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A fast and robust surface sample acquisition system for a Venus lander

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ABSTRACT

JPL and Honeybee Robotics have designed, built and successfully tested a fast end-to-end sample acquisition and transfer system for the Venusian surface. This full scale prototype system uses a rotary-percussive drill designed to penetrate to a 5 cm depth in saddleback basalt in 15 min under full Venus surface conditions of 470 °C and 92 bar pressure and supercritical CO_2 atmosphere. The drill features a hollow bit that collects particulate samples created during the drilling process. Sample transfer from drill to lander is done pneumatically using the motive force provided by the high pressure Venus atmosphere to entrain the particles in a high density flow. A cyclone particle separator removes the particles from the flow inside the lander and deposits them into an airlock, while the gas itself flows into a low pressure dump tank. Two samples are provided from the drill, one near the surface and one at 5 cm depth. Cross contamination between the near surface and at depth samples is minimized by collecting, but not analyzing, a third sample in between the two primary samples. The airlock is designed to depressurize and cool the particulate samples and then present them to science instruments for composition analysis. The entire drilling and sample transfer process completes in 30 min, thereby allowing it to support almost any kind of future short duration Venus lander mission. Results are presented for the first end-to-end drilling and sample transfer experiment conducted in a new specialized test chamber that replicates Venus surface conditions.

1. Introduction

The need for and importance of new geochemical measurements of the Venusian surface is well documented given the limited data obtained from prior missions (Committee on the Planetary Science Decadal Survey, 2013; Treiman et al., 2013). However, acquiring and analyzing samples collected on the surface of Venus is a difficult undertaking because of the high temperature (470 °C) and high pressure (92 bar) environment. Only the Soviet Union in the 1970s and 1980s has taken on that challenge with successful sampling missions in 1981 with the Venera 13 and Venera 14 landers, and in 1985 with the VeGa 2 lander (Huntress and Marov, 2011). The sampling system used on these missions is described in detail in Bar-Cohen and Zacny (2021). Suffice it to say here that the basic design consisted of a rotary drill capable of reaching a 3 cm depth in 2 min followed by pneumatic sample transfer of the particulate material created by the drill into the lander where a composition analysis was performed by an X-ray fluorescence spectrometer. All of the Venus rock samples were measured to be basalt with some variation in composition at the different landing sites.

A defining characteristic of all of these prior Soviet Venus lander missions is that the surface operational lifetime was very short, typically an hour or two (Huntress and Marov, 2011). Although in some instances the mission effectively ended once the communication relay spacecraft moved out of range, more generally the lifetime was dictated by thermal considerations. Specifically, the electronic and battery components of the lander could not tolerate the high temperature surface environment and would therefore fail once sufficient heat transfer had occurred through the insulated pressure vessel of the lander and into these sensitive components. This short mission paradigm continues to the present day with some extensions to lifetime through improved thermal insulation and higher operating temperature limits for electronics and batteries. For example, a recent NASA study for a Venus Flagship Mission predicted that the surface lifetime of a lander would be 8 h (Beauchamp et al., 2021). Significantly longer lifetimes than this must await substantial

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technological advances in nuclear powered cooling systems or science instrumentation, energy storage and electronics that are capable of much higher temperature operation.

Until then there is a clear requirement for fast sample acquisition, transfer and analysis on a Venus lander mission that lasts even as long as 8 h. It calls for a very different approach to that used, for example, on the NASA Mars missions over the past decades in which multi-year long missions allowed for much slower sampling processes. Of particular note is that on the time scale of hours it is not possible to have significant ground-in-the-loop interactions that inject human judgment and provide direction to the lander's sampling system on where to drill or how to recover from faults. Therefore, a fast, automated, highly robust system is required.

The Jet Propulsion Laboratory (JPL) and Honeybee Robotics teamed up to design, build and test an end-to-end sampling system that could be used on a short duration Venus lander mission such as is described in the recent Venus Flagship Mission Study (Beauchamp et al., 2021). This paper presents the first comprehensive description of the complete sampling system and end-to-end test results and, as such, complements previous publications that largely focused on the high temperature actuators and drill components (Rehnmark et al., 2017, 2018; Zacny et al., 2017, 2022). This paper also describes the unique test facility constructed at JPL that enabled full scale drill and sample transfer testing under the very challenging high pressure, high temperature, carbon dioxide gas conditions found on the Venusian surface.

2. Sampling system architecture and design

The mission requirements imposed on the Venus sampling system design were:

- The system will acquire both an at-the-surface sample and an at-depth sample 5 cm deep at the sampling location. This enables a composition gradient to be measured and hence quantification of the effects of surface chemical weathering. The 5 cm depth is a compromise between the uncertainty of how deep the chemical weathering effect goes and how difficult it is to quickly drill even deeper into the Venusian surface.
- Each of these two samples will consist of a minimum of 2 cubic centimeters of material.
- The sampling device will accommodate rock as hard as saddleback basalt, which is deemed to be the most challenging rock that could be expected at the landing site on the basaltic plains of Venus.
- No intact rock cores will be needed, particulate samples will be sufficient.
- The sample collection hardware outside of the lander will tolerate the full Venus temperature and pressure environment until the samples are transferred inside the lander.
- The drill will reach its required 5 cm depth in 15 min
- The sampling system will be fully autonomous.
- Two copies of the sampling system will be used to provide block redundancy to the mission. Both copies will operate simultaneously after landing and provide sample material to the instruments for analysis.

The JPL and Honeybee Robotics team devised an architecture that incorporated key elements of the Soviet system from the prior missions, namely use of a drill to obtain subsurface material and pneumatic sample transfer to move the particulate sample from the drill into the lander. One change from the Soviet system was to switch to a rotary-percussive drill that allows for rapid penetration of much harder rocks, including Saddleback basalt. Another notable departure from the Soviet system was the addition of a multi-chamber airlock and associated valving system to provide two separate samples for each drill as per the mission requirement. The overall architecture was intended to provide a brute-force approach, much like a drill press in a machine shop for which the drill and its deployment mechanism are sufficiently strong and robust to operate across a wide range of surface roughness, contact angles and rock hardness. The autonomous operation requirement is therefore met not by careful surveying of the landing site and selection of the best drilling location, but by a highly robust design that can successfully drill into almost any terrain that happens to be under the drill. Further redundancy is provided by the mission featuring two copies of the sampling system to mitigate the small chance of encountering highly unfavorable terrain at the drilling location that prevents sample collection and transfer.

Although simple in concept, the final detailed sampling system design is complicated due to the many components and subtle features that maximize performance and improve sample transfer efficiency. These details are schematically illustrated in Figs. 1 and 2 and are described in the remainder of this section. Details of the full-scale prototype and its testing will be presented in Sections 3 and 4.

The block redundant sampling systems collect rock powder samples and present them to the science instruments inside the pressure vessel. A rotary percussive drill (Fig. 1, Component 2) with a powder collection bit collects samples at 3 depths. At each depth, powder is pneumatically moved out of the bit in a short, few second transfer event and dropped through a vibrating, thermal isolation tube (Fig. 1, Components 8, 10) into an airlock (Fig. 1, Component 11) inside the Lander. The high-pressure atmosphere itself provides the motive force for the transfer event with the gas flowing through the drill and tubing and into a small low-pressure tank mounted outside the lander (Fig. 1, Component 7). The piston-shaped airlock has 3 sample cups, one for each transfer event. Once filled, the airlock slowly de-pressurizes all samples and moves them to the instruments. Only the first and last sample in each airlock are analyzed. The middle sample serves as a buffer to limit cross-contamination of the near surface and at depth samples. Each of the two block redundant sampling systems operate simultaneously and are completely independent. Fig. 2 illustrates key steps in the sample acquisition and transfer process. Except for the hot interfaces of connecting structures and tubes, all components inside the pressure vessel are thermally managed to experience no more than 50 °C, enabling use of standard temperature actuators, mechanisms and seals. The external drill (Section 3.1) and drill deployment device (Section 3.2) do operate at full Venus temperature and pressure and therefore contain specialized components and materials of construction designed to withstand the extreme operating regime.

The overall sampling system architecture minimizes software, fault paths and test complexity. All activities of the sampling system start after landing according to a pre-determined time schedule, and all tasks are given more time than the worst-case need. The drill feed rate is pre-set slower than it can progress in its worst-case rock so that a drill force sensor is not required for feedback control. If an activity does not complete in its allocated time, the sequence moves forward to preserve the overall operations timeline. Note that at the time of landing the drill is stowed approximately 1 m above the landing footpads to provide clearance for rocks and thereby avoid damage. This is a conservative design feature based on expected landing site conditions (Rabinovitch and Stack, 2021). After landing, the drill deployment device (DDD; Fig. 1, Component 3) lowers the drill to the surface and engages a stabilizer. Both the DDD and the drill feed itself have plain lead screws (as opposed to ball screws) and magnetic detents to ensure no movement happens until commanded. The surface stabilizer is preloaded to at least 1000 N against the surface by lowering and then stalling the DDD (Fig. 1, Components 1 and 3). The drill feed then lowers the bit to the surface and drilling commences. The drill and bit are designed to be robust to significant surface topology variation and angles up to 30° (see Section 3.1 for details). The drill penetrates into Venus rock or regolith and acquires three samples of more than 2 cc each, approximately from 0 to 2.5 cm, 2.5–4.0 cm and 4.0–5.5 cm depth intervals. Drill depth is determined using a high temperature Linear Variable Differential Transformer (LVDT).

The pneumatic sample transfer system (Fig. 1, Components 4–7, and

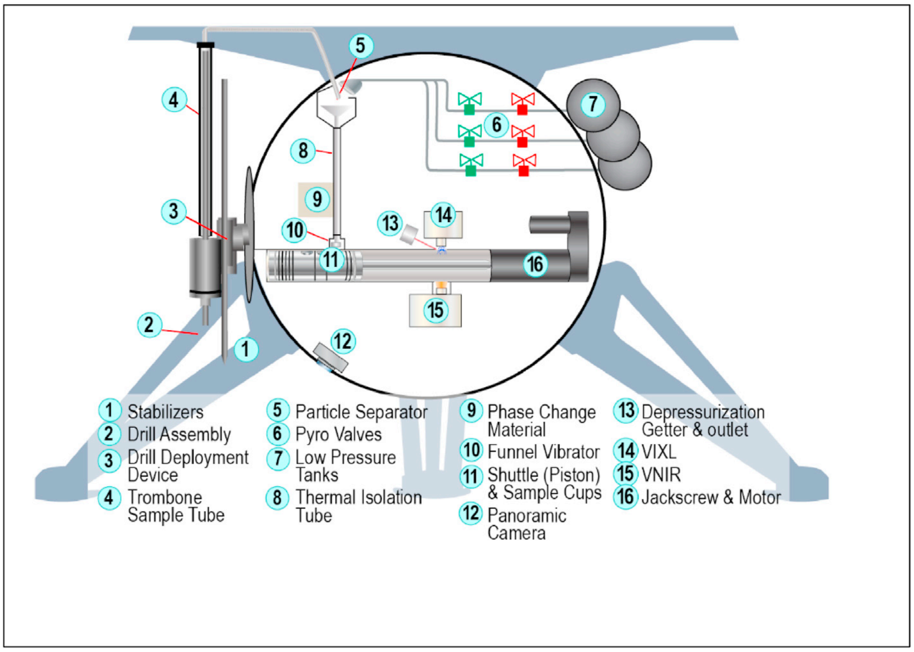

Fig. 1. Schematic diagram of the Venus sampling system. VIXL and VNIR represent hypothetical science instruments that interrogate the samples provided by the rest of the system.

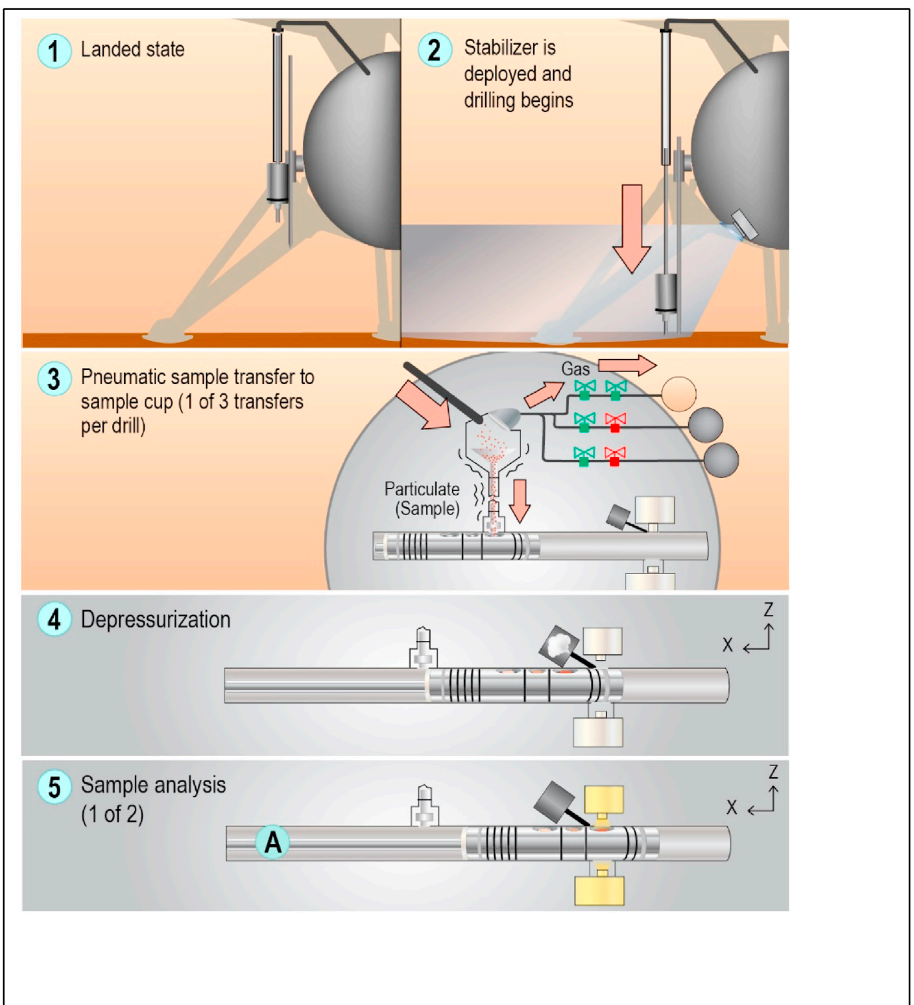

Fig. 2. Schematic diagram showing details of the sample transfer and airlock operations. The green valves in Step 3 denote open, red denotes closed.

Step 3, Fig. 2) pulls sample from the drill bit, moves it into the lander, separates particles from the flow using a cyclone separator, and places the sample particulates in the funnel of the vibrating tube. A trombone-like arrangement of an 8 mm tube sliding inside a 9.5 mm tube allows the moving drill bit to be connected to the fixed lander tubing. The transfer is initiated by opening a pyro valve that connects the transfer tubing to a low-pressure dump tank through a filter and orifice. This allows the 92 bar Venusian atmosphere to provide a powerful short-term flow to move the sample from the drill bit, similar to what was successfully used on the Venera 11, 12 and VeGa 2 missions. After the transfer, a different in-line pyro valve is used to seal off the tank so that it cannot participate in subsequent transfer events. Therefore, 3 tanks are required to move the 3 separate samples collected from each drill.

After the sample enters the lander, it passes through a particle separation cyclone. Gas goes to the low-pressure tank and the separated particles fall via gravity into the funnel of a vibrating tube (Fig. 1, Components 5, 8–10, and Fig. 2, Step 3). The vibration facilitates movement of the sample from the cyclone to the airlock at the bottom of the cyclone where all the particulate collects. A 3 mm mesh screen, vibrated by the funnel, is used to ensure no clumps of material form through self-adhesion and potentially block the 8 mm throat and tube and prevent or greatly limit further sample transfer. The funnel and tube vibration mechanism are near the bottom in the benign thermal environment past the thermal isolation zone. The airlock piston (Fig. 1, Component 11, and Steps 3–5, Fig. 2) moves the samples from high pressure to low pressure to allow instrument analysis. The airlock is protected from Venus temperature by the low-conductivity thermal isolation inlet tube. Electric heaters warm it before landing to 45 °C to avoid condensation of high-pressure CO_2 on the cooler airlock surfaces. 200 g of thermal phase change material at the airlock inlet interface prevents heat flow down the tube from increasing the interface temperature beyond approximately 56 °C. The airlock is moved in one direction towards the instruments by a motorized jackscrew actuator operating near 30 °C (Fig. 1, Component 16). Redundant energized Teflon seals at both ends of the piston ensure the Venusian atmosphere cannot make it into the lander no matter the piston position. The sample cups are in large overflow cavities to ensure particulates do not get on sealing surfaces, and seals between sample cups minimize cross contamination of the samples. As an extra precaution, wipers precede seals to sweep away errant particulates and ensure proper sealing. After collecting all samples, the piston translates to depressurize the sample slowly through filtered orifices that pass the gas through a Zeolite getter (Fig. 1, Component 13, and Step 4, Fig. 2) that absorbs CO_2 and prevents pressure buildup inside the Lander.

Once analysis of the first near surface sample in the airlock is complete, the airlock piston moves to skip the intermediate sample, and place the at-depth sample in view of the instruments. This approach limits cross-contamination and ensures the second sample analyzed is from the greatest depth (Fig. 2, Step 5). No attempt is made to verify presence of a sample in any of the cups, the pre-programmed system simply presents and measures each in turn and relies on the block redundancy to ensure at least one pair of samples is acquired and measured.

3. Prototype hardware description and laboratory setup

JPL and Honeybee Robotics constructed full scale prototype hardware for the sampling system described in Section 2 above and tested it to verify performance. This section describes the prototype hardware along with the Venus environmental test facilities used for the test program. The test results will be presented in Section 4.

3.1. Rotary-percussive drill

The prototype Venus drill was designed and fabricated by Honeybee Robotics (Figs. 3 and 4). It leveraged twelve years of drill and Venus actuator technology development at the company (Zacny et al., 2011, 2013; Kumar and Bar-Cohen, 2014). A rotary-percussive design was used to increase penetration rate and reduce drill walk biases. The design

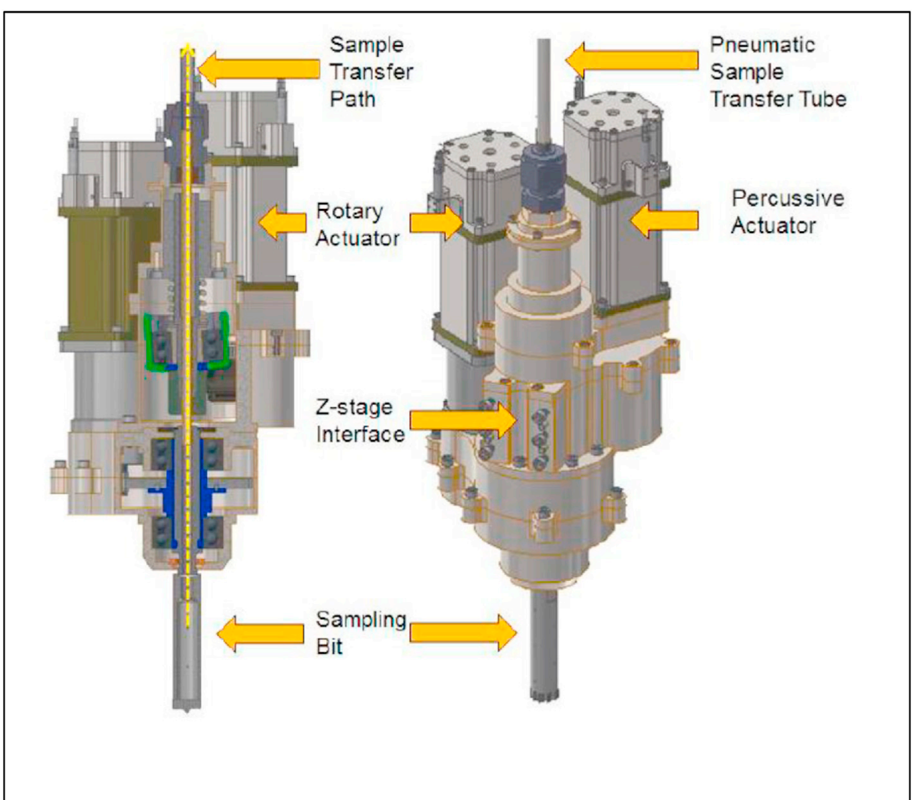

Fig. 3. Schematic of prototype Venus drill.

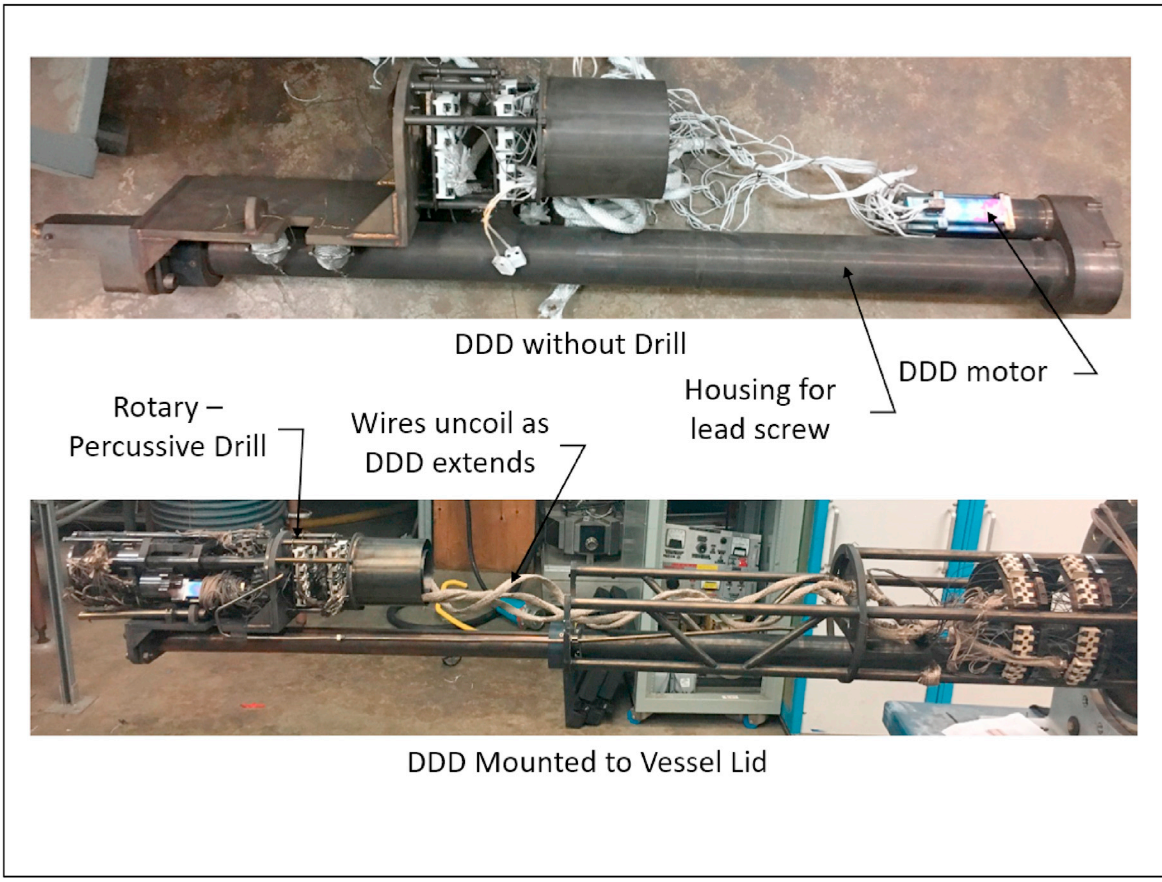

Fig. 4. Drill deployment device (DDD) and Prototype drill hardware.

features independent auger and percussor drive trains and incorporates a hollow drill stem for pneumatic transport of cuttings from the bit up through the center of the drill to a rotary coupling at the top of the drill. Drill position is measured by a high temperature Linear Variable Differential Transformer (LVDT). Both the auger and the percussor use the same type of high temperature, brushless DC motor but different output gear trains. In principle it should be possible to drive both the auger and percussor off a single motor, a future modification that would lead to a less massive drill. The brushless actuators provide feedback using a high temperature Pulsed Injection Position Sensor (PIPS) system for commutation, speed and position control.

The basic Venus drill design parameters are summarized in Table 1. Further details on the design and testing of the drill can be found in Rehnmark et al. (2017, 2018) and Zacny et al. (2017, 2022).

3.2. Drill deployment device (DDD)

The drill deployment device (DDD, Fig. 4) was used to move the drill system from the top of the vessel lid (to simulate the lander) approximately 1 m to the rock at the bottom of the vessel (to simulate the ground). The DDD was powered by one of the same type of Honeybee high temperature brushless DC motor that drives the percussion and rotation parts of the drill. This motor drives a lead screw that lowers the drill system to the ground and then preloads it against the surface. The preload is carried through a metal rod that is offset from the drill bit which helps to stabilize the system during drilling. The electrical wires connected to the drill are originally stored and restrained in a cylindrical housing to protect them and then they uncoil as the DDD and then the drill deploy.

Table 1
Venus drill design parameters.

Bit Diameter	2 cm
Weight on Bit	105 N
Spindle Speed	120 rpm
Spindle Torque	1.1 N-m
Net Spindle Power	13.7 W
Percussive Energy	2 J/blow
Percussive Frequency	980 blows/min
Net Percussive Power	33 W
Target Penetration Rate	0.5 cm/min

3.3. Pneumatic sample transfer system

The pneumatic sample transfer system was designed and built at JPL and then interfaced to the Honeybee drill and the JPL Large Venus Test Chamber (LVTC). The laboratory setup is shown in Fig. 5. It is functionally equivalent to the mission system shown in Fig. 1 with the airlock, particle separating cyclone and set of three identical valve and low-pressure dump tank assemblies to pneumatically move the drill particulates to the airlock. Note that there is no lander mockup, the various components are simply placed on a table with connecting tubing to the top of the chamber and then inside to the drill. The distance and hence tubing length from the drill to the airlock in the laboratory setup is approximately 5 m, which is double that expected for a real Venus lander. The number of tubing bends (90° elbows) is approximately the same, ~4.

Fig. 6 shows the prototype airlock in more detail. The piston diameter is 63 mm and the length is 230 mm. The three sample cups are clearly shown in the figure with the middle one smaller than the other two since it serves merely to separate the two main samples and minimize cross-contamination. The large cups are 36 mm in diameter and sized to hold the expected mass of sample even if the lander is tilted at up to 30°

Fig. 5. Laboratory setup showing Large Venus Test Chamber (covered in white insulation) and pneumatic plumbing system.

due to local topography. O-rings are used to seal the piston against the cylinder. The electric motor that translates the piston inside the cylinder for this prototype is a grossly oversized off-the-shelf device chosen for experimental convenience.

The feed into the airlock uses a simple cyclone particle separator to remove the particulates from the high-speed flow of gas. The gas flows through an 8 mm inner diameter tubing until it reaches the cyclone, which is 63 mm in diameter and 130 mm tall. Centrifugal force pushes the particles against the wall of the conical cyclone, wall friction separates the particles from the flow and then the particles fall into the airlock due to gravity.

Further details on the design evolution of the pneumatic transfer system plus results from early prototype testing in a separate laboratory facility can be found in Reference (Lambert and Rabinovitch, 2017).

3.4. Large Venus Test Chamber

Testing at Venus surface conditions of the end-to-end sample acquisition and transfer system required a new environmental test facility given the large size of the components and the need to demonstrate up to 1 m of translation of the drill deployment device. As a result, JPL designed and fabricated the Large Venus Test Chamber (LVTC) shown in Fig. 7. This chamber has an internal cylindrical working space 2.4 m long and 32 cm in diameter, all of which can provide up to 530 °C temperature and 103 atm pressure of pure CO_2 gas, pure N_2 gas and all combinations in between. Electrical resistance heaters on the outside of the cylindrical pressure vessel provide the high temperature environment. The entire chamber is wrapped in thermal insulation as shown in Fig. 7. It typically takes 3–4 h to load gas and heat up the chamber to achieve Venus surface conditions for a drilling and sample transfer test.

The chamber is mounted on a frame that allows it to rotate by 90° from a vertical to a horizontal orientation. The horizontal position greatly facilitates loading of the relatively heavy drill assembly inside the chamber for testing. Fig. 8 shows one such loading event. After the equipment has been installed inside the chamber and all electrical and pneumatic connections made, the chamber is rotated back into the vertical position for testing where the gravity vector is properly aligned with the drilling direction.

4. Prototype test results

The prototype drill, pneumatic transfer system, cyclone and airlock all were tested by themselves in the laboratory prior to integration and end-to-end testing. Much of this precursor work has been reported elsewhere, but we will summarize those drill and pneumatic sample transfer results first before describing the end-to-end test results at the end of this section.

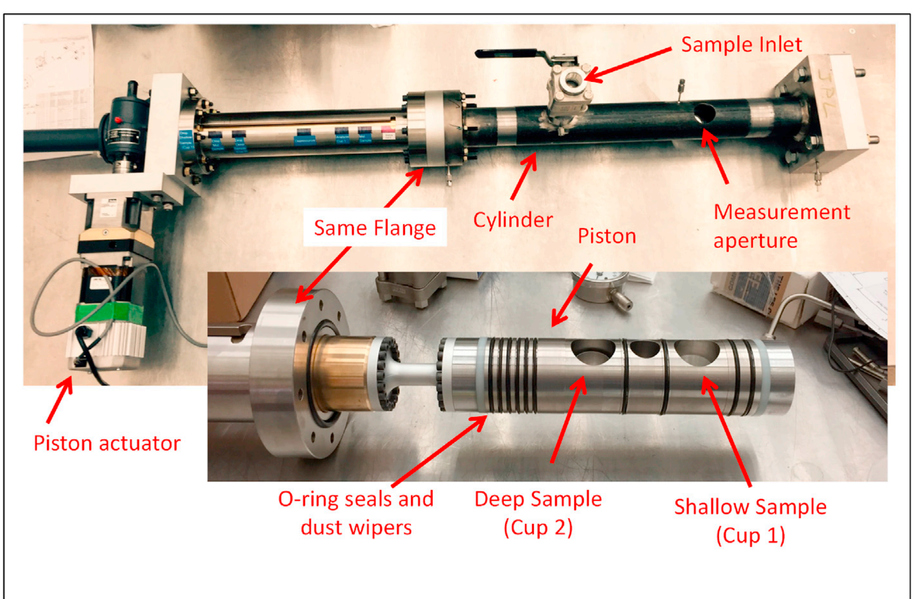

Fig. 6. Prototype airlock.

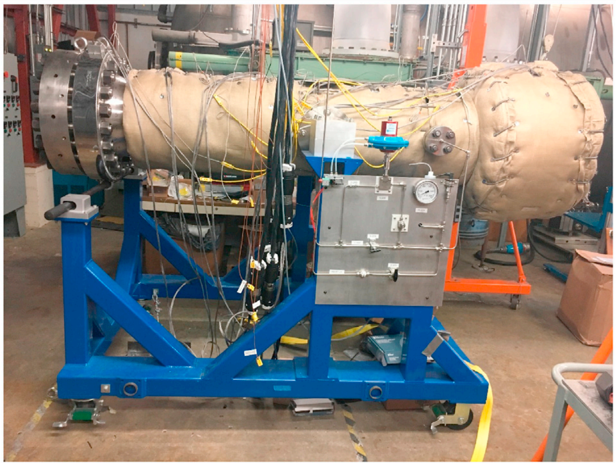

Fig. 7. The JPL Large Venus Test Chamber in the horizontal orientation. The chamber is connected to the blue frame that allows for rotation between the horizontal and vertical positions. Gas injection and venting is controlled through the silver panel in the foreground. Thermal insulation has been temporarily removed from the left flange.

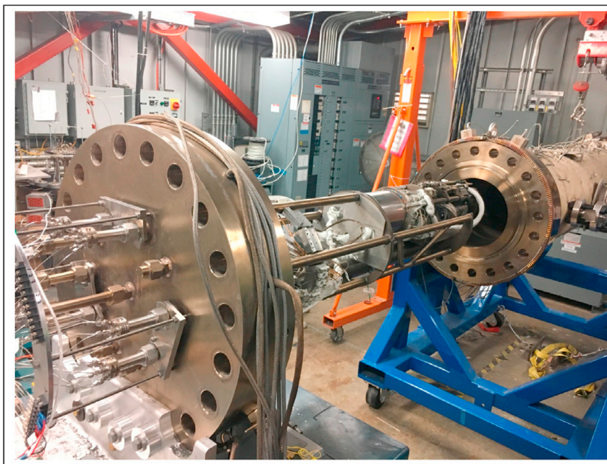

Fig. 8. Loading of the drill assembly into the LVTC. The drill is bolted onto the top flange of the LVTC (left) and inserted into the chamber (right) while in the horizontal orientation.

4.1. Drilling-only tests

The Honeybee drill and its high temperature brushless DC motors have been extensively characterized in a series of laboratory experiments as reported in Rehnmark et al. (2018). Actuator performance curves (torque vs current, speed vs current and motor efficiency versus torque) all showed good agreement with theoretical design predictions. A peak motor efficiency of 80% was demonstrated at a torque of 0.1 N-m, falling to 60% at 0.3 N-m, with the actuator power output ranging from 55 to 110 W across this torque range.

Initial drilling experiments were conducted in a second small JPL Venus chamber called the Venus Materials Test Facility (VMTF). As reported in Ref. 4, the results showed that the drill reached a 5 cm depth in 13 min at 480 °C and 92 bar of CO_2 gas. This initial drilling-only experiment did not have pneumatic sample transfer capability, but post-test inspection showed lots of particulates inside the hollow drill bit that were available for transport. The success of this preliminary drilling experiment led to the subsequent testing of the complete end-to-end drilling and sample transfer system.

4.2. Pneumatic sample transfer tests

Pneumatic sample transfer experiments without drilling were performed to quantify the efficiency of the cyclone particle separator and overall particulate mass transfer as a function of flow speed and particle size (Lambert and Rabinovitch, 2017). These preliminary experiments were performed in a lab separate from the LVTC but employed similar tubing diameters and lengths that were later used in the end-to-end tests. For each test, approximately 10 g sample of particulates were loaded into a tube serving as a proxy drill bit embedded into a rock. These particulates were taken from prior tests with the Honeybee drill (Section 4.1 above) and then sieved into three different aliquots: 10–15 μm, 32–50 μm, and 300–600 μm particle diameter ranges. Generally only one aliquot was used in any given experiment, allowing for determination of the effect of transfer efficiency on particle size.

The flow rate goes from zero up to a maximum value and back down to zero during a test given the finite volume of the low-pressure dump tank and the amount gas available at Venus surface conditions in the chamber. Flow speed is regulated passively by employing a fixed-size metering orifice that is placed in series with the shut-off valve between the Venus chamber and the cyclone to give different flow profiles. Three different orifice sizes were tested and different particle size aliquots used at each orifice to yield a matrix of test results for the two main variables. Two particle mass measurements were made at the end of each transfer experiment, one at the bottom of the cyclone representing the mass that would have been delivered to the airlock, and the other on a filter at the entrance to the low-pressure dump tank, representing a loss of material that was not properly separated by the cyclone. Any mass not accounted for by these two measurements was presumed to be deposited on the walls of the connecting tubing of the system prior to reaching the cyclone.

The results are summarized in Table 2. It can be seen that the cyclone efficiency is highest with the larger particle sizes and slower flow speeds (smaller flow metering orifice), an expected result given the nature of the device that relies on centrifugal force and gravity to separate the particles from the flow. The flow corresponding to the smallest orifice (0.025″) showed a lot of material left at the drill bit location in the rock, indicating insufficient aerodynamic force to entrain the particles. The 0.037″ diameter orifice showed the best transfer efficiency overall and near perfect cyclone efficiency except for the very smallest particle sizes of 15 μm and below. We concluded that the 0.037″ diameter orifice was the optimum for this application and subsequently used it in the end-to-end experiments described next.

4.3. Combined end-to-end sample acquisition and transfer test

We were able to perform two end-to-end experiments of the complete system in the LVTC before the end of the development program. The first test failed completely due to a mechanical problem with the transfer tubing in the drill deployment device that prevented all sample transfers. That problem was fixed by making changes to the tube clamps that provided more clearance for the thermal expansion of the tubing and accommodation for axial misalignment of the sliding parts of the trombone. After that, the second end-to-end test successfully transferred particulate material to the airlock that had been drilled at Venus surface conditions. The details of this second test will now be described.

The end-to-end test was prepared by loading a flat sample of saddleback basalt into the LVTC and aligning it such that the Honeybee drill would enter perpendicular to it. The basalt rock used had a density of 2650 kg/m3, unconfined compressive strength of ~120 MPa and an elastic modulus of ~59 GPa (Peters et al., 2008). The LVTC was loaded

Table 2
Results from preliminary pneumatic sample transfer tests.

Orifice Diameter (mil)	ParticleSize (μm)	SystemEfficiency (%)	CycloneEfficiency (%)	Total Sample Mass (g)	SampleCollected at Cyclone (g)	Sample Collected at Tank (g)	Sample Left at the rock (g)	Unaccounted Sample (g)
62	32–50	70.6	77.4	10.2	7.2	2.1	0.0	0.9
62	300–600	74.5	81.7	10.2	7.6	1.7	0.0	0.9
37	10–15	9.0	39.1	10.0	0.9	1.4	2.3	5.4
37	32–50	90.0	100.0	10.0	9.2	0.0	0.4	0.5
37	300–600	87.0	100.0	10.0	8.7	0.0	1.1	0.2
37	All sizes	76.1	93.7	11.7	8.9	0.6	0.6	1.6
25	32–50	87.0	100.0	10.0	8.7	0.0	1.1	0.2
25	300–600	29.0	100.0	10.0	2.9	0.0	7.1	0.0

with CO_2 gas and heated over a 4 h period to reach conditions very close to nominal Venus surface conditions, namely a temperature of 462 °C and a pressure of 91 bar. Once steady-state conditions were achieved the test began with the activation of the drill deployment device that lowered the drill approximately 1 m until the stabilizer contacted the rock. Drilling commenced shortly thereafter; however, the LVDT position sensor failed on this test and therefore no real-time data was available on drilling depth achieved. As a result, the pneumatic sample transfer events were triggered off elapsed time rather than achieved drilling depth: the appropriate valves were opened and samples were transferred at 6, 9 and 17 min after the start of drilling. The airlock was moved after each transfer to line up the next sample cup for the following transfer. The drill was stopped after the last transfer event and the chamber allowed to cool down overnight with post-test inspection occurring on the following day.

Fig. 9 shows the rock particulates that were successfully transferred to each of the three sample cups in the airlock. The amount of material in each cup was measured to be 0.3, 1.2, 2.0 g. Overall, this is less material than expected and the reason for it became apparent upon inspection of the rock and drill after the test. The drill only reached a 0.9 cm depth and not the 5 cm depth as expected. As a result, less material was pulverized by the drill and hence less was available for transfer to the airlock. Post-test inspection revealed that one of the wires to the drill became mechanically disconnected during the experiment and that stopped the percussion function of the drill at an unknown but nonetheless early stage of the experiment. This wire failure explains why the drill did not penetrate at the expected rate and hence produced so much less pulverized material for the airlock. Less clear is the explanation for why the first sample cup gathered much less material than the other two cups. Although we do not know the actual drill penetration rate versus time, there is no reason to believe the rate was 4–6 times smaller at the beginning that would correspond to the much reduced amount of sample deposited in the first cup. Our working hypothesis is that the first particles to move tend to stick to the initially clean surfaces of the connecting tubing between drill and airlock. Furthermore, once those surfaces become coated with particles, the "stickiness" of the surface is much reduced and subsequent particles move largely unimpeded. This effect certainly reduces the collection efficiency but, if true, would not cause cross-contamination between the material collected at different depths and deposited into the different sample cups.

The disconnected wire problem is presumably solvable with more careful routing of the wires and addition of some mechanical support to avoid entanglement and provide better resistance to the vibration environment of the operating drill. However, this solution and the first cup missing mass hypothesis described above could not be implemented and tested before the end of the research program. This unfortunate circumstance is mitigated by the overall evidence that the pneumatic sample transfer system worked as intended despite the reduced amount of material available for transport and the low efficiency for the transfer event into the first collection cup. The total amount of material received in the airlock was approximately 38% of the total excavated by the drill, with a roughly equal amount left behind on the rock itself around the drill bit and the rest presumably deposited on the walls of the connecting tubing or lost to the dump tanks. Options for reducing the amount of particulates sticking to the connecting tubing include electro-polishing

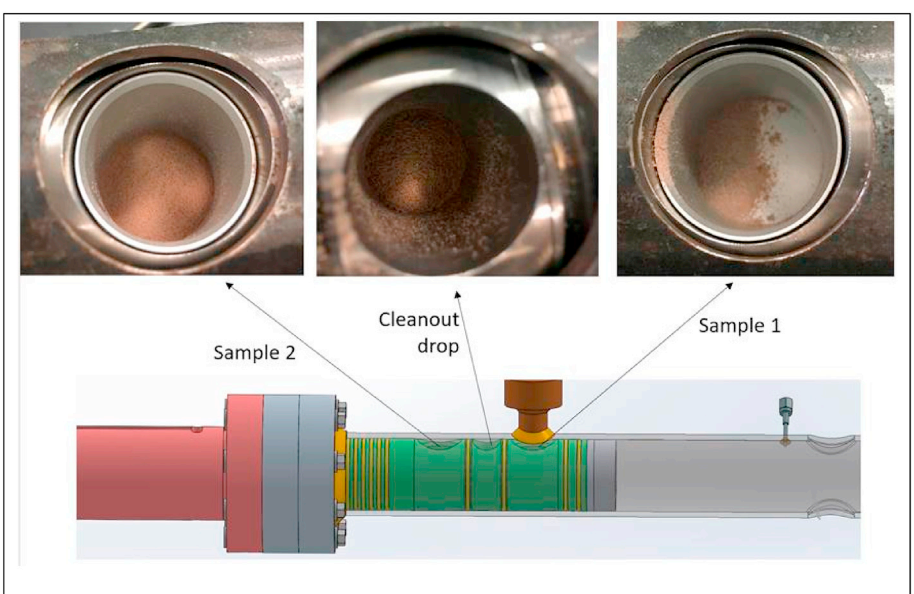

Fig. 9. Successfully transferred particulates shown in all three cups of the airlock.

inside surface to reduce roughness and taking steps to more fully ground the hardware to mitigate against electrostatic forces that cause the particulates to adhere to the tubing.

5. Conclusions

JPL and Honeybee Robotics designed, built and successfully tested a fast end-to-end sample acquisition and transfer system for the Venusian surface. This full-scale prototype system used a rotary-percussive drill that functions at full Venus surface conditions and was capable of achieving a 5 cm depth in saddleback basalt in 15 min. The drill featured a hollow bit that facilitated the pneumatic movement of particulate samples created by the drilling process to the lander for sample analysis. The pneumatic system used the motive force of the high-pressure Venus atmosphere to move the particulates into the lander. A cyclone particle separator removed the particles from the flow and deposited them into an airlock, while the gas itself flowed into a low-pressure dump tank. Two science samples were provided from the drill, one near the surface and one at depth, with a third sample in between collected to minimize cross-contamination between the other two primary samples. The airlock received all samples as designed then depressurized and cooled them and had them ready for scientific analysis. The final end-to-end system test succeeded in moving samples into each of the three sample collection cups, but a failure of a connecting wire disabled the percussion feature of the drill early in the experiment and resulted in much less drill penetration than expected. Although particulate samples were successfully delivered to each of the three sample cups, it appears that the pneumatically transported particles tend to stick to the clean inside wall of the connecting tubing, resulting in low efficiency of the first transfer event, but much less so in subsequent transfers. Future versions of the sampling system will have to address these unresolved problems and improve upon the drill depth achieved and transfer efficiency of the overall system.

Credit author statements

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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