Application of Pneumatics in Delivering Samples to Instruments on Planetary Missions

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Abstract—**Traditional sample acquisition, transfer and capture approaches rely on mechanical methods (e.g. drill or a scoop) to acquire a sample, mechanical methods (e.g. robotic arm) to transfer the sample and gravity to capture the sample inside an instrument or a sample return container. This approach has some limitations: because of reliance on gravity, it is only suited to materials with no or little cohesion. Because of the sample transfer requiring mechanical system, the instrument or sample return container need to be easily accessible.**

Pneumatic based systems solve these problems because the pneumatic force can exceed the gravitational force and the sample delivery tubing can be routed around other spacecraft elements, making instrument or sample return container placement irrelevant to the sampling system.

This paper presents background to pneumatic system applied to planetary missions and provides examples how this could be accomplished on planetary bodies with significant atmosphere (Venus and Titan) and on airless bodies (the Moon, Europa, Ceres).

TABLE OF CONTENTS

1. INTRODUCTION 1
2. APPLICATIONS OF PNEUMATICS IN SPACE MISSIONS 2
3. BACKGROUND TO SAMPLE ACQUISITION, TRANSFER, AND CAPTURE 3
4. CASE STUDY: TITAN 6
5. CASE STUDY: MOON 8
7. SUMMARY 9
ACKNOWLEDGEMENTS 9
REFERENCES 9
BIOGRAPHY 10

1. INTRODUCTION

A vast majority of planetary surface missions require sample acquisition and in situ analysis to reach their scientific and exploration goals. The most notable examples of such missions include Viking 1 and 2 landers, Mars Phoenix lander, and the Curiosity rover. All four of these missions used a scoop to deliver a sample to either a sample processing/sieving system or directly into an instrument.

The above-mentioned sample transfer approaches relied on gravity, since the sample would gravity fall out of the scoop. As such, they worked well with material that had no cohesion and in turn flowed easily. However, if material becomes cohesive, the cohesion forces dominate and gravity driven sample transfer fails. This behavior, in fact, has been observed on Mars Phoenix mission. The icy soil inside the Phoenix scoop, called the Icy Soil Acquisition Device or ISAD, failed to gravity fall out of the scoop when the scoop was placed above the instrument's inlet port (Figure 1). The problem was traced back to sintering between the icy soil grains and the aluminum scoop walls. The sintering process was caused by the "warm" scoop, which was exposed to the direct sunlight.

Another problem with traditional gravity driven sample transfer and processing methods is difficulty with metering samples for instruments that require known sample volumes. For example, GCMS requires approximately 50 milliliters, and if the sample has any significant cohesion, metering out such a small volume would be difficult or even impossible. Curiosity rover drilling system creates a mini

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hole in order to examine cuttings and in particular, determine whether they are cohesive (Figure 2). If cohesion is observed, further drilling and sample acquisition for delivery into instruments will not be performed, since cohesive cuttings would clog the sample processing system.

The approach the Curiosity follows for avoiding cohesive materials only works on mobile exploratory platforms. If the mission is lander-based, and the site it lands on has only cohesive material, the sample transfer operation will most likely fail and in turn the mission's science goal will not be achieved.

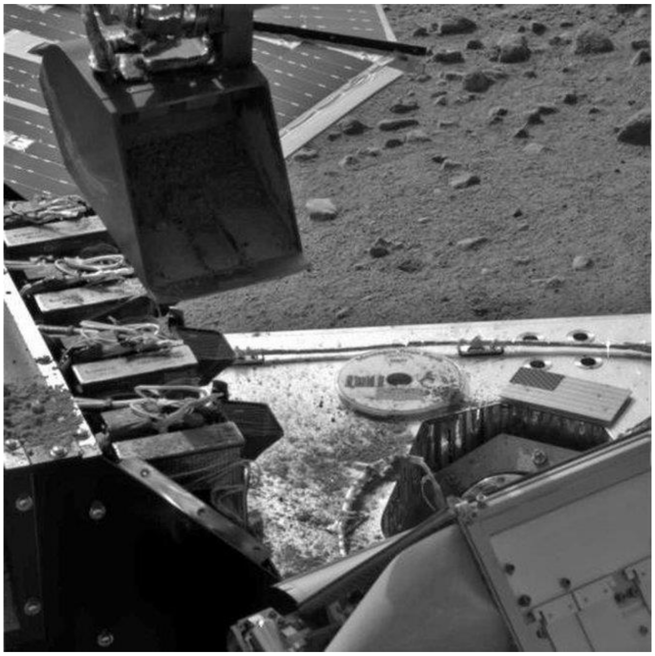

Figure 1. The Mars Phoenix's Icy Soil Acquisition Device (ISAD) encountered problems when delivering cohesive samples. In addition, poor control of scoop placement resulted in sample being spilled onto adjacent cups.

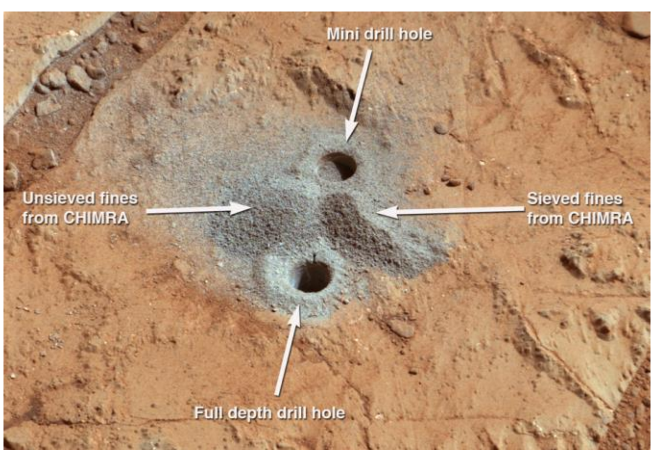

Figure 2. Mini drill hole on Curiosity is drilled to determine if cuttings are cohesive and in turn can be processed by the sieving system.

The past worked clearly illustrates the risk of relying on gravity to transfer and meter out the samples. The risk is significantly higher on landers, which have limited site selection ability, and lower on rovers, that can drive further and seek out material that will be more cooperative (but not necessarily of the same scientific value).

This paper describes pneumatic sample transfer and metering that can be applied to various instrument types. Pneumatic transfer can generate significantly higher forces than either gravitational or cohesive forces.

2. APPLICATIONS OF PNEUMATICS IN SPACE MISSIONS

The pneumatic approach works on planetary bodies with atmosphere (Venus, Titan), and in bodies with little or no atmosphere (Mars, Moon, Europa). The main difference is how the pneumatic transfer is achieved. On planetary bodies with atmosphere, pneumatic transfer can be achieved via a blower (as in traditional vacuum cleaners) that creates suction at the blower end, while on planetary bodies having little or no atmosphere, pneumatic transfer is achieved using compressed air that is injected behind the sample.

The potential of pneumatics for sample acquisition and transfer was recognized early in planetary exploration. For example, a prototype of the "Wolf Trap" (named after its inventor, Wolf Vishniac) was developed in the 1960s and used a small high-pressure gas tank to blow dust into a chamber containing a culture medium [1]. If biota were present in the dust, their growth would cause time-variation of turbidity, indicated with a simple optical detector. The instrument was not flown, however.

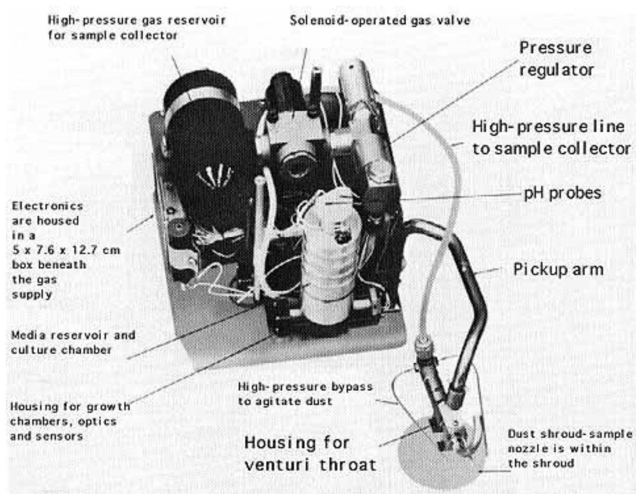

Figure 3. Breadboard of the Vishniac Wolf Trap life detection instrument, prototyped for the Viking lander but not flown. This system used a pneumatic sample acquisition and transfer [2].

The first actual use of pneumatic sample acquisition on another planet was demonstrated on Soviet Venera 13 mission (Figure 4). The sample was vacuum suctioned onto a shuttle, which was then pneumatically moved into an instrument port. The suction was achieved using vacuum in the transfer line that was opened to draw in Venus atmosphere and the drilled cuttings.

The shuttle transfer to the instrument was also achieved using gas generated from a pyrotechnique device. Upon accelerating, the shuttle hit a hard stop, just before the instrument, and the sample was sprayed onto an observation tray underneath the X-ray fluorescence spectrometer. Hence, the pneumatic transfer was only used to acquire a sample but not to meter out the sample or position the sample underneath the instrument's sensor head. Nevertheless, the sample transfer method was highly reliable and very simple. The entire transfer chain required actuation of just four pyrotechnique devices.

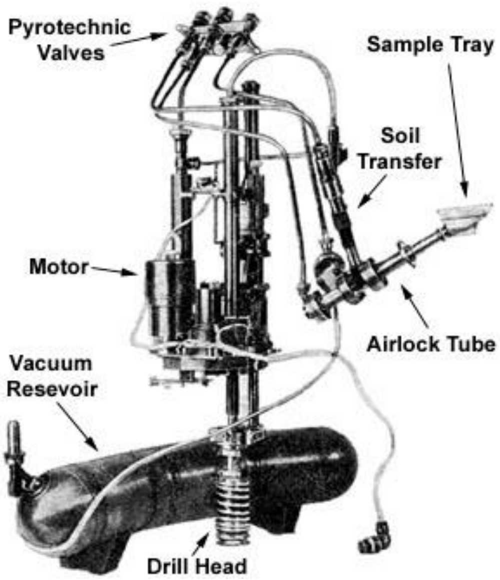

Figure 4. Venera 13 demonstrated pneumatic sample acquisition on Venus [3].

The use of pneumatic system for sample acquisition and transfer into an instrument cup was first proposed and demonstrated for lunar exploration and In Situ Resource Utilization (ISRU) tasks [4]. The pneumatic approach was further expanded into numerous applications such as regolith mining [5], regolith delivery to a carbothermal reactor [6], sample delivery to a sample return container [7, 8, 9], trenching/cleaning rocks [10,11], and drilling [12]. Additionally, the Viking lander carried jets fed by a small CO_2 tank to blow dust from the camera windows : although they were operated on several occasions, they were not found to be necessary [13].

The pneumatic transfer was also tested at $1/6^{th}$ g and vacuum and demonstrated significant efficiency ratio. With just 1 gram of gas, close to 6000 grams of JSC-1a lunar soil simulant was transferred to a container [14].

Sullivan et al., [15] tested pneumatic transfer of particles at $1/6^{th}$ g and 1 ATM pressure for the purpose of lunar ISRU. The primary application was to enable pneumatic transfer of lunar regolith on the Moon in a closed loop pneumatic cycle. During the tests, it was determined that the choking velocity (velocity required to keep particles afloat in a vertical transfer) for 150 µm glass spheres at lunar gravity was 1/2-1/3 the velocity required at 1 g.

Honeybee Robotics also developed sample processing system that included crushing, sieving, sample transfer, and metering [16]. The second and third steps were achieved using pneumatic system, while the final step used traditional gravity fed metering. It was determined that the gravity metering worked well with non-cohesive samples. However, even with non-cohesive samples, some level of cross contamination was observed. The pneumatic sieving approach using Air-Jet Sieve as well as pneumatic sample transfer worked well with cohesive and non-cohesive samples.

3. Background to Sample Acquisition, Transfer, and Capture

The sample delivery chain can be divided into three steps: 1. Sample Acquisition, Sample Transfer, and Sample Capture. These steps are further described below.

Sample Acquisition

Sample acquisition refers to acquiring a sample from an excavation device, whether it's a drill or a scoop, or some other passive or active system. In the case of pneumatic system, to acquire a sample, sufficient gas force needs to be applied to a particle to exceed local gravity and/or any other cohesive or electrostatic forces.

On Venus and Titan, sample acquisition can be achieved using a suction approach, whereby a blower at the back end, would draw in atmospheric air. The sample acquisition can also use Venturi effect, whereby a blower could generate air flow for Venturi nozzle. Venturi principle is used in dredging operations and to mine diamonds from the bottom of the oceans off the coast of Namibia. As mentioned earlier, direct suction was used on Venera missions; but instead of a blower a suction was achieved when the seal between the outside and vacuum inside the sample transfer tube was broken. This of course implies that the Venera approach could only work once. If the pneumatic system uses a blower, sample acquisition can occur every time the blower is turned on.

Figure 5 and Figure 6 show two examples of incorporating pneumatic system with a drill. The obvious advantage of having a drill is that it can access material from greater depths and that it can penetrate competent materials/rocks. In Figure 5, the hollow drill bit allows material to be suctioned as it is being drilled into an instrument. In Figure 6, the drill needs to bring material to the surface (e.g. using an auger) before it can be suctioned into an instrument. The main advantage of the latter approach is that the two systems (drill and pneumatics) are decoupled; this allows parallel development effort and use of pneumatics independently from the drill.

Sample acquisition approaches using a blower were proposed and further evaluated for Venus [17] and Titan [18, 19]. The test data demonstrated efficient and effective transfer with a range of materials, representing various degree of cohesion and particle sizes.

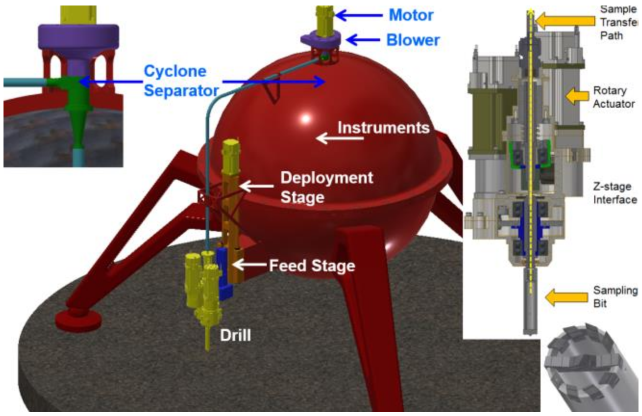

Figure 5. Venus sampling system uses hollow drill bit that generates fine powder and blower-based suction system for sample delivery. This approach could also work on Titan.

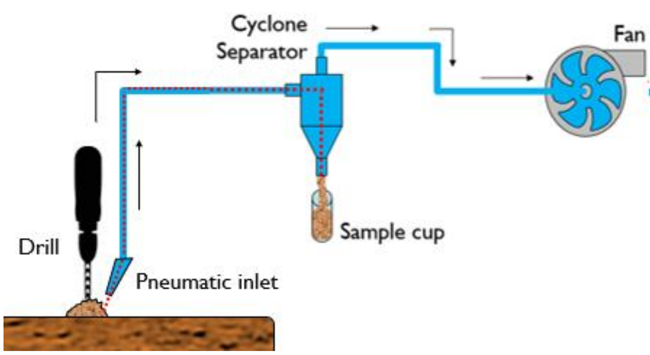

Figure 6. Drill can access material from greater depths and penetrate rocks, while pneumatics can move the sample into instruments.

On Mars, the Moon, and Europa, sample acquisition can be achieved using compressed air that accelerates particles into a transfer tube or a container. There are again many variations of how this can be achieved. For example, gas can be injected into the regolith and later 'escape' into vacuum while accelerating regolith particles (Figure 7). This is also observed when spacecraft propulsive lands on a planetary surface covered with regolith. During landing, gas from rocket thruster penetrates regolith underneath the thruster. Once the engine shuts off, the gas pressure inside the regolith is no longer sustained by the gas pressure from the engine thrust, and the gas escapes upwards, carrying regolith with it (Curiosity's weather station was damaged by rocklets being blow upwards this way).

If particles are captured inside a sampling tube, gas could be injected at the bottom of the tube and move the sample directly into a container (Figure 7). The sampling tube could be either pushed into the surface during landing (passive option) or pushed into the surface after landing (e.g. using a preloaded spring).

Compressed gas could also be used as a "broom" to sweep particles from the planetary surface or the scoop into a container or a transfer tube (Figure 8). For this to happen, gas jets need to be at a relatively shallow angle to the horizontal and pointed towards the collection container [20]. Several nozzles could be placed in strategic locations to enable more efficient transfer; some could be pointed towards the surface and some towards the sample container. The firing of the gas jets would need to be synchronized; the jets pointed towards the ground would fire up first to stir up the sample and the jets pointed towards the container would fire some fraction of a second later to move the loosened up regolith into the container.

Figure 9 shows a combination of the pneumatic sample acquisition and a drill. In this example, the drill is used to either bring samples from greater depths to the surface and/or to pulverize competent formation (e.g. rock).

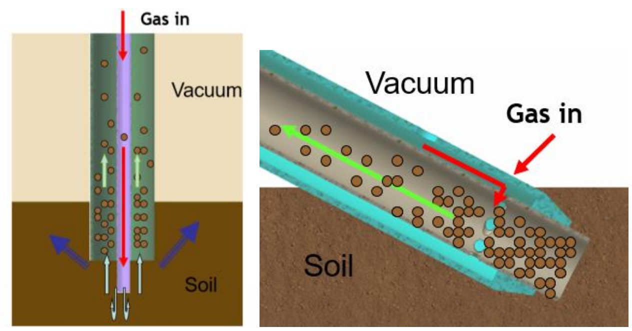

Figure 7. Options for pneumatic sample acquisition.

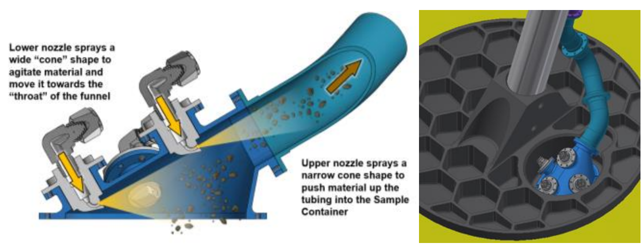

Figure 8. PlanetVac style sample acquisition.

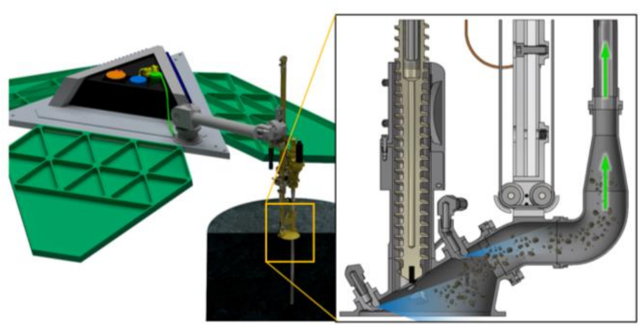

Figure 9. Implementation of the PlanetVac sample acquisition with a drill, enables sampling from greater depths and/or sampling of rocks.

In selecting the best approach for the pneumatic acquisition, other requirements such as spacecraft accommodation or allowable sampling bias needs to be considered. In particular, some sample acquisition approaches could be used to preferentially acquire finer material; this could be an advantage or a disadvantage. If minimizing sample bias is critical to the mission success, approaches such as PlanetVac would be more desirable (Figure 8). PlanetVac captures all the particles and in turn the final sample is a good representation of the original sample, in terms of particle sizes.

Sample Transfer

Once the sample has been acquired using either atmospheric air or compressed gas, it needs to be transported from the point of acquisition to either an instrument, or a sample return container. The critical aspect of such a transfer is to keep the particles afloat in the gas stream; this requires having velocities above choking and saltation velocities, which control vertical and horizontal flow, respectively. Additional gas nozzles could be placed along the transfer tube to boost the air or gas flow. Appropriate sizing of the tubes is critical to maintain pressure difference.

The main advantage of the pneumatic transfer is that the point of acquisition and point of delivery can be literally anywhere on the spacecraft. Unlike scoops deployed by robotic arms, that are constrained by kinematic position of the arm, and placement of instruments, pneumatic transfer lines can be routed around potential obstacles. As such, sample acquisition hardware can be placed where it's best for sample acquisition, and instruments can be placed in the best location for performing analysis.

There are other advantages of using pneumatics in sample transfer. For example, heating of sample is minimized or even can be prevented altogether. When the atmospheric air is used for sample transfer, the sample will experience the same temperature as it has been exposed to before. When using compressed gas, the sample temperature will more likely go down as opposed to up, since gas temperature will drop as it is released from a pressurized gas tank. However, since gas has very low thermal inertia and transfer happens very fast (seconds), the probability of thermal alteration is virtually null.

The pneumatic transfer also offers significant reduction in cross contamination between sampling events. Air or gas can be used before or after each sampling event to clean up the transfer lines of any residue, and even to thermally precondition the lines prior to transfer.

Sample Capture

Sample capture is characterized by separating particles from a gas stream; that is particles need to be captured into a container while gas needs to be vented to the outside. During this step, sample bias could occur since it might be very difficult to capture all of the particles. The sample bias will favor fine particles (microns in size, and less), which are difficult to remove from the airstream.

Sample capture approaches are a function of a mission profile (in-situ analysis vs sample return) as well as the type of instruments that require a sample. In general, there are three approaches to sample capture: Modified Cyclone, Deflector Plate, and Tea Strainer (Figure 10 and Table 1). Cyclone separators could also be considered; however because sample separation in cyclones rely on gravity, their application would be constrained to a non-cohesive materials only.

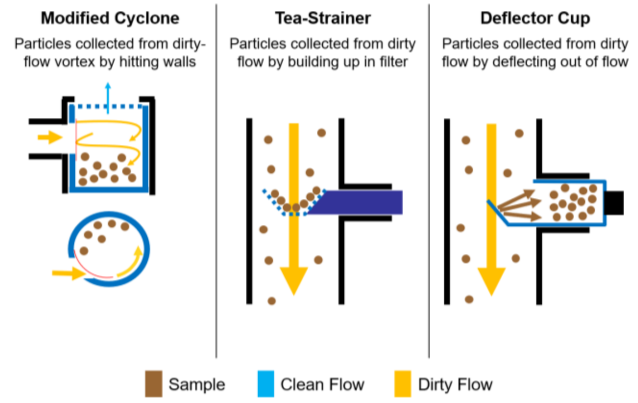

Figure 10. Sample capture options.

Table 1. Attributes of the sample capture options.

	Modified Cyclone	**Tea-Strainer**	**Deflector Cup**
Operational Mechanism	Solids in vortex flow hit walls and slow down	Mesh catches solids suspended in flow	Solids deflected out of flow and into sample cup
Cross-Contamination	Uncollected sample passes through system		
	Scalable for single-use sample cups		
Self-Metering	Yes (full sample cup)	Yes (clogged filter)	Yes (full sample cup)
Sample Bias	Larger particles	Depends on mesh	
	All particles	First particles	
Collection Efficiency	Efficient (>99%)	Inefficient (<5%)	

In the Modified Cyclone, the tapered cyclone section is removed, and the sample is captured inside the main body. The gas and particles enter the main body off center, which allows the cyclonic effect. Friction against the wall slows the particles down, while gas escapes through the filter on top. Hence the size of this filter dictates the sample particle bias. In this approach, all sample is captured inside the container. The container could be removed and transferred to instruments and new container could be inserted into the feed station. This approach has been used for PlanetVac-Xombie test campaign [21].

In the Deflector Plate approach (Figure 11), a cup with a deflector plate is inserted directly into a transfer tube. Some particles will naturally flow around the deflector plate and out, while some will hit the plate and deflect into a cup underneath. This approach is well suited for instruments that require extremely small, and known sample volume, such as GCMS.

The Tea Strainer approach is similar to the Deflector Plate – the difference is that the Deflector Plate is a screen. Hence the sample is captured directly into the screen. The Tea Strainer can then be presented in front of the instruments such as a microscopic imager, LIBS, RAMAN, LDMS, and other. Figure 11 shows the Tea Strainer and the Deflector Cup prototypes after successfully capturing very cohesive material.

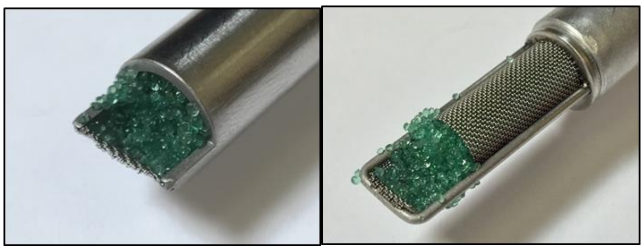

Figure 11. Successful tests using cohesive material were performed with a Deflector Cup (left) and Tea Strainer (right).

Figure 12 shows possible orientation of cups in a carousel. Some other orientations (e.g. at 45°) are also possible and should be driven by instrument placement and requirements.

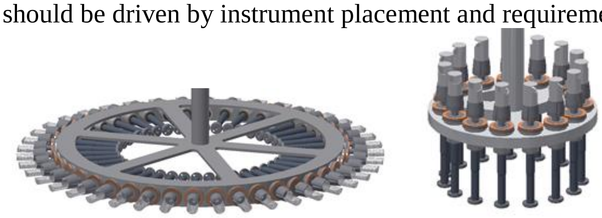

Figure 12. Cups can be placed in horizontal or vertical orientation, depending on instrument requirements.

Each of the cups will be inserted into the air stream to capture the material, pulled out, and placed or inserted into an instrument as shown in **Figure 13**.

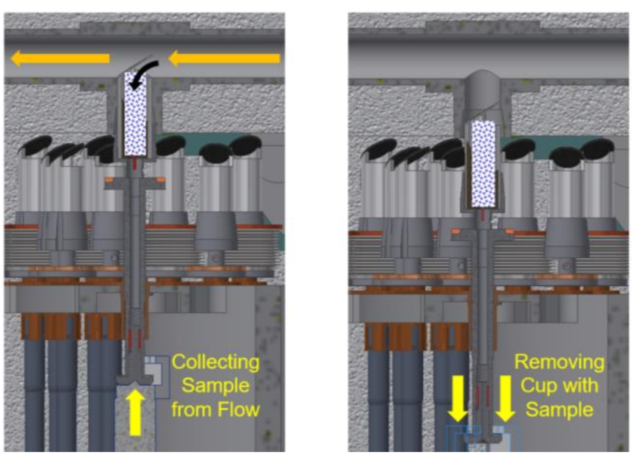

Figure 13. To capture a sample, the cup is inserted into air stream.

4. Case Study: TITAN

This section presents an example of the end to end sample acquisition, transfer, and capture for Titan. This approach could also be used on Venus.

Likely constituents of Titan's surface include water ice (which at Titan's surface temperature of 94K is hard as rock), water-ammonia ice (i.e. frozen ammonia hydrate), and photochemically-derived organics (not just hydrocarbons, but nitrogen-bearing molecules too). The latter, likely polycyclic aromatic hydrocarbons (PAHs) and material resembling laboratory analogs "tholin" forms giant sand dunes: the fact that they form dunes suggests the material is somewhat resistant to abrasion, but this is in part due to the low energies of aeolian transport on Titan: microindentation measurements show that tholins at 94K have Young's modulus and fracture toughness an order of magnitude smaller than silicate sand [23]. Simpler organics (benzene, alkanes; acetonitrile or acrylonitrile) may also be present, perhaps as evaporite deposits- these materials at 94K are waxy solids with hardness comparable with soft rocks (talc, halite etc.) [24].

Dry sand is of course rather easy to transfer pneumatically (noting the density of organics is less than for terrestrial rocks, and that Titan's atmosphere is denser than ours). Solid ice or organics will require a drill to generate fines for transfer: tests on a prototype drill have shown that ice and paraffin wax form suitable cuttings at 94K with either rotary-percussive or rotary-only drilling, ammonia-water softened under rotary-only drilling, but generated good cuttings with rotary-percussive action [25].

Since Titan has a hydrological cycle (with methane rather than water as the working fluid), the possibility exists that damp materials, with appreciable cohesion, could be encountered [26]. Indeed, the ground at the Huygens landing site was assessed to be damp with methane and ethane.

To assess the performance of pneumatic transfer of cohesive materials, we have performed tests with a laboratory mockup of the Titan system and evaluated the flow speeds required for efficient transport. A 10:1 mixture of silicate sand and canola oil was used as a 'pathological' benchmark material (vegetable oil was used to avoid material disposal concerns; sand made damp with water tended to quickly dry in the airstream and so was not a challenging test).

Very fine-grained materials such as wheat flour and crushed paraffin wax could be transferred at rather low flow speeds (just 1-2 m/s), although some material adhered to the transfer hose due to triboelectric charging. The use of an electrically-conductive hose will mitigate this effect.

As Figure 14 shows, even the challenging oil:sand mixtures can be effectively conveyed with air velocities of 30 m/s or less (with terrestrial air, 4x lower in density than Titan atmosphere): a simple centrifugal blower is readily able to provide such airflow with power of a few hundred Watts. Such high transfer velocities also minimize size-fractionation effects in cohesionless samples, in that all sizes (up to the width of inlet apertures) are efficiently conveyed. Since the pneumatic transfer system draws in ambient air, the sample is maintained at ambient temperature (and thus is not altered by heating). The blower can be operated for a period before drilling in order to chill down the pipework.

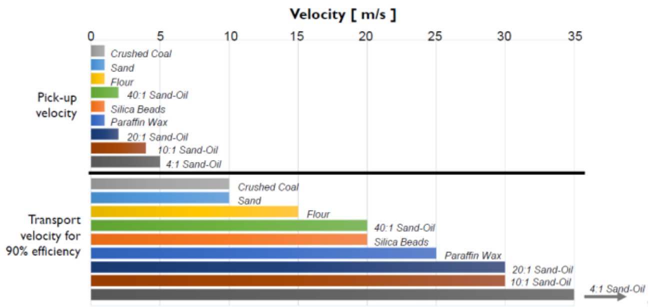

Figure 14. Transport velocity measurements from testbed experiments.

Figure 15 shows experimental setup that was used to show case THE end to end system. The sample acquisition subsystem included the Drill with a tapered Drill Bit, and Suction Nozzle to the side of the Drill Bit (the nozzle vertical motion was independent from the drill bit). The sample transfer included the Transfer Tube, Suction Hose, and Blower (not shown). The sample capture included the Feed Stage with the Cup having a Deflector.

The sequence included the following steps:

Feed: during this stage the Drill would move down towards the rock until the load cell registered resistance, indicating the drill bit touched the surface.

Sample Acquisition/Drilling: during this stage, the Drill would rotate (and percuss, if necessary) to penetrate target depth.

Sample Transfer: during this stage, which can occur at the same time or after the Drilling stage, the sample would be vacuum suction through the Transfer Tube, Feed Station, and escape through the Suction Hose.

Sample Capture: during this stage, which occurred at the same time as Sample transfer, some of the suctioned material in the air stream would hit and deflect off the Deflector plate and ballistically enter the Cup.

During the experiment shown in **Figure 15**, the drilled material included gypsum, which upon drilling, created extremely cohesive powder. Such a cohesive material would be extremely difficult to transfer using a scoop, and even more difficult to meter out into a small cup. Significant residue would be left behind in any non-pneumatic transfer approach.

The level of cohesion could be visually estimated by the fact that upon completion of drilling, some of the material stuck to the outside of the drill bit. In actual implementation, both the drill bit would have brushes to clean up the Suction Nozzle and the Suction Nozzle would have brushes to clean up the Drill Bit. The Suction Nozzle brushes would be more compliant (weaker) so as to deflect when passing through the brushes attached to the Drill Bit. The different in bristles stiffness is important in preventing damage to the brushes.

Drilling to 2 cm depth and transferring the sample took approximately 1 minute. Upon inspection of the cup, it was noticed that the cup was full of sample, successfully demonstrating sample acquisition, transfer, and capture of cohesive material.

The blower was turned on after the test to clean up the Transfer Tube and Feed Station.

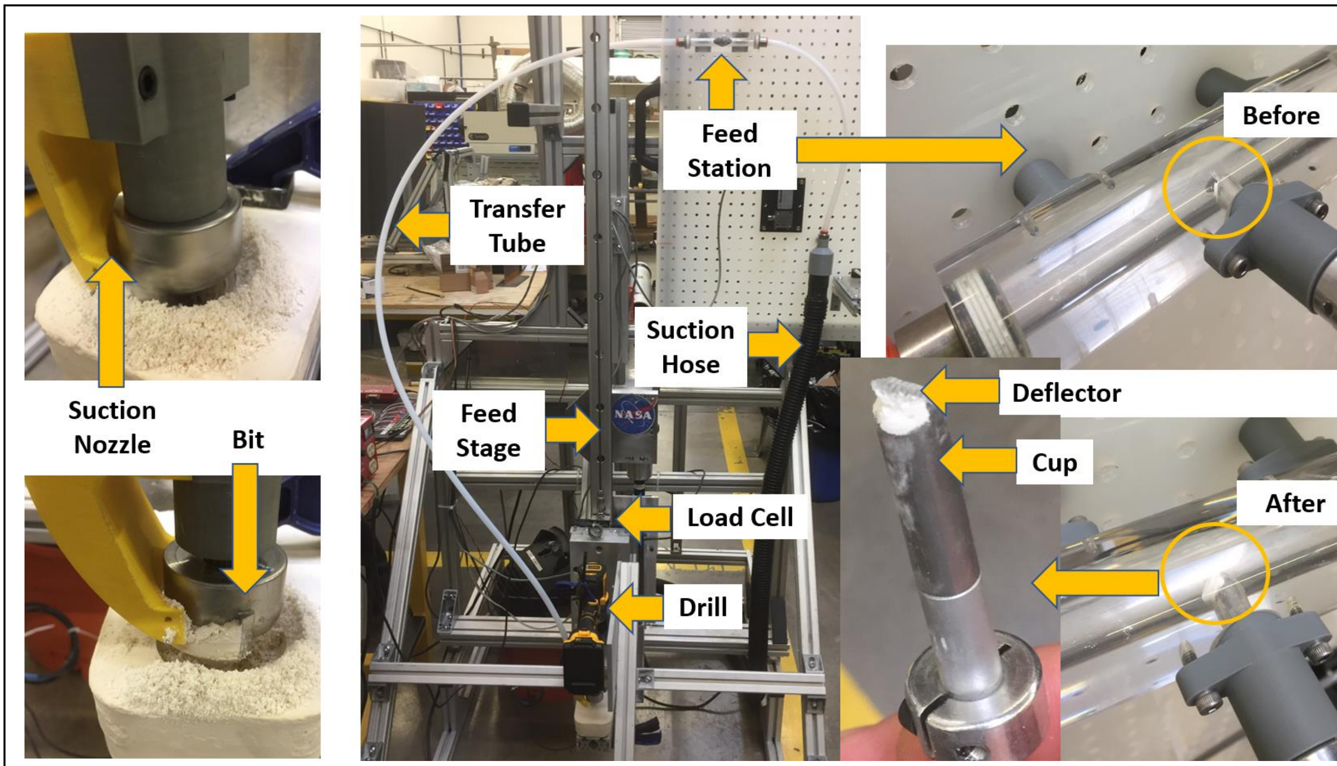

Figure 15. Experimental setup for suction-based sample acquisition, transfer, and capture.

5. Case Study: The Moon

This section presents an example of the end to end sample acquisition, transfer, and capture for the Moon and other airless bodies, such as Ceres and Europa.

Figure 16 shows experimental setup that was used to show case the end to end system. The sample acquisition subsystem included the PlanetVac with required nozzles attached to a compressed air. The sample transfer included the Transfer Tube and the Outlet Hose (Optional). The sample capture included the Feed Stage with the Sieve, Cup #1 and Cup #2. The purpose of the Sieve with 1 cm holes was to bias sample towards the coarse fraction in Cup #1 and capture finer material in Cup #2. Depending on the mission profile, the desired sample could be in Cup #1 (coarse material) or Cup #2 (fine material).

The sequence included the following steps:

Sample Acquisition: during this stage the compressed air (100 psi) would be directed towards the sample via the nozzles, stir up the material underneath, and push it up the Transfer Tube.

Sample Transfer: during this stage, which occurred at the same time as the Sample Acquisition, the sample would flow through the Transfer Tube, the Feed Station, and escape through the Outlet Hose.

Sample Capture: during this stage, which occurred at the same time as Sample Transfer, coarser fraction of the material in the air stream would hit and deflect off the Sieve and ballistically enter the Cup #1. The finer fraction would pass through the Screen and be collected in Cup #2.

During the actual experiment, the material included crushed aircrete with density of 0.42 g/cc. This low density aircrete was used to simulate lower gravity on for example the Moon (given that lunar Basalt or Anorthosites has a density of ~ 3g/cc, scaling for 1/6th gravity requires particle to have a density of ~0.5 g/cc during tests at 1g). Since gravity has significant effect on pneumatic transfer, the analog material density needs to be appropriately scaled for gravity.

During the 20 second experiment, 100 cc (~52 g) of sample was captured in Cup #1, and 800 cc (478 grams) of material was captured in Cup #2. Inspection of particle size distribution of the original material, the Cup #1 Sample, and the Cup #2 Sample, indicated that Cup #1 had predominantly coarse material and the Cup #2 had predominantly fine material (Figure 17). In fact, Cup #2, did not have material greater than 1 cm (the size of the Sieve opening) and only a few 5 mm particles (Table 2).

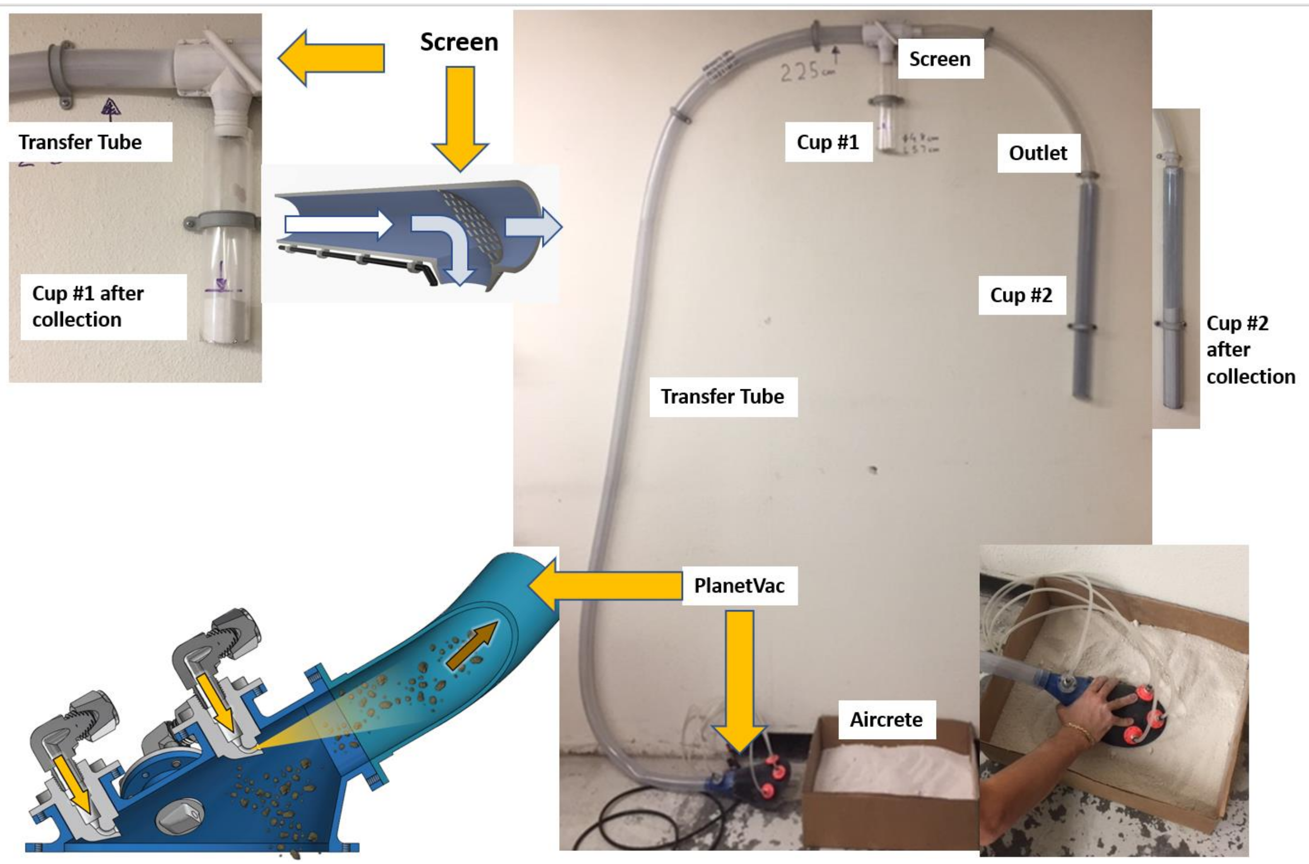

Figure 16. Experimental setup for compressed gas-based sample acquisition, transfer, and capture.

Figure 17. Coarse material was captured in Cup #1 (Left) and finer material was captured in Cup #2 (right).

Table 2. Particle size distribution of the original material as well as sample in Cup #1 and #2.

Particle sizes (mm)	Original Material (%)	Cup #1 (%)	Cup #2 (%)
10	1.7	22.9	0.0
5	1.7	8.5	0.2
3-4	3.5	14.3	3.1
1-2	4.4	20.2	18.8
< 1	88.7	34.1	77.9

6. SUMMARY

This paper presented numerous approaches to pneumatic sample acquisition, transfer, and capture. Pneumatics offers significant benefits over traditional gravity driven approaches and in turn is well suited on planetary missions, where material to be sampled is of unknown cohesion. Pneumatics also offers ability to place the instrument or sample return container at some distance from the sample acquisition hardware since transfer tubing can be routed around potential obstacles. Gas can be used to clean up transfer hoses and in turn minimize cross contamination.

Currently, pneumatic based approaches have been implemented on CAESAR [20] and Dragonfly [18, 19, 22] New Frontiers candidate missions, the P-Sampler on Mars Moon eXplorer, Lunar Heat Flow Probe [12], and PlanetVac [8, 21].

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