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DEMONSTRATION OF COMET SAMPLE COLLECTION BY PENETRATOR

Ralph D. Lorenz(1), William V. Boynton(1), Carl Turner(1)

(1)Lunar and Planetary Laboratory, University of Arizon, 1629 E. University Blvd., Tucson AZ 85721-0092, USA, E-mail: rlorenz@lpl.arizona.edu, wboynton@gamma1.lpl.arizona.edu

ABSTRACT

We describe laboratory tests to investigate and demonstrate the acquisition and encapsulation of a subsurface sample from a comet analogue using a coring penetrator. The penetrator imbeds itself in the target, coring out a sample during the impact itself. Mechanisms seal the sample in a canister and the canister is spring-ejected from the rear of the penetrator where it can be retrieved in free-flight by a mother spacecraft, which thus need not perform a landing. We describe the penetrator vehicle, sample preparation and testing technique using the large airgun at the University of Arizona, and the performance results which indicate the technique is an attractive option for comet nucleus sample return.

1. INTRODUCTION

The acquisition of samples from planetary bodies is a key step in their exploration – a returned sample allows a much more powerful arsenal of analytical techniques to be applied than is possible with in-situ investigations by spacecraft. However, the acquisition of a sample poses considerable technical challenges.

On small bodies, one particular challenge is the unknown physical environment (small scale topography, possible presence of gas jets, wide range of possible mechanical strength, variable and low gravity, etc.) which makes designing a lander extremely difficult. Then a sample acquisition mechanism (e.g. drill) presents further difficulties.

A much more affordable approach is to remove the desired sample with a small, expendable vehicle. Although kinetic samplers such as that to be used on the Japanese MUSES-C spacecraft can inexpensively acquire a mixed surface particulate sample, much more information can be derived if the target is not fragmented, end especially if vertical stratigraphy of the target surface can be preserved. This is particularly the case for volatile-rich comets. Hence, we propose a coring penetrator which can cut a cylindrical sample core using the kinetic energy of impact. The sample can be encapsulated in a sealed canister prior to ejection from the cometary surface.

Retrieval of the canister could possible employ a tether to the canister, although a safer and more flexible option is to use a telescoping sample capture mechanism .

2. PENETRATOR DESIGN

A key feature in our design is a strongly flared body (figure 1) shape to minimize the sensitivity of penetration depth on target strength – to ensure a modest penetration depth in both hard and soft targets. This approach is described in Boynton and Reinert [Ref.1]

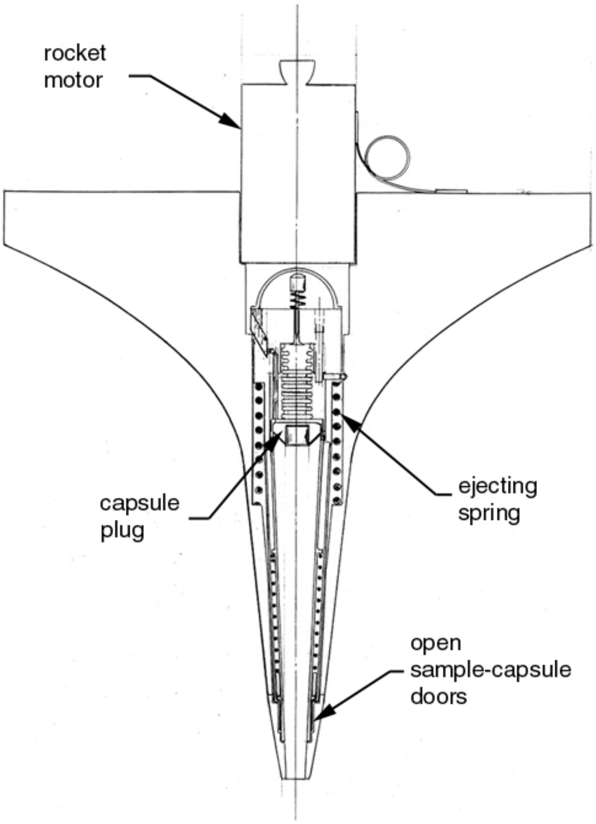

Fig. 1. Possible flight configuration of penetratorSolid rocket motor would accelerate penetrator into target and be jetissoned. Sample capsule would be ejected from the rear, through the space formerly occupied by the rocket motor.

A useful characteristic of the large radius flared end is that suitable choice of radius and mass distribution can ensure that – unlike most penetrators – the longitudinal axis is that with the highest moment of inertia. This characteristic makes spin-stabilization a viable option even for long coasts to the target, when energy dissipation in conventional penetrators would evolve the motion into a flat spin. Since penetration performance is strongly dependent on angle of attack at impact, the ability to passively ensure near-normal impact is a considerable advantage.

The shape and dimensions of the penetrator used in our tests are driven by the bore of the air cannon used to accelerate them : a flight unit might well be flared to a greater extent. An inert dummy penetrator was manufactured from steel for initial penetration tests. This unit (figure 2) had a straight 2.54cm-diameter hole in the center, and a mass of 20.3 kg.

Fig. 2. Penetrator test article. Note the conical nose with tapering bore to prevent bridging during sample acquisition.

Nose-shape optimization was performed via a series of tests with small (8-cm diameter, ~ 1.5kg) Lexan penetrators, with replaceable nozzles fired from the small airgun , principally into targets of FOAMGLAS, an open cell glass foam with reproducible and convenient mechanical properties (which have led to its use in previous comet penetration investigations [2]). A sharp lip on the nose gives the cleanest and most reliable core sampling, although is susceptible to mechanical damage either during handling or if multiple impact tests are performed. Hardened steel was used to minimize these problems

Raked noses (i.e. where the conical nose is cut at an angle less than 90 degrees to the longitudinal axis) were also investigated, but not found to enhance performance significantly.

Fig. 3 Small Lexan penetrators used to investigate and optimize nose characteristics for sample coring.

Fig. 4 Some of the internal springs and cylinders making up the sample encapsulation mechanism

The sampling penetrator design itself comprises several concentric cylinders – the sample canister, a mid-tube and the body of the penetrator itself. Several springs and other parts (several dozens) perform door-closing, and sample tamping and ejection functions.

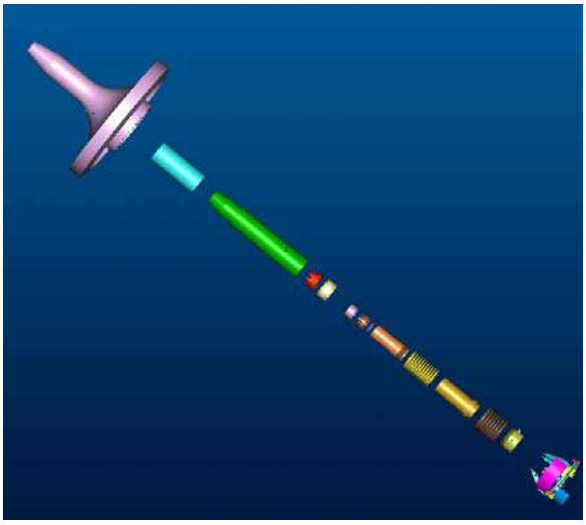

Fig. 5 Exploded view of flight-like penetrator components

3. AIRGUN TESTS

3.1 Air Gun

An 8-cm bore air gun facility has existed at the University of Arizona for over a decade, originally for the CRAF (Comet Rendezvous and Asteroid Flyby, sadly cancelled in 1992) penetrator. This gun has been used more recently in penetration tests of DS-2 forebodies [3] , and in studies of impact heating and triboelectric charging [4]. This facility was used in the nose-shape optimization trials, but was both too narrow for the coring penetrator and too short to accelerate the larger mass at acceptably low chamber pressures, the tank on the original gun being rated to only about 5 bar.

Thus a new gun was constructed, again in the basement of the LPL building. The barrel of the gun had a bore of 19cm and a useable length of 3.3m. The air tank used to drive the projectile was typically fired at a (gauge) pressure of only 0.7 bar. Larger pressures were not needed owing to the large volume of the airtank which kept the base pressure behind the projectile high, even as the volume behind it increased rapidly during acceleration. The pressure tank is rated to about 4 bar, but with our present configuration, this would have led to the projectile puncturing the concrete floor of the target area. Although higher pressures create elevated noise and safety concerns, the high rating leaves open expansion of the performance envelope for future tests.

Fig. 6. Airgun facilities at the University of Arizona : behind mesh safety screen is framework supporting main airgun – green airtank at upper right. Ceiling ipen at top to LPL loading area for insertion of penetrator into breech of gun. On extreme right is small 3-inch gun used in previous experiments. Penetrator is in foreground.

A pressure-sensor technique developed for launch speed determination from air cannons [5] is inaccurate for progressively longer barrels and was not used in these tests. A simple speed-gate was used wherein the projectile's time of passage between two positions marked with pencil leads is determined electrically by the open circuits induced as the projectile breaks the leads. Time was recorded simply using aport on a PC. No other realtime data acquisition was performed on these tests and the penetrator itself was not instrumented.

3.2 Target Preparation

It is of course well-known that comets are substantially made of water ice, and this substance therefore was the focus of our efforts. Handling ice targets large enough for penetration tests presents significant logistical challenges - it may be noted that the extensive tests for the DS-2 penetrators destined for the Martian polar terrain performed over 6 full-speed impact tests, but only two into ice targets, because of the difficulty of handling ice targets.

Targets were prepared in a large square steel bin. The bin was equipped with large wheels to permit feasible (if laborious) transport of the target to the base of the airgun. :When full with ice, the target had a mass of some 230kg. Since the thermal history of ice and ice-sand targets is a critical determinant of their mechanical properties, the bin was instrumented with a network of 22 thermocouples logged by a PC overnight as the target chilled. A pipework array permitted the injection of liquid nitrogen to achieve strong and even cooling. Over 100 liters of LN_2 was used per shot. A typical target temperature during firing was approx 190K (approx -80^{o}C)

To support the manufacture of tens of tests, an ice-making machine was procured. This facility produces >100kg of ice per day, precrushed into chunks of ~1cm. The ice machine was modified with a big door at one side towards its base and was mounted on a stand to allow easy scooping of flaked ice directly into a target bin.

A large domestic kitchen chest freezer was obtained and modified : . the lid was removed and replaced with a manufactured styrofoam lid. The base had a 1 inch exterior grade plywood on it to prevent the wheels of the ice bin from breaking the plastic interior wall of the freezer.

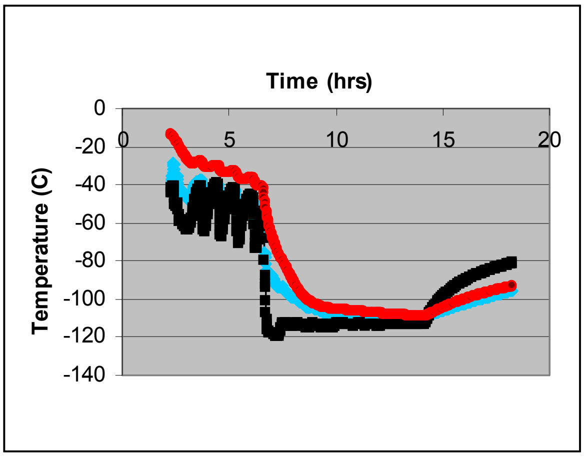

Fig. 7 Temperature history (at 3 different points in the target) of an ice target (October 2003) as it chilled overnight. Initial oscillations are due to application of a thermostat system to control the supply of liquid nitrogen. After a few hours the valves were simply held open until the following morning (~14 hrs after start) where the target was allowed to begin warming to ambient.

After the bin was filled with ice, it was wheeled into the freezer. The freezer's cooling capability proved inadequate to significantly chill this massive target, so target chilling was performed primarily with liquid nitrogen.

In order to create an artificial stratigraphy in the ice to determine the preservation of that stratigraphy in the sampled core, food coloring dye was sprayed onto the target as successive layers of ice were added. Stratigraphy created this way was somewhat irregular and had characteristic layer thicknesses of around 5cm, due to seepage of the dye through the ice. Coloured layers a factor of two or more thinner could be made by freezing dyed water in plastic plates and placing the puck of coloured ice into the target as it was assembled, where it subsequently annealed in place.

After a shot it took about 10 hours for the target to melt out, even assisted by a fan to blow ambient (outdoor – therefore warm) air over the target. Target preparation followed a two-day cycle, permitting two to three shots per week, with one of two target bins being filled and chilled while the other was shot and melted.

Additional logistic matters included a drain pipe to prevent the accumulation of meltwater on the floor after tests, and a security fence to control access to the icemaking equipment which was in an open loading bay in the LPL building.

3.3 Target Documentation

Several methods were used to characterize the target. Density was determined simply by weighing just prior to target installation, the volume of the target being known as the rigid container was filled to a consistent depth. The bulk density of the target material was determined to be between 550 and 750 kg/m^3

At the low temperatures of these tests, a shear vane gauge (where a cruciform vane is rotated to determine shear strength) had insufficient range to capture a strength measurement.

A conventional cone penetrometer was used (ROCTEST model HAS-5 – operator leans on handles to apply force along a rod to a cone, the stress on which is reported by a pressure gauge between the handles) : in some low density targets this indicated a strength of around 7 MPa although the coldest, densest targets exceeded the capability of this instrument (the operator could not apply enough weight onto the cone to cause penetration) and we estimate the strength at around 20 MPa.

In addition, a Shore D hardness was estimated with a small Durometer (wherein a metal pin is pushed into the target.) This measurement samples only one or two millimeters into the sample, and thus is not representative of the bulk target strength, and may be significantly affected by small-scale heterogeneities in the sample, and if the surface of the target is warming on exposure to air. Shore D values of 30-55 were obtained : although hardness and tensile strength are different physical properties (with the former only defined by the test method) it is encouraging that Shore D values of 45 are typical of plastics with tensile strengths of 10-20 MPa.

Note that our intent was principally to have reproducible conditions, rather than to explore the parameter space of target strength and density.

3.4 Firing Procedure

The target bin was moved by elevator to the basement, and wheeled beneath the gun (the barrel of which ended 1.75m above the floor) where it was securely held in place by two restraining bolts. The rubber wheels had very little compliance and are not believed to affect the penetration dynamics.

The projectile was prechilled, to prevent local melting on the walls of the penetrator after emplacement. It was removed from the freezer (generally it was stored with the target bin, to share cooling from the LN2) and lifted, using a small hydraulic crane, over the access hatch in the floor of the LPL loading dock. Just below this hatch is the breech of the airgun, some ~7m above the floor of the LPL basement two floors down. The operator climbed the gantry of the airgun to correctly insert the projectile in the breech and lock it in place, then installing the pressure pipe from the tank and firing valve.

4. PERFORMANCE

4.1 Penetration Performance

In general the firing conditions of the gun (i.e. the firing pressure of 0-1 bar) was chosen deliberately to cause full penetration, without going too deep (again to evaluate the capture performance under consistent conditions, rather than to explore penetration capability). Thus the penetration depth was of the order of 40cm. At the impact speeds of ~ 17 m/s, this penetration depth corresponds to average decelerations of ~40g. Gravity drops (no pressure) gave impact speeds of ~ 8 m/s.

The 5cm diameter of the projectile means the swept volume of target material was of the order of 200 cm^3 (somewhat less in that the nose was hollow, but compensated by the flare at the back). The kinetic energy of the 20kg penetrator at 18 m/s is around 3200 J, and thus the energy per unit volume dissipated in the target (a quantity which has the dimensions of strength) is around 16 MPa – again rather consistent with our strength estimates above.

Fig.8 Video frame (using normal camcorder) showing streaked image of penetrator entering target bin. Note the speedometer sensors at top, and the bin location framework.

It was observed that the penetrator typically tilted by a few (<5) degrees, although up to 15 degrees in two of the ~30 shots. It is believed that target inhomogeneities were responsible, as the vertical gun barrel did not permit substantial misalignments. The projectile was in each instance tightly embedded in the target, which bore a very detailed impression of the projectile, indicating coherent compaction and comminution.

Fig. 9. Penetrator embedded in target. Green ice is due to dye applied to ice at ~3cm depth to investigate stratigraphy preservation. Note the bar at back of penetrator, for actuating sample mechanism.

4.2 Sample Recovery

After the shot, two actuations are performed (initiated by hand, although in flight these would be performed by pyrotechnic devices.) One actuation is a tamper to preserve the stratigraphy of the acquired sample. In the event that the sample tube is incompletely filled (a situation that was in fact rather rare in our tests) the sample could rattle around and disaggregate, such that different depths in the acquired column would be mixed. Accordingly, a tamper is pushed by spring down into the sample tube to constrain the sample. It must be acknowledged that very soft or porous targets may be deformed somewhat by this process, but vertical composition and structure is largely retained.

The other actuation is the sample doors. These are four sections of a cone that are pushed forwards and inwards to close the front of the sample chamber, through which the sample enters on impact. The door springs are strong enough to cut through the sample, although in three tests the door closure failed. In test #2, this was due to a single large ice cube that was unluckily sited at the apex of the door closure path. In test #9 one door did not deploy for unknown reasons, and in test #32 it is believed excessive chilling of the penetrator prior to the shot formed frost which seized the door mechanism prior to firing.

Fig 10. Nose-on view of the sample canister after successful acquisition of an ice target, showing the cruciform arrangement of the four conical nose doors, tightly shut in this instance.

Finally, a third actuation would be performed, namely the ejection by spring of the sample capsule. The capsule is ejected at several meters per second, requiring considerable spring energy which presents difficult assembly and safety issues, and the sample must be restrained by a tether. This actuation was only attempted twice because of the substantial effort involved, but did not succeed.

4.3 Sample collection Performance

The sample collection performance was documented by inspection of the penetrator after its removal from the target. The penetrator often had to be warmed with a heat gun to suppress the adhesion of the sample to the walls of the sample capsule, but typically could then be removed as a single piece.

Fig. 11 Opening sample canister – blue-dyed ice inside. Note the thick orange rubber glove and frosting on the canister body – the sample is still at ~-60°C.

Fig. 12. Ice core recovered from penetrator. Note the narrow section at front, corresponding to the deepest part of the core. Note that the colors of dyed ice layers remain distinct – straigraphy has been preserved with a vertical resolution comparable with the core diameter.

The overall length of the acquired sample, and its structural integrity were apparent from visual inspection. The preservation of target stratigraphy was also apparent at this point. A better quantitative measure of the acquired sample mass was made by melting the sample and pouring the result into a measuring cylinder.

This sample mass was compared with the theoretical limit of the volume of the sample chamber multiplied by the bulk density of the target material. The resulting Sample Collection Ratio (SCR) was generally in the range of 75-100%

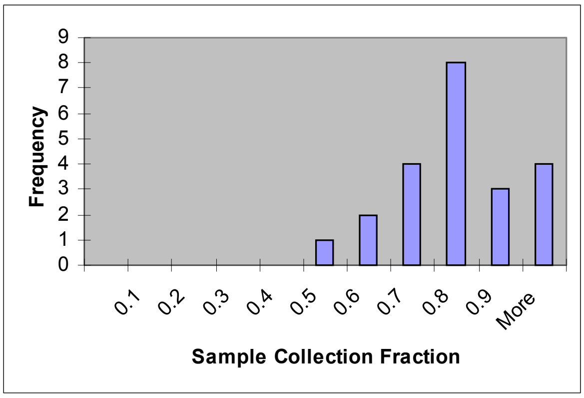

Fig.13 Sample collection fraction (based on target volume but sample mass – sample compaction can give SCR>1. In 21 tests only 3 gave <70% collection

4.4 Other Targets

In addition to the flaked ice targets a handful of tests were performed into dry sand. This is of course an unlikely constitution for a cometary surface. Two tests with the dummy penetrator yielded penetration depths similar to those for ice. One test with the full penetrator led to seizing of the mechanism threads which were not protected from the sand, and the sample drained out between the doors. Note that a brand new sampler may have performed acceptably – it is possible the doors were partly deformed after repeated ice impacts.

Rather better performance, indeed broadly equivalent to pure ice targets, was found with mixed sand-ice targets (approx 20kg of sand per target, or ~ 5% by volume) : sand and ice layering was well-preserved.

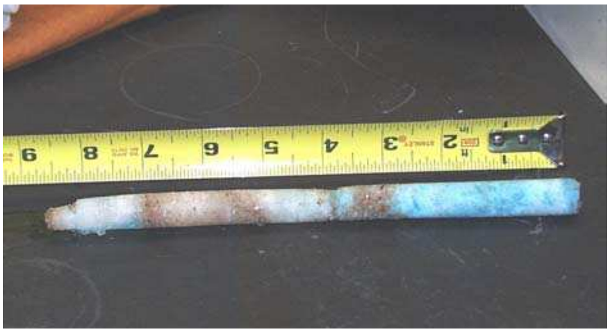

Fig. 14. Layering preserved in narrow sand-ice core.

5. SAMPLE EJECTION

The sample ejection process is the most hazardous part of the tests reported here – the sample ejection spring is sized to launch the canister backwards at ~ 5 m/s (enough to jump 26 inches). If the spring were released without engaging the canister, operator injury might result – and recall that the spring release is performed manually in the test configuration.

Accordingly, the sample ejection was performed only once at the end of the project. Two initial attempts failed : the first because of over-energetic penetration, puncturing a phone-book used as a buffer at the bottom of the target bin – the compression of ice in the sample canister deformed the capsule and prevented release ; the second failed because the projectile thermal history had permitted a frost deposit to form between the mid tube and the sample. After removal of the frost and adjustment of the retention pins, the ejection was performed successfully.

6. CONCLUSIONS

We have designed a sampling penetrator and demonstrated its ability to deploy in likely cometary (porous ice) targets and eject an encapsulated stratigraphy-preserving sample.

This demonstration indicates that sampling penetrators are a viable option for comet nucleus and other sample return missions.

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