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IMPACT CRATERING IN REDUCED-GRAVITY ENVIRONMENTS: EARLY EXPERIMENTS ON THE NASA KC-135 AIRCRAFT

M.J. Cintala¹, F. Hörz¹, and T.H. See²; ¹Solar System Exploration Division, NASA Johnson Space Center; ²Lockheed EMSCO, Code C23; both in Houston, TX 77058

As outlined at last year's workshop^{1,2}, a variety of reasons exist for performing impact experimentation at reduced gravity-levels. The execution of such experiments, however, will require familiarity with reduced-g environments, as well as with the idiosyncracies associated with the change in gravitational acceleration. Since there has been little low-g cratering experimentation in general³ and no impact experimentation specifically performed in flight (although some ground-based work has been done⁴), a series of impact-cratering experiments has been initiated on the NASA KC-135 Reduced-Gravity Aircraft. The intent of this program is threefold: (1) to acquire experience in low-g experimentation, (2) to develop an observational understanding of the changes in the cratering process at reduced g -levels, and (3) to collect scientifically useful data in the process. This report describes the apparatus, the experimental environment on the KC-135, and some early results regarding cratering in sand targets.

The Low-Velocity Impact Facility: The ideal impact facility would utilize a projectile accelerator capable of launching projectiles of a variety of types and sizes over a wide range of impact velocities. The availability of funding for this initial facility, however, required a more modest approach. The accelerator is a Sheridan 5mm pellet pistol, which has been modified to be mounted vertically and fired electronically. Impact velocities of ~50-130 m/s (with 0.96g, cylindrical lead pellets) are attainable by varying the pressurization in the gun's pump chamber. The impact chamber is a 51.8x51.8x45.8-cm aluminum-framework box, with tempered-glass walls to permit photography and viewing of experiments; its lid is hinged for access to the interior. Since this facility does not yet support vacuum capability, all experiments to date have occurred at aircraft-cabin pressure, typically 0.83 atmospheres. Data collection relies principally on photography (high-speed motion picture, still, and video cameras), while acceleration and atmospheric-pressure information is recorded digitally with a microcomputer. Projectile velocities are measured *via* interruption of infrared photodiodes separated by a fixed distance; an independent oscillator circuit is used for timing. Experimentation during flight is invariably performed under somewhat hectic conditions due to the compressed timeline necessitated by the aircraft's high rate of fuel consumption; in order to maintain efficiency at a level as high as possible, the computer is also employed as an event sequencer -- operating the cameras, firing the gun, measuring and recording projectile velocities, and recording event times.

Experimental Environment on the KC-135: Gravity levels ranging from -0.1 to ~2 g 's can be supported by the KC-135 for tens of seconds; the flight profile is selected by the investigators in concert with the flight crew. Depending on a number of factors related to the overall experimental program on a given flight, up to 50 parabolas can be accommodated on a typical 2.5-hour flight. Moderate- to high-frequency vibrations of noticeable amplitude are minimal during a typical parabolic maneuver, although low-frequency oscillations of varying amplitude around the targeted g -level are not unusual (Fig.1). While the pressurized cabin provides a comfortable, shirt-sleeve working environment, normally routine operations are often made more difficult due to the variable- g environment. Experimenters have been known to sleep well following a typical flight.

Early Results: The early developmental flights have provided the opportunity to collect limited data on crater dimensions and growth times as functions of g -level and impact velocity. A coarse-grained, polymineralic sand (1.57 g/cm³ and 32.5° angle of internal friction) was employed as the target. Comprised predominantly of quartz and feldspar (see Table 1 for its grain-size distribution), the sand filled the chamber to a depth of 15

cm; comparison with earlier findings⁴ leads to the conclusion that the volume of target material was sufficient to obviate noticeable edge-effects during formation of the largest craters at 1g. No anomalous phenomena that might have been related to the finite target-depth were observed during flight, but this parameter remains to be examined in more detail before serious experimentation is conducted at the lower *g*-levels, especially when higher projectile energies are employed. A total of 27 shots have been performed to date, covering a range of 0.082 to 0.534 *g*'s. Crater dimensions were obtained from 35mm photography after completion of each experiment; crater growth-times were derived through analysis of ejecta-plume shapes from 16mm motion-picture photography at 250 frames/s, yielding a time resolution of 0.04 s. Due to limitations in attainable impact velocities, a variation of only a factor of 6 in impact energy was possible. For comparison, experiments with the JSC Vertical Impact Facility can be performed with impact energies covering almost 4 orders of magnitude. Crater Diameters: The limited range of projectile velocities resulted in craters with rim-crest diameters varying over an interval of only 11 to 18 cm. This limited size range nevertheless is sufficient to demonstrate well-defined gravity and velocity (or energy) dependences (Fig. 2). The diameters of craters formed at two fixed energy levels (and velocities, since the projectile mass was constant for each shot) are presented for a range of *g*-levels. Not only does this figure illustrate the inverse relationship between crater diameter and gravitational acceleration, but the relatively unscattered data attest to the suitability of the KC-135 as a scientific test bed: the precision of these data is comparable to those obtained in ground-based laboratories. The slopes of the two least-squares fits -- which are statistically indistinguishable owing to the small number of data points -- are very near the value of -0.165 obtained in ground-based experiments.⁴ Crater Growth-Times: The times required for crater growth were obtained by counting the number of 16-mm frames from the time of impact to the time that the profile of the ejecta plume near the target surface changed from a continuous, concave-outward curve to a discontinuous intersection between the expanding curtain and the target surface. Data for the same 14 craters are illustrated in Figure 3 and, once again, the small number of actual data points will not permit the assertion that the two slopes are distinguishable. Confidence intervals notwithstanding, both fits are substantially different from that obtained in the drop-platform experiments,⁴ which is included in the figure as the dashed line. The slopes of the fits to the KC-135 data are also outside the theoretical limits as determined through dimensional analysis;⁵ the causes of these differences are not yet understood. The target sands, for example, were different in both sets of experiments represented in Fig. 3; it has been demonstrated that variations in bulk density and angle of internal friction can play a nontrivial role in determining the outcome of a cratering event.⁶ The drop-platform data⁴ were collected with impact velocities of 6.4 km/s, while those displayed here were at a maximum of 0.111 km/s. Finally, there is a small but undetermined effect due to the atmospheric pressure differences between the two experiment series. On the other hand, the limits placed on the gravity exponent by the dimensional analysis are -4/7 to -5/8, which is expected to hold "for all materials and impact conditions."⁵ Clearly, more work will be required to determine whether these variations are indeed real and, if so, to evaluate their possible causes.

Summary: Impact experimentation on the NASA KC-135 Reduced-Gravity Aircraft has been shown to be possible, practical, and of considerable potential use in examining the role of gravity on various impact phenomena. With a minimal facility, crater dimensions and growth-times have been measured, and have demonstrated both agreement and disagreement with predictions. A larger facility with vacuum capability and a high-velocity gun would permit a much wider range of experimentation.

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Table 1. Grain-size Distribution of target sand

Size (mm)	Mass Fraction
>0.500-1.000	0.264
>0.250-0.500	0.660
>0.125-0.250	0.075
≤0.125	0.001

Figure 1. An example of the acceleration history during an impact experiment on the KC-135. The g-level on the vertical axis was sampled 4 times per second; the time of gun firing and impact is indicated just before 40 s. Note the small oscillations around the targeted level of 0.16g.

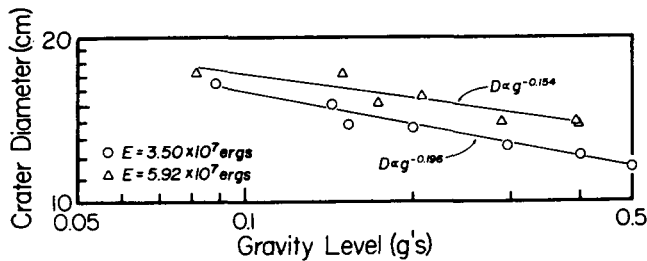
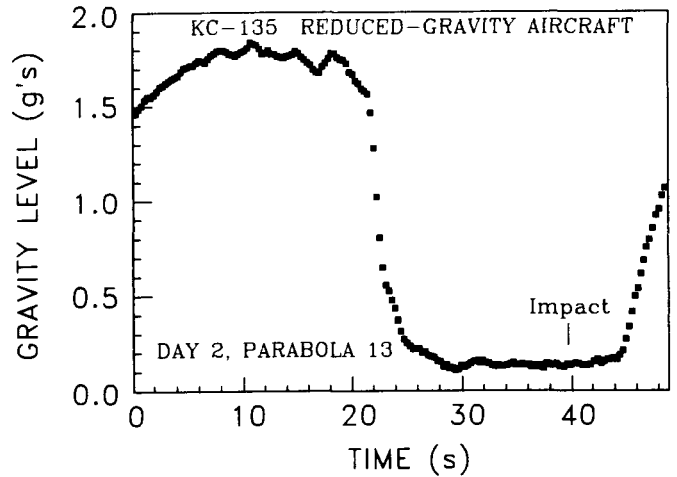


Figure 2. Crater diameter as a function of g-level for two fixed impact energies. The lower energy impacts occurred at ~83 m/s, while the others took place at ~111 m/s. These slopes can be compared with -0.165, the value obtained from drop-platform experiments.¹ Note the modest scatter in the data, attesting to the stability of the KC-135 as a test bed.

Figure 3. Crater formation-time as a function of g-level for the same craters treated in Figure 2. The dashed line possesses the slope determined for high-velocity impacts in the drop-platform experiments.¹ The slopes for the KC-135 data are beyond the limits suggested by dimensional analysis,⁵ but the reason for the disparity is unclear. See the text for possible causes.

