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A sample collector for robotic sample return missions I: Temperature effect on collected mass

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Abstract

Sample return is playing an increasingly important role in solar system exploration. Among the possible mission on the horizon, are sample return from asteroids, comets, the Moon and Mars. A collector initially intended for near-Earth asteroids is the touch-and-go-impregnable-pad (TGIP). Here we explore the effect of temperature on its collection capabilities. Temperatures expected on near-Earth asteroid mission targets range from −43 to 36 °C. Experiments were conducted at −75, −50, −25, 23, 65, and 105 °C. It was found that the mass of sample collected by the TGIP increased almost linearly to 23 °C and then leveled off at higher temperatures. We also found that the collector did not lose its ability to collect samples after being subjected to −75 °C temperatures (essentially frozen) and then thawed. These experiments have shown that the TGIP can operate effectively at temperatures expected on near-Earth asteroids, especially if collection is performed on the sunward side of the asteroid.

Keywords: Sample return missions; Near-Earth asteroids; Hera mission; Temperature dependence; Sample collection

1. Introduction

1.1. Mission overview

Solar system exploration has currently entered a phase in which sample return has assumed an increasingly important role. There are several sample return missions underway: Genesis (Burnett et al., 2003), Stardust (Brownlee et al., 1996), and Hayabusa (Muses C) (Fujiwara et al., 2000). The Hera Near-Earth Asteroid Sample Return Mission was a proposed Discovery class mission (Sears et al., 2004a,b). The first part of the mission would involve a detailed one month reconnaissance of the asteroid. This would allow for a comprehensive knowledge of the surface of the asteroid to be obtained, which would permit scientists to determine the most scientifically valuable sites for sample collection. The spacecraft then used a hover-descent-touch-ascent sequence to allow the touch-and-go-impregnable-pad (TGIP) to collect sample from the surface. The TGIP has been designed as a simple, passive collector which can collect ∼100 g per sample with particles ranging from dust to centimeter-size clasts. TGIP collectors are located at the end of each of two robotic arms similar to those of the Mars Polar Lander. Once the collection sequence was complete, each sample was to be examined by an on-board camera, to ensure successful collection, and then stowed in a sample return canister. If the collector was damaged or if the collector and sample would not fit in the sample return canister, the collector could be jettisoned and replaced. The TGIPs are stacked in order

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to protect the samples from physical and chemical damage during the rest of the mission.

1.2. The sample collector design

The present sample collector for this mission went through a number of designs starting with the Honeybee Robotics collector (Sears et al., 2002, 2004a) and the Adhesive Pad collector of SpaceWorks, Inc. (Franzen et al., 2004) before the present design was conceived. Fig. 1 shows the design of the collector as it currently stands. The prototype collector is 12 cm in diameter and 2 cm deep. The collection substance is a silicone compound that is essentially a high viscosity version of the silicone oil (thickened with silica) that is used in NASA's Cosmic Dust program. One centimeter of substrate (~110 g) is evenly housed inside a retractable aluminum ring. This permits the substrate to be pushed down into the sample and allows room for larger fragments to be collected. Once collection is complete, the substrate and sample are retracted back into the aluminum ring housing for protection during stowage.

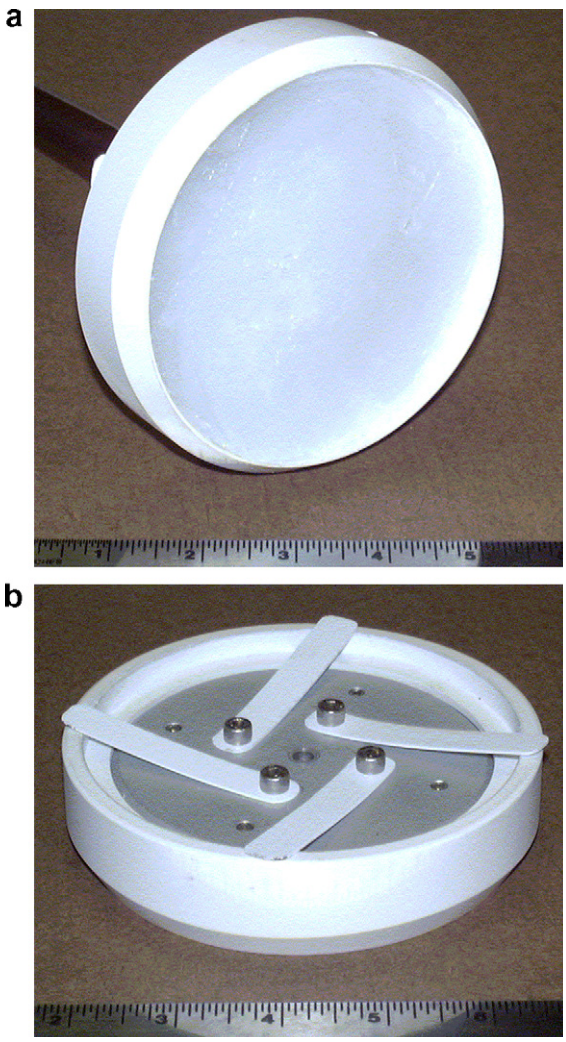

Fig. 1. (a) Laboratory prototype version of the Hera sample collector loaded with silicone substrate. (b) Backside of the collector. Springs and retractable outer ring are visible.

1.3. Environmental conditions and earth-impact

The three environmental factors that are crucial to the success of the sample collector are vacuum, radiation, and temperature. The vacuum of space can cause outgassing that could change the properties of the silicone substrate (for example, vacuum hardening) and damage the spacecraft by, for example, producing condensates that could obscure optics. Thus, NASA has developed strict criteria that define flight readiness (ASTM Standard E 595-93). These criteria include a total mass loss (TML) of $\leqslant 1.0\%$ and collected volatile condensable material (CVCM) of $\leqslant 0.1\%$. It is also important, of course, that the collector can withstand long term vacuum exposure without degrading its sample collection capabilities. The results of these tests will be reported elsewhere. The collector must also be robust to the radiation exposure that would occur during the mission. Ideally, the collector should have no chemical or physical change (i.e., darkening and/or hardening) when exposed to radiation that would be detrimental to its ability to collect samples. Results from radiation experiments by Venechuk et al. (2008) appear elsewhere in this issue. In addition, in the event of a parachuteless re-entry, the stresses of impact on Earth should be considered. This has been examined in a study by Azouggagh-McBride et al. (2008) also appearing elsewhere in this issue. In the present paper, we consider the effect of temperature on the effectiveness of the collector.

An approximate estimate of the temperature of the subsolar (warmest) point of a near-Earth asteroid at approximately 1 AU can be estimated by calculating the equilibrium temperature (assuming a black body) using the following equation:

$$T_{\mathrm{eq}} = \left[\left[\frac{F_o}{r_{\mathrm{au}}^2}\right]\left[\frac{(1-A_{\mathrm{b}})}{4\varepsilon\sigma}\right]\right]^{\frac{1}{4}} \qquad (1)$$

where F_{o} is the solar constant, r_{au} is the distance the object is from the sun in AUs, A_{b} is the bond albedo, ε is emissivity, and σ is the Stefan–Boltzmann constant (Lewis, 1995). We took our data from the Near-Earth Object Program website (http://neo.jpl.nasa.gov/cgi-bin/neo_elem) and the literature (Gaffey et al., 1993; Cox, 2000; Binzel et al., 2001, 2002, 2003; Sears et al., 2001, 2003) and calculated the case when each asteroid was assumed to be S, C, and M since taxonomic class for many of the near-Earth asteroids is not known. Average bond albedo and emissivities were also used for each of the asteroid classes. This calculation suggests that the temperature of various taxonomic classes vary at most by only ~7 °C, all else being equal (Table 1). Table 1 shows the calcu-

Table 1
Near-Earth asteroids that have low ΔVs (close to that required to go to the moon) according to unpublished calculations of Leon Gefert and Melissa Franzen

Asteroid name/designation	Class	*a* (AU) (distance)	$T_{\text{black body}}$ (°C) (Class S)	$T_{\text{black body}}$ (°C) (Class M)	$T_{\text{black body}}$ (°C) (Class C)
1993-BX3	–	1.39	−30	−33	−35
2000-EA14	–	1.11	−1.1	−5	−7.0
1989-UQ	B	0.91	–	–	21
(4660)-Nereus	XE	1.48	–	–	−43
1998-KY26	CO	1.23	–	–	−20
(3361)-Orpheus	Q or V	1.20	−12	–	–
1998-VD32	–	1.10	1.0	−3.1	−5.1
2000-AG6	–	1.01	12	8.1	5.9
1998-SF36	$S_{(IV)}$	1.32	−23	–	–
1989-ML	X	1.27	–	–	−24
2000-AF205	–	1.03	10	5.5	3.4
1997-UR	–	1.45	35	−39	−40
(4581)-Asclepius	–	1.02	11	7.2	5
1993-PC	–	1.15	−5.6	−9.4	−11
1996-FG3	C	1.05	–	–	1.0
2000-AH205	S_k	1.14	−4.6	–	–
1999-AO10	–	0.912	28	24	21
(6239)-Minos	–	1.15	−5.3	−9.1	−11
1998-HL3	–	1.12	−2.6	−6.4	−8.4
2000-CH59	–	0.863	36	32	30

lated equilibrium temperatures for each of the asteroids considered as possible mission targets by Sears et al. (2001). The overall temperature range between asteroids located at 0.8–1.5 AU is between 36 and −43°C. More sophisticated treatments are possible, considering the conduction of heat from the front to the interior and back of the asteroid and the effect of shadowing for instance, but in view of the dominance of distance from the Sun in determining asteroid surface temperature this treatment is adequate for our present purposes.

2. Experimental details

Collectors were loaded with ~100 g of silicone substrate, in a 1 cm layer essentially free of gas bubbles, and then the collector was weighed. A sand–gravel mixture, consisting of 60 weight percent sand (300–425 μm grains) and 40 weight percent gravel (⩽1 cm in size) was used to model the asteroid regolith. The collector and sample regolith were then stored at −75, −50, −25, 23, 65, and 105 °C until thermocouples placed in the substrate and sample were stable for 30 min. The collector and sample pan were then placed on the laboratory bench, and the collector was positioned over the sample pan and pushed into the sample by hand using constant force. Trial experiments with weights and a balance indicated that the applied force (40 N) was constant to within ~20%. The collector was then weighed again to determine the amount of sample collected. In addition to these measurements, two of the −75 °C samples were allowed to warm to room temperature to see if the collector recovered its room temperature collection ability. We refer to these as the "temperature fluctuation recovery experiments."

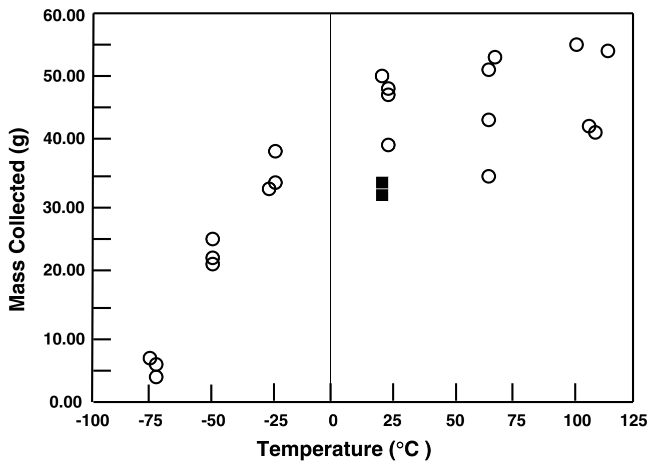

Fig. 2. Temperature dependence on the amount of sample collected by the prototype TGIP. While at −75 °C the effectiveness of the collector is reduced to about 13% of its room temperature level, the effectiveness increases linearly with temperature until 23 °C, above which it levels off. With modern research techniques, even 5 g would be considered a large amount of sample, but a judicious choice of conditions would ensure that the collector was used above 0 °C. The two overlapping black squares represent instances where the collectors were stored at −75 °C and then warmed to room temperature prior to sample collection to see if this affected their sample collection abilities. As can be seen, the ability of the substrate to collect samples was not significantly reduced by the low temperature excursion.

3. Results

Fig. 2 and Table 2 show the results of our experiments. At low temperatures the efficiency of the collector was reduced, being ~ 13% at −75 °C of the mass collected at room temperature. The mass collected increased approximately linearly as the temperature increased from −75 to

Table 2
Average sample mass collected at the corresponding temperature[a]

Temperature (°C)	−75	−50	−25	23	65	105	Temp. fluctuation recovery
Average mass collected (g)	6.06	22.97	34.71	46.14	45.30	54.44	33.87

[a] Experimental uncertainty on temperatures is typically 2.0 °C, based on accuracy of thermocouple and temperature gradients throughout the substrate and on masses is 10%, based on replicate measurements.

Fig. 3. The surface of the collector after sample collection. (Top left) −75 °C, (top middle) −50 °C, (top right) −25 °C, (bottom left) 23 °C, (bottom middle) 65 °C, (bottom right) 105 °C. Notice the frost on the samples below freezing and the small amount of substrate that flowed in the oven of the 105 °C sample; however, the substrate remained intact and still collected ample sample.

23 °C. Above 23 °C the amount of material collected leveled off.

The black squares in Fig. 2 represent the mass collected by the collector that had been cooled to −75 °C and then allowed to warm to room temperature. Apparently, the substrate recovered its ability to collect material to at least 80% of its original capacity, and within error may have been the same as the samples that did not experience the low temperature excursion.

Fig. 3 shows the collectors with their regolith samples in place. In all cases, significant amount of material was collected and firmly retained by the substrate. In these laboratory experiments, frost formed on the cold samples but this would not be the case for collectors in a vacuum. A small amount of flow occurred to the substrate for the warmest two temperatures the collector experienced, but this did not affect its collection efficiency.

4. Discussion

Our results suggest that over a very wide range of plausible asteroid surface temperatures our collector retains high collection efficiency. Even if the coldest temperatures used in our experiments are encountered on a mission, a scientifically significant mass of sample would be collected.

The reduction in collected mass as temperature decreased is due to the silicone substrate becoming increasingly viscous. At −75 °C, the substrate was essentially a frozen solid. This, along with the cold temperatures, caused the spring mechanism on the back of the collector to become rigid and unable to achieve its full motion. Spring mechanism motion was restored as temperature increased and achieved its full extent of movement at about room temperature.

The scatter in the amount of mass collected at higher temperatures is due to several factors. At high temperatures, the substrate in the collector tended to slightly flow and this left the substrate somewhat uneven. Thus, fewer samples were collected in the area where the substrate layer was thin. Another cause of scatter in the amount collected is small differences in the force applied. This was particularly important at high temperatures because the spring mechanism was free to move. However, the factor having the largest probable influence on the scatter in mass recovered was the heterogeneity of the surface and the relative proportions of sand and gravel collected.

Our experiments have shown that the silicone substrate used in these trials does not lose its ability to collect samples by temporary excursions to low temperatures and that the substrate can be flown on the spacecraft without much concern for storage temperature. What matters is mainly the temperature at the time of sample collection.

It is also apparent from these data that even if the mission calls for the collector to be used on an asteroid whose surface is well below 0 °C, battery or chemically powered heaters could be placed inside the substrate to bring it up to a sufficient sampling temperature just before the collection sequence begins. Alternatively, it might be that a judicious choice of collection longitude might be sufficient to warm the collector, for instance if the spacecraft is kept on the Sun-asteroid line it will be collecting at the subsolar point on the surface. More detailed calculations for estimating the temperatures on asteroids will need to be completed to get a better sense of the range of temperatures that may be associated with the target asteroid.

5. Conclusion

Sample return missions require a robust collector that can operate over a significant temperature range. The temperature experiments reported here (−75–105 °C) were conducted to determine if the operating temperature range of our collection substance (silicone substrate) is sufficient for sample collection on near-Earth asteroids. It was found that the mass of sample collected by the TGIP increased nearly linearly to 23 °C and then leveled off to between 45 and 55 g per collection at higher temperatures. Temperature fluctuation recovery experiments were performed which concluded that the collection substance does not lose its ability to collect sample after being frozen and then thawed. These experiments have shown that the TGIP can easily operate at temperatures expected on near-Earth asteroids and possibly in many other applications.

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