Sample Handling in Extreme Environments

Louisa Avellar

Jet Propulsion Laboratory

Major: Mechanical Engineering

USRP Spring Session

10 May 13

Sample Handling in Extreme Environments

Louisa Avellar[1], Mircea Badescu[2], Stewart Sherrit[3], Yoseph Bar-Cohen[4]
NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109

Harsh environments, such as that on Venus, preclude the use of existing equipment for functions that involve interaction with the environment. The operating limitations of current high temperature electronics are well below the actual temperature and pressure found on Venus (460°C and 92 atm), so proposed lander configurations typically include a pressure vessel where the science instruments are kept at Earth-like temperature and pressure (25°C and 1 atm). The purpose of this project was to develop and demonstrate a method for sample transfer from an external drill to internal science instruments for a lander on Venus. The initial concepts were string and pneumatically driven systems; and the latter system was selected for its ability to deliver samples at very high speed. The pneumatic system was conceived to be driven by the pressure difference between the Venusian atmosphere and the inside of the lander. The pneumatic transfer of a small capsule was demonstrated, and velocity data was collected from the lab experiment. The sample transfer system was modeled using CAD software and prototyped using 3D printing. General structural and thermal analyses were performed to approximate the proposed system's mass and effects on the temperature and pressure inside of the lander. Additionally, a sampler breadboard for use on Titan was tested and functionality problems were resolved.

I. Venus Sample Handling Design

A. Background

Between 1961 and 1984, the Soviet Union sent a number of probes and landers to study Venus. While the majority of the missions did not drill into the surface, three missions, Venera 13, Venera 14, and Vega 2, drilled into the surface to collect samples for analysis. The three landers used the same design for the sample acquisition and transfer system.

The Soviet sample acquisition and transfer system used a series of four pyrotechnic valves (pyros) to transfer the soil to a capsule, enclose the capsule in an airlock, depressurize the sample, and fire the capsule to the science instruments. When the capsule reached the science instruments it struck a grating and the soil poured out of the end of the capsule, through the grating and into a soil receiving cup [1].

Although the Soviet's system was reliable as a result of careful design and extensive testing in simulated Venusian conditions, the system is undesirable for use on future missions for several reasons. The reasons include the fact that the Soviet pyro system weighed five times what NASA specifies the sampling system to weigh [2]. Additionally, pyros consume a lot of electricity to function, which is undesirable because resources are limited on landers. Perhaps the most important reason that this system is undesirable is because it can only be used once. Once the pyros are fired they cannot be used again. NASA has specified that the sample acquisition system is to transfer samples to science instruments on board the lander for as long as the lander is still functioning – at least six times during the three hour mission duration. The design process is further complicated by the surface conditions on Venus; the atmospheric conditions are 460°C and 92 atm. For reference, the atmospheric conditions on Earth are 25°C and 1 atm. Current high temperature electronics are not sufficient for operation at Venus ambient conditions, resulting in lander configurations where the science instruments are inside of a pressure vessel that is kept close to Earth-like temperature and pressure. Furthermore, the extreme conditions on Venus severely limit the use of sensors and actuators outside of the lander, necessitating simple designs that rely on passive components.

---

[1] USRP Spring Intern, Mechanical Engineering, University of California at Berkeley
[2] Senior Member of Technical Staff, Advanced Technologies (352C), MS 67-119, NASA JPL, Pasadena CA, 91109
[3] Senior Member of Technical Staff, Advanced Technologies (352C), MS 67-119, NASA JPL, Pasadena CA, 91109
[4] Group Supervisor, Advanced Technologies (352C), MS 67-119, NASA JPL, Pasadena CA, 91109

The purpose of this project was to evaluate the different options for sample transfer, choose one, design and test components for the system, and develop a viable concept for sample delivery.

B. Venus Sample Transfer System Options

JPL's Nondestructive Evaluation and Advanced Actuators (NDEAA) lab conceived of two systems for the transfer of powder samples: a string driven system and a pneumatically driven system [3].The premise of the string driven system is that the powdered sample would be loaded into capsules which would then be pulled to the science instruments in the lander by retracting a string connected to the capsule. Figure I.1 shows an example of a string driven system. The premise of the pneumatically driven system is to take advantage of the pressure difference between Venus's atmosphere and the inside of the lander. After a sample is loaded into the capsule, valves open to the atmosphere and inside of the lander that apply a pressure difference across the capsule. The pressure difference results in a force that pushes the capsule through the tube. Figure I.2 shows an example of a pneumatically driven system.

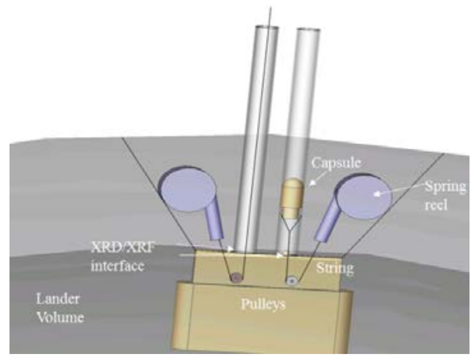

Figure I.1: Example string driven system [3].

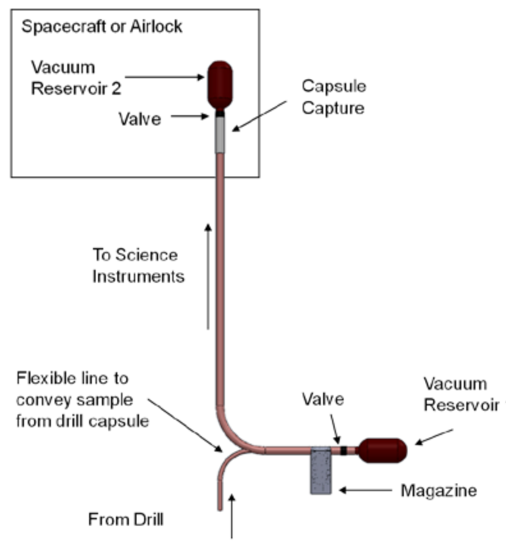

Figure I.2: Example pneumatically driven system.

The string driven system has several advantages:

- The capsule would not necessarily need to be closed, simplifying the capsule design and filling.
- Besides the sample and capsule, nothing needs to enter the lander. This limits the thermal load introduced into the lander by the system.
- It may be possible to design the system so that no actuators function outside of the lander allowing standard, rather than high temperature, components to be used.

However:

- If there were six strings (one for each capsule) but one transfer tube, the strings could tangle during launch, landing, or device operation. Tangled strings could mean the end of the device's functionality.
- The tangled string problem could be solved by having separate tubes for each capsule, but this would add weight and complexity to the system.
- Airlock design could be complicated because the strings would have to pass through the airlock. As capsules are retracted the size of the string bundle would change, meaning that the airlock would have to reliably seal a variable diameter hole.
- This system has the potential to be very slow.

Similarly, the pneumatically driven system has several advantages:

- The pressure differential is already part of the lander.
- The capsule will be transferred at high speed.
- Similar systems have been in use on Earth for decades and have proven to be reliable.

But:

- The capsule must be closed to prevent losing the sample. This adds complexity to the capsule.
- The system will require actuators to drive valves outside of the lander in Venus ambient conditions.

- If the inside of the lander is used as the low pressure reservoir for driving the system, the system will increase the temperature and pressure inside the lander.

After comparing the pros and cons of each type of system, the pneumatically driven system was selected due to its ability to transfer samples rapidly.

Pneumatic transfer does not necessarily require containing the sample in a capsule. While not using a capsule would reduce the complexity and weight of the system because capsules and capsule storage would not be required, it might be difficult to reliably transport the small amount of sample required over a long distance. The layout of the capsule-less pneumatic conveying systems is very important: turns and vertical displacement severely reduce the efficiency of the system and can potentially catch a portion of what is being conveyed [4]. In the following configuration these effects are assumed to be minimal or easily overcome for the short distance between the drill and the capsule. Furthermore, transferring loose sample through an airlock would be more challenging than transferring a single, rigid object, complicating the system. The loose sample would also have the potential to get in the airlock's seals, which would compromise the quality of the seals.

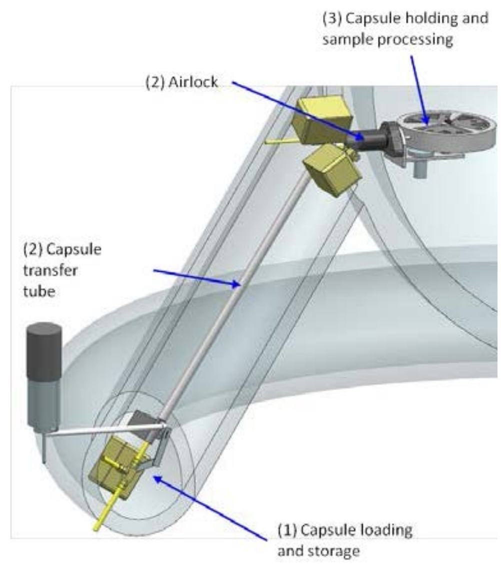

Figure I.3: System configuration with labeled subsystems.

C. Description of the pneumatic sample transfer system

The pneumatic sample transfer system consists of three subsystems: (1) capsule loading and storage, (2) capsule transfer and airlock, and (3) capsule holding and sample processing. Figure I.3 shows the system configuration with labeled subsystems. For the following configuration, the inside of the lander is assumed to be approximately Earth pressure and can be used as a low pressure reservoir. However, a separate low pressure reservoir could be used, if desired. The entire system is expected to have a mass of approximately 1.932 kg, not including valves, actuators, screws or ball bearings.

1. Capsule Loading and Storage

i. Capsule

The capsule loading and storage subsystem contains two main components: the capsules and the magazine. With the exception of the window and its support structure, both capsules have the same architecture and they function in the same way. Grates in wall of capsule (rectangles on the left side of the outside view of the capsule) allow air conveying the powdered sample to enter the capsule. When pressure is applied to the outside of the capsule, the radial one-way valve (black trapezoid on the left side of the section view of the capsule) opens inward and allows air to flow through the capsule from left to right. However, if the high pressure is applied in reverse, the radial valve closes and air cannot flow back through the grate. This seals the sample inside of the capsule.

When air is flowing from left to right in the capsule (when the radial valve is open), this valve allows the air to exit the capsule. This valve will also open to depressurize the capsule if the pressure inside of the capsule is higher than the pressure outside of the capsule while the radial one way valve remains closed. When pressure is applied to the right side of the capsule, the skirt seals the capsule in the tube to prevent air from blowing around the capsule and the second one-way valve closes, sealing the capsule. The filter prevents the sample from leaving the sample collection area through the second one-way valve.

The window and window support structure (the bar that passes through the center of the capsule to connect the front end to the back end) are the only structural differences between the two capsule designs. The capsule without the window would be made entirely from beryllium. The structure of the window capsule could be made from any material, but the window would be made from Mylar or Kapton. X-ray Diffraction (XRD) and X-ray florescence (XRF) are the science experiments intended to be performed on the sample. The experiments are performed by bouncing X-rays off of the sample and measuring the energy of the reflected photons. Beryllium, Mylar and Kapton all diffract very little so their effects on the results would be minimal [5]. However, Mylar and Kapton both have melting points less than 460°C, the ambient temperature on Venus, so their use would not be desired.

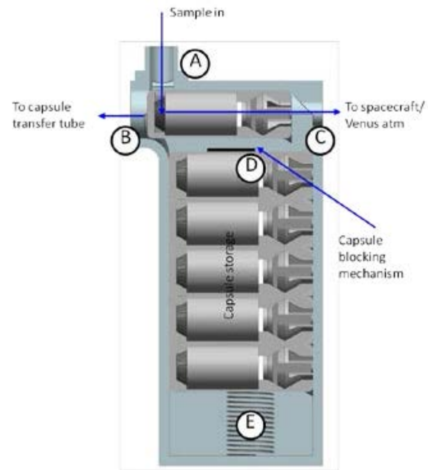

Figure I.4: Magazine with capsules.

ii. Magazine

Figure I.4 shows the magazine with six capsules. Point A in Figure I.4 labels the sample inlet. The sample inlet is connected to the sample inlet tube, which runs from the drill to the magazine. This tube does not contain a valve – it is open to the Venusian atmosphere at all times – but the capsule seals it in the magazine. The sample inlet lines up with the radial valves so that air conveying the sample can flow from the sample inlet, through the capsule, and exit the capsule at point C in the figure. Point C is the port to which a valve controlling the airflow through the magazine is connected. When the valve is closed, there is no air flow. When the valve is open to the lander, a pressure differential is created across the capsule between the high pressure sample inlet and the relative vacuum of the lander, allowing air conveying sample to flow through the capsule. When the valve is open to Venus atmosphere and a second valve is opened to the lander at the destination point in the capsule transfer tube, a pressure differential is created across the capsule which pushes the capsule to its destination.

iii. Subsystem Operation

When the system is ready to transfer another capsule into the main lander body, valve C opens to Venus atmosphere, and a second valve at the other end of the transfer tube F opens to the lander, and the pressure differential pushes capsule through transfer tube. The actuator that opens valve C also drives the four-bar capsule blocking mechanism B. The mechanism pushes a slider into the magazine that prevents the next capsule from being inserted into the transfer tube while capsule transfer is in process.

2. Capsule Transfer and Airlock

When the capsule reaches the airlock this process is complete. A simple structural analysis was performed to determine an appropriate tube wall thickness for mass estimation purposes. The capsule is pushed through the capsule in at D into one of the slots in drum from the capsule transfer tube. Flexures inside of the slots slow down, stop, and hold the capsule. They prevent the capsule from hitting the outer barrel wall and bouncing back down the capsule transfer tube. The drum rotates inside the barrel on ball bearings. The barrel and drum are sealed with two X shaped seals on the ends and one seal around its circumference. To seal against the Venusian atmosphere, these seals must contact the drum with a pressure greater than that of the atmosphere, resulting in a large torque (approximately 19 N·m) required to rotate the drum. Due to the large amount of torque required to rotate the drum, it is rotated by an external gear along its circumference through the slot, B, rather than using an axle.

When the capsule is aligned with capsule out, a valve to Venus atmosphere and valve to the lander open and the capsule is pushed into the capsule holding and sample processing subsystem in the same way it was pushed to the airlock subsystem.

3. Capsule Holding and Sample Processing

The carousel, A, contains slots for each capsule. When the carousel is in position, valves B and C open to the lander and Venus atmosphere, respectively, providing the pressure differential that pushes the capsule into the carousel. Valve B is stationary with respect to the carousel; it opens to whichever slot is in line with the airlock. The carousel is mounted on an axle which is rotated via a motor mounted beneath the carousel. The carousel is rotated to bring the capsule to the science instruments as well as to put a new slot in line with the airlock. The system does not discard the capsules. Each capsule slot contains one-way flexure traps that allow the capsule to enter, but not exit, the slot. A spring in the slot slows the capsule down and then pushes the capsule against the traps for a consistent position of the sample collection area of the capsule. Piezoelectric actuators in the side walls of the slot vibrate the capsule, and, as a result, the sample. The slots also contain filters in the through section that allows the air to pass through the carousel. These filters are to prevent any particles from entering the lander and endangering other electronics. Vertical holes for instrument viewing pass through the carousel perpendicular to the slot at the location of the sample collection area of the capsule. A slot circular slot runs around the bottom of the carousel, allowing the instrument to be close to the capsule.

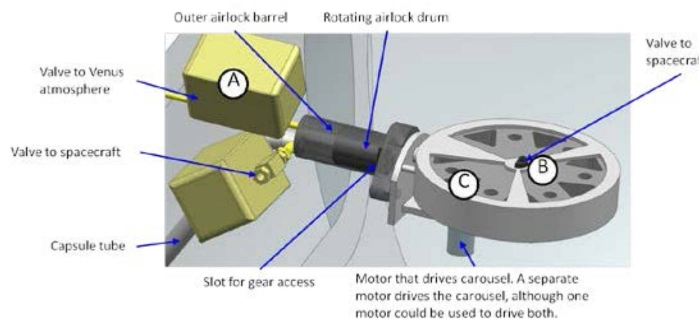

Figure I.5: Close up of the capsule holding and sample processing subsystem.

4. Effects of System Operation

The operation of this system is expected to raise the temperature and pressure inside the lander to at most approximately 360 K and 1.34 bar due to the pneumatic driving. These numbers were calculated using a constant volume tank charging model with ideal gas assumptions. The heat contained by the capsules as a result of their temperature is expected to raise the temperature by a further 15%. These effects could be mitigated by the use of phase change materials for thermal control. Another option is to not use the inside of the lander to provide the low pressure, but to use a separate pressure vessel located elsewhere on the lander, perhaps in a leg. Using a material for the capsules with a lower heat capacity than that of beryllium would significantly reduce the heat transferred into the lander by the capsule.

D. Pneumatic Transfer Demonstration

1. Experiment Description

Capsule transfer via a pressure difference in a tube was demonstrated. Four Teflon capsule simulators were machined and are shown in Figure I.6: Small, Medium, Small Extra Long (Small XL) and Medium Extra Long (Medium XL). The purpose of the Extra Long (XL) capsules was to better represent the proposed capsule design by having a length to diameter ratio closer to three-to-one than to two-to-one. Both the Small and Small XL capsule have skirts made of ordinary paper and attached with tape.

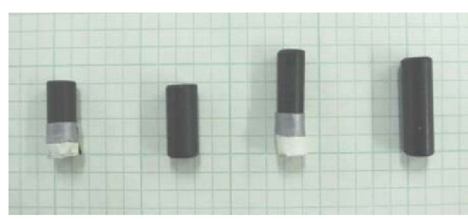

Figure I.6: (left to right) Small Capsule, Medium Capsule, Small XL Capsule, Medium XL Capsule (small squares are 0.51 cm (0.2”) square)

The capsules were placed into a clear PVC tube and the tube was connected to a pressurized air tank with a regulator at the valve. Three tests were performed: horizontal straight tests (Figure I.7.A); vertical with two turns tests (Figure I.7.B); and, horizontal with one turn tests (Figure I.7.C). The first set of tests was performed with all of the capsules. The second set of tests was performed with only the Small and Medium capsules. The third set of tests was performed with only the XL capsules. Velocity data was not determined for the third set of tests as the purpose of these tests was to show that the capsule was capable of moving through small turns. For the horizontal tests, the tubing was secured to aluminum profile stock. The profile stock was marked in 2.5 cm (1”) intervals. For the vertical test, the tubing was secured to the side of a tall table. The side of the table was marked in 2.5 cm (1”) intervals. The turns both had radii of approximately 10.2 cm (4”). The test was performed by slowly opening the valve on the air tank until the capsule began to move. A Cannon 1 high speed camera was used to capture the motion of the capsules.

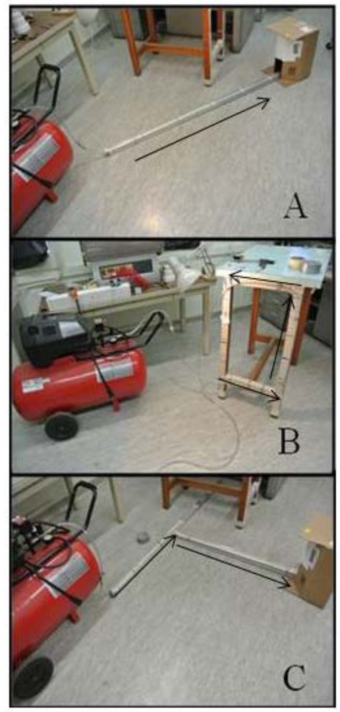

Figure I.7: (top to bottom) Horizontal Straight Test Setup, Vertical with Two Turns Test Setup, Horizontal with One Turn Test Setup (arrows show path)

2. Results and Discussion

For the horizontal straight tests, the data was processed by recording the frame number at which the capsule reached each distance mark. The frame number was converted to time with a resolution of approximately 0.83 milliseconds. Each set of position data exhibited two phases of motion of the capsule: an acceleration phase and a constant velocity phase. Linear regression was used on the constant velocity phase data points to determine the speed of the capsule. The regression lines were plotted with the data points to check that they were reasonable. Ten data points were used for each regression calculation. In general, the Small capsule achieved the highest velocity, followed by the Medium, Small XL, and Medium XL capsules. For the horizontal straight tests, the minimum and maximum velocities attained were: Small – 4.6 m/s and 9.0 m/s; Medium – 1.1 m/s and 7.0 m/s; Small XL – 2.5 m/s and 4.2 m/s; and, Medium XL – 1.5 m/s and 3.4 m/s.

For the vertical tests, the position and frame number data was recorded in the same way and the capsule’s movement through the turns was disregarded. Each set of position data exhibited a constant velocity in the horizontal section after the pressure was applied and before the first turn; a short acceleration phase after the first turn; a phase of constant velocity in the vertical section between the first and second turns; a short acceleration phase after the second section; and, a constant velocity phase in the horizontal section after the second turn. The initial acceleration of the capsule was not captured by the camera due to limited frame size. The first constant velocity section was typically much slower than either of the subsequent two sections. The vertical section was generally slower than the final horizontal section, although there are three exceptions in the Small capsule data.

Both pneumatic capsule pipeline and simple ballistic models were used to try to find an approximate value of the pressure applied across the capsule. Unfortunately, neither model resulted in an acceleration phase that agreed with the data obtained during the acceleration phase of the capsule’s movement, suggesting that the models are insufficient. However, this could also be attributed to neither the applied pressure differential nor the conveying air velocity being known, resulting in estimations that could be incorrect being used for the calculations.

Although an electro-pneumatic transducer that could have controlled the pressure very precisely was available for use in this experiment, the transducer did not provide a high enough air flow rate to move the capsule. As a result the pressure was controlled via the pressure regulator on the compressed air tank, but the regulator did not allow for fine control of the applied pressure. The applied air pressure was not well controlled or measured in either the straight horizontal tests or the vertical tests, so the conclusions that can be drawn from their data are limited. However, because the needle on the pressure gauge at the regulator never moved it is known that the pressure applied across the capsule was less than 5 psig, the lowest pressure marked on the dial. Despite the shortcomings of the experiment, it was successful in demonstrating that pneumatic transfer is a viable option for rapid capsule transport.

At the time of this report, a version of the system described was being 3D printed. The purpose of this system is to demonstrate the functionality of the configuration.

E. Future Work

Further development of the technologies presented in this report will be necessary for the operation of this system on Venus. The every component, especially the airlock drum and barrel, will need to be further refined and tested. High temperature valves, actuators, and seals will also need to be developed and tested.

II. Titan Sample Transfer Testing

A. Titan Sampling Needle

A proposed system for sampling on Titan acquires its sample by plunging a needle into ice, retracting the needle, melting the ice sample and drawing it up to science instruments. A sample collection system was designed a modeled based on a two stroke piston.

Compressed N_2 gas is stored in the N_2 chamber. The chamber is opened and the gas is allowed to expand in the cylinder, pushing the needle down against a spring. The needle pushes through the elastomer and into the ice. The needle is hollow and collects the sample in its middle. As the needle reaches the bottom of its stroke, the exhaust port is exposed, allowing the high pressure N_2 gas to escape. As the pressure pushing the needle down decreases, the spring begins pushing the needle back up into the cylinder. The elastomer reseals the cylinder. The elastomer is placed in the heater so it can be maintained at an appropriate temperature. The ice sample is melted and drawn from the needle into the inlet. The hose connecting the needle to the inlet is bellowed and it expands and contracts as the needle is deployed and stowed again.

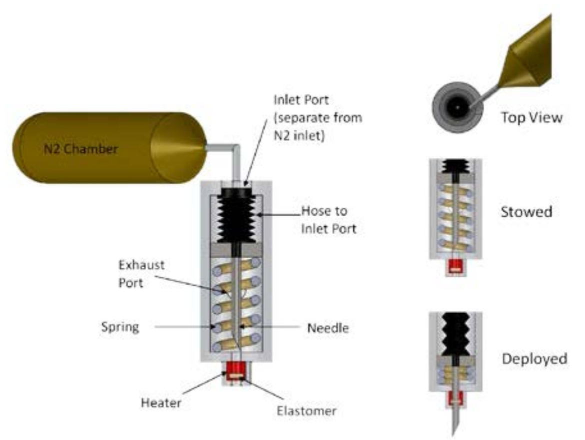

Figure II.1: Titan Sampling Needle

B. Titan Sampler Breadboard

The purpose of the Titan sampler breadboard is to demonstrate the design's abilities to draw a sample from a sample inlet, through a filter to science instruments. Much of the breadboard had been assembled, but to be completed a solvent reservoir and a liquid collection tank/manifold were added to the system. The solvent reservoir is a 0.19 L (6 oz) squeeze bottle with a hole cut into the bottom. The bottle is turned upside down and attached to the system via approximately seven inches of clear PVC tubing secured onto the bottle's nozzle. The purpose of the reservoir is to hold solvent until it is needed.

The first liquid collection tank was a 0.95 L (32 oz.) rigid bottle with four holes cut into the bottom. One of the holes has a nozzle hot glued in it, while the other three have approximately 45 cm (18") of the same clear PVC tubing hot glued into the holes and sealed with duct tape. The bottle is turned upside down and other ends of the tubing are secured onto the setup. The vacuum tank is attached to the liquid collection tank/manifold via clear PVC tubing secured onto the nozzle. The purpose of the liquid collection tank/manifold is to add connections to the vacuum pump and to collect liquid pulled from the system before it can enter the vacuum pump.

Demonstration video clips were created that showed the four different functionalities of the sampler (Figure II.2). Water colored blue with food coloring was used to simulate the sample. Water colored yellow with food coloring was used to simulate the solvent. The demonstration clips show:

1. Sample pulled unfiltered to the liquid collection tank (valves 2 and 3).
2. Sample pulled through the filter to NMR (valves 3 and 4).
3. Sample pulled through the filter to GEC EL (valves 3 and 5).
4. Solvent pulled through the filter to GEC EL (valves 1 and 5).

Initially, the sampler was not working as intended; water did not flow easily through the filter resulting in excessively long (approximately 30-40 minutes) operation times. The long operation times resulted in the valves reaching undesirably high temperatures. A fifth demonstration was performed to show that the solvent reservoir and valve 1 worked:

5. Solvent pulled unfiltered to the liquid collection tank (valves 1 and 2).

The lines were drained between each test.

After creating the initial clips, the filter was removed from the system and replaced with a filter with a larger frit size. Due to concerns that the liquid collection tank/manifold was leaking and thereby reducing the effectiveness of the vacuum, a new liquid collection tank/manifold was made. The new liquid collection tank/manifold is a section of 2” pipe threaded at both ends. One end is connected to a cross with the other three ports interfacing with the sampler via approximately 45 cm (18”) of clear PVC tubing. The vacuum pump is attached to the liquid collection tank/manifold via clear PVC tubing secured onto a fitting at the other end of the tube. With the new equipment, tests 1 through 4 were able to be completed successfully.

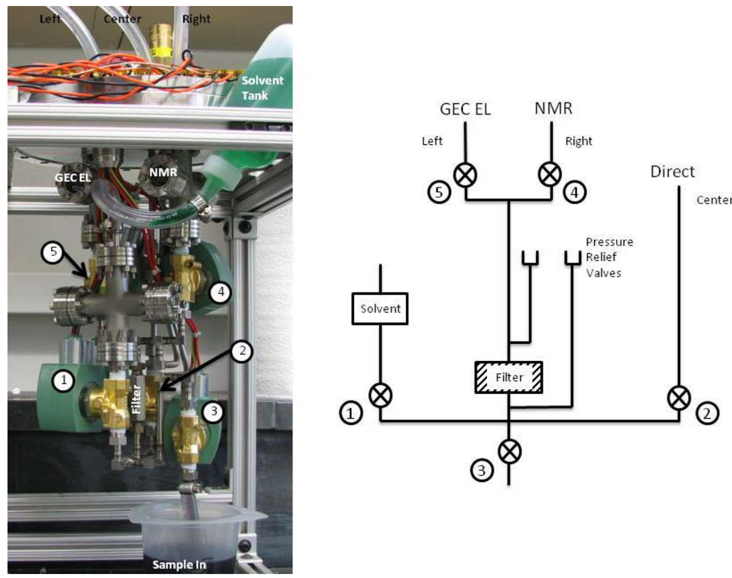

Figure II.2: Titan Sampler Setup and Schematic (Sample is purple and solvent is green)

Acknowledgements

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the Undergraduate Student Research Program (USRP) and the National Aeronautics and Space Administration (NASA). Louisa Avellar would like to thank the entire Advanced Technologies group for their support, especially Yoseph Bar-Cohen, Mircea Badescu and Stewart Sherrit. Louisa would also like to Michael Pauken (353K) for his assistance on the thermal analysis and Advanced Deployable Structures (352D) for the use of their high speed camera.

References

[1] ESKOS, "The Venera/Vega Projects: An analysis of the operational experience obtained in the study of the atmosphere and surface of Venus," 1994.

[2] E. Kolawa, "Extreme Environment Technologies for Future Space Science Missions," 2007.

[3] Y. Bar-Cohen, "Powder Sampling in Support of SAGE," 2012.

[4] D. Mills, M. Jones and V. Agarwal, Handbook of Pneumatic Conveying Engineering, CRC Press, 2004.

[5] D. Blake, "MSL Science Corner: Chemistry & Mineralogy," NASA JPL, [Online]. Available: http://msl-scicorner.jpl.nasa.gov/Instruments/CheMin/. [Accessed 22 4 2013].

[6] M. Pauken, *Senior Engineer (353K),* 2013.

[7] "Example Problem with Complete Solution: Charging a Tank with Compressed Air," B-Cubed, 2006. [Online]. Available: http://www.learnthermo.com/examples/ch05/p-5e-2.php. [Accessed 27 March 2013].

[8] "Metals - Specific Heats," The Engineering Toolbox, [Online]. Available: http://www.engineeringtoolbox.com/specific-heat-metals-d_152.html. [Accessed 23 4 2013].

[9] "Property Tables and Charts (SI Units)," 11 August 2006. [Online]. Available: https://highered.mcgraw-hill.com/sites/dl/free/0073529214/395307/appdxs1_2.pdf. [Accessed 23 April 2013].

[10] J. Gere, "Appendix H: Properties of Materials," in *Mechanics of Materials*, Belmont, Thomson, 2004, pp. 914-915.

[11] Beryllium Science & Technology Association, "Properties of Pure Beryllium," 2013. [Online]. Available: http://beryllium.eu/about-beryllium-and-beryllium-alloys/properties-of-beryllium/properties-of-pure-beryllium/. [Accessed 24 April 2013].

[12] OnlineMetals.com, "15-5 PH Stainless Steel Condition A (annealed)," 2013. [Online]. Available: http://www.onlinemetals.com/alloycat.cfm?alloy=15-5. [Accessed 24 April 2013].

[13] *Course Handout, UC Berkeley ME108 Sp12 Professor H Dharan, Formula Sheet,* 2012.

[14] *Course Handout, UC Berkeley ME108 Sp12 Professor H Dharan, Stresses in Thick-Walled Cylinders from "The Design and Selection of Mechanical Elements", pp. 561-570,* 2012.