state detector (such as those found in commercial handheld XRF devices) eliminates the need for cryogenic cooling for a penetrator instrument. Multi-channel analyzer electronics need not be incorporated into the penetrator instrument.

![Figure 5](source: Princ. Of Instrumental Analysis, 5ed, Skoog, Holler & Nieman; ISBN-0030020786)
A possible design geometry implementing an XRF spectrometer in a subsurface penetrator instrument is sketched in Figure 6. This design does away with the need for open-space cavities, due to the potential of catastrophic deformation of the penetrator or its components during an estimated impact of 1750 m/s. This is feasible given the components used are all solid devices. Fluoresced x-rays scattered back to the solid-state detector would be the detected signal as with Figure 1.

Advantages & Conclusions of Applying XRF to Penetrators

Penetrator instruments have the ability to utilize (and improve on) currently available handheld XRF technologies. There are distinct advantages:

- The small physical dimensions of the penetrator are comparable to current handheld XRF spectrometers
- The geometry required to construct a working XRF spectrometer is feasible within the penetrator package
- Power & battery requirements of a portable handheld XRF spectrometer can be scaled to a similar degree for a penetrating instrument, giving many hours of data acquisition
- A solid calibrated radioactive source can be used as the excitation medium
- Current terrestrial detectors can detect $\gamma$-rays in the range 10 keV – 2 MeV; this can be further optimized
- All components are fully solid-state and can be engineered with no open cavities, allowing for a high probability of the electronics surviving the impact
- The penetrator itself can serve only as the data acquisition front-end: all analysis, interpretation, and reduction can be done offline allowing a minimum amount of electronics in the package
• Terrestrial technologies are proven, widely used, and ‘off-the-shelf’ requiring little initial R&D investments in their development and testing

• In-situ elemental analyses of lunar regolith or rock can be done using several penetrating instruments; this gives the possibility of surveying large regions of planetary bodies at once

• The energy dispersive XRF spectrometer concept proposed here requires no moving parts in the excitation and detection components of the spectrometer

• The absence of collimators and a crystal diffractor, as well as the closeness of the detector to the sample can result in a many-fold increase in energy reaching the detector

• A basic XRF penetrator design is simple and cost-effective: it need only consist of (a) the radioactive source, (b) a solid-state energy dispersive detector, (c) electronics for radioing measurements, (d) battery pack.

• This type of instrument can potentially be used on numerous other planetary bodies aside from the Moon (comets, asteroids, other Solar System planets, etc) to characterize their elemental abundances for Z > 8.

Complimentary Measurements

RF Attenuation

As mentioned previously, regolith samples from the Apollo missions showed low RF absorption at the UHF wavelengths, however possible compositional differences in the regolith at the south pole may have higher attenuation.

It is proposed that the RF attenuation will be indicative of regolith composition, both spatially and quantitatively. The availability of high-resolution topographical information, derived from Lidar instruments to be flown on various upcoming missions, will allow modelling of the RF path to reveal the location and thickness of regolith along the RF path to the receiver. A scan of the surrounding hills and crater walls can be performed by both earth based antennas, using the rotation of the moon, and from spacecraft in lunar orbit. Accurate location of the penetrators landing sites is required, using traditional techniques based on a combination of descent tracking on the earth-side of the moon and accurate orbit propagation. Multiple penetrators should be able to provide wide area coverage with much overlap, allowing a 3-dimensional map of attenuation to be generated, revealing the extent of various deposits.

Modelling of attenuation factors and optimum RF frequencies is necessary to quantify the science value of this experiment; however this may not be possible until the regolith composition is determined more accurately, for example by the XRF aboard the penetrator.

One issue remaining to be solved in the implementation of this technique is creation of an omni-directional, or well calibrated, antenna pattern that will not distort at impact. A calibrated but non-omni-directional antenna pattern will require knowledge of the resting attitude of the penetrator, which is not provided by the currently planned suite of instruments.

Penetrometry

The density of lunar regolith, as sampled by the Apollo and Luna missions, has been found to be remarkably uniform; the uppermost regolith ranges from 1.3 to 1.5 g/cc³, generally increasing to 1.8 g/cc³ at depths up to 3 m (Carrier et al., 1991). Interestingly, the density profile of regolith grows less coherent with depth at some of the sampled sites. Hydrogen migrating to the poles from cometary impacts may form layers, although recent radar imaging implies these sheets should be no more than centimetres thick.
We propose that a sufficiently sensitive accelerometer, sampling at a depth resolution of 0.5 mm, would be capable of measuring the density profile of the entry column to rule out such layers. If the hydrogen exists in the form of ice, a density ~0.9 g/cc³ may be expected (Cocks et al., 2002).

As mentioned previously, the deceleration is dependant almost entirely on density at the high impact velocities being considered. The small effects of target resistance on the measurements must be accepted as noise in the measurement. More significant problems arise from the unknown shock wave propagation mechanics, which are yet to be modelled. Another significant noise source is the triboelectric effect, described by (Lorenz and Shandera, 2002), caused by the change in capacitance through the system due to compression of insulated wires and components during the impact, as well as rubbing between dissimilar materials (i.e. the regolith and the penetrator).

It is thought that careful design and extensive testing can remove or significantly reduce these detrimental effects, allowing density profiling that is not possible with lower velocity impacts. This technique is deserving of further research.

**Thermal**

The regolith temperature and thermal properties are of particular interest in determining the survivability of volatiles in the theorized cold traps, as mentioned previously in this paper. As a minimum, three temperature sensors will be included in the penetrator, one near the tip, one near the tail and one in the electronics package. It is desirable that these sensors operate down to 100K, and similarly that the telemetry system be able to operate at that temperature to relay the data. As it may take months for the temperature to return to ambient following the impact, the penetrator must conserve power in order to take and relay measurements for at least three months after impact, at a very low duty cycle.

**PENETRATOR DEVELOPMENT**

**Penetrator State of the Art**

Although the acceleration design goals exceed the limits of existing technology, a review of the current state of the art shows great promise.

During the development of Lunar-A, test results indicated that “semiconductors and ICs which are plastic molded are mechanically more robust than normal space use parts and can withstand up to 10,000g environment.” (Hayashiet al., 1995) (100,000 m/s²), however no penetrator studies report results beyond this.

Another application of high shock tolerant electronics is in gun-launch systems. Development of high-g electronics for the High Altitude Research Program (HARP) was performed as early as 1960, for peak launch accelerations of the order of 2 x 10⁶ m/s² and flight velocities of 1500 m/s (Letarte and Moir, 1960). Packages removed from the target butt, although not being designed to withstand the impact force, were usually substantially intact. In many cases the transmitters would continue to operate when power was re-applied, despite peak decelerations at impact estimated to be as high as 5 x 10⁶ m/s². It was recognised that “survival of electronic packages after extreme impacts would have tremendous application, an important one being the hard landing of equipment on the moon” (Letarte and Moir, 1960), and a program was started to develop packages with impact forces in mind. Unfortunately no information has been found on the further development, and it is not known if it was continued.

A recent effort to develop gun-hardened telemetry systems for gun-launched projectiles was undertaken by the US Army under the Hardened Subminiature Telemetry and Sensor System (HSTSS) program. The circuits developed for this program are approximately 25mm in diameter, and are capable of transmitting data at rates in excess of 20Mbps.(Burke et al., 2003). Components for HSTSS were tested up to 1 x 10⁸
m/s², with system tests up to $3 \times 10^5$ m/s². An important guideline for circuit design coming out of this development is that “the key to designing a resonator that can survive extremely high-shock levels is to make it small. This reduces its total mass so that it less likely to dismount and it reduces the stress within the crystal so that it is less susceptible to breakage” (Osgood et al., 2001).

**Current Designs**

The focus of development has been on the telemetry transmitter system and accelerometer for penetrometry and impact characterization. The transmitter is based on a commercial IC containing two separate silicon dies in one plastic moulded package. One die holds the RF circuitry and the other contains a microcontroller with on-board analog-to-digital converters and all necessary transmitter interfaces for data rates up to 40kbps using frequency modulation. The transmitter frequency is defined by an external oscillator (typically a crystal), and has a wide operating range in the UHF portion of the spectrum. A block diagram of the circuit is shown in Figure 7.

![Transmitter Block Diagram](image)

Although crystal oscillators have desirable characteristics, the peak acceleration levels of the penetrator cause the electro-mechanical crystals to shatter unless they are well supported and the physical dimensions are very small. This is supported by our test results, as none of the commercial-off-the-shelf (COTS) crystals tested survived after launch and impact. Although the test series was by no means exhaustive, and further tests are planned for different crystal oscillator housings, it was considered necessary to investigate alternative oscillators that do not use crystal filters.

Tests have shown that ceramic capacitors and inductors survive high shock loads with little change in their characteristics, and it is therefore inferred that ceramic resonators could be used to replace crystals. Unfortunately none of the commercially available ceramic resonators operate in the required frequency range.

To maintain a simple, workable system at minimal expense a discrete inductor-capacitor (LC) frequency reference design is used. The disadvantage of an LC circuit is poor frequency stability, particularly with temperature, though by careful design and component selection, and with rugged mechanical construction it is possible to achieve high overall stability (Sheets and Graf, 2002). The most thermally sensitive component in the circuit is the capacitor. Temperature compensating ceramic dielectric materials, such as NP0 (C0G) available in modern surface mount capacitors, achieve +/-30ppm/°C temperature stability. If necessary, it is expected that better stability can be achieved by screening parts and by implementing additional temperature compensation and control.

The UHF transmitter frequency was selected near 450MHz. Long-term frequency drift is not considered an issue at this stage of development and receiver operation over a wide frequency range is necessary to locate
the transmitter carrier frequency for each penetrator. During testing the penetrator is expected to experience temperature changes due to firing from the launcher, in supersonic flight and at impact, causing rapid frequency changes, though these should settle after a short period. The receiver currently used for testing has a receiver selectivity of 15kHz/-6dB. It is therefore necessary to maintain any frequency jitter and short-term drift to within about 30ppm.

Accelerations during impact are recorded using a piezoelectric accelerometer. The component used during development is rated to measuring deceleration up to $1 \times 10^6 \text{ m/s}^2$. It is hoped that the sensor, or a similar piezoelectric device, can be used up to and above the required acceleration rate of $4 \times 10^6 \text{ m/s}^2$ by removing material from the actuating mass. A block diagram of the accelerometer circuit is shown in Figure 8.

![Accelerometer Block Diagram](image)

**Figure 8.** Accelerometer Block Diagram

## Test Apparatus

Testing is performed at the Columbiad Launch Services test range. Various gun launch systems are in operation at the range, all using powder propellants, offering a range of launch and impact conditions. Testing of payloads up to 60mm diameter and 4kg mass is possible, at controllable acceleration loads from 5,000g upwards and flight velocities up to 1,500m/s. An upgrade to the main launch system has recently been completed and is undergoing characterisation, with expected launch velocities up to 2,000m/s. The system also allows vertical launches into the upper atmosphere, with which it is possible to investigate atmospheric entry and penetrator glide characteristics for penetrators to planets with atmospheres. The main launcher is shown in Figure 9.

![The Columbiad Industrial Sounding System; a 10 Meter Long Powder Propellant Gun Launcher](image)

**Figure 9.** The Columbiad Industrial Sounding System; a 10 Meter Long Powder Propellant Gun Launcher (Image: Columbiad Launch Services)

A small diameter launcher based a 12-gauge shotgun barrel was used primarily for component testing and circuit development. The major equipment of the test range is shown in Figure 10, and consists of the launcher, a chronograph for measuring flight velocity, multiple yaw cards for accessing aerodynamic stability and a sand box for impact and retrieval (the sand can be replaced by other materials for impact testing). Figure 11 shows the second yaw card and the sand box during penetrator recovery following a test. The majority of markings on the yaw cards are from the sabot petals which have separated from the penetrator in flight.
The penetrator vehicle developed by Columbiad Launch Services for this launcher configuration, designated the “Gnat”, is shown in Figure 12 with the sabot petals on the main body and the rear fins clearly visible. A shotgun cartridge provides simple mounting in the 18mm gun-launcher, as shown in Figure 13. This it is a sub-calibre projectile with fin stabilisation. A full-calibre projectile was also developed, and although the lack of fins resulted in unstable flight it was still useful for component shock testing. Launch velocities for the Gnat are between 350 and 400m/s, with launch accelerations between 8.5 x10^4 and 1.1x10^5 m/s^2. No direct measurement of impact deceleration has yet been made, however the position of the impactor in the sand box has been used to determine the deceleration based on a linear deceleration profile (as mentioned previously, this is an acceptable assumption). Impact accelerations are thus calculated to vary between 1.5x10^5 and 5 x10^5 m/s^2. The variation in penetration depth is due to aerodynamic instability of the full-bore projectiles (L/D around 2.5) resulting in nearly side-on impacts.

Small circuit boards are mounted inside the Gnat projectile and then potting material is drawn in under vacuum and allowed to harden, thus supporting the components during the impact.
Attempts were made to increase the impact accelerations of the Gnat launcher to about $4 \times 10^6 \text{ m/s}^2$, to be representative of the accelerations in the proposed mission. Unfortunately the low impact velocity and small frontal area dictate high target resistance, as indicated in Equation 1. Test outcomes included penetrator ricochet (when using hardened steel), and target splitting which makes determination of the impact accelerations difficult as the accelerometer has yet to be commissioned. One test appeared to be successful, with the penetrator deflected into the target box at low velocity leaving a cavity in the sandstone target with the depth expected for a deceleration rate of $6.1 \times 10^6 \text{ m/s}^2$. The penetrator, shown post-impact in Figure 14, was made of mild steel with a conical nose (dimensions shown in Figure 15). Deformation is restricted to the nose portion of the penetrator, which is an encouraging result, though a small amount of bulging was evident in the forward end of the internal cavity. As the nose is sacrificial, only necessary to reduce impact forces and protect the electronics in the penetrator body, a new penetrator materials concept was devised. The body of the new penetrators is to be hardened by heating and submersion in an oil bath. This stiffens the body, lessening deformation that may damage the payload. The nose section remains softer, and can deform to dampen the transient shocks produced when the penetrator strikes rocks or higher density layers during the penetration event. This also reduces the likelihood of ricochet during testing.
Component Testing

Firings of the large Industrial Sounding System (60mm calibre launcher) were conducted with dummy-mass projectiles to become familiar with the operation of the range, to observe the effects observed at the target butt and to test improvements to the range instrumentation. Testing will resume with active payloads once the barrel extension commissioning is completed.

All component tests have been performed with variants of the Gnat projectile at acceleration levels below requirements to gain confidence in the components and the design strategy. Discrete surface-mount components (resistors, capacitors and inductors) have survived testing with no failures to date. Of four transmitter IC’s tested one was damaged during removal from the Gnat projectile, however the remaining three showed no apparent degradation and both the microcontroller and RF portions continue to operate. This was seen as the biggest technical risk item, and it is now necessary to test the chip at the full required acceleration levels.

Lithium batteries were tested in various packages. Batteries containing only flat elements, such as button (watch) batteries, showed minimal degradation following the test, and retain charge for months following testing, showing little increase in internal leakage current.

A limited number of crystal oscillators were also tested, none of which survived.
Upcoming tests include launches of radio circuits and temperature and accelerometers sensors, at both low impact acceleration levels ($5 \times 10^5 \text{m/s}^2$), required to survive gun launching, and design shocks levels for the penetrator ($4 \times 10^6 \text{m/s}^2$).

**CONCLUSIONS**

The baseline mission comprises a lunar impactor with an impact velocity of 1750m/s and design levels for impact deceleration survival of $4 \times 10^6 \text{m/s}^2$. While the high velocity impact regime introduces some new complications, it shrinks and simplifies the impactor design for airless bodies by doing away with deceleration rockets. This opens opportunities to piggyback very small payloads on future lunar and planetary missions. The cost of each penetrator will be very small compared to the same types of rover-missions currently proposed, though limited mobility requires that missions include a number of penetrators or else accept an unreasonable risk of failure either from missing localised ice deposits or an unsuccessful penetration event.

Proposed science instrumentation includes:

- An evolved gas analyser incorporating an interferometer, for detection of water and possibly other volatiles
- An x-ray fluorescence spectrometer for regolith composition analysis of heavier elements (atomic mass > Oxygen). The proposed energy dispersive XRF requires no moving parts, and is suitable to adaptation to a penetrator.
- A novel Penetrometry approach to detect density layers based on acceleration measurements
- RF attenuation measurements, to generate a 3-dimensional map of RF absorption in the local regolith and higher regions (hills and crater walls)
- Temperature measurements to determine regolith and cold-trap thermal properties
- A mission involving several penetrates to survey large areas of the south pole region, allowing greater probability of finding ice deposits and comparisons between cold trap (permanently shadowed) regolith and regolith from the same region that is regularly exposed to sunlight.

The following issues have been identified, for which further testing and/or analysis is necessary:

- Impact forces (accelerations), including performing penetration tests into regolith stimulant at the full impact velocity and various angles of attack and L/D.
- Impact heating, and the effect on both the penetrator and the surrounding regolith.
- Decent trajectory analysis and terrain modelling to confirm delta-V requirements for access to the permanently shadowed regions.
- Verification of the proposed density profiling technique.
- Development of the proposed instrumentation

Test results thus far are encouraging, with successful structural tests above design impact accelerations. Component tests have only been performed at 12% of the design impact acceleration due to launch equipment availability. The launch equipment, instrumentation and methods continue to be improved, and testing at full impact acceleration level is now possible.
**NOMENCLATURE**

\[ F = \text{impact force (N)} \]
\[ a = \text{projectile radius (m)} \]
\[ \psi = \text{calibre-radius-head} \]
\[ s = \text{ogive radius (m)} \]
\[ \rho = \text{target density (kg/m}^3{)} \]
\[ R = \text{target resistance parameter (MPa)} \]
\[ V = \text{strike velocity (m/s)} \]
\[ K = \text{First target resistance component, chosen to fit experimental data (MPa)} \]
\[ k = \text{Second target resistance component, chosen to fit experimental data (MPa)} \]

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**REFERENCES**


