Miniature Piezoelectric Shaker Mechanism for Autonomous Distribution of Unconsolidated Sample to Instrument Cells

Stewart Sherrit, Kent Frankovich, Xiaoqi Bao, Curtis Tucker

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA

ABSTRACT

To perform in-situ measurements on Mars or other planetary bodies many instruments require powder produced using some sampling technique (drilling/coring) or sample processing technique (core crushing) to be placed in measurement cells. This usually requires filling a small sample cell using an inlet funnel. In order to minimize cross contamination with future samples and ensure the sample is transferred from the funnel to the test cell with minimal residual powder the funnel is shaken. The shaking assists gravity by fluidizing the powder and restoring flow of the material. In order to counter cross contamination or potential clogging due to settling during autonomous handling a piezoelectric shaking mechanism was designed for the deposition of sample fines in instrument inlet funnels. This device was designed to be lightweight, consume low power and demonstrated to be a resilient solid state actuator that can be mechanically and electrically tuned to shake the inlet funnel. In the final design configuration tested under nominal Mars Ambient conditions the funnel mechanism is driven by three symmetrically mounted piezoelectric flexure actuators that are out of the funnel support load path. The frequency of the actuation can be electrically controlled and monitored and mechanically tuned by the addition of tuning mass on the free end of the actuator. Unlike conventional electromagnetic motors these devices are solid state and can be designed with no macroscopically moving parts. This paper will discuss the design and testing results of these shaking mechanisms.

KEYWORD: piezoelectric devices, shaking mechanisms, powder movement, fluidization, vibration

1. INTRODUCTION

The controlled movement of powder is an important technological objective in many industries. A variety of industrial process requires the movement or distribution of powder in the manufacturing chain. Terrestrial examples include powder metallurgy[1] and food and pharmaceutical industry where powdered material are conveyed and distributed to containers for packaging and distribution[2]. Industrial applications are generally less constrained compared to aerospace systems where the application may be severely limited by mass, volume and power requirements. An interesting space application that utilizes the application of this technology is in the autonomous distribution of powdered mineral samples for in-situ analysis on extraterrestrial bodies. Examples of current base-lined instruments that require powder for in-situ analysis include Mars Science Laboratory (MSL's) CHEMIN x-ray diffractometer (XRD) and SAM's Gas Chromatograph Mass Spectrometer (GCMS) which have been rescheduled to launch in 2011. The development of a powder handling system for Mars is complicated by the fact that limited information about the sample is unknown before sampling. A variety of mechanisms can conspire to impede the flow of powdered material. The particles can adhere to the funnel wall or each other through a variety of forces including "chemical bonding, cementation, ice bridges, capillary forces, van der Waals forces, and electrostatic forces" [3]. In the present system the device requirements were for the movement of dry powder and non reactive materials on open surfaces. From a design point of view these system requirements restrict potential particle adhesion due to van der Waals and electrostatic forces, although this may not be the actual situation in the polar regions as has been demonstrated by sample handling results from the Phoenix lander[4]. Many different phenomena can produce polarization and free charge. These include ionizing radiation, triboelectric, pyroelectric and piezoelectric processes. Whatever the possible cause of adhesion, techniques including mechanical, electromechanical or electrostatic means can be used to counter or reduce the effect[5]. This paper discusses the design and testing of miniature piezoelectric shaking mechanisms based on flextensional transducers driven by piezoelectric stack actuators that have been demonstrated to move powdered materials under Mars analogue conditions into the CHEMIN Instrument test cells. The choice of piezoelectric actuation was dictated by the need for compact, solid state actuation and the fact that similar actuators were base lined for the sample test cells to vibrate the powder while it was interrogated by the X-ray beam[6, 7]. The shaker mechanism was designed to produce fluidization of the powder (which has been pre-screened using a 150 micron sieve) to improve flow through a 1mm sieve (1mm US standard # 18 testing sieve) and 2.7 mm diameter inlet tubes.

2. BACKGROUND

The original electromechanical shaking mechanism design for the CHEMIN instrument inlet funnel is shown in Figure 1. In this design 3 flextensional actuators (CEDRAT APA 120S) were connected to the funnel through the hexapod supports (also shown). The actuators are driven at 50-1000 Hz frequencies to produce extensional displacements normal to the mounting plane of the hexapod. Although the actuation was sufficient to produce particle flow through the sieve on the inlet funnel, the shaker design suffered some critical deficiencies. Since the actuators support the funnel mass by their placement in the support load path they generated significant reaction vibrations in the hexapod supports and into the alignment bench. This design also required the actuators to support the funnel mass during launch vibration and pyro shock testing.

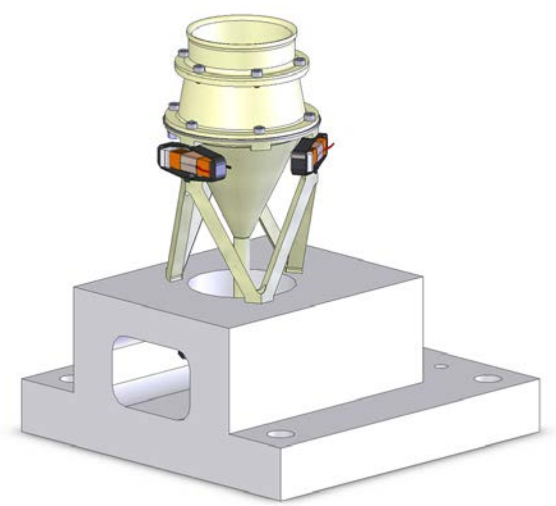

FIGURE 1: Original funnel shaker mechanism CAD model on a vibration testing block. Three actuators mounted between the funnel and the hexapod support structure vibrated the funnel during transfer of the sample fines to the CHEMIN test cells. This shaker design configuration supported the funnel mass during random vibration and pyro shock tests.

The output of the three actuators were monitored along with strain gages for each actuator. The actuators were instrumented to determine if voltages produced by the piezoelectric stack actuators would exceed the acceptable levels for the drive electronics. During the tests voltage outputs were observed that indicated that a debond in each of the actuators had occured. An indicative spectra of the voltage of one of these debonds is shown in Figure 2, which shows the random vib time data at 0 db for P004 actuator and the asymetric voltage output from this actuator. A destructive post mortem analysis of the actuators indicated that the polymer bond (shim and flexure, and in 2 cases between the shims) had delaminated. These results suggested that the intial funnel shaker design allowed for tensile stresses outside the normal operating limits of the Cedrat APA-120S actuators. It should be noted that there was no indication or evidence of a failure in the piezoelectric stacks/material and that the Funnel actuators would likely have been functional after the vibe tests albeit with some what reduced properties and the potential for working life reduction.

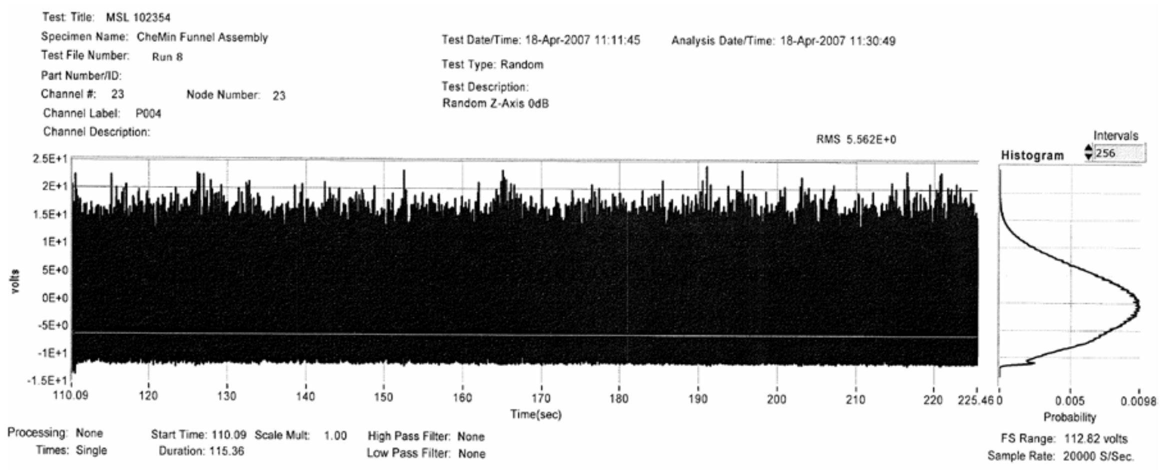

FIGURE 2. The random vibration voltage-time data at 0 db for Actuator P004 of the original design. Notice the asymmetric voltage output from this actuator.

3. ACTUATOR REDESIGN

In order to meet the original schedule for the shaker mechanism a rapid re-design was initiated. A variety of alternative designs were considered and in some cases tested before focusing on the final configuration shown in Figure 3. The flextensional actuators are shown in Figure 4. These actuators were redesigned to meet the

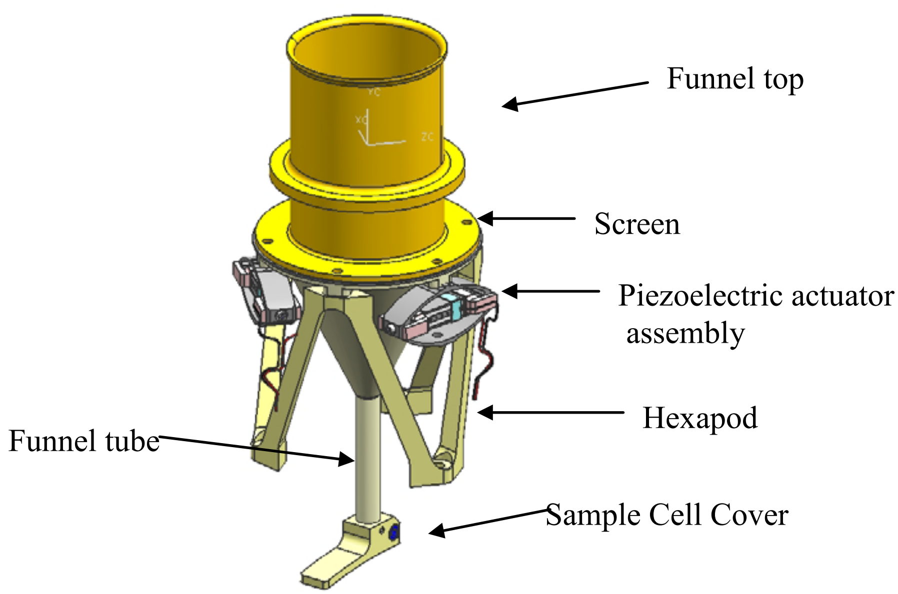

FIGURE 3: A CAD model graphic of the redesigned funnel shaking mechanism for the CHEMIN instrument including actuators assembly, funnel, hexapod and sample cell cover. The redesigned flextensional actuators are mounted offset at 120 degrees from the previous design and out of the load path.

functional and environmental requirements for the Mars Science Laboratory. The titanium flextensional actuators were manufactured using Electrical Discharge Machining (EDM). The end caps were fabricated using Invar to reduce the thermal stress in the piezoelectric stack that is generated over the operational temperature range. The piezoelectric stacks (PI – 885.31) were manufactured by PI-Ceramic (piezoelectric ceramic division of Physik Instrumente (PI)).

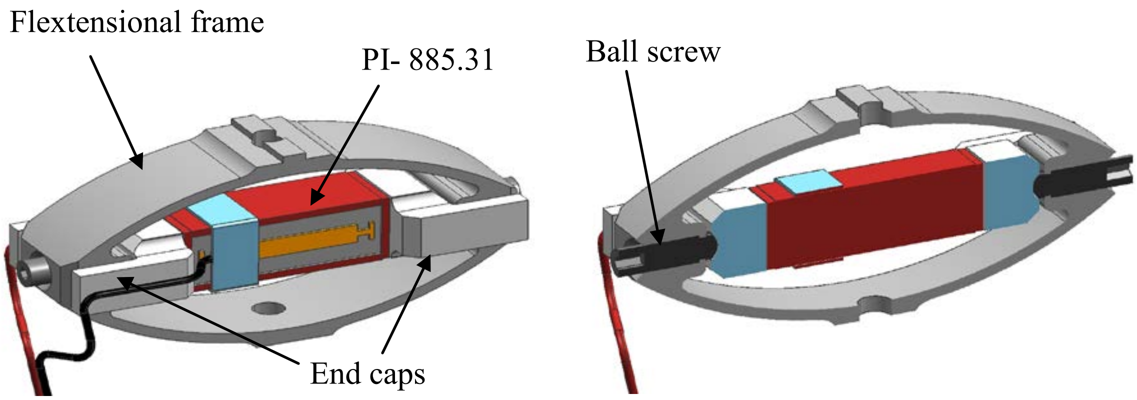

FIGURE 4: A close up isometric view of the titanium flextensional actuator and a cross section showing the ball screw which allows for the compressive pre-stress and tensile stress relief.

The actuators were bonded (3M - 2216) to the end caps and a prestress of 15 MPa was applied using the set screw. The pre-stress was monitored using the voltage output of the piezoelectric connected in parallel with a 10 microfarad capacitor as measured on a high impedance multimeter (Keithley 2002). A signal of 3 Volts corresponds to a 15 MPa compressive stress in the stack. Prior to applying the pre-stress the set screw threads were coated with epoxy (3M- 2216) and allowed to set under load. The ball of the set screw is captured by an indent in the base of the end cap to ensure the piezoelectric and end caps are maintained horizontally in the flextensional frame. In addition the ball screw mechanism produced axial loading in the piezoelectric and insured the piezoelectric did not experience tension. The tabs on the end caps were used to maintain the end caps while the prestress was applied. The actuator was modeled using ANSYS Multiphysics over the operational temperature range to determine the thermal stresses that would be induced in the piezoelectric. The actuator was fixed at one actuation face and a thermal stress of -80 K was applied. The maximum von Mises stress in the piezoelectric stack was found to be 3.7 MPa and occurred at the corners of the inactive layer of the piezoelectric stack. The maximum axial stress (Sx) in the piezoelectric stack was found to be compressive and in the range from 0.6 to 1.9 MPa. The axial stress for an 80 K temperature shift is shown in Figure 5. The maximum von Mises stress occurring in the metal structure was estimated to be less than 200 MPa and was found to occur at the screw-flextensional interface of the ball screw. The new actuator shown in Figure 4 was designed to be stiffer to increase the launch vibration survivability. The blocked-free resonance frequency was calculated to be 2.5 kHz compared to the Cedrat APA 120S actuators which had a blocked-free resonance frequency of 1.4 kHz. In addition to the system design shown in Figure 3 the actuators were designed to allow for mechanical tuning and modifications as is shown in Figure 6.

The nominal actuator as utilized for the CHEMIN instrument is shown in Figure 6a. Optional features that could be incorporated included mass loading the actuator as is shown in Figure 6b to reduce the resonance frequency and increase the reaction force and creating a free mass resonator to produce impacts on the funnel as is shown in Figure 6c. The free mass is allowed to move in the vertical direction along a smooth rod between a fixed gap. This mechanism has been used in previous research to produce low power, low mass drills[8,9].

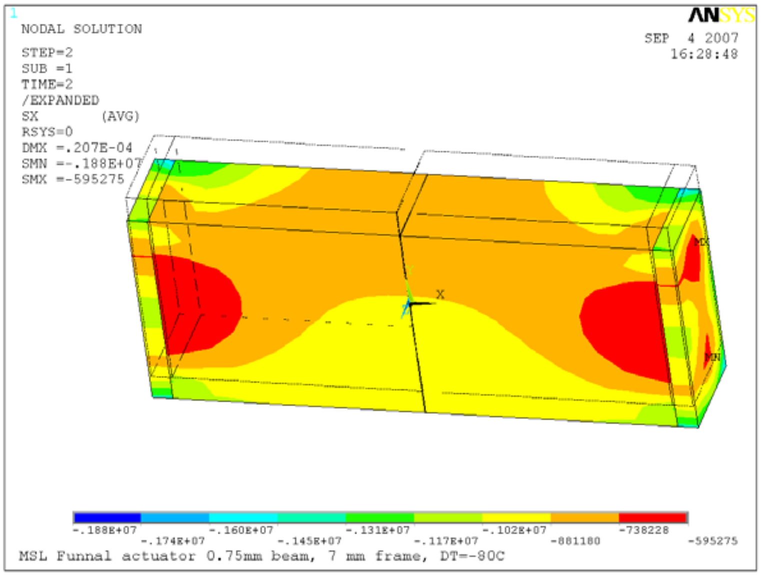

FIGURE 5: A close up of the stress Sx distribution in the piezoelectric for a -80K temperature shift.

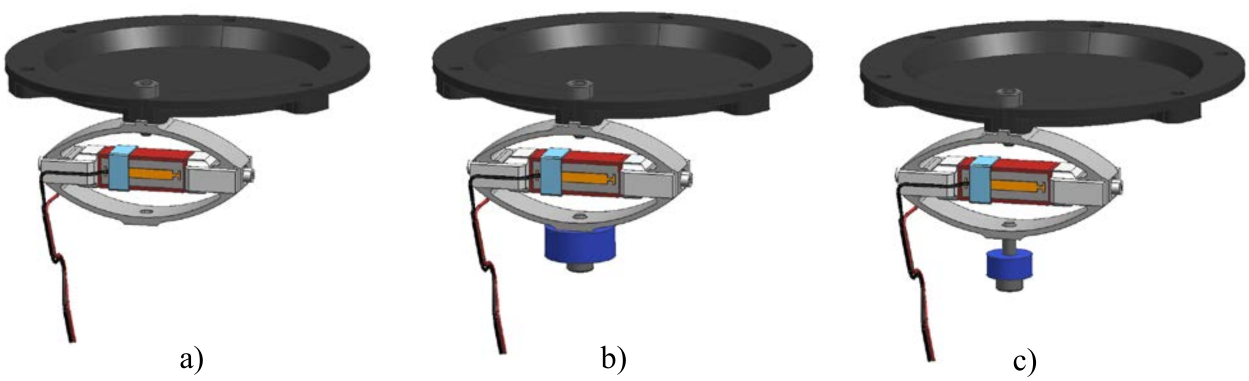

FIGURE 6: A CAD graphic of the actuator mechanism mounted on the funnel rim out of the load path. The other end of the flexure can be modified to a) be free, b) drive a fixed mass, or c) drive a free mass at a lower resonance frequency and produce impacts.

In addition to the actuator redesign other features were also changed to aid in the movement of powder. The funnel chimney was plated with gold to insure good electrical conductivity and the sieve was redesigned to a frustum shape from a flat disc to reduce the areas where incoming powder could potentially be trapped.

4. SHAKER EVALUATION

The cross contamination tests were performed in the vacuum chamber. Test #0 was a bench top test performed out of the chamber in ambient air using the quartz and corundum powder samples produced for these tests. The results of that test showed little dusting of the sample on the funnel chimney. The cross contamination was negligible to the level of instrument error <1%. After the bench top test (test #0) we designed and built a sample transfer and collection mechanism that incorporated the funnel and hexapod and could be installed inside a vacuum chamber. The apparatus is shown in Figure 7. The funnel was tilted at an angle of 20 degrees to horizontal and the sample powder was dumped so that it contacted the inside of the funnel at the top to simulate a worst case scenario for sample transfer. Samples of quartz Q (4 samples) and corundum C (six samples) where dropped into the funnel in the following order QCCCQCQCQC. In tests #1-3 the funnel vibrator (1 actuator driven with a 7 Volt peak signal with a frequency sweep of 11 to 12 kHz over 5 seconds for a total of 300 seconds) was not activated until after deposition of the sample. The results of test # 1 showed marginal cross contamination in a least one sample (sample 8 up to 1 % quartz in corundum). The cross contamination measurements for tests #0,#1 and #4 are shown in Table 1. After test #1 a visual inspection of the funnel chimney showed a considerable layering on the left and right sides of the funnel. A photograph of this layering is shown in Figure 8. The coating was observed from the right to left sides of the funnel extending almost a third way up the center point. The sample bottles were capped and measured by means of XRD analysis using A Bruker AXS model D8 Discover X-ray diffractometer equipped with a General Area Detector Diffraction System (GADDS) using CuKα radiation (λ = 0.1542 nm). The system was employed to obtain powder XRD patterns for the samples as collected. Peak identifications were made based on standard powder diffraction files from the International Centre for Diffraction Data (ICDD), 2000. Amount of contamination (in wt%) was determined based on standards with known concentrations of both quartz in corundum and corundum in quartz. The conditions of each of these tests are listed in Table 2. The significant layering seen in Figure 8 and a visible streak of quartz powder in one of the corundum samples raised concerns about cross contamination and powder buildup on the chimney wall. In an effort to determine the cause of this layering effect two other tests were performed in the chamber. One test at ambient pressure and temperature (test #2) and one at Earth ambient temperature and Mars ambient pressure (test #3). In each of these tests no significant layering was noticed. Only a slight dusting of the funnel wall was noted. These tests were performed to investigate the layering effect and no samples were collected for analysis. The results of tests #2 and #3 suggested the cause of the buildup was temperature or a temperature delta between the sample and the chimney wall. The layer was found to be predominately (80 wt%) quartz.

TABLE 1. The results of the cross contamination studies for the Quartz and Corundum samples from tests 0, 1 and 4. All data is in weight percent.

Contamination of quartz with corundum or corundum with quartz			
Sample	Test 0	Test 1	Test 4
1 Quartz	<1%	<1%	<1%
2 Corundum	<0.5%	<0.5%	<0.5%
3 Corundum	<0.5%	<0.5%	<0.5%
4 Corundum	<0.5%	<0.5%	<0.5%
5 Quartz	<1%	<1%	<1%
6 Corundum	<0.5%	<0.5%*	<0.5%
7 Quartz	<1%	<1%	<1%
8 Corundum	<0.5%	0.5-1.0 %**	<0.5%
9 Quartz	<1%	<1%	<1%
10 Corundum	<0.5%	<0.5% *	<0.5%

* Possible contamination - right at detection limit.
** Minor contamination

As was discussed previously the sticking phenomena can be divided into four general causes, electrostatic forces, Van der Waals forces, chemical (or phase change) and mechanical. The samples used in tests #0-3 were as received with no sample preparation or bake-out was performed. Since the layering effect only occurred at low temperature and the pressure and type of gas did not appear to affect the layering appreciably, it was reasoned that the likely source was water from the powder sample freezing to the funnel wall. To evaluate this theory a fourth and final test (test #4) was undertaken. In this test the samples were baked out for 3 days at 105 ^{o}C in an oven. The samples were transferred to the test apparatus in an aluminum block to maintain temperature while they were mounted in the vacuum chamber (the process took about 5 minutes) and the samples were above ambient temperature when the chamber was sealed, evacuated and backfilled with CO_2. The chamber was cooled for 12 hours using a liquid nitrogen cold plate. The funnel temperature was -32 ^{o}C at the beginning of the test and increased 2-3 ^{o}C during the test. A reduced but still significant layering of the powder was observed after completing test #4 as is seen in Figure 8.

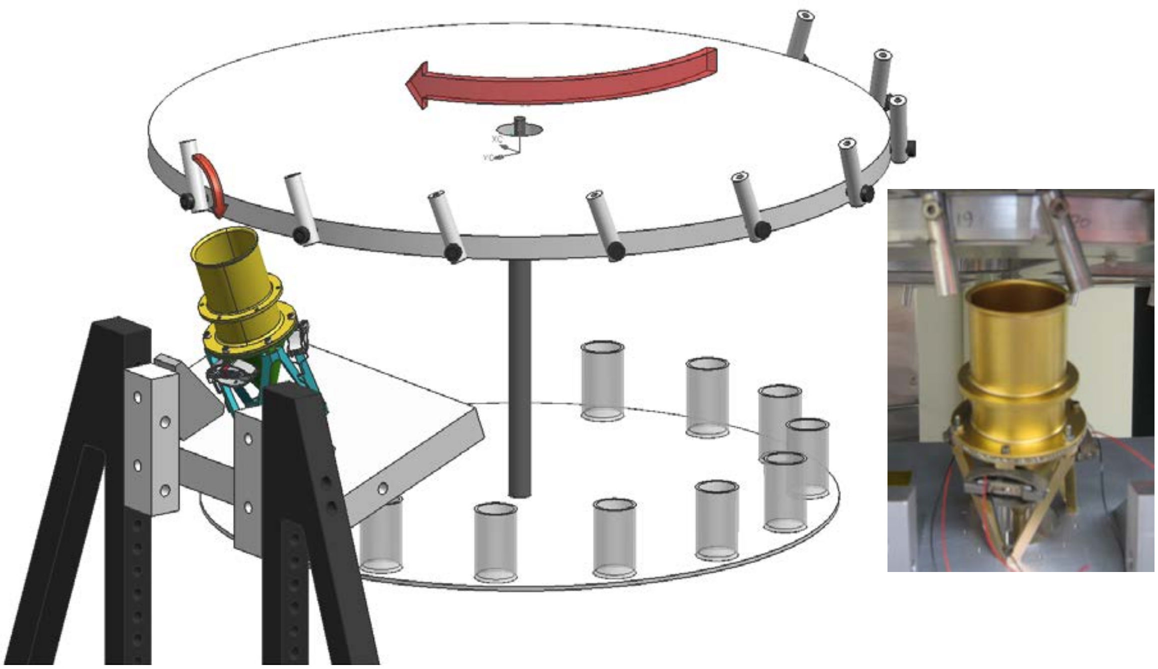

Figure 7. The experimental setup for tests 1 and 4. The top carousel was rotated using a mechanical feed through and the sample containers came into contact with a tip rod that dumped the powder into the inlet funnel which is mounted at 20 degrees to the vertical. In tests 2 and 3 sample bottles were not used to collect for cross-contamination studies. Inset picture shows the funnel in the chamber and portion of the carousel.

Figure 8. Powder coating on the on the left and right sides of the chimney of the funnel for test #4. The sample tube dumps in a swinging motion and rests finally on the left edge of the funnel.

The overall results found in Table 1 suggest cross contamination is kept to less than 1% even when the funnel wall is dusted by residue from previous samples.

TABLE 2: Test Matrix for the CHEMIN funnel cross contamination test.

Test #	In Chamber	6 Torr CO_2	At -30-35 ^oC	1/ Sample History 2/ Funnel on/off during dump	Cross Contamination Results
0	no	no	no	1/ As supplied 2/ off	None
1	yes	yes	yes	1/ As supplied 2/ off	Layering on chimney
2	yes	no	no	1/ As supplied 2/ off	No layering on chimney
3	yes	yes	no	1/ As supplied 2/ off	No layering on chimney
4	yes	yes	yes	1/ Dried* 2/ on	Layering on Chimney

* Dried for 72 hours at 105 degrees Celsius.

5. SUMMARY

The layering of the baked out powder samples produced a layer on the chimney funnel that was almost as significant as the sample that had not been baked out. This suggested another mechanism for the sticking of the powder to the funnel rather than the formation of ice bridges. Electrostatic sticking can occur when charge produced on a crystal face induces an image charges on a grounded conducting surface. The force of attraction is then proportional to $kQ^2/(2D)^2$ where Q is the charge and D is the separation between the charge and the ground plane and $k=1/4\pi\varepsilon_o$ where ε_o is the permittivity of free-space. A similar attraction for dipoles is also present. This means that charged particles will be attracted and stick to a grounded metallic surface (if charge compensation doe not occur). If this sticking is electrostatic in nature how are the charges being generated on a crystal surface? There are four processes that we are aware of to produce charge on a crystal due to interactions with other crystals; Dielectric via electric field, Triboelectric via friction or fracture of a crystal, Piezoelectric via a stress relief or Pyroelectric due to polarization due to a change in temperature of the material. The layering effect we have characterized is found only in measurements when the funnel is at low temperature (-30 ^oC to – 35 ^oC). Given that samples on the carousel are at a higher temperature due to a more circuitous thermal path to the nitrogen N_2(*lq.*) it is likely that quenching of the particles is occurring and a pyroelectric charge is being produced which interacts with the grounded funnel to produce sticking. This suggests that the sticking or layering in this case may be a peculiarity of the quartz. Since the nominal actuation scheme met the cross contamination requirements the alternate actuation schemes with mass and free mass tuning were not implemented.

ACKNOWLEDGMENT

The authors would like to thank Bob Anderson and William Abbey for measuring and analyzing the x-ray spectra for the contamination tests. Research reported in this manuscript was conducted at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under a contract with National Aeronautics Space

Administration (NASA). Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

REFERENCES

[1] See "Powder Metallurgy" Journal publishing methods of handling powder and particulate for processing, Maney Publishing, http://www.maney.co.uk/

[2] M. Mracek, J. Wallaschek, "A system for powder transport based on piezoelectrically excited ultrasonic progressive waves", Materials Chemistry and Physics **90**, pp. 378–380, (2005)

[3] Howard A. Perko, John D. Nelson, and Jacklyn R. Green," Review of Martian Dust Composition, Transport, Deposition, Adhesion, and Removal" Proceedings of Space Proceedings of Space 2002: the Eighth International Conference and Robotics 2002, the Fifth International conference and exposition/demonstration on robotics for challenging situations and environments., Bryan E. Laubscher, Stewart W. Johnson, Samuel E. Moskowitz, Phil Richter, David Klinger, Editors Albuquerque, New Mexico, USA, March 17–21, 2002,

[4]NASA - Phoenix news release, http://www.nasa.gov/mission_pages/phoenix/news/phoenix20080829a.html, Downloaded Jan 20, 2009

[5]G.A. Landis: Mars Dust Removal Technology, AIAA Journal of Propulsion and Power 14 [1], 126 (1998).

[6] Philippe C. Sarrazin, David F. Blake, Powder Handling Device for Analytical Instruments"US Patent #7113265, 2006

[7]P. Sarrazin, S. Chipera, D. Bish, D. Blake, S. Feldman, D. Vaniman and C. Bryson, Proceedings of the Lunar and Planetary Science XXXV, 1794, (2004)

[8] S. Sherrit, B.P. Dolgin, Y. Bar-Cohen, D. Pal, J. Kroh, T. Peterson "Modeling of Horns for Sonic/Ultrasonic Applications", Proceedings of the IEEE Ultrasonics Symposium, pp. 647- 651, Lake Tahoe, Oct 1999

[9]X. Bao, Y. Bar-Cohen, Z. Cheng, B.P. Dolgin, S. Sherrit, D.S. Pal, S. Du, T. Peterson, "Modeling and Computer Simulation of the Ultrasonic/Sonic Driller/Corer (USDC)", IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, **50**, pp. 1147-1160, Sept. 2003