Pneumatic Sampler (P-Sampler) for the Martian Moons Exploration (MMX)

Dylan Van Dyne[1], Kris Zacny[2], Lisa Thomas[3], Sherman Lam[4], Yuka Matsuyama[5], Dara Sabahi[6], Gale Paulsen[7],

Honeybee Robotics, 2408 Lincoln Ave, Altadena, CA, 91001, USA

Yasutaka Satou[8], Hiroki Kato[10], Hirotaka Sawada[10], Tomohiro Usui[10], Masaki Fujimoto[10], and Takane Imada[10]

Japan Aerospace Exploration Agency, 7-44-1 Jindaiji Higashi-machi, Chofu-shi, Tokyo, Japan

Robert P. Mueller[9]

NASA Kennedy Space Flight Center, Florida, 32899, USA

Michael Zolensky[10]

NASA Johnson Space Center, 2101 E NASA Pkwy, Houston, TX 77058, USA

Leonard Dudzinski [11]

NASA Headquarters, 300 E. Street SW, Suite 5R30, Washington, DC, 20546, USA

A Pneumatic Sampler (P-SMP) is being provided by Honeybee Robotics with support from NASA Planetary Missions Program Office (PMPO) for JAXA's Martian Moons eXploration (MMX) mission. The goal of this mission is to closely survey the Martian moons Deimos and Phobos, and then to collect regolith from Phobos and return it to Earth. The P-SMP will be mounted to a leg of the lander and will be responsible for collecting surface regolith alongside the JAXA provide Core Sampler (C-SMP). The Sampling Funnel of the P-SMP utilizes two sets of sampling nozzles: one set of nozzles pointed directly at the surface to kick-up and loft material into the sampling head, and a second set of nozzles to direct the oncoming material into the sample return canister further up the lander leg. A robotic arm mounted underneath the lander will then remove the sample canister and place it inside the sample return capsule for Earth return. Several iterations of the P-Sampler have been designed and tested inside a vacuum chamber with Phobos regolith simulant. In all tests, the P-Sampler successfully acquired the sample, even in an extreme scenario where the sampling head was mounted 10 cm above a surface covered with gravel.

---

[1] Engineering Manager, Exploration Systems
[2] V.P., Exploration Systems, AIAA Member
[3] Director of Program Management, Exploration Systems
[4] Mechanical Engineer, Exploration Systems
[5] Mechanical Engineer, Exploration Systems
[6] Engineering Consultant, Exploration Systems
[7] Director of Systems and Mechanical Engineering, Exploration Systems
[8] Research Scientist
[9] Senior Technologist, Exploration Research and Technology Programs
[10] Planetary Scientist, Astromaterials Research and Exploration Science
[11] Chief Technologist, Planetary Science Division

I. Introduction

The Martian Moons eXploration (MMX) mission, led by the Japanese Aerospace Exploration Agency (JAXA), will focus on the exploration of the two Martian moons – Phobos and Deimos (Figure 1). The spacecraft will perform close-up remote sensing and observations of both moons and collect samples from Phobos for Earth sample return.

MMX has set the two mission goals: (1) determining the origin of the Martian moons and (2) observing processes in the circumplanetary environment of Mars, based on remote sensing, in-situ observations, and laboratory analyses of returned samples of Phobos regolith [1-2].

Figure 1: The Martian Moons eXploration (MMX) mission, developed by the Japanese Aerospace Exploration Agency (courtesy: JAXA)

To fulfill the mission goals, MMX employs a double sampling approach: Coring Sampler (C-SMP) and Pneumatic Sampler (P-SMP) as shown in Figure 2. The C-SMP, a core soil tube deployed by a robotic arm, will provide access to the building blocks of Phobos beneath the surface (>2 cm), and will collect a mixture of near surface material. The P-SMP, on the other hand, will selectively sample the surface veneer and provide a reference for the surface component with the C-SMP.

The double sampling system not only enhances the scientific merits of MMX, but also reduces risks associated with the sampling operation of Phobos. Without enough knowledge of the physical properties, chemical properties, and the geotechnical conditions of the surface of Phobos (e.g., compositions, temperature gradient/variation, porosity, grain size distribution), having two sampling systems that utilize entirely different sampling approaches is prudent.

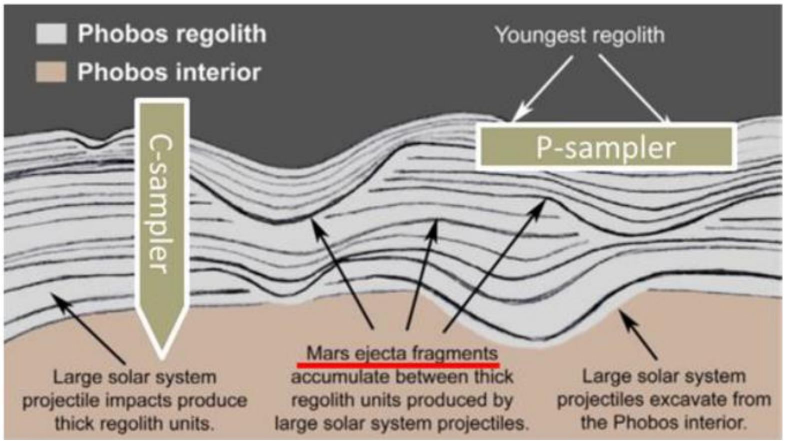


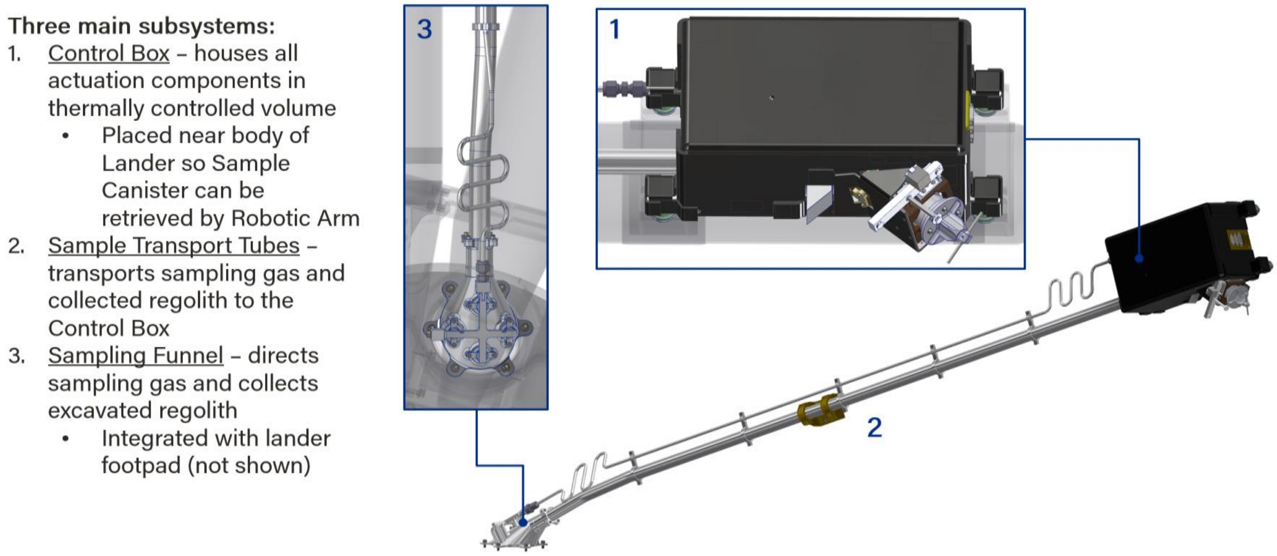
Figure 2: C-Sampler and P-Sampler will address MMX goals #1 and #2, respectively. The Phobos stratigraphy is after Ramsley and Head 2013 [1]

II. MMX P-Sampler

A. Design

The P-SMP system will enable MMX to utilize a high-reliability surface sample acquisition system [3]. The P-SMP uses pneumatics to release pressurized gas that can loft and entrain particles in a controlled flow of gas to excavate and transport samples. The P-SMP enables MMX to collect samples without deploying physical hardware (as it's normally done using conventional sampling systems).

P-Sampler consists of three subsystems: Control Box, Sampling Funnel, and Sample Transport Tubes (Figure 3).



Three main subsystems:

1. Control Box – houses all actuation components in thermally controlled volume
    - Placed near body of Lander so Sample Canister can be retrieved by Robotic Arm
2. Sample Transport Tubes – transports sampling gas and collected regolith to the Control Box
3. Sampling Funnel – directs sampling gas and collects excavated regolith
    - Integrated with lander footpad (not shown)

Figure 3: Overview of P-SMP Design

The Control Box houses several subsystems, including the Pneumatic Subsystem, Sample Canister, Hold Release Mechanism, Momentum Separator and Beam-Breaker system for sample verification. The Control Box is mounted at the top of the lander sub-leg so that the Robotic Arm on the lander can access the Sample Canister.

The Pneumatic Subsystem, responsible for releasing gas to excavate and transport sample, is rated to use 5000 psi of ultra-pure Nitrogen gas for sampling. It is comprised of a Pressure Tank, Pressure Transducer, Service Valve, and two Solenoid Valves in series. It is designed to be completely reusable (automatically resettable), extremely clean (limited materials and zero lubricants), and very reliable (redundant seals and high reliability actuators). By using high performance solenoid valves, the Pneumatic Subsystem can be commanded to release gas by a simple open and close operation or pulsed up to 16 Hz to provide different effective gas flow rates and pressures.

The Sample Canister Assembly (SCA) is responsible for collecting and retaining captured samples and resides within the Hold Release Mechanism (HRM). It consists of the Sample Canister, the Release from Manipulator Mechanism (RMM), and Grip. Both the RMM and Grip are provided by JAXA partners in Japan. The Sample Canister is designed to interface with the RMM and includes accommodations for sample retention immediately after sampling and after withdrawal from the HRM.

The HRM utilizes a Pin Puller to hold (and eventually release) a spring-loaded lid that constrains the SCA. In consideration ofr the RMM in the SCA and the operational envelope of the Robotic Arm, the HRM constrains the SCA as two separate rigid bodies, and upon release exposes the SCA so that it can be pulled out and swung down by the Robotic Arm. The HRM also includes redundant switches to confirm the release of SCA.

The Momentum Separator separates the regolith from the sampling gas directly before the Sample Canister and houses the Beam-Breaker sensors. The Beam-Breaker sensors detect the transit of particles through their field of view via voltage pulses, which are held by the Peak Hold system. The Peak Hold system compiles all signals from the Beam-Breaker sensors into a temporary "peak" voltage that can be read and reset by the spacecraft. This allows the spacecraft telemetry systems to receive feedback on collected regolith without having to poll faster than 1 Hz.

The Control Box is an "endoskeleton" architecture to ease access and reduce mass. With this architecture, the back plate of the control box becomes the main structural element, and all other components are directly bolted to this frame. This saves mass as well as provides access to the high-pressure pneumatic system during verification testing.

The Sampling Funnel consists of three sets of nozzles: Excavation Nozzles, Transport Nozzles and Retro-thrust Nozzles. Excavation Nozzles are pointed down and are designed to fluidize Phobos material and eject it upwards, into the Sampling Funnel. Transport Nozzles are designed to push the material up the Sample Tube and into the Sample Canister within the Control Box. Retro-thrust Nozzles are pointed directly opposite of the Excavation Nozzles – these are designed to counter the gas momentum of the Excavation Nozzles and in turn reduce the impulse of the operation – critical in the miniscule gravity well of Phobos. In early phases of the project, the Sampling Funnel was relocated from the bottom of a lander pad to the side, up to 10 cm from the surface. In the latest lander design, the Sampling Funnel is mounted into one of the four lander pads, giving it direct access to the surface regolith after landing.

The Sampling Gas and Sample Return Tubes reside between the Sampling Head and Control box and are responsible for transporting ultra-pure nitrogen gas and fluidized Phobos regolith, respectively. Both Tubes are designed to accommodate the difference in thermal expansion between the aluminum P-Sampler and the composite Lander Leg.

Both tubes connect to the Sampling Head and Control Box. The Sample Transport Tube is fixed relative to the lander leg. On either end, the tube has sliding interfaces with the Control Box and the Sampling Head/Funnel to compensate for thermal expansions differences between the aluminum P-Sampler and composite lander leg. In contrast, the Gas Tube is fixed on both ends since it needs to maintain a pneumatic seal. However, multiple U-bends on both ends give the Gas Tube axial compliance to accommodate changes in length due to thermal expansion / contraction.

B. Concept of Operations

P-SMP will be operated once the lander has successfully landed on the surface of Phobos. At this stage, it has not been decided whether the C-SMP or the P-SMPR will be activated first. This decision will probably occur once the spacecraft performed evaluation of the Phobos surface. It should also be noted that the MMX spacecraft will drop a German-French built MMX Rover on the surface. Once on the surface, the rover will perform in-situ analysis of the Phobos material, which in turn will help in operating of the C-SMP and P-SMP.

P-SMP operations on the surface are fully autonomous and lasts for a few seconds. The steps can be summarized as follows:

1) Gas valves open to release ultra-pure Nitrogen gas. Gas is injected into the surface and stirs up surface material. Phobos material is then ejected back towards P-SMP where it intercepts the second set of nozzles (so called transport nozzles) that propel material towards Sample Canister.
2) As material moves towards the Sample Canister, it passes by the Beam Breaker. If the Beam Breaker sensors do not meet the preset threshold, gas valves are open at different parameter sets. This continues until the Beam Breaker sensor confirms sampling operation is successful. At that point, the sampling operation is complete.
3) Once the MMX lander is in Phobos orbit, the robotic arm lightly grasps Grip on SCA and HRM on P-SMP is commanded to open by the spacecraft. The robotic arm withdraws the SCA by swinging “down” and away. The SCA is inserted into the Sample Return Capsule (SRC), where the spring pins on the RMM detent to separate the Sample Canister from the Grip. At that point, the Sample Canister is safely inside the SRC.

III. Testing

Testing has been crucial to the development of the P-SMP. The P-SMP shall sample from a largely undefined surface from a height and angle that is difficult to predict. Such circumstances, therefore, preclude the use of analysis when developing the functional parameters of the instrument. To address this, the P-SMP development program has defined a process that relies on extensive testing. This process can be described as follows: 1) Define – Research and define baseline sampling conditions, 2) Test – Utilize pneumatic prototype hardware to test in baselined conditions, 3) Analyze – Observe and record data to analyze the effectiveness of the pneumatic sampler, and 4) Design – Strategically update the design to improve sampling performance and define limitations for the MMX application of pneumatic sampling.

To date, over 250 sampling tests of the pneumatic sampling technology have been performed for the MMX application. Testing was performed between two campaigns through the lifecycle of the project: Breadboard testing before the instrument Preliminary Design Review (PDR), and Brassboard testing before the instrument Critical Design Review.

A. P-SMP Breadboard Testing

Breadboard testing conducted before the PDR was performed to characterize the performance of the P-SMP and to optimize the design based on the best knowledge of the Phobos surface. At this phase of the project, the Sampling

Funnel was placed alongside the lander pad, with a maximum sampling height of 10 cm that had not been initially considered during the proposal phase. The test campaign then focused on determining the effectiveness of the pneumatic sampling technology in various configurations with different simulants. In total, over 200 tests were performed. The different configurations varied gas flow rate, Sampling Funnel height, gas pulse duration, and nozzle geometries. Simulants included beach sand, crushed Aircrete, and 3M glass bubbles. Tests were conducted inside a vacuum chamber, and the gas control surfaces were constructed from 3D printed plastic components (Figure 4). Data collected for each test includes, gas pressure, flow rate, reaction force, and mass captured.

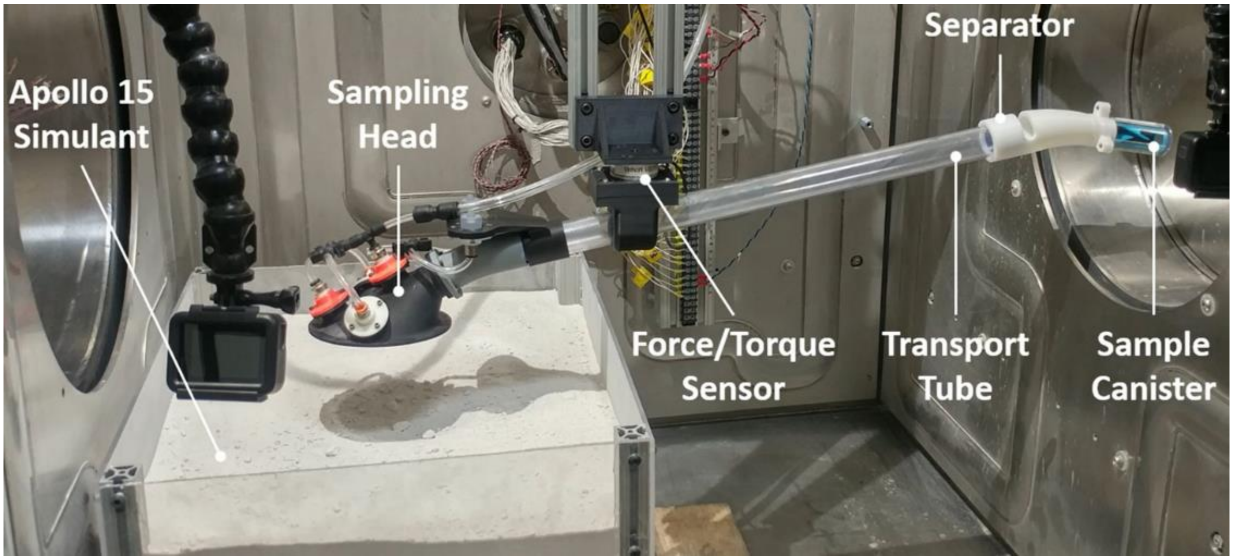


Figure 4: P-SMP Breadboard Test Setup

Table 1 summarizes test data from several sampling tests where the only parameter varied was the height of the Sampling Head above the surface. In particular, three heights were selected: 10 cm, 5 cm, and 2.5 cm. The 10 cm represents the worst-case scenario; it was expected that the surface of Phobos is relatively “fluffy” and as such the spacecraft footpads will sink upon landing (as opposed to stay on top of the regolith surface). All other parameters were kept constant. The data clearly shows a dependence of the sampling efficiency (i.e. mass of sample captured) as a function of sampling height. This is expected since at shorter distances, the ejected regolith by the excavation nozzles is more likely to hit the Sampling Head. In fact, the mass of sample delivered to the sampling head should be somewhat proportional to $1/H^2$, where the H is the distance to the surface (similar to the solar power density as a function of a distance from the Sun). Nonetheless, even at the extreme case of 10 cm, significant amounts of the sample were captured.

Table 1: Effect of Sampling Funnel Height Above the Surface on Sample Captured

Height [cm]	Sample Mass [g]
10	1.7
10	2.2
10	2.2
10	1.1
10	1.1
5	8.8
2.5	10.0

Table 2 shows the test data with the gas flow rate being varied, where gas is measured in Standard Liters per Minute (SLPM). All other parameters were kept constant. It is apparent that the mass of sample captured is directly proportional to the flow rate. This is intuitively correct; if the P-SMP’s sampling efficiency (mass of sample/mass of gas used) is constant, greater mass of gas used will lead to more of the sample captured.

Table 2: Effect of Gas Flow Rate on Sample Captured

Flow Rate [SLPM]	Sample Mass [g]
32	0.02
36	0.80
35	0.82
41	0.81
57	1.87

Table 3 shows the effect of pulse duration on the sample mass. All other parameters such as the Sample Head height above the surface (10 cm), gas pressure (5 psig), and gas flow rate (40 SLPM) were kept constant between the tests. During these tests the Retro-Thrust Nozzles were not used. The data shows that the mass of sample captured is directly proportional to the duration of the pulse. The table also shows excavation efficiency defined as mass of sample captured divided by the mass of gas used. Hence the higher the number the more efficient system is. The system is most efficient for longer pulse duration and least efficient for shorter pulse durations. Note that "No data" in the excavation efficiency column signifies that the gas flow rate data was unavailable for that particular test.

Table 3: Effect of Sampling Duration on Sample Captured

Duration [sec]	Sample Mass [g]	Excavation Efficiency [g/g]
2	1.71	No data
2	2.19	No data
2	2.22	1.2
2	1.06	0.6
2	1.11	No data
1	0.65	0.7
1	0.61	0.7
1	0.35	0.4
1	0.38	0.4
0.5	0.04	0.1
0.5	0.11	0.3

Table 4 lists the trade study data where particle sizes of simulants were the test parameter. In particular, the test used Coarse and Fine Aircrete. The other parameters such as the Sample Head height above the surface (10 cm), gas pressure (5 psig), gas flow rate (45 SLPM), sampling duration (2 sec) were kept constant between the tests. During these tests Retro-Thrust Nozzles were not used. It was found (as expected) that P-SMP captures higher mass of the sample if sample particles are smaller. It's very likely that jets of gas from Excavation Nozzles push the coarse material aside and sample finer material. As such, the gas energy is 'wasted' in moving the coarse material aside.

Table 4: Effect of Particle Size on Sample Captured

Simulant	Sample Mass [g]	Average [g]
Aircrete (90% coarse, 10% fines)	1.10	1.33
	1.55	
Aircrete (90% fines, 10% coarse)	1.71	1.66
	2.19	
	2.22	
	1.06	
	1.11	

Table 5 shows test data from tests where particle density was the main variable. All other parameters such as the sampling height (10 cm), gas pressure (5 psig), flow rate (45 SLPM), and pulse duration (2 sec) were kept constant. During these tests the Retro-thrust Nozzles were not used. The data shows that the P-SMP captures more material (in terms of mass, not volume) if the material is of lower density.

Table 5: Effect of Particle Density on Sample Captured

Density [g/cc]	Sample Mass [g]	Average [g]
Sand	1.87	1.43
	0.99	
Aircrete	1.71	1.66
	2.19	
	2.22	
	1.06	
	1.11	

Table 6 shows the test data when the Retro-thrust nozzles were being used to reduce the impulse of the P-SMP during sampling. As expected, when the gas flow was split between the two types of nozzles, the mass of the sample captured dropped by 50%. This conclusion confirms other findings related to the mass of sample captured as a function of the mass of gas used (see Table 2 and Table 3).

Table 6: Sample Captured With and Without Retro-thrust Nozzles

Retro Nozzles	Sample Mass [g]	Average [g]
No	1.71	2.04
No	2.19	
No	2.22	
Yes	1.23	1.10
Yes	0.97	

Table 7 was compiled to determine whether the data was repeatable. There are two data sets, each captured under the same test parameters. In the first set, the average mass of 1.66 g with standard deviation of 0.56 g and in the second set the average was 0.62 g with a standard deviation of 0.15 g. Considering this is an excavation system, the data repeatability is very good.

Table 7: Repeatability

Sample Mass [g]	Average [g]	Std Dev [g]
1.71	1.66	0.56
2.19		
2.22		
1.06		
1.11		
0.65	0.62	0.15
0.61		
0.35		
0.38		

In addition to nominal tests, various extreme cases were conducted, including a thick layer of gravel covering fine material (Figure 5). During this test it was found that high pressure gas effectively moved the coarse material aside to reach fines underneath. A mass of 0.68 gram was acquired during the 2 second pulse duration.

Figure 5: Sampling Test in Extreme Conditions

As a result of Breadboard testing, the following conclusions were made: 1) The P-SMP technology in this application successfully met the sample collection and impulse requirements at sampling heights ranging from 0 to 10 cm, 2) it also successfully collected samples of various simulants, and 3) sensitivity studies show that the P-Sampler is tolerant to position and orientation variability from landing, within the requirements set upon by the MMX spacecraft.

B. P-SMP Brassboard Testing

Brassboard testing conducted before the Critical Design Review (CDR) was performed to validate the sampling requirements imposed on the P-SMP with an updated interface driven by Lander design revisions. Named the Engineering Brassboard 1 or EBB1, it used gas and sample transport geometry that was identical in form to the planned parts for the Protoflight Model (PFM). This includes the gas tube from the Control Box, the Sampling Funnel Assembly, Sample Transport Tube, Momentum Separator, Hold Release Mechanism, and Sample Canister Assembly. A full scale, partial mock-up of the lander pad was 3D printed to replicate the sampling interface. The pneumatic system for EBB1 was comprised of readily available consumer high pressure solenoid valves and tank which were located on a test cart outside the chamber but used the same flow orifice planned for the PFM.

Figure 6: Engineering Brassboard 1 Test Setup

For every test, the EBB1 was tested in a vacuum chamber with a pressure below 10 Torr and used a Phobos simulant developed by University of Central Florida named Phobos Giant Impact, or PGI-1, which is formulated based on the Phobos Giant Impact theory [4]. At the conclusion of each test, a flight representative Hold Release Mechanism was actuated to gain confidence in its ability to actuate in a dusty environment. Parameters such as the lander pad placement, lander pad angle, start pressure, and pulse width were varied from test to test. For every test, data was collected to measure the gas pressure, flow rate, pressure in the Sampling Funnel, reaction impulse, Peak Hold response, and sample collected. Video was also taken from two different angles to collect data on the regolith scattering behavior of the P-SMP for use by JAXA. In total, 17 different configurations were tested, with 1-3 trials performed per configuration, for a total of 48 tests (Figure 6).

EBB1 collected samples in every test except one, and exhibited the same trends seen in Breadboard testing with regards to samples collected at varying heights and the usage of gas. Figure 7 is an example of the data captured for each test. (The complete test data is available in supplementary material.) This test, titled EBB1.13-1, was performed with the bottom of the lander pad on top of the regolith simulant, the nominal starting pressure (4,300 psi), and pulse width modulation control of the gas (4 Hz cycling at 25% duty cycle for 2 seconds). The chart in the upper left corner of the figure shows the commanded states of the valve, and the chart in the upper right corner of the figure shows the pneumatic response, which yields a lower effective flow rate than if the valve had been commanded to open at 100% duty cycle. The chart in the lower left corner of the figure shows measure impulse from the sampling operation to be well below the 10 Newton-second requirement, and the chart in the lower right shows the state of the Peak Hold circuit in response to sample transiting past the Beam-Breaker sensors. Two separate trials were run in this configuration with similar results, yielding 4.98 and 5.18 grams of sample captured.

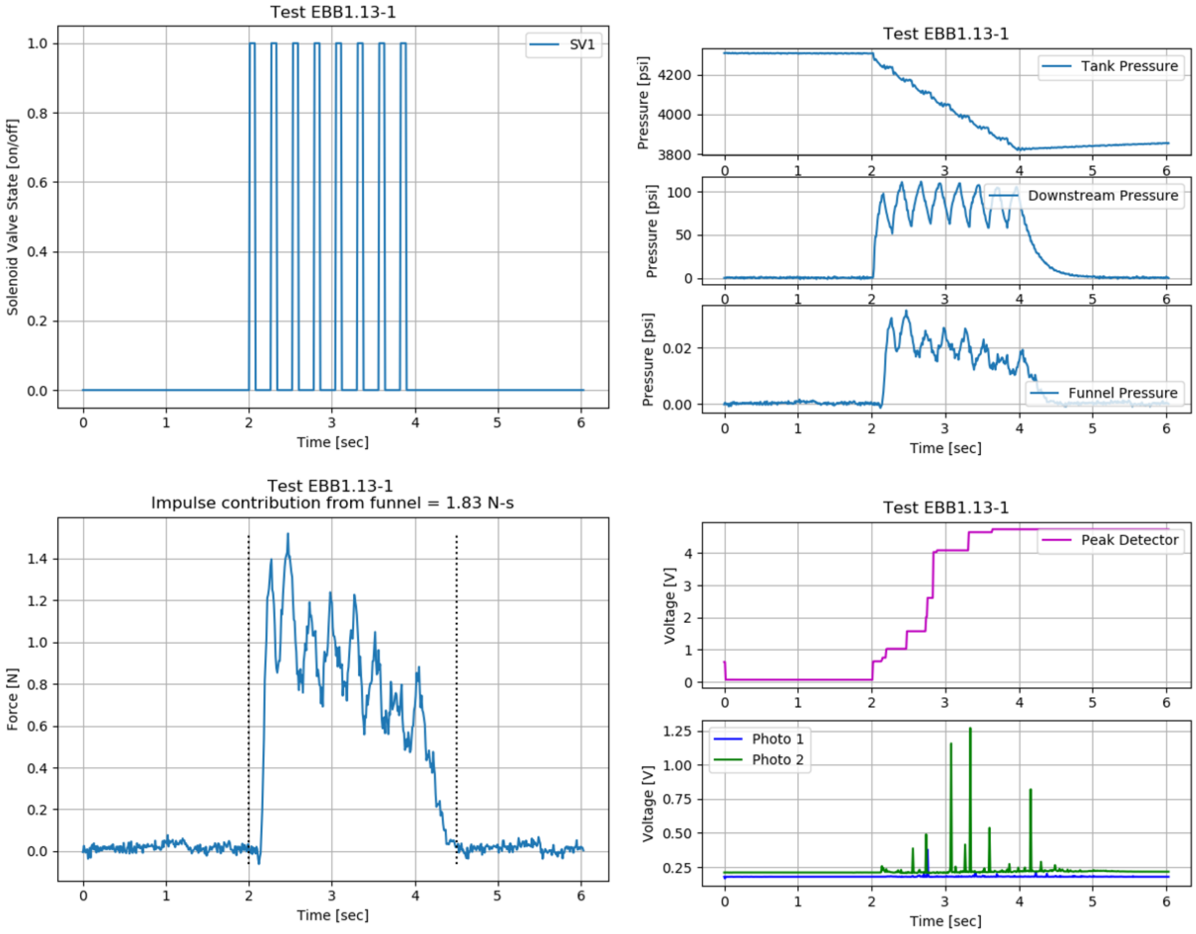


Figure 7: EBB1 Example Test Data Captured

The only test that did not yield a measurable amount of sample was extremely pathological, with approximately 3 centimeters of Aircrete rocks placed between the bottom of the lander pad and the top of the simulant, and additional rocks blocking the “tunnel” through the lander pad. Pneumatic control for this test is identical to that shown in Figure

7. The first trial of this test yielded 0.95 grams of sample, while the second yielded no measurable change in mass of the sample canister, so a captured amount of sample could not be determined. However, during an actual sampling attempt, the P-SMP could use the feedback from the Peak Hold system to increase its chances of capturing sample in such a case. For example, in this test the Peak Hold system did not register a meaningful change in voltage, only 0.05 volts within the 5-volt range. Using this feedback, the spacecraft could be programmed to actuate the P-SMP again, but instead of cycling the valves via pulse width modulation to minimize gas usage, they could be opened at 100% duty cycle for up to another 6 seconds, drastically increasing its ability to collect sample (Table 3). (EBB1 test data shows that the P-SMP has approximately 8-10 seconds of “usable” pressure when opened at 100% duty cycle.) Additionally, if pre-landing surveys indicate that the Phobos surface may be very difficult to sample from, the heaters attached to the pressure tank could be heated to increase pressure from the nominal 4,300 psi to the maximum operating pressure of 5,000 psi before landing to increase the total flow rate of the P-SMP.

EBB1 successfully validated all sampling requirements. It also established an updated operating envelope for the P-SMP with the updated interface, which was introduced between the Preliminary and Critical Design Reviews.

Figure 8: EBB1 Extreme Sampling Test

C. P-SMP Future Brassboard Testing

The future plan for the P-SMP includes verification of the sampling requirements by demonstration with a model called Engineering Brassboard 3 (EBB3). The EBB3 will use the same control surfaces as the EBB1, but will also include a pneumatic sub-system comprised of spare flight components assembled in the same manner as the PFM. The EBB3 will therefore be able to verify all sampling requirements for the project, while the PFM can be built and maintained to the strict contamination control standards imposed by planetary protection requirements. Due to cycle limits on the flight pressure components, the EBB3 test matrix will be abbreviated from EBB1, and be focused on just 3-4 different sampling scenarios that have not yet been confirmed. This testing is expected to be completed in December 2021 ahead of the protoflight build of the P-SMP.

IV. Conclusions

This paper presents the application of pneumatics in sample acquisition and delivery for the Phobos sample return mission. The data presented herein illustrates the advantages of pneumatic sampling in its capability to repeatedly adapt to varying surface conditions as well as its ability to capture sample without being in contact with the surface. Samples of Phobos regolith simulants were captured from various heights and even with a layer of rocklets covering the fines, demonstrating the robustness of this sampling architecture.

The P-sampler will begin its build phase in early 2022 and will be launched to the Martian sphere in 2024. If successful, the P-SMP will enable the MMX mission to collect and return Phobos material to Earth, which may contain material from Mars itself, by 2029.

V. Acknowledgments

The P-SMP project is funded by NASA's Science Mission Directorate Planetary Science Division (PSD) and managed by the Planetary Missions Program Office (PMPO) at NASA's Marshall Space Flight Center. Special thanks go to Thomas Statler, the PSD Program Scientist, and Bradley Zavodsky, the PMPO Mission Manager, for overseeing development of the P-SMP.

We would also like to thank Dan Britt and Anna Metke of University of Central Florida for providing the Phobos Captured Asteroid-1 (PCA-1) and Phobos Giant Impact (PGI-1) simulants.

VI. Optional Supporting Materials

A. References

[1] Ramsley, K. R. and Head J. W., "Mars impact ejecta in the regolith of Phobos," Planetary and Space Science 87, 115-129, 2013.

[2] Kawakatsu et al., "The Importance of Phobos Sample Return for Understanding the Mars-Moon System," 70th International Astronautical Congress (IAC), 2019

[3] Zacny et al., "Pneumatic Sampler (P-Sampler) for the Martian Moons eXploration (MMX) Mission," IEEE, 7-14, 2020

[4] Landsman, Z.A., et al., "Phobos regolith simulants PGI-1 and PCA-1," Advances in Space Research, 2021