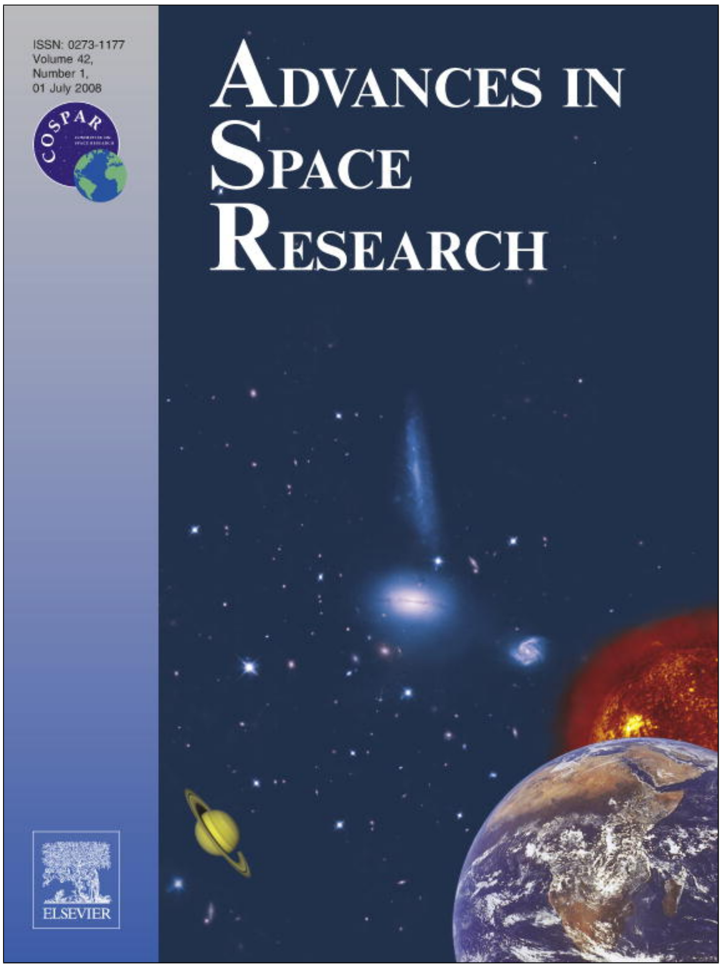
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A sample collector for robotic sample return missions III: Impact survivability studies

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Abstract

Laboratory impact tests have been performed on experimental versions of a proposed robotic sample collector for extraterrestrial samples. The collector consists of a retractable aluminum ring containing an impregnable silicone compound that is pressed into the surface of the body to be sampled. As part of a comprehensive program to evaluate this idea, we have performed tests to determine if the samples embedded in the collector medium can survive the impact forces experienced during direct reentry, such as that of the recent Genesis sample return mission. For the present study, samples of sand, rock, glass, and chalk were subjected to decelerations of 1440–2880 g using drop tests. We found that even the most fragile samples, chosen to be representative of a wide range of the types of materials found on the surface of asteroids that have currently been studied, can withstand impacts of the intensity experienced by a sample return capsule during direct reentry.

Keywords: Impact studies; Sample collection; Hera mission; Near-Earth asteroids; Sample return; Sample survivability

1. Introduction

We have entered a new phase of solar system exploration in which sample return is becoming increasingly necessary in order to answer questions about the origin and history of solar system bodies such as Mars, asteroids, and comets. Unfortunately, these kinds of missions are very costly and it is essential to find ways to reduce their cost. The Hera mission is a proposed Discovery class mission that will collect and return samples from near-Earth asteroids and return them to Earth. One mode of return being considered is direct reentry in which parachutes are not used during atmospheric descent and by design, the sample return capsule (SRC) impacts at high-speed into the soil of the Utah Test and Training Range (UTTR). A series of drop tests were performed by Fasanella et al. (2001) at UTTR during November 1998 and September 2000. Penetrometers with high-speed digital data acquisition systems recorded behavior during impact (Table 1). Impact velocities ranged from ~6 to ~45 m/s and impact decelerations ranged from ~85 to ~1700 g. While parachute landings, especially with capture in the air, can bring the landing forces to essentially zero, equipment failure can sometimes result in impact velocities and forces of this order (*viz*. the Genesis mission) and it seems sensible to plan for them.

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Table 1
Data of tests conducted at the UTTR (Fasanella et al., 2001)

Test	Description	Diameter (m)	Mass (kg)	Velocity (m/s)	Peak decelerations (g)
1	Drop hammer	0.203	2.98	5.74	85
2	Helicopter	0.408	12.05	34.97	1195
3	Helicopter	0.408	12.05	43.15	1482
4	Helicopter	0.408	12.05	44.9	1656
5	Helicopter	0.408	24.5	31.94	614
6	Helicopter	0.408	24.5	39.42	812
7	Helicopter	0.408	24.5	45.35	1016
8	Bucket truck	0.514	11.02	16.7	500
9	Bucket truck	0.514	18.54	19.1	300
10	Bucket truck	0.514	18.91	16.7	210
11	Balloon	0.514	18.91	21.8	325
12	Balloon	0.514	18.91	25.8	510
13	Helicopter	0.66	24	35	1080
14	Helicopter	0.66	24	40	1295

Scientific requirements of the sample collector were outlined at a workshop of meteorite and asteroid specialists in the summer of 2001 (Sears et al., 2004b), and subsequently a design that met these criteria and the constraints of being flown on a low-cost mission was developed through several iterations into the current collector design (Sears et al., 2002, 2004a; Franzen et al., 2004, 2007) The current design is known as the touch-and-go-impregnable-pad (TGIP) and consists of a 1 cm thick inert substrate held in a 12 cm aluminum retractable ring that is pressed into the surface of the extraterrestrial body. The substrate is very similar to the silicone oil used in NASA's Cosmic Dust Program. The substrate has a National Lubricating Grease Institute consistency grade of 3–4. In theory, the substrate should encase the samples and protect them from physical and chemical harm during collection, subsequent flight, and reentry. Elsewhere we describe tests we have performed to evaluate the collector's temperature and radiation characteristics (Franzen et al., 2007; Venechuk et al., 2007). Here we report the results of tests we have performed in which a prototype TGIP, loaded with various kinds of samples, was subjected to impact stresses comparable to those expected during impact in the UTTR.

2. Experimental details

Two experimental setups were used to simulate the high deceleration forces of direct reentry impacts. The first setup consisted of a 5 cm in diameter miniature SRC (Fig. 1a and b) suspended on a chain 54.6 cm (21.5 in.) from an aluminum backstop. An impactor was used to accelerate the SRC. The impactor, the SRC, and an oscilloscope were all wired into a battery powered circuit. The oscilloscope was used to capture the electrical impulse over time within the circuit whenever the circuit is closed. In this experimental setup the circuit is closed whenever metal to metal contact is achieved which is when the impactor impacts the SRC and the SRC hits the aluminum backstop. This allowed for determination of an impact time on the oscilloscope by measuring the time between initial closing of the circuit through contact of the impactor with the SRC to opening of the circuit when the impactor is no longer in contact with the SRC and then the average impact time for all experiments was used in subsequent calculations. Velocity was estimated by dividing the distance between the SRC and the aluminum backstop by the time it took for the SRC to reach the backstop. This allowed for the calculation of the force experienced by the impacted

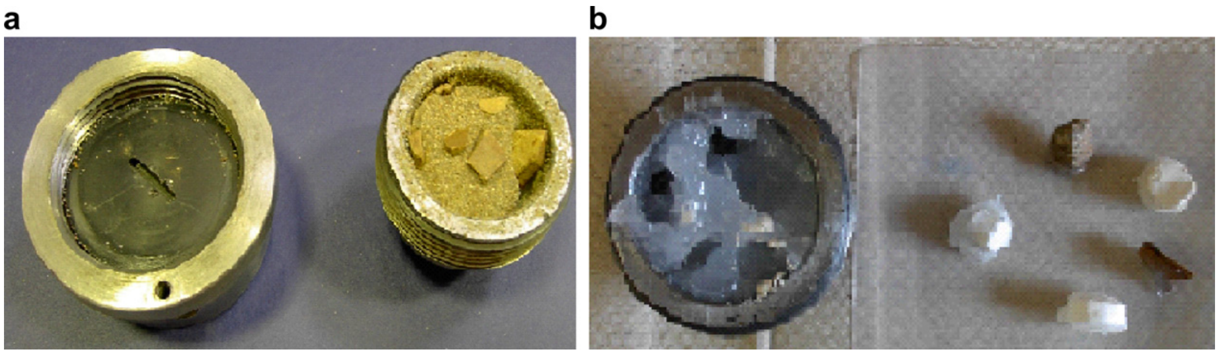

Fig. 1. (a) Sample collector loaded with rocks and sand after the impact of 1850 g. (b) Sample of rocks, chalk, and a mint after the impact of 1880 g. Notice that none of the sample was fragmented, chipped, or crushed by the impact.

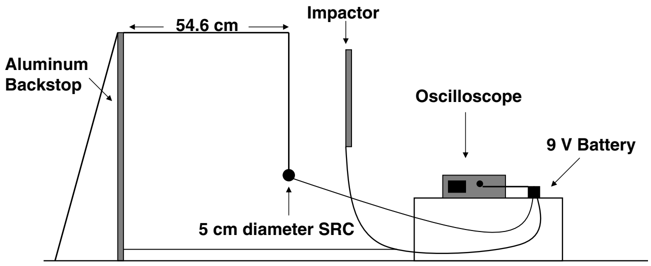

Fig. 2. Schematic of the first experimental setup. The impactor, the SRC, and the oscilloscope were all wired into a battery powered circuit which allowed for determination of an average impact time on the oscilloscope and the calculation of velocity by dividing the known distance between the SRC and the aluminum backstop with the time it took for the SRC to reach the backstop once it was impacted by the bat. This allowed for the calculation of the deceleration experienced by the impacted SRC.

SRC. The average impact time was determined first and then the time for the velocity calculations was experimentally established. This experimental setup was designed to reduce the deformation of the SRC and to produce the required decelerations. Two types of samples were loaded in the SRC. The first sample (Fig. 1a) was 14.15 grams of 300–425 μm sand and ~5 mm sandstone rocks. The second sample consisted of 15.91 grams of chalk, rocks, and a mint. The mint was used to represent a more fragile and easily crushable sample based on a relative scale in comparison to rocks and sand which are representative in these experiments of the more typical types of materials that might be found on an asteroid's surface. Fig. 2 shows a schematic of this experimental setup and Table 2 summarizes the data from this experiment.

For the second experimental setup a steel SRC was designed in which the prototype collector was placed (Fig. 3). The SRC is 16.3 cm in length, 12 cm inside diameter, and had a mass of 7.4 kg. A 1.3 cm thick aluminum plate the diameter of the sample collector was placed in the SRC, then the collector was placed face down on top and, finally, another 1.3 cm thick aluminum plate was placed on top of the collector. The lid was placed on the SRC and the entire assembly was screwed together with four bolts. As in the first experiment a circuit was built between the SRC, a 5 cm steel plate, and an oscilloscope and the SRC was dropped on top of the steel plate to determine the impact time via the oscilloscope. The collector was loaded with the sample of rocks, sand (210–300 μm), chalk, and glass, and then dropped 10 times from 3.7 m, taking pictures of the sample in the collector after each impact. Table 3 summarizes the data from this experiment.

Table 2
Data for impact tests for the miniature SRC

Test	Sample	Mass (g)	Impact time (ms)	Avg. velocity (m/s)	Avg. deceleration (g)
1	Sand, rocks	14.15	0.5	9.02	1850
2	Chalk, rocks, mint	15.91	0.5	9.14	1880

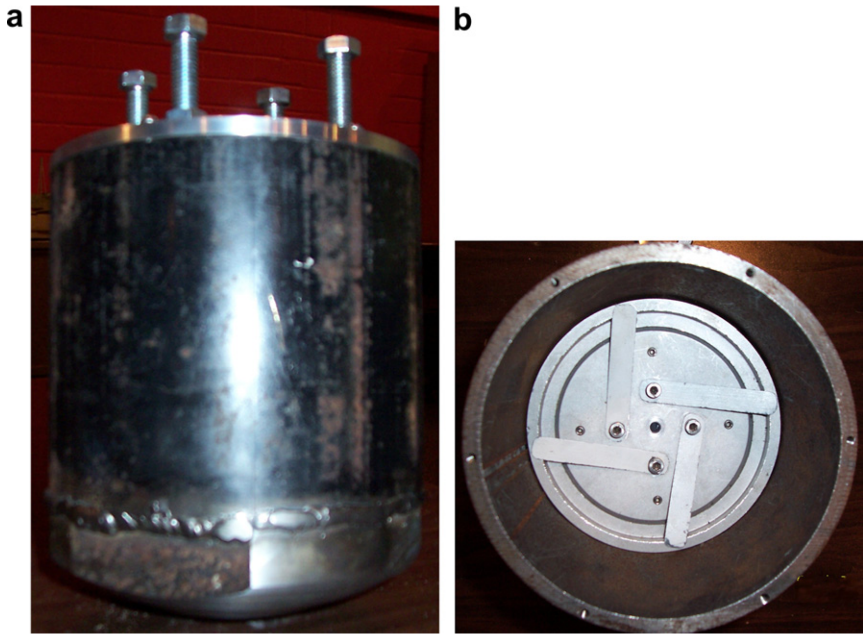

Fig. 3. (a) SRC built for holding the prototype sample collector. The bolts located at the top are screwed down onto the top aluminum plate that sandwiches the sample collector. The SRC is mass heavy at the bottom to ensure that it lands with collector and sample facing the steel plate on the ground. (b) A view of inside the SRC and the top of the collector before the final aluminum plate is placed on top of the collector and the lid is bolted down.

Table 3
Data collected from the drop tests of SRC on to a metal plate

Test	Height (m)	Impact time (ms)	Avg. deceleration (g)
1	3.7	0.3	2890
2	3.7	0.6	1440

3. Results

The results from the first experiments with the miniature SRC are shown in Table 2 and Fig. 1. The first test consisted of sand and rocks as a sample. The sample in the second test included chalk, rocks, and a mint. It was found that the average impact time for these experiments was 0.5 ms and the average preimpact velocity was ~9 m/s. Calculations show an average deceleration between 1850 and 1880 g. Fig. 1a shows the miniature SRC with sample after impact. The rock and sand sample showed no sign of any visual changes and has survived the impact. Fig. 2b shows the samples once they have been removed from the SRC after impact. The sample did not appear to fragment, chip, or be crushed by the impact. Thus, if samples similar to those used in these experiments are found on asteroids they should have no difficulty surviving impacts on the order of ~1850 g.

Table 3 and Fig. 4 show the results from the second experiment. Here the impact time varied between 0.3 and 0.6 ms. The average decelerations ranged between 1440 and 2890 g. Fig. 4 shows a series of photographs after progressive numbers of impacts. The first photograph is (Fig. 4a) a picture of the sample and collector before any impacts. The same sample was impacted 10 times. In comparing the pictures (Fig. 4), it is difficult to see any change in the sample in terms of damage. The substrate has clearly shifted a little in the collector. However, the substrate still retained the sample in the collector and has moved to encompass the sample and protect it. There were no visible alterations in the sample, even after the 10th impact, even though the aluminum plate cracked due to the stresses that were exerted on it during the impact tests.

4. Discussion

The experiments performed here had average velocities and masses that fell near the lower range of experiments conducted at the UTTR (Fasanella et al., 2001). However, impact times during our laboratory experiments were shorter than those of Fasanella et al. (2001) at the UTTR where the surface was clay. The shorter impact times of our experiments caused higher peak decelerations so that our experiments fell into the high range of the UTTR tests and in some experiments exceeded their maximum peak decelerations. In short, we have achieved decelerations during our experiment that are similar to or greater than those experienced by a SRC during a parachute-less direct reentry.

The samples used in these experiments were mainly sand, sandstone rocks, glass and chalk. These materials were chosen to bracket the range of physical properties likely to be

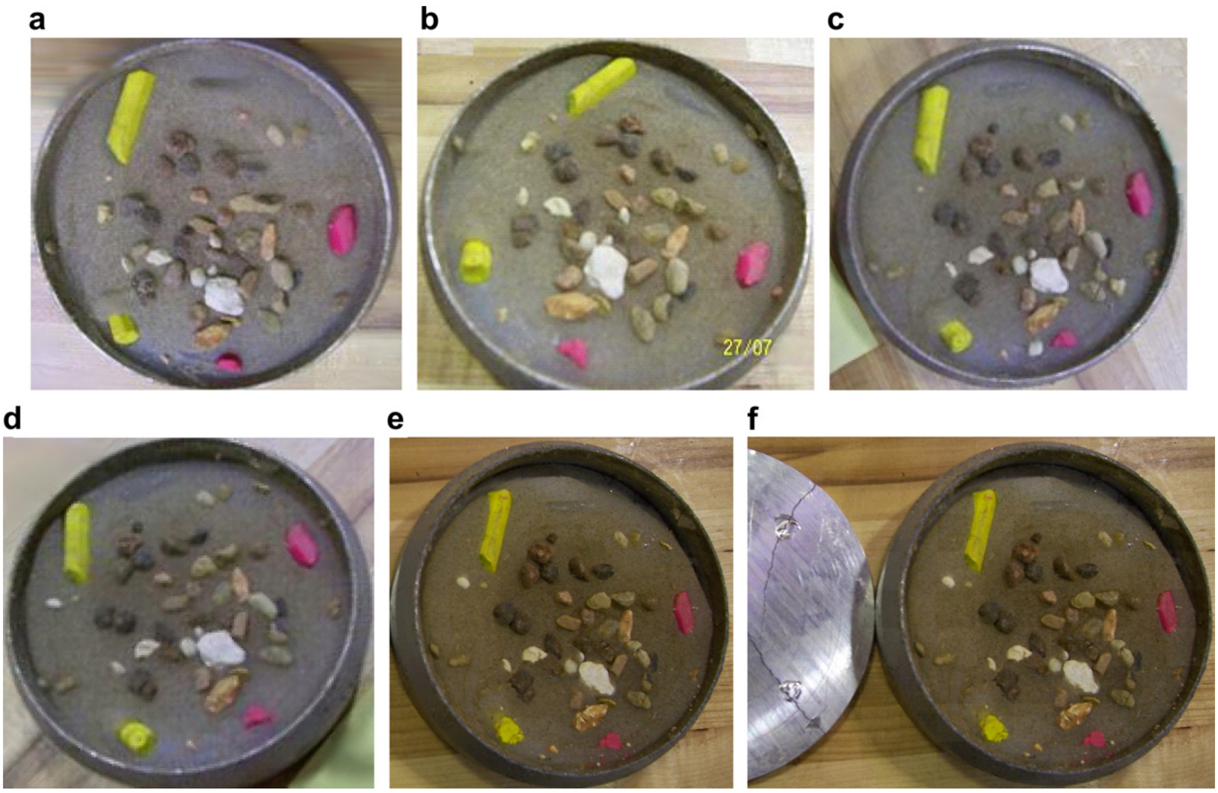

Fig. 4. (a) The sample of rocks, sand, chalk and glass before the impacts. (b) The sample after the first impact. (c) The same sample after the second impact. (d) The same sample after the third impact. (e) The same sample after the tenth impact. (f) The sample after the tenth drop test. Note the fractures in the aluminum plate and the slight shift of the collection substrate at the top right of the TGIP.

found in asteroid surface material. However, relatively little is known about the surface of asteroids so we must extrapolate from the surface of the moon and meteorites. The critical properties are density, grain size, and porosity. The median particle size on the moon is 40–130 μm, however, particles smaller than 20 μm and as large as several millimeters can be found in the top 1 cm of lunar soil (McKay et al., 1977). The bulk density of the first 15 cm of soil is 1.50 ± 0.05 g/cm^3 (Mitchell et al., 1974) and the average porosity is $52 \pm 2\%$ (Carrier et al., 1991). The porosity range is 7–52% for an asteroid, with a median of 30–40% (Britt et al., 2002). The density range suggested for asteroids is 0.96–3.44 g/cm^3 depending on the type of asteroid (Britt et al., 2002). The sand used in our experiments was 210–300 μm in size which is slightly higher than the lunar median particle size but falls on the smaller end of the total size range of particles found in the top 1 cm of lunar soil. The density range of sand is 1.44–2.40 g/cm^3 (Ohlhoeft and Johnson, 1989). The smaller end of the density range falls near the bulk density of lunar soil. The sandstone rocks used in the experiment were used to represent the larger particles found on the lunar surface. The stones in general were less than or equal to 1 cm in size. The mean bulk density of sandstone is 2.22 g/cm^3 (Ohlhoeft and Johnson, 1989), which is denser than the average lunar soil. The porosity is 17.49% (Ohlhoeft and Johnson, 1989) which is much less porous than lunar regolith. If we assume the chalk used is similar to natural chalk the density is 2.23 g/cm^3 and the porosity is 35–47% (Hancock and Skinner, 2000). The porosity of the chalk most closely resembles that of the porosity of the lunar soil. Glass used in our sample was to represent the glass and agglutinates found on the moon. The objective was to represent something on the asteroid's surface that was more fragile than typical regolith materials.

The second test consisted of dropping the SRC 10 times of which two drops were wired as before to obtain the necessary data to determine the deceleration (Table 2). The sample, composed of rocks, sand, chalk, and glass inside the capsule, withstood the repeated impacts. The chalk and glass showed no signs of stress. They were not shattered, chipped, or crushed in any way that could be observed by the unaided eye. The rocks in the sample were not fractured or chipped. The sand was held firmly in the collection substance and was not found loose in the SRC after the impacts. The collection substrate seemed to "suspend" the particles thus protecting them and also keep the particles in place relative to each other even though the substrate did shift slightly in the TGIP. The collection substrate protects the sample during the impact phase of the mission.

5. Conclusions

The first experiment shows that the sample can withstand SRC decelerations of 1850–1880 g. The result of the second experiment demonstrates that the sample of rocks, sand, chalk, and glass withstood repeated impacts with decelerations of 1440–2890 g. This is due to the collection substance "suspending" the sample into it causing the particles to remain in a fixed position relative to each other and protecting the sample from the impact forces.

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