LABORATORY SIMULATIONS OF SMART-1 IMPACT ON THE MOON. R. Robin-Williams and M. J. Burchell, School of Physical Sciences, University of Kent, Canterbury, Kent CT2 7NH, United Kingdom. M.J.Burchell@kent.ac.uk.

Introduction: The European Space Agency's Smart 1 spacecraft was deliberately crashed onto the Moon's surface on Sept. 3rd 2006 after a highly successful programme of science and technology development (http://www.esa.int/SPECIALS/SMART-1/index.html and [1]). This provided an opportunity for study of a relatively well controlled high speed impact on the lunar surface. The impact was observed from Earth by astronomers who obtained images of the associated impact light flash and ejecta cloud. The impact occurred at a speed of 2 km s^{-1}, at a very shallow angle of incidence (~ 1° from horizontal). Pre-impact predictions for the size of the crater placed it in the range 3 to 10 m in size, with a depth of ~ 1 m.

It has long been known that glancing impacts at high speeds are very different to vertical impacts (e.g. see [2]). The introduction of a forward component of motion, and the reduction of the vertical component of the impact speed can significantly influence not only the subsequent crater size and shape and also the volume and direction of the ejecta cloud, e.g. [3]. Indeed, at very shallow angles (as here) there can be ricochet of the impactor in the forward direction.

In this work we report on a new set of laboratory impacts carried out into fine sand at speeds of around 2 km s^{-1}. Based on the results and naïve scaling to impacts of m scale objects under similar conditions, predictions are made for the crater shape and size and the volume of the associated cloud of ejecta from the impact of the Smart 1 spacecraft on the Moon.

Experimental Set-up: The experiments were carried out using the two stage light gas gun at the University of Kent [4]. The projectiles were 2.03 mm dia. aluminium spheres and the angle of impact was varied from shot to shot and ranged from 1° to 10° from the horizontal. The target was fine sand (Lower Greensand, Leighton Buzzard, Beds. UK), similar in some respects to the JSC Lunar Simulant. It was free from silt, clay and organic matter. The grain shape was sub-rounded and grain size was 90 – 150 µm (at least 85% of grains within these limits). The sand was placed in a long tray which could be inclined to the horizontal. This tray was then placed in the light gas gun and its angle of inclination measured in-situ. After a shot, the tray was removed and the resulting impact crater imaged and measured.

As well as the sand in the tray, there was a vertical target of aluminium sheets placed at the far end of the tray when in the gun. Any ricocheting projectile hit this aluminium, leaving an impact crater. The location of this crater relative to the centre of the main crater in the sand was measured and the angle of ricochet obtained.

Results: 8 impacts are reported**.** All speeds were within 2.0±0.1 km s^{-1}. Two impacts were at 1°, one at 1.2°, two at 2°, two at 5° and one at 10.2°. All angles are accurate to 0.1°. Examples of the shape of the craters are given in Figure 1. At 1° the crater was no longer circular, but could be considered as a series of connected circular craters (each decreasing in size), with shock waves frozen in the surrounding sand. This is in line with what was reported previously [2]. Fig. 2a shows the ratio of the crater length to width vs. impact angle, showing significant deviations from circular only below ~5° (all crater lengths, widths are rim to rim). Fig 2b show the ratio of crater depth to crater length, the fall at low angles is mostly due to increased crater length rather than a sharp reduction in depth.

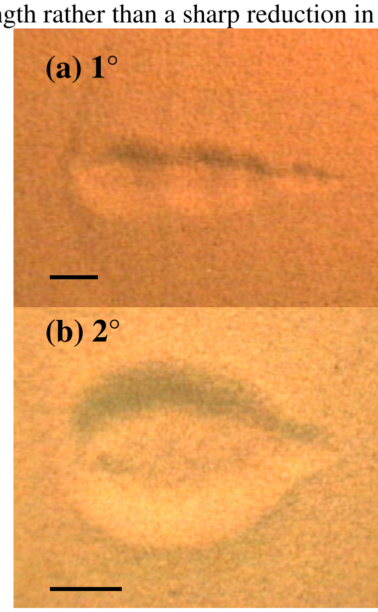

Figure. 1. Impact craters viewed from above, impacts were from the left. Impact angles were (a) 1°, (b) 2°. (1 cm scale bars are shown).

The volume of sand ejected by flight from the crater (defined as the material removed from the crater site – i.e. the crater rim walls raised by flow of material are not included in this value) is normalized to projectile mass and shown in Fig 2c vs. angle of incidence.

In all cases, a ricocheting projectile was detected downstream (via impact on an aluminium target) and the angle of ricochet relative to the surface was obtained (Fig. 3). This does not follow an angle of incidence equals angle of reflection relationship. For shallow angels of incidence (≤ 2°) it is in the range 0.5 to 1° and for incident angles of 5 - 10° it was ~2.5°. This effect has been previously observed [2]. The ricocheting projectile speed was estimated by the size of the crater in aluminium target using a calibration obtained from direct impacts onto the target at known speed. At 1° the ricochet speed was between 1.75 and 2.0 km s^{-1}.

Extrapolation to Smart 1: To extrapolate to Smart 1 scales we took the impact angle as 1° and the spacecraft mass as 290 kg at impact. Based on the data in Fig. 2 we predict that the Smart 1 ejecta cloud contained 16 m^3 of lunar surface material. Taking a mean material density of 2500 kg m^{-3}, this implies some 39,000 kg of displaced lunar material. Scaling the crater volume and applying a model of the crater shape (based on Fig 1a), we predict that for Smart 1 the crater would be some 14 m long, 4 m wide (maximum) and 1 m deep (below original surface) with rim walls of similar height. Smart 1 itself should have ricocheted at an angle of 0.5 - 1° at a speed of 1.75 – 2 km s^{-1}.

Discussion: The above extrapolation to Smart 1 scales is based solely on the assumption that ratios of properties are scale independent. This almost certainly fails, as some of the consequences of the impact processes depend on impactor size (i.e. on the time for a compression wave to traverse the impactor). However, given that Smart 1 had a complicated structure, was non homogeneous and contained voids, and had a distinctly non spherical shape it is difficult to allow in detail for all these variations.

Conclusion: Based on a set of laboratory experiments it is predicted that the Smart 1 impact crater on the Moon will have a distinctly non-circular appearance when seen from above. Given the extreme shallow angle of incidence this may possess a complicated appearance. Although small in size (17 x 4 m), this will add to the natural population of such non-circular craters, e.g. see [5], which are held to be due to oblique incidence impacts (e.g. see [6] for a recent interpretation of the statistics of these craters based on laboratory experiments).

References: [1] Foing B.H. (2006) *Adv. Spa. Res.* 37, 6-13. [2] Gault D. E. and Wedekind J. A. (1978) *Proc. LPSC 9th*, p. 3843–3875. [3] Anderson J. L. B. and Schultz P. H. (2003) *JGR, 108*, E8, 5094. [4] Burchell M.J. et al. (1999) *Meas. Sci. Technol.* 10, 41–50. [5] Bottke W.F. et al. (2000) *Icarus* 145, 108–121. [6] Burchell M.J. and Whitehorn L. (2003) *Monthly Notices of the Royal Astronomical Society* 341, 192–198.

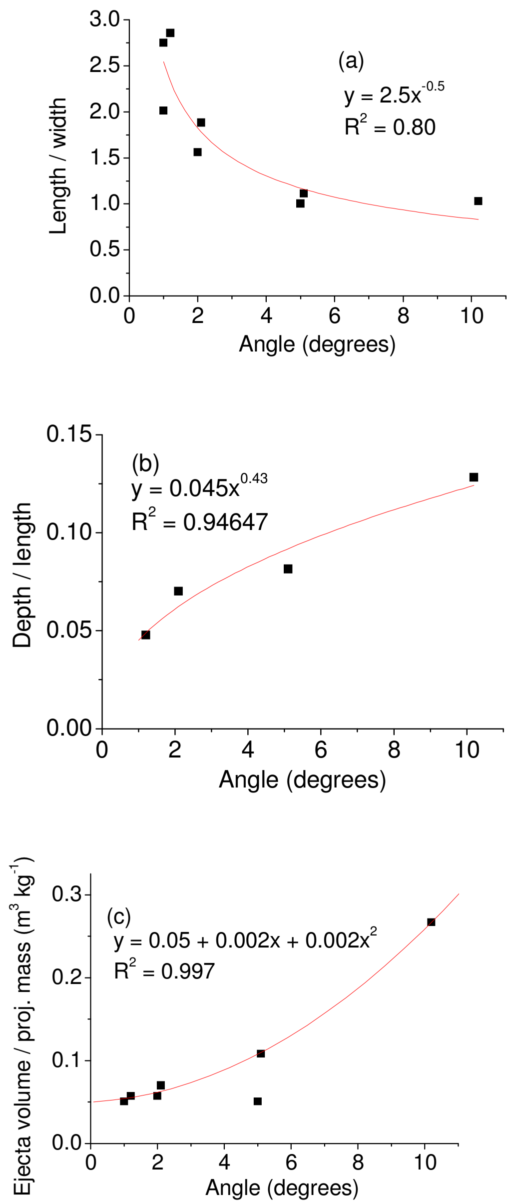

Figure 2. Crater parameters vs. impact angle.

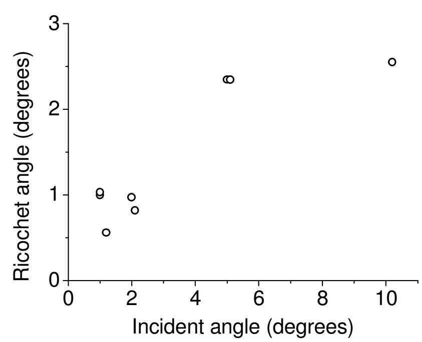

Figure 3. Ricochet angle for aluminium projectiles.