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Initial Considerations of a Dust Dispenser for Injecting Tungsten Particles in Space

Ryan J. Ilardo
Praxis, Inc.
Alexandria, Virginia

Michael F. Zedd
Control Systems Branch
Spacecraft Engineering Department

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This document reviews exploratory work to design, build, and test a table-top sized tungsten particle dispenser. A small canister and dispenser system within a vacuum bell jar is described to provide qualitative and quantitative observations of the dispensed particle stream. We selected tungsten carbide spheres and irregular tungsten powders all under 100 microns, driven by previous work. That work investigated the benefits of identical spherical particles, approximately 30 microns, filling an orbiting ring about the Earth to enhance drag, causing small pieces of orbital debris to enter the atmosphere. Using only gas or a gas-driven piston to propel the particles, many tests showed that increasing pressure yielded increasing stream velocity and higher velocity in vacuum than in air. Speed goals could be achieved and controlled, but because the speed and mass flow rate were directly linked, an abrasive blaster design was used to first mix the particles with the gas before exiting a conical nozzle. The clumping of particles is unwanted as it changes ballistic properties and decay rate. Clumping was seen with irregular powders, and methods to mitigate this problem are discussed. A summary of trends from testing, designs, and topics for the future end this report.

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INITIAL CONSIDERATIONS OF A DUST DISPENSER FOR INJECTING TUNGSTEN PARTICLES IN SPACE

ABSTRACT

This document reviews exploratory work to design, build, and test a table-top sized tungsten particle dispenser. A small canister and dispenser system within a vacuum bell jar is described to provide qualitative and quantitative observations of the dispensed particle stream. We selected tungsten carbide spheres and irregular tungsten powders all under 100 microns driven by previous work. That work investigated the benefits of identical spherical particles, approximately 30 microns filling an orbiting ring about the Earth, to enhance drag causing small pieces of orbital debris to enter the atmosphere. Description of the test setup, procedures, and high-speed video for data recording are a prelude to actual testing. Using only gas or a gas-driven piston to propel the particles, many tests showed that increasing pressure yielded increasing stream velocity and higher velocity in vacuum than air. Speed goals could be achieved and controlled, but because the speed and mass flow rate were directly linked, an abrasive blaster design was used to first mix the particles with the gas before exiting a conical nozzle. The clumping of particles is unwanted as it changes ballistic properties and decay rate. Clumping was seen with irregular powders and methods to mitigate this problem discussed. Separate samples were exposed to humid air for months to qualitatively examine oxidation. A summary of trends from testing, designs, and topics for the future end this report.

BACKGROUND

This report documents FY14 accomplishments that produced several versions of laboratory table-top-sized dust canisters and dispensers. Experiments with these dispensers represent the first steps to understanding how to handle and inject very small tungsten particles.

Beginning in FY11, the theoretical studies by the plasma physicists and astrodynamicists, showed the merits of a ring of orbiting tungsten dust causing small pieces of orbit debris to fall into lower orbit, eventually reentering the atmosphere. [1] [2] [3] The tungsten dust particle collides head-on with orbital debris and the tungsten vaporizes along with a bit of the aluminum debris. Aside from reducing the orbital angular momentum of the aluminum due to collision, the aluminum's partial vaporization affects a negative delta velocity to also lower the orbit.

Our earlier research indicated that tungsten spheres, of identical diameters, are the key to maintaining the shape and integrity of the approximate 15-30 km elliptical diameter cross-section orbiting dust ring about the Earth. The initial orbit is 1,100 km circular at 90° inclination. With each particle having the same size, area, and mass, their identical ballistic properties cause the ring to uniformly decay to lower orbit, thus giving a snow-plow effect to debris particles. All particles should be the same diameter although they could range between 30-60 microns. The smaller diameter particles decay sooner than the larger diameter particles (30 microns decay in 12 years, 60 microns in 26 years), allowing the mission designers the ability to establish the ring's lifetime.

Table 1 shows size properties for pure tungsten with density of 19.3 gm/cm^3. The 10,000 kg total mass is a postulated quantity of tungsten to fill the ring (well, somewhat, as with 30 microns, it is only 1 particle in a cube 10 m on a side).

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Table 1: Size properties of pure tungsten spheres.

										number of
				drag area			spherical			spheres in
diameter	Radius			area across diameter			volume	mass		10,000 kg
microns	microns	mm		mm^2	m^2		m^3	kg		trillion
30	15.0	0.015		0.000707	7.0686E-10		1.41372E-14	2.7285E-10		36.7
60	30.0	0.03		0.002827	2.8274E-09		1.13097E-13	2.1828E-09		10.9
90	45.0	0.045		0.006362	6.3617E-09		3.81704E-13	7.3669E-09		4.6

In this final year of this four-year research effort, the mechanical systems contribution to a dispenser is in order. This report is for the 6.2 program “Elimination of Space Debris Through Induced Drag Enhancement”. We have not previously worked with micron-sized tungsten particles, so devoting about one-quarter of this research program to investigating how to handle and eject these particles is an important bridge to gaining acceptance of the entire program and its possible transition to the greater space-debris removal community.

PURPOSE AND INTRODUCTION

We began to learn how to work with tungsten particles as fine as corn starch, which must be ejected as individual particles. Several designs for dispenser systems are discussed along with their testing.

As mentioned, the particles are ideally uniform in shape and size and they must not clump so as to maintain each particle as a separate tiny spacecraft. All particles require the same ballistic properties so as to decay at the same rate and maintain the integrity of the orbiting ring. The particles' exit speeds and directions should be controlled to allow the orbital mechanics of relative motion to form the tungsten ring, over the course of weeks. That is, there would be a number of separate particle dispensing operations at different locations (mean anomalies) around the orbit such that the orbiting ring is of uniform density and very small eccentricity. The appearance is of a giant hula-hoop around Earth.

Additionally, we need to gain know-how to safely handle the fine tungsten particles on a small, laboratory, scale. The particles, all less than 100 microns, easily fall when poured, yet they spread on the bell jar floor requiring a container to confine the ejected particles and a removable paper floor cover to roll up and funnel the particles for reuse. Research of tungsten safety and handling was necessary to assure ourselves of our personal safety with this new material.

Several qualitative observations on material clumping were made and documented. The clumping of particles could be due to their surface irregularities linking a particle to its neighbor or neighbors, or electrostatic attraction, or oxidation on its surfaces. Clumping changes the ballistic properties of the ejected particles.

In the coming sections, we discuss the tungsten materials and our investigations into its safety and handling. We then describe the laboratory set-up and canister and dispenser concepts. Visual data was captured and examined with high-speed video recording and image analysis software. We show that under certain conditions, the particles are more uniformly ejected using piston instead of gas. A summary of observed trends are presented.

A discussion of our exposing dishes of tungsten and tungsten carbide particles in room air to see if humidity affected their visual appearance is presented.

As might be expected with these preliminary explorations into tungsten dust dispensing, several observed trends are discussed and summarized along with designs and topics for the future.

PROCEDURE

The procedures to execute the goals, discussed above, occurred in approximately the following order:

- Selecting the tungsten particles
- Investigating the safety of tungsten to humans
- Determining the size of the experiment laboratory space
- Determining the size of the canister and dispenser combination
- Obtaining a high-speed video system for data recording
- Performing the experiments
- Collecting results, and interpretation

Selecting the Tungsten Particles and Investigating its Safety to Humans

Our first inquiries for the purchase of tungsten were to obtain several kilograms of pure tungsten spheres 30 microns in diameter. The immediate second focus, even before buying the product was its safety around humans. We asked if it was alright to touch the product. What if it was inhaled? What if it was spilled? Is it flammable? If the product is exposed to air, especially in the humid summer, does it rust?

As a reminder, tungsten was selected several years ago as the dust material because of its high density, to most efficiently vaporize aluminum debris, its low cost, and ready availability. An initial web search of tungsten suppliers yielded no manufacturer that produced pure tungsten spheres near the size we wanted. Pure tungsten dust is available in the size range we wanted; however, it is highly irregular being made by grinding from larger stock. Buffalo Tungsten provided the pure tungsten dust. We also purchased a quantity of tungsten carbide spheres, with diameters in our desired range, because of their shape and improved resistance to oxidation. The product is spherical cast tungsten carbide powder manufactured by Tekna Plasma Systems. This company does manufacture pure tungsten spheres, yet we did not purchase this product. Upon arrival, we did not open any package for several months as we researched its safety.

Table 2 lists the four types of products and their size range. The three tungsten powders are grinded particles and the tungsten carbide powder are spheres. Lot ST-371 was selected because most particles are the smallest at less than 30 microns, lot C100-3196 was selected because most particles fall in a range of 15-38 microns, and lot C110-3186 was selected because most particles are larger than 40 microns. Overall, these particles cover a range of sizes from about 10-75 microns. The tungsten carbide spheres are cast in a narrow size range selected close to 30 microns. At the time of purchase, it is unknown if these spheres could be manufactured, in large quantity (10,000 kg), with nearly the same size held to within tight tolerance. We purchased off-the-shelf materials. Appendix 1 lists material and chemical properties of these products. Appendix 2 provides a longer description and micrographs of these particles.

Table 2: Size properties of acquired tungsten.

Type	Size Range (microns)	
	micron range	weight %
Tungsten Powder Lot No: ST-371	0-10	19
	10-20	35
	20-30	19
	30-40	9
	40-50	6
	>50	12
Tungsten Powder Lot No: C110-3186	0-10	0
	10-20	1
	20-30	3
	30-40	10
	40-50	23
	50-75	51
	75-100	11
	>100	1
Tungsten Powder Lot No: C100-3196	<15	10
	15-38	80
	>30	10
Tungsten Carbide Powder	38-45	100

The pure tungsten powders have a product density of 19.3 gm/cm^3 the tungsten carbide has a density of 15.6 gm/cm^3. Irrespective of type, the tap densities are all about 10 gm/cm^3.

Initial visual inspection of the dust indicated a clear difference in their physical characteristics. The tungsten carbide showed no indication of clumping and proved to be very easy to handle and seemed to flow like a fluid. On the other hand, all three of the pure tungsten samples showed visible signs of clumping when rotating the containers and were noticeably more difficult to handle. This presents a concern for the use of pure ground tungsten. It's unclear however whether the clumping is due to the material or shape difference since no pure tungsten spheres were purchased.

Before we proceeded with dispensing the dust, it was necessary to research the safety and chemical properties with the main focus being on the impact to humans and oxidation. In regards to oxidation at room temperatures the information that has been found is somewhat limited and has often proven to be contradictory. In air at room temperature, the oxidation rate of tungsten and tungsten carbide increases with increasing humidity. [4] Tungsten carbide produced a smaller oxidation layer compared to tungsten. This was determined using electron spectroscopy for chemical analysis. At elevated temperatures however, >500°C, it has shown that both tungsten and tungsten carbide oxidize at accelerated rates compared to room temperatures. This has been indicated by multiple sources.

Our attention turned to investigating the safety of these materials, especially considering these powders. The powder is susceptible to handling issues where spillage may be difficult to clean and room air currents might cause some flyaway from an open container. Different articles and Safety Data Sheets prepared by different companies found on the World Wide Web had similar points for the same issue. Table 1 gives examples from different companies.

Table 3: Comparison of safety data sheets for tungsten.

	Buffalo Tungsten	Plansee	Midwest Tungsten Service	Science Lab.com
Eyes	• Irritation • Flush with large amounts of water for 15 minutes • Wear eye protection	• Irritation	• Irritation • Flush with water for 15mins • Wear eye protection	• Irritation • Remove contacts
Inhalation	• None • Remove from exposure • Threshold Limit Value (TLV) 5mg/m^3	• Breathing protection in presence of dust • TLV 5mg/m^3	• Irritation • Remove from exposure	• Irritation • Rest in well-ventilated area
Ingestion	• Gastrointestinal irritation possible • Remove from exposure	• None	• Irritation • Drink large amounts of water	• Irritation • Do not induce vomiting
Skin	• Irritation possible • Wash with soap and water • Wear gloves	• Irritation possible • Wash with soap and water	• Irritation • Wash with soap and water • Wear gloves	• Irritation • Wash with water and non-abrasive soap
Fire	• Non-flammable for large pieces • Particles < 1 micron can be ignited in air by friction • Ultra-fine powders may ignite spontaneously in air • Use dry powder as extinguishing media	• Non-flammable for large pieces • Increased fire hazard during dust formation	• Non-flammable for large pieces • Dust may present moderate fire hazard if exposed to ignition source • Cover burning material to exclude oxygen • Use a respirator approved for toxic dusts and fumes	• May combust at high temperature • Keep away from ignition sources • Material in powder form, capable of creating a dust explosion with ignition source
Toxicity	• None	• None	• Inert	• Not available
Handling and Storage	• Maintain good housekeeping to practices to prevent dust accumulation • Suction dust for cleanup with approved filter • Keep container closed	• Suction dust for cleanup • No special measures required for storage	• Maintain good housekeeping practices to prevent dust accumulation • Vacuum or wet cleanup	• Keep container dry and away from heat

Much like most metallic particles, the inert tungsten is slightly hazardous in case of skin contact (irritant), eye contact (irritant), ingestion, or inhalation. Yet one company seems to be overly cautious in its warnings such as tungsten is corrosive to eyes and skin. The amount of tissue damage depends on length of contact. Eye contact can result in corneal damage or blindness. Skin contact can produce inflammation and blistering. Inhalation of dust will produce irritation to gastro-intestinal or respiratory tract, characterized by burning, sneezing and coughing. Severe over-exposure can produce lung damage, choking, unconsciousness or death. [4]

We maintained good housekeeping practices to prevent dust accumulation. We poured the dust from heights no greater than a few inches from the supply jar into the funnel for entry into the canister. Clean-up of the several tens of grams of material remaining on the bell jar floor involved rolling stiff paper into a funnel to pour into a container. Appendix 2 summarizes additional safety and handling information.

One separate concern to note is the possible ignition of the dust. Many fine particles of certain materials can ignite when an ignition source is present or enough energy is generated. For example, could the kinetic energy due to the speed of the ejected dust be greater than its minimum ignition energy? A study from 2004 detailed the required ignition energy needed to ignite a tungsten dust cloud of given density and particle size. [5] With pure tungsten dust at a size of 5 to 12 microns and cloud densities from 350 to 7500 g/m^3, the cloud could not be ignited with an ignition source of 10 kJ. In our small size experiments we expect to dispense approximately 16.4 cm^3 (1 in^3) of material. If we assume a velocity of 10 m/s the maximum energy available would be 8 J. Additionally the testing will be performed with nitrogen, an inert gas, which will reduce the concern for ignition. Some of the tests will also be performed in vacuum and in these cases there is no concern for ignition of the dust due to the lack of oxygen.

Determining the Scale of Laboratory Space and Sizes of Canister and Dispenser

As concepts for the dust experiments were discussed, different sizes of laboratory setups were visualized. We considered a tent to contain the dust and prevent room air currents from corrupting the experiments. Room air currents due to air handling and open doors would seem to impact the flow of particles – something unacceptable for several reasons. There was thought that the particles would float and either descend very slowly or not at all in an air-filled container. To avoid this and simulate the space environment, the vacuum jar came to mind because we could not evacuate a tent. Now we could easily test in air and in vacuum. A limitation of the vacuum jar was its small interior dimensions. Considering the orbit application, once the dust exits the nozzle it will continue on its given path with the only interactions occurring being particle to particle. Assuming the particles are exiting at the same velocity these interactions or collisions should be minimal. This results in the need to only analyze particles in the short distance after they exit the nozzle and proves the vacuum jar to be sufficient for our testing and analysis. Of course, we could not eliminate gravity.

Certain hardware was available immediately at hand. Several glass bell jars, a solid collar base with access ports, the separate solid floor, a vacuum pump, and myriad hoses, valves, and connectors allowed us to pursue a small scale set up. The size of the canister and dispenser must then fit inside. Initially, many tests were done without evacuating the chamber; therefore, a series of repeated tests were accomplished more rapidly. This allowed us to quickly gain an understanding of the broad test conditions, such as inlet pressure, mass of material, and outlet geometry needed to achieve a controlled dispense. Figure 1 below shows the experimental setup.

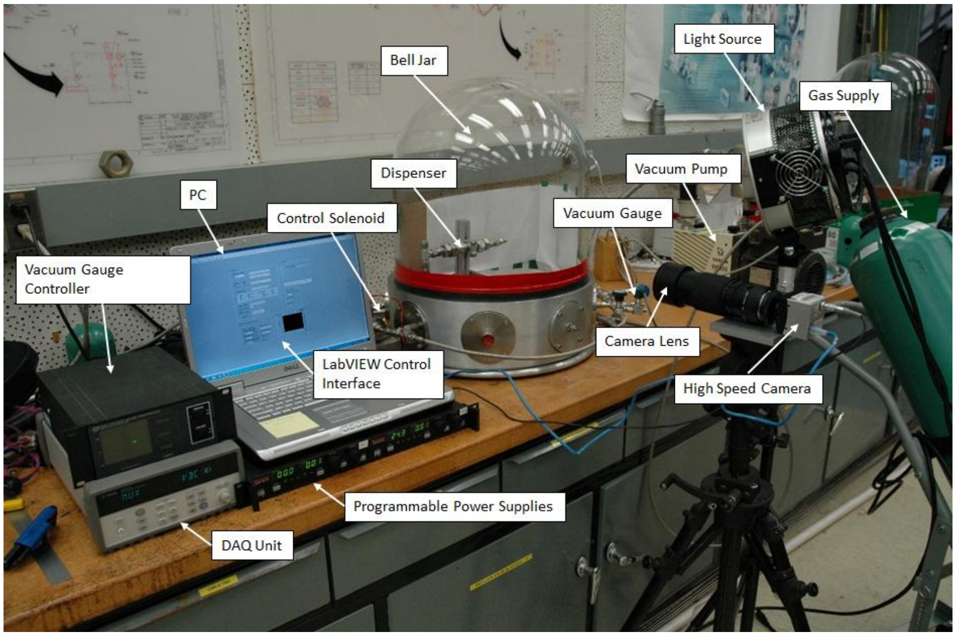


Figure 1: Test setup and components.

The jar prevents room air currents from disturbing the flow and keeps the particles confined within the jar and its floor. The jar also allows for the ability to test in a vacuum environment. The jar has an inside diameter of 17 inches and overall height 23.5 inches. The nitrogen gas supply is connected to the supply pressure gauge and control solenoid. The solenoid is a fast-acting valve that opens and closes the desired duration allowing the nitrogen to pulse through the canister and dispenser. By implementing this control we can pulse the air supply as fast as 20 ms. A pressure sensor was placed just prior to the tungsten canister to measure the supply pressure and transient performance. This can be seen in Figure 2 below. To prevent the bell jar from being pressurized a vent is located on the base. Attached to the vent is a 5 micron filter that prevents dust particles from leaving the bell jar. Additionally a high speed camera was used to capture images of the particles as they exited the dispenser. A detailed description of the tests and data analysis method is outlined in the following sections.

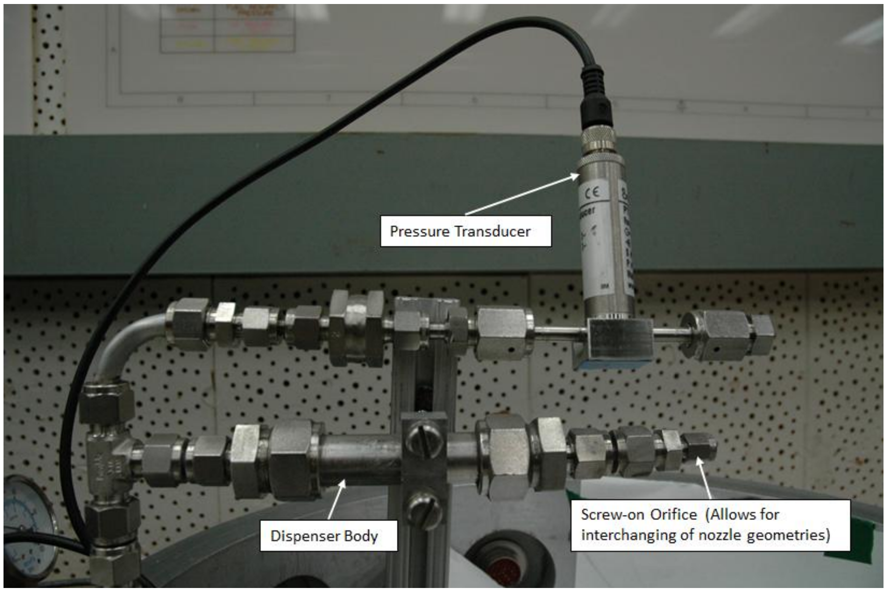


Figure 2: Close-in photograph to identify components of canister and dispenser.

Test Setup and Procedures

The benefit to the setup shown in Figure 1 is the ability to test a wide range of differential pressures; that is, pressure differences between the controlled gas supply and either the vacuum or atmospheric pressure within the bell jar. Additionally, this set-up can test very small amounts of tungsten, yet is modeled for larger amounts. The exit is designed to adopt different geometries and our build needs only inexpensive and readily available parts. The control and data acquisition were accomplished using LabVIEW. A data acquisition (DAQ) system was used to acquire the pressure sensor and solenoid signals while a programmable power supply was used for precise control of the solenoid. An outline of the test procedure is below.

Test procedure

1. Remove canister, fill with dust, and mount back in bell jar.
2. Check gas line connections.
3. Back out regulator on compressed gas bottle prior to opening the bottle.
4. Confirm solenoid is closed prior to opening gas bottle.
5. Open bottle slowly, then adjust regulator until the pressure gauge indicates the desired supply pressure.
6. Pump down if a vacuum test.
7. In the LabVIEW graphical user interface (GUI) enter the desired milliseconds to pulse the control valve. Turn on the DAQ.
8. Prior to actuating valve ensure camera recording.
9. Once ready press the "Disperse" button on the GUI to actuate the valve.
10. Once all the dust has settled, slowly vent chamber if vacuum test.
11. Carefully remove glass bell jar.
12. With the proper personal protection equipment remove dust from the floor of the bell jar. For convenience a removable floor cover was created for the chamber.
13. After the dust has been collected, weigh it to determine how much was dispersed.
14. Remove canister from setup and fill with dust. If different material is being added to canister make sure to purge canister first.
15. Repeat steps as desired.

The system was tested with three different outlet nozzles and supply pressures ranging from 5-60 psi. These ranges of supply pressures were determined based off an initial analytical model that showed ~20 psi as the necessary pressure to achieve 5 m/s velocity, suggested as a maximum speed in early dispenser analysis. The performance will be analyzed using a high-speed camera and image analysis software.

High-Speed Video as the Method for Data Collection

One of the challenges with this testing was how to acquire data and analyze the performance of the dispenser. Table 4 shows a summary of the pros and cons of the methods considered. High speed video image capture seemed an obvious choice by recording the tungsten flow in front of a graduated board. Only after using it, did some disadvantages become evident: The camera is a two-dimensional visualization of the flow and it could not show individual particles nor if they were constantly hitting one another. Traditional particle image velocimetry (PIV) is an optical method of flow visualization used to obtain instantaneous velocity measurements and related properties in fluids, typically along a two-dimensional slice. The simultaneous velocities of many points in the flow are determined. The fluid is seeded with tracer particles which are assumed to follow the flow dynamics. The fluid is illuminated such that the tracer particles are visible. The motion of the seeding particles is used to calculate speed and direction of the flow being studied. Although not documented here, we did use white aluminum particles mixed in a 50/50 ratio with the tungsten carbide in anticipation that the camera would allow us to better follow individual particles. It did not work well.

Stereo PIV measures a second plane at right angles to the first plane – along the cross-section of the flow, relying on the stereoscopic principle of PIV to yield information on all three components of velocity. Laser sheet imagery is another flow visualization technique in which a thin sheet of light is introduced perpendicular to the flow, illuminating the particles. The local flow velocity might then be determined by digital particle image velocimetry. One disadvantage is the flow region must be visible to the source of laser light. Our particle stream is too dense to permit light to pass through.

Very early in our thought process, a turn-table concept matured. The concept was to have a platform mounted on a vertical axis that spun the platform above the floor. On the floor would be a circle of upward facing sticky tape of several feet in diameter. On the rotating platform is a small pressurized tank of nitrogen gas supplying the canister of tungsten. Upon remote command, a valve would open to allow the gas to exhaust the tungsten from canister and nozzle. The spin rate of the platform is recorded during dispensing. After completion of tungsten release, somehow the location of particles on the tape would be measured to estimate the exit speeds. This concept was not developed.

Table 4: Data analysis methods considered for measuring dust velocity.

Method	Hi Speed Video	Traditional PIV	Surface Flow Stereo PIV	Laser Sheet Imaginary	Turn Table
Pros	• Easy to setup • Low cost • Available • Relatively quick data analysis	• Velocity vectors, angles, and speed distribution	• Velocity vectors, angles, and speed distribution	• Velocity vectors, angles, and speed distribution	• Relatively cheap
Cons	• Difficult to measure velocity distribution	• Dust flow is too dense	• Only provides surface measurement • No equipment available • Expensive	• Dust flow is too dense	• Velocity is indirectly determined • Data analysis is very time consuming

Finally a camera and recording system built for high-speed video and slow-motion playback was chosen as the main method of data collection. The driving factors for this decision was cost, simplicity, and availability. The camera used was from FastecImaging with a 1280 x 1024 resolution CMOS sensor with recording rates of 506 fps at full resolution and up to 100,000 fps at reduced resolution. The camera provided more than 3 seconds of recording time at full resolution. The electronic shutter could be controlled down to 2 μs giving high quality images of particle motion. In addition to the camera, a high quality lens was used to produce images that allowed for individual tracking of particles. This gave the ability to directly measure the exit velocity of the particles and visually identify clumping. A sample image from one of the videos taken can be seen in Figure 3 just as particles first leave the orifice before the stream is developed.

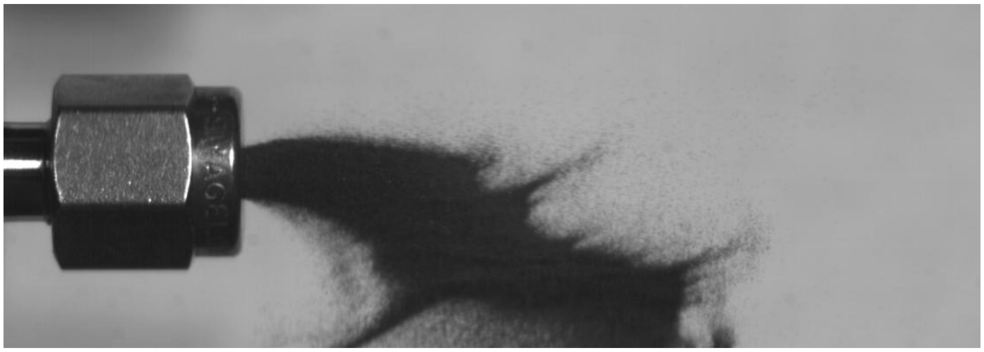


Figure 3: Transients seen only in the early portion of dispensing.

One of the methods for calculating the particle velocities was to implement particle tracking using ImageJ, an image analysis software. However, due to the small particle sizes and a high density stream this proved to be ineffective. The second option was to trace the stream over a given time and distance to determine velocity. An example of this method can be seen below in Figure 4. In this example the particle stream was traced over a distance of 0.8 inches. The time difference from point t_1 to t_2 is 0.0119 s. This results in an exit velocity of 67.2 in/s (1.71 m/s).

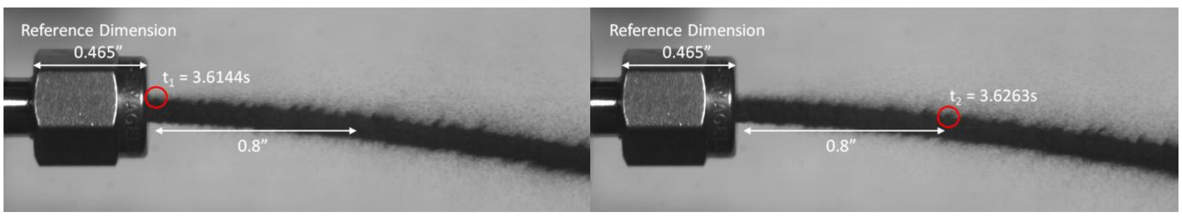


Figure 4: Tracing of particle stream. Distance travel is 0.8" in 0.0119 s. This is a velocity of 67.2 in/s or 1.7 m/s.

The second method used in determining the initial exit velocity of the particles was done by modeling the trajectory of the particles given an initial exit condition and then matching that trajectory to an image. The equations used were that of a projectile traveling in air considering cases with and without air resistance. When ignoring air resistance the only force acting on the particle after it leaves the dispenser is gravity. The particle motion can be modeled using simple kinematics where the acceleration of the particle in both the x and y directions are given by equations (1) and (2) where g is the acceleraton due to gravity.

$$\boldsymbol{a_x = 0} \qquad (1)$$

$$\boldsymbol{a_y = -g} \qquad (2)$$

With the acceleration terms defined the path of the particles can be mapped using equation (3) and (4) below and an initial outlet condition.

$$\boldsymbol{x = x_0 + v_x t + \frac{1}{2} a_x t^2} \qquad (3)$$

$$\boldsymbol{y = y_0 + v_y t + \frac{1}{2} a_y t^2} \qquad (4)$$

Where x_0 and y_0 represent the initial position, v_x and v_y the velocities, a_x and a_y the acceleration, and t is the time. While the equations above are fairly simple they become more complicated with the addition of air resistance. When considering air resistance the additional forces of drag must be considered in the x and y directions as well as the change in these parameters over time. To overcome this we can evaluate the particle's position from x_n to x_{n+1} over a very small time interval Δt. The drag forces, $D_x(t)$ and $D_y(t)$ at time t, can be determined using equations (5) and (6) below where ρ_{air} is the air density, $C_x(t)$ and $C_y(t)$ are the drag coefficients at time t, A is the reference area, and $v_x(t)$ and $v_y(t)$ are the particle velocities at time t.

$$D_x(t) = \frac{\rho_{air} C_x(t) A \left(v_x(t)\right)^2}{2} \tag{5}$$

$$D_y(t) = \frac{\rho_{air} C_y(t) A \left(v_y(t)\right)^2}{2} \tag{6}$$

The drag coefficients for spherical particles are represented by equations (7) and (8).

$$C_x(t) = \frac{24}{R_{e_x}} \tag{7}$$

$$C_y(t) = \frac{24}{R_{e_y}} \tag{8}$$

Where R_{ex} and R_{ey} are the Reynolds numbers shown in equations (9) and (10) below.

$$R_{e_x} = \frac{\rho_{air} v_x(t) d}{\mu} \tag{9}$$

$$R_{e_y} = \frac{\rho_{air} v_y(t) d}{\mu} \tag{10}$$

Where d is the particle diameter and μ is the dynamic viscosity of air. With the drag forces now determined, the accelerations $a_x(t)$ and $a_y(t)$ at time t can be calculated and are shown in equations (11) and (12), where m is the particle mass.

$$a_x(t) = \frac{-D_x(t)}{m} \tag{11}$$

$$a_y(t) = -g + \frac{D_y(t)}{m} \tag{12}$$

The positions of the particle from $t = 0$ to t in Δt intervals can be determined by equations (13) and (14).

$$x(t + \Delta t) = x(t) + v_x(t)\Delta t + \frac{1}{2} a_x(t)\Delta t^2 \tag{13}$$

$$y(t + \Delta t) = y(t) + v_y(t)\Delta t + \frac{1}{2} a_y(t)\Delta t^2 \tag{14}$$

Figure 5 below shows the resulting trajectory from these equations given an initial exit condition defined by the initial velocity and exit angle relative to the horizontal. In the example shown the velocity is 1.78 m/s at an angle of -3.0 degrees. This is an initial velocity of 1.777 m/s in the x-direction. The trajectory is projected over the same image as seen in Figure 4. Compared to 1.71 m/s using the first method there is a 3.9% difference in the measurements. It's important to note that the trajectory graph is scaled to the image within ±0.005 in.

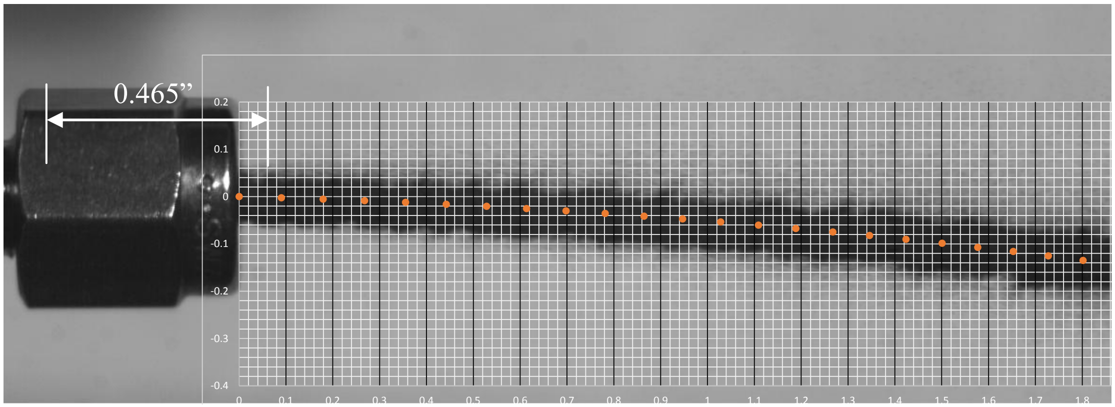


Figure 5: Trajectory model of v_x = 1.78 m/s overlaid on image of video.

Supply Pressure Initial Analysis

In building the dust canister and dispenser system described above, one of the first technical issues is the nitrogen gas supply pressure and the exit velocity of the tungsten. The more pressure, the faster the exit velocity as shown below. To develop an understanding of the necessary supply pressures, a model was created that estimated the average velocity of the particles given a pressure differential along the dispenser (from gas inlet to orifice exit). This was done by using Newton's Second Law and assuming a constant mass system, in which the mass entering is the same as that leaving. For simplicity the transient behavior in the beginning and at the end of the dispersion was ignored, as well as the drag and friction between the dust and walls. Due to this it was expected that the actual supply pressures would be higher than those calculated as shown in Figure 8. A free body diagram (FBD) of the system can be seen in Figure 6 below, where V_i is the initial velocity, V_e is the exit velocity, P_{supply} is the supply pressure, d_e is the exit inner diameter, and l_e is the exit length. P_{atm} is the atmospheric pressure (14.7 psi) within the bell jar, which is zero for vacuum conditions.

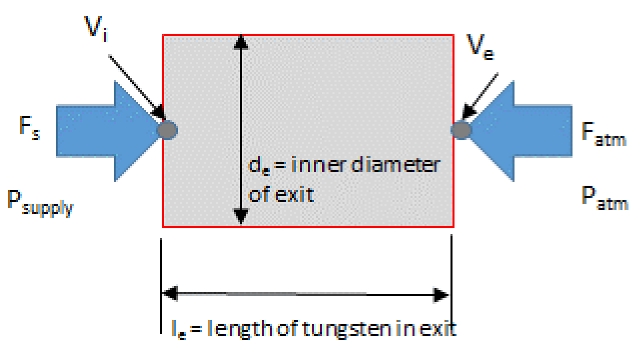


Figure 6: FBD of canister nozzle.

Performing a force balance on the above FBD yields Equation (15). Where F_s is the supply force, F_{atm} is the force due to atmospheric pressure, m_t is the tungsten mass, and a_t is the acceleration of the tungsten as it leaves the exit.

$$F_s - F_{atm} = m_t a_t \tag{15}$$

Expanding equation (15) using the known pressures and exit geometry gives us equation (16), where A_e is the exit area, A_i is the inlet area, and ρ_t is the tap density of the tungsten.

$$P_{supply}A_e - P_{atm}A_e = \rho_t A_e l_e a_t \tag{16}$$

Rearranging equation (16) and solving for a_t gives us equation (17).

$$a_t = \frac{\left(P_{supply} - P_{atm}\right)}{\rho_t l_e} \tag{17}$$

Assuming the acceleration is constant through the exit length, l_e, we can calculate the velocity by equation (18) where the initial velocity is assumed to be very small.

$$V_e = \sqrt{{V_i}^2 + 2a_t l_e} \tag{18}$$

By substituting equation (17) into (18) we get equation (19) in which the exit velocity of the tungsten is directly related to the pressure differential and tap density of the tungsten.

$$V_e = \sqrt{\frac{2\left(P_{supply} - P_{atm}\right)}{\rho_t}} \tag{19}$$

With a tap density of 10,000kg/m^3 the exit velocity given a supply pressure differential can be seen in Figure 7 below. This resulted in testing that focused in the range of 5-60psi.

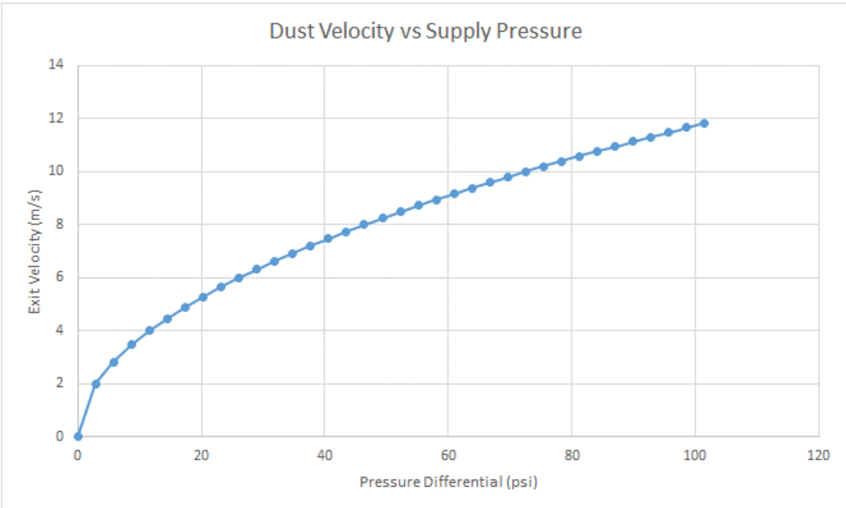


Figure 7: Kinematic model of tungsten velocity vs. supply pressure.

A range of test conditions covered supply pressures between 5-60 psi and orifice sizes of 0.0625, 0.125, and 0.2 inches. Initially, all the tests were performed with nitrogen gas propelling tungsten carbide in the air of the chamber. Later, several representative tests were repeated in a vacuum to compare conditions with and without drag and with the piston. Finally, a few representative tests were repeated using the pure tungsten particles.

RESULTS

There are several subsections in this results area to allow us to separate the chronological development of our various investigations. The first results came from the faster pace testing under the bell jar in air. Testing in air saved about 30 minutes of pump-down time that would achieve the vacuum of approximately 1 Torr. Rapid testing means learning quickly about some early test set-up omissions: such as the need to more strongly support the dispenser to the chamber's floor; have better lighting for the high-speed video; and to use a sufficient quantity of particles to eject.

A group of tests varied the inlet nitrogen gas pressure used solely to push the particles out. Similarly, the nozzle (orifice) diameters were varied. These studies investigated different pressures and orifices and the resulting velocity and mass flow rate of the particle stream, as well as controllability. This was done in air and vacuum. Our data was recorded as video and either the resulting movie or stills from the movie were used to analyze the dispensing event. Additionally, the ejected particles were weighed to determine their mass and estimate the mass flow rate as a function of the test duration. Test duration was typically under 3 seconds.

Some tests showed pulsing, oscillations, or repeating shapes within the stream, as will be shown in the following sections. This was more evident with larger orifices and higher exit velocities. Separately, we used a piston in between the gas and the tungsten to provide a uniform cross-sectional push. We observed that generally, with the piston-driven flow, the onset of uncontrolled flow occurred at higher velocities.

Control of stream cone angle using pneumatics to push the particles out was difficult with nozzles of varied cone angle. The expansion of the stream of solid particles at the nozzle did not happen at low velocities. The performance may be different with the absence of gravity, but could not be tested in our experiments. An alternative design is one which is modeled after the industrial sandblaster, where the stream of particles is first mixed with a gas before being ejected. This showed promise for future development as the stream showed evidence of conical expansion as well as more precise control of mass flow rates.

Other tests investigated the dispenser's sensitivity to dust characteristics. While the velocities and the mass flow differences were minimal, the appearances of the start-up transients in the exiting dust were quite interesting. The irregular particles of tungsten appeared to clump as they first exited and then appeared more uniform in the developed stream. The spherical tungsten carbide did not clump.

Several samples of pure tungsten and tungsten carbide were placed in the open air for several months and then micrographs were made of the particles. The eye showed little difference over time in their appearance. To the eye, there was no rust or oxidation.

Orifice Size Test Results

Exit velocity test results are lower than the analytical model, as expected, because friction and drag were ignored. Velocities show low sensitivity to orifice size at a given pressure. This was also expected based off the model. Reduced orifice sizes yield better control; however, the dispensing time increases. At larger orifice sizes and higher velocities, controllability becomes more difficult, but allows for significantly higher mass flow rates.

Figure 8 compares the results of the analytical model to those from testing with the results in vacuum indicated with dotted lines. Orifice sizes mattered little in terms of exit velocity. Note that at a given supply pressure the friction between the dust and the walls and air drag yields a lower velocity than the analytical model, which ignored these effects. Or for a desired exit velocity, a higher pressure is needed to overcome friction and drag compared to the analytical model.

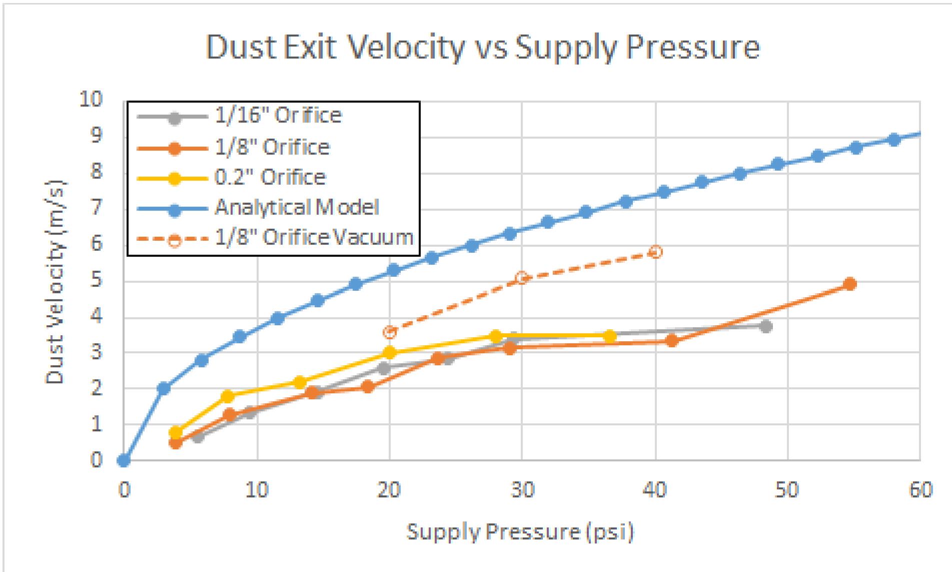


Figure 8: Dust velocity as a function of supply pressure.

Figure 9 compares the mass flow rates of three orifice diameters. As expected, there is larger mass flow with increased supply pressure or increased orifice diameter. Mass flow rate was calculated based on the weight of the ejected material divided by the release duration.

The mass flow rate model shows that the mass flow rate is directly related to exit velocity. Where $\dot{m}$ is the mass flow rate, ρ is the density, A is the cross-sectional area at the exit plane, and v is the exit velocity. When the density and area are constant, the mass flow rate is directly related to velocity. Figure 8 and Figure 9 are related to one another for the same testing conditions.

$$\dot{m} = \rho A v \tag{20}$$

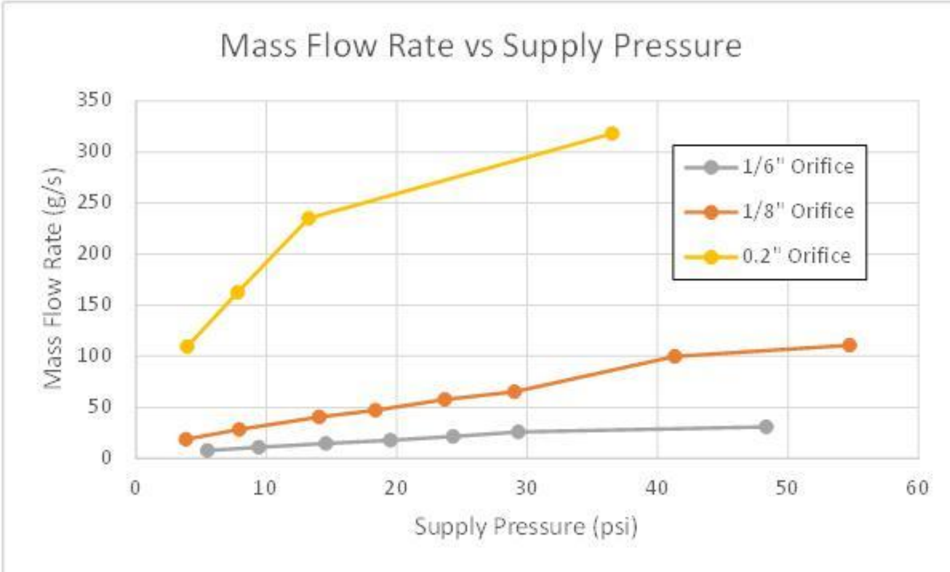


Figure 9: Mass flow rate with respect to pressure and orifice size.

Finally, one can extrapolate these results to estimate the dispensing duration of one large canister holding 10,000 kg of particles. This can be seen in Figure 10. The larger orifice and larger pressure reduce the dispensing time. The point is that the concept of operations for dispensing (based on one dispenser) orifice must be redeveloped. This is an indication that many small orifices, with their attendant control, will be required to dispense more particles more rapidly.

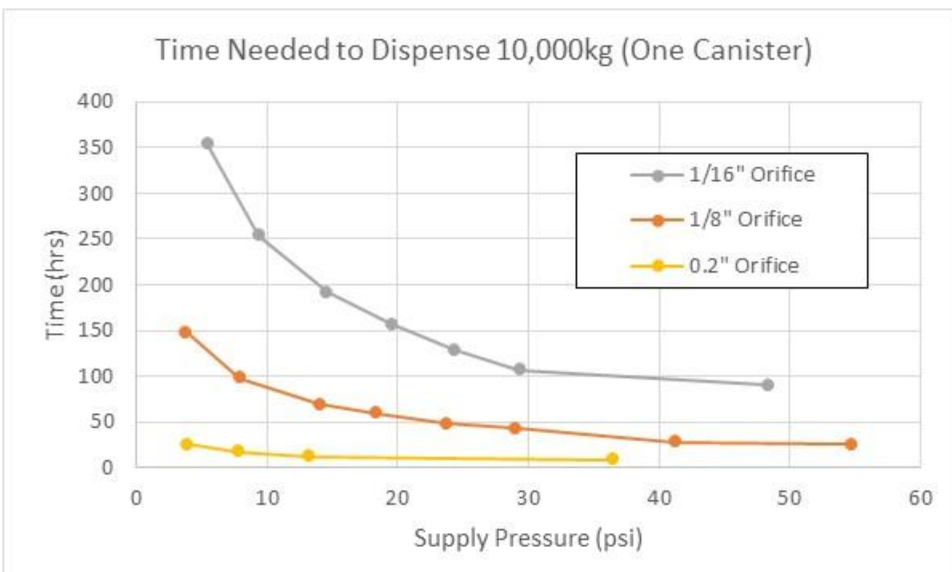


Figure 10: Required time to disperse 10,000kg of dust at a given supply pressure and orifice size.

It is important to understand the limitation of this concept as a result of the link between velocity and mass flow rate. Since the system is pushing primarily tungsten through the orifice, at a bulk density of 10,000kg/m^3, the resulting mass flow rate is directly related to the velocity at which the tungsten is moving. There is no way to change the bulk density of the tungsten. This means that for a given orifice if one wants a desired dispersion time they must adjust the velocity as needed to get the required mass flow rate. However, changing the velocity of the particles may not be an option. One could change the orifice size as shown in Figure 9, but if this change in dispersion time is desired after the spacecraft is in operation this is no longer an option. An alternative design is presented in the “Investigation of Abrasive Blaster Design” section that allows for control of mass flow rate while not impacting exit velocity. Additionally a hardware option is presented in the “Other Designs Based on the Preliminary Design” section that incorporates multiple outlet geometry options.

Investigations of Piston Design

One extension of the design was to build a dispenser that incorporated the use of a gas driven piston to push the dust particles out. The piston serves two primary purposes. The first is to act as a barrier between the gas and dust particles. This limits the interaction that the gas has with the particles and prevents the dust from being disturbed and swirled around as the canister is emptied. The result of this is a more controlled dispersion at higher velocities, which gives the ability to increase the mass flow rates and maintain good controllability. An example of the uncontrolled compared to controlled dispersion, at the equivalent exit velocity, is shown in Figure 11 and Figure 12.

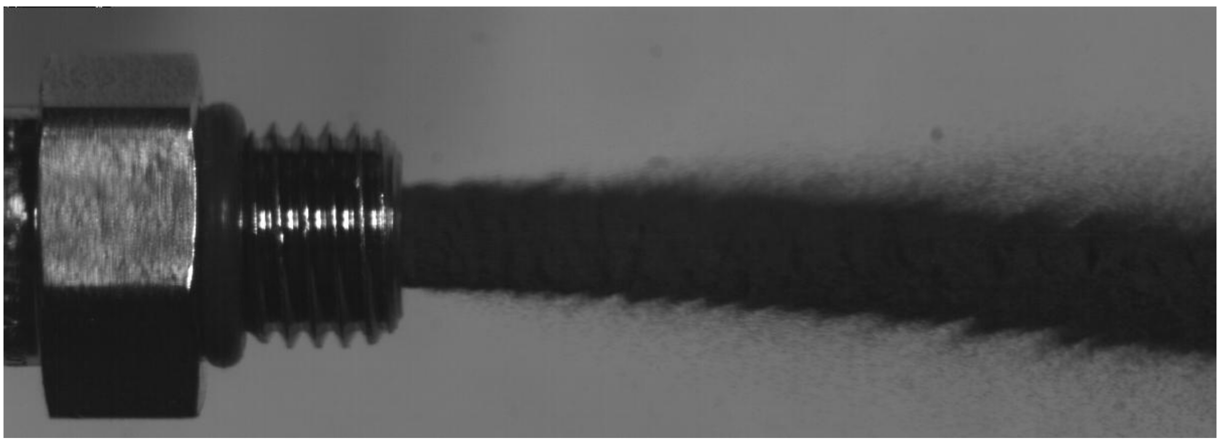


Figure 11: Dispersion with piston at an average v_x of 3.5m/s.

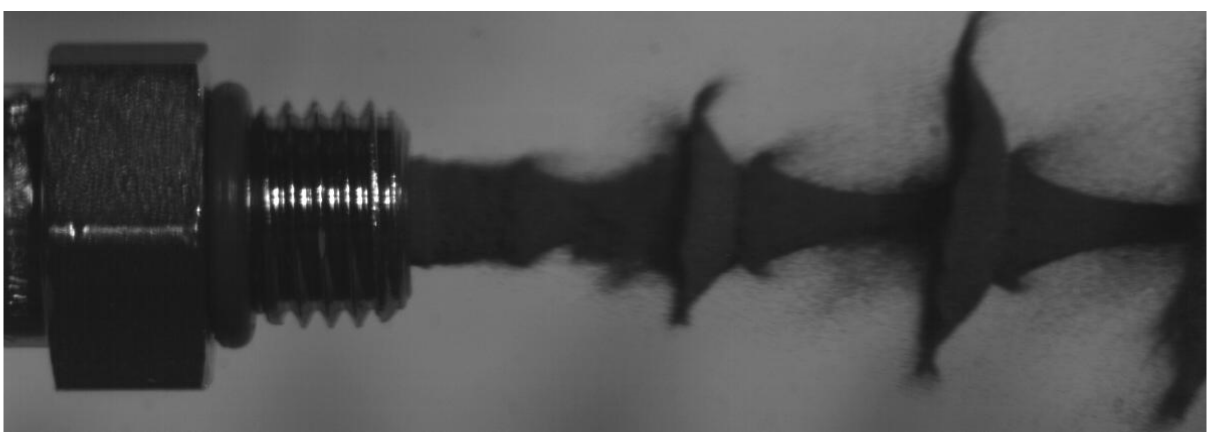


Figure 12: Uncontrolled dispersion of tungsten particles. Gas driven.

Use of the piston did not prevent all uncontrolled streams, but generally delayed their onset to higher exit velocities. Figure 13 below shows the velocities at which uncontrolled streams were observed with and without the use of a piston. With the use of a piston the exit velocity at which the dispersion became unstable was increased from approximately 3m/s to 4.8m/s. In both instances the orifice size was controlled to a 0.2” diameter.

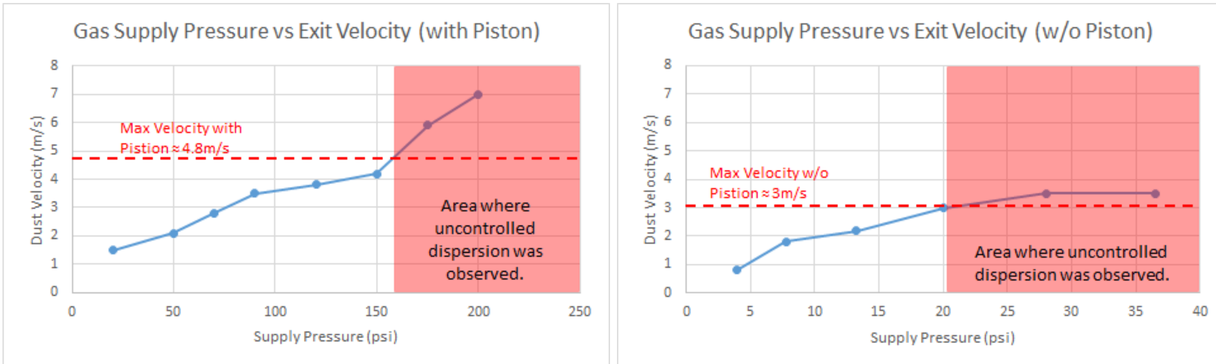


Figure 13: Area of observed uncontrolled dispersion with and without piston.

To further increase the operating region of the piston design, a nozzle was attached to the exit to help prevent the oscillation from occurring. The two nozzles tested had the same throat diameter as the previous orifice of 0.2", but with half-cone angles of 2 and 5 degrees. Drawings of the nozzles can be seen in Figure 14 below. The nozzles were tested in the area where uncontrolled dispersion was seen when using the piston. This relates to an approximate exit velocity of greater than 5m/s. Figure 15 below shows the images from that testing. While the image quality may not be very good, a clear difference can still be seen in the way the dust exits. The conical nozzle stopped the stream oscillations, yet the stream was still not uniform as seen in Figure 15. Ideally a uniform cone shape is desired.

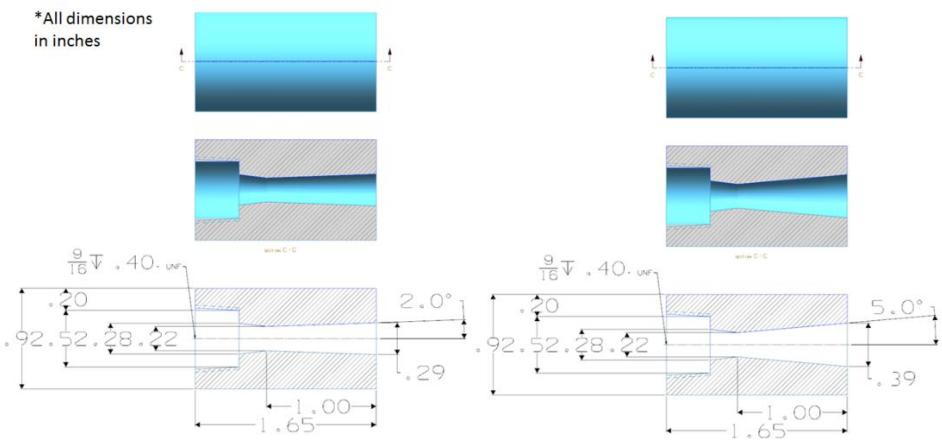


Figure 14: Drawing of nozzles used for dispenser testing.

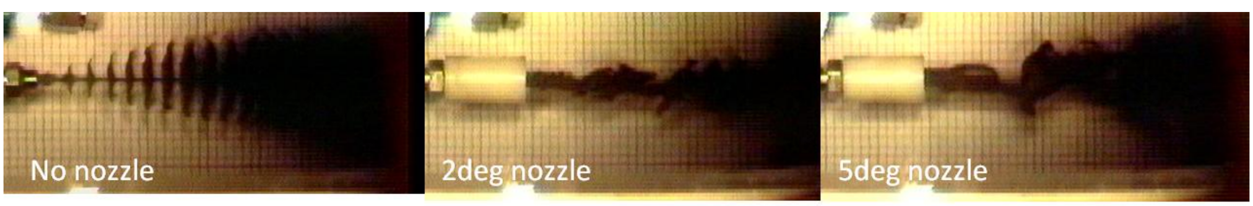


Figure 15: 0.2" diameter orifice results without and with nozzles.

It has been shown that the piston provides an improvement in controllability with larger orifice sizes. This can be of benefit if there is a desire to increase mass flow rate. As mentioned previously with the gas and piston designs, since we are primarily pushing only tungsten the only way to change the mass flow rate of the system is to change the exit size or velocity. It is important to note that if lower mass flow rates are acceptable the use of the piston is not needed for control of the stream. An example of this can be seen below in Figure 16. In this particular case a 1/8" diameter orifice was used without a piston at a supply pressure of 60psi. This results in an exit velocity of 5m/s. As seen in the image the stream is very uniform and stable.

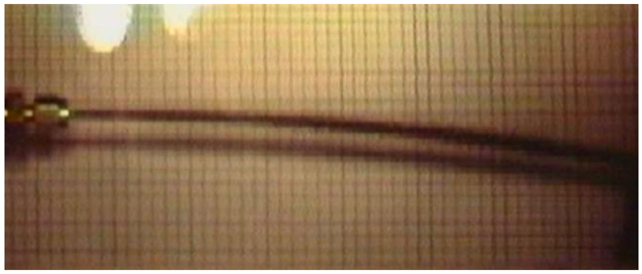


Figure 16: Image of dispersion with 1/8" diameter orifice at 60psi.

When using small orifices the piston is not needed to improve control, however, there is a secondary purpose to this design. The piston acts as a support mechanism considering an application in which one large canister is used that can perform multiple dispersion events. If only gas was used the particles would start to move around after the first dispersion event due to the void that is created. The piston eliminates this void. The other benefit to the piston is it can be packaged in a large range of cylinder diameters and has almost no limitation on stroke. Before deciding on the piston design there were other options considered. A frictionless rolling diaphragm was investigated, but this design is limited to short stroke applications. A bladder was also considered, but this design is also stroke limited and has an unknown durability to dust particles since this mechanism is typically used in hydraulic and pneumatic systems.

One observation to note with the piston is the ability of the dust particles to get between the piston and cylinder walls. The concern with this is the possibility for an increase in friction and possible seizure. This is less of a concern considering this is a one-time use dispenser, in which no cycling is taking place, but still a mitigation method should be incorporated to prevent this. This could be done by using a scrapper or wiper in the piston design which would remove fine dust particles from the walls of the canister, thus preventing the particles from getting trapped between the walls.

Investigation of Abrasive Blaster Design

The pneumatic and piston driven designs presented previously proved to be sufficient in dispensing the fine particles, but they do have some clear limitations and challenges. They can very easily achieve the desired exit velocities by adjusting the supply pressure, but the control of cone angle is more difficult. Since we are pushing a solid particle it is difficult to expand the material via a nozzle in order to achieve a very specific cone angle, especially at our low operating velocities. As mentioned previously the performance may be different in space with the absence of both gravity and drag, but can't be confirmed in our experiments. Additionally the mass flow rate is linked directly to the speed at which the particles are ejected. Because of this there is no way to increase or decrease the mass flow rate without impacting the exit velocity, something that may be desirable in the space applications. A design that can overcome these issues is that of an abrasive blaster. Abrasive blasting is the process of cleaning and finishing materials by forcibly propelling a stream of abrasive material against a surface under high pressure. A pressurized fluid, typically air, is used to propel the blasting media. This is a very common procedure in industry.

In air blasting the abrasive media is introduced to the flow by either direct pressure or an induction method such as siphoning or gravity feed. In the direct pressure method an abrasive, or in our case tungsten, is fed from a pressurized container into a blast hose. In conventional blasting systems the pressurized air, usually at 70 to 140psi, is fed to both the air hose and pressure vessel. This permits the media to free fall and mix with the air stream prior to exiting the nozzles. The rate at which the media is mixed is controlled by a metering valve between the pressure vessel and air hose. Note that the density of the stream, now a combination of air and tungsten particles can be varied. The abrasive material exits the nozzle at velocities ranging from 85 to 260m/s and with a specific geometry depending on the nozzle design. Some traditional nozzle designs that are used are straight bore and venturi designs including both long and short.

When using the siphoning method the blast gun and nozzle are connected to a compressed air line as well as a flexible hose which carries the abrasive media. Instead of the media being pressurized and pushed into the air flow, it is instead pulled into the flow by a partial vacuum that is created in the blast gun. The last method is the induction of the media using gravity. This is similar to the siphoning method, in which the media is mixed with the air at the gun, except that the media is introduced into the nozzle by means of both a partial vacuum and gravity.

All these methods have their advantages and disadvantages. Unfortunately one thing that they all have in common is none of them will work in a space application as is. All these methods use gravity or vacuum to assist in introducing the media to the air flow. This can be overcome by creating a design that introduces the media, or tungsten, solely by using a pressurized gas. A schematic of this concept can be seen in Figure 17. A gas flow line is fed to a nozzle and is controlled via a flow/speed controller. Separately a second feed line introduces the tungsten particles into the air flow prior to reaching the nozzle allowing enough time for the two media to mix before ejection.

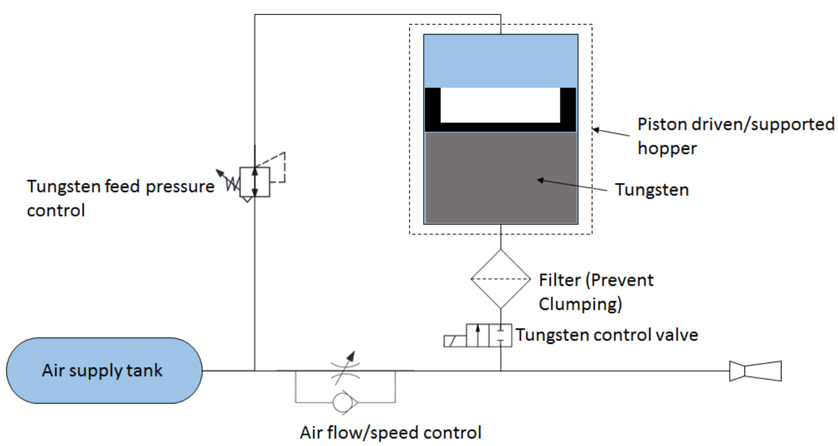


Figure 17: Hopper canister design schematic.

A pressure controller is also used to give precise control of the rate at which the tungsten is introduced. Prior to the tungsten reaching the gas flow the particles must pass through a filter that will be used to prevent any clumps from exiting the system.

This design provides the advantage of being able to separately control the rate at which the gas and tungsten flow. The gas flow controller would control the final exit speed of the particles while the tungsten feed controller would control the relative mass flow rate of media. A prototype of this concept was constructed and tested and the results can be seen in Figure 18 below. The supply gas pressure was set to 50psi while the tungsten feed pressure was varied. The change in tungsten mass flow rates can clearly be seen. It was also observed that with this design the tungsten particles were carried by the gas flow. This presents the option to design different nozzles allowing for manipulation of the particle stream. As seen in equation (20), the user can now vary the density and thus have the ability to control mass flow rate separate from velocity. This dispenser design offers the ability to change the velocity and density should the release method warrant.

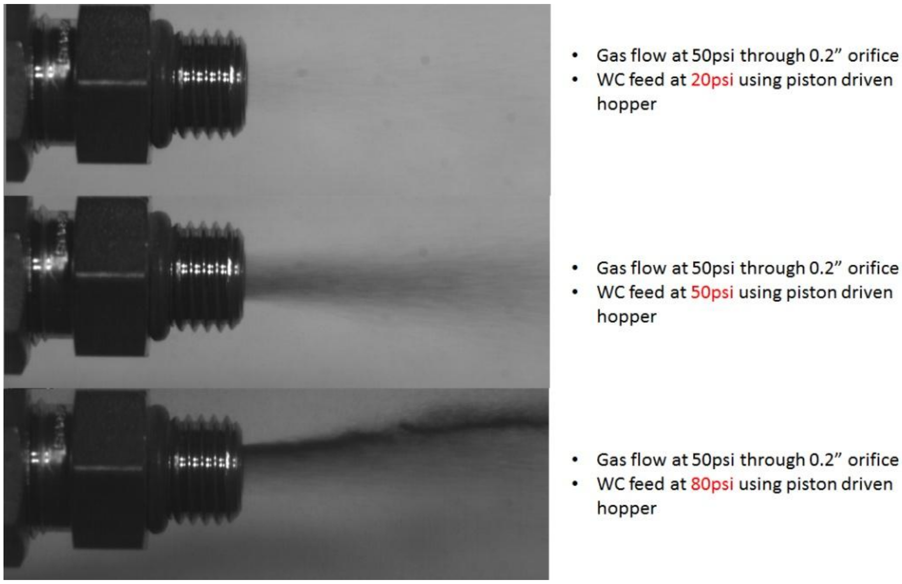


Figure 18: Test results of tungsten hopper design.

With the gas and piston dispensing methods there were no nozzles shown when the dispersion was controlled. This is because under controlled dispersion at our low velocities the nozzles proved ineffective at manipulated and expanding the flow. With the blaster, in which the mixture is part gas, the gas can be expanded through a nozzle which can be used to manipulate the flow path of the particles exiting the canister.

This design gives a few advantages over the gas and piston designs. By using a separate gas flow to carry the particles we can eliminate the initial transient behavior, seen in Figure 3 and Figure 20, as the tungsten particles exit the canister. This initial transient is where clumping was observed with the pure tungsten samples and is outlined in the following section. In the previous designs the mass flow rate of tungsten particles was directly related to the speed at which they exit the canister. However, with the abrasive blaster design we can increase the mass flow rate of particles while keeping the exit speed constant.

With these advantages come some challenges. With added control comes an increase in parts and complexity. The required amount of gas needed also increases. In abrasive blasting, media such as aluminum oxide, glass beads, and walnut shell are used. All these materials have bulk densities in the range of 400-2000 kg/m^3, a fraction compared to the 10,000 kg/m^3 for tungsten and tungsten carbide. There is also a significant difference in the particle speeds. Traditional abrasive blasting operates at speeds of 85-260 m/s while our max speed is 5 m/s. Lastly the space application lacks the presence of gravity which may impact how the particles and gas mix. All these application differences may impact how the mixture forms and additional research would be needed to determine the best method for introducing and mixing the high density tungsten particles.

Dispenser Sensitivity to Dust Characteristics

While tungsten carbide seemed to be ideal, due to its size and shape, it is lower in density compared to that of the pure tungsten. The tungsten carbide has a density of 15.6 g/cm^3, 19% lower than the pure tungsten at 19.3 g/cm^3. This lead to the question as to whether there is a performance difference between the different dusts. The types of dust that were tested can be seen in Table 2. The main difference between the particles is their shape and size. While the tungsten carbide is spherical in shape the pure tungsten is mainly irregular. Detailed images of the different types can be seen in Appendix 2 and Figure 19 below, with some observations of the different samples outlined in Table 5.

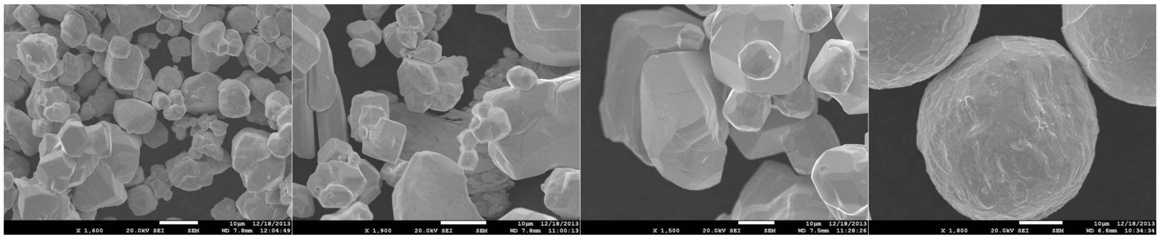


Figure 19: From left to right: tungsten powder ST-371 @ 1,600X, tungsten powder C100-3196 @ 1,900X, tungsten powder C100-3186 @ 1,500X, tungsten carbide spheres @ 1,800X.

Table 5: Summary of observations of tungsten samples.

Sample	Physical Characteristics	Observations
Tungsten Powder Lot No: ST-371	• 1-40 µm, ⅓ in the 10-20 µm range • Highly irregular shapes and sizes, rough, and angular	• Particles appear to be attached to one another rather than separate particles
Tungsten Powder Lot No: C100-3196	• 15-38 µm • Highly irregular shapes and sizes, rough, and angular	• Some elongated pieces were observed • Particles appear to be attached to one another rather than separate particles
Tungsten Powder Lot No: C110-3186	• 30-75 µm, ½ in the 50-75 µm range • Highly irregular shapes and sizes, rough and angular	• Particles look to be attached to one another forming clusters
Tungsten Carbide Powder	• 30-45 µm • Highly **regular** shapes and sizes • Manufacturer states 10-20% could be angular	• Each particles looks to be separate from all the others • No clumps were observed

The main observation was the difference in shape and the appearance of clumps in the pure tungsten samples. The clumps as seen in the micrographs were also observed during both the handling and dispersion of some of the material. Figure 20 below shows a comparison of the four different materials being ejected at a pressure of 30psi. Both the ST-371 and C100-3196 samples show clear signs of clumping while the tungsten carbide all looks to be ejected as individual particles. The concern with the larger clumps is that they would have different ballistic properties within the same release and thus a varied orbit decay among the particles, which is unacceptable.

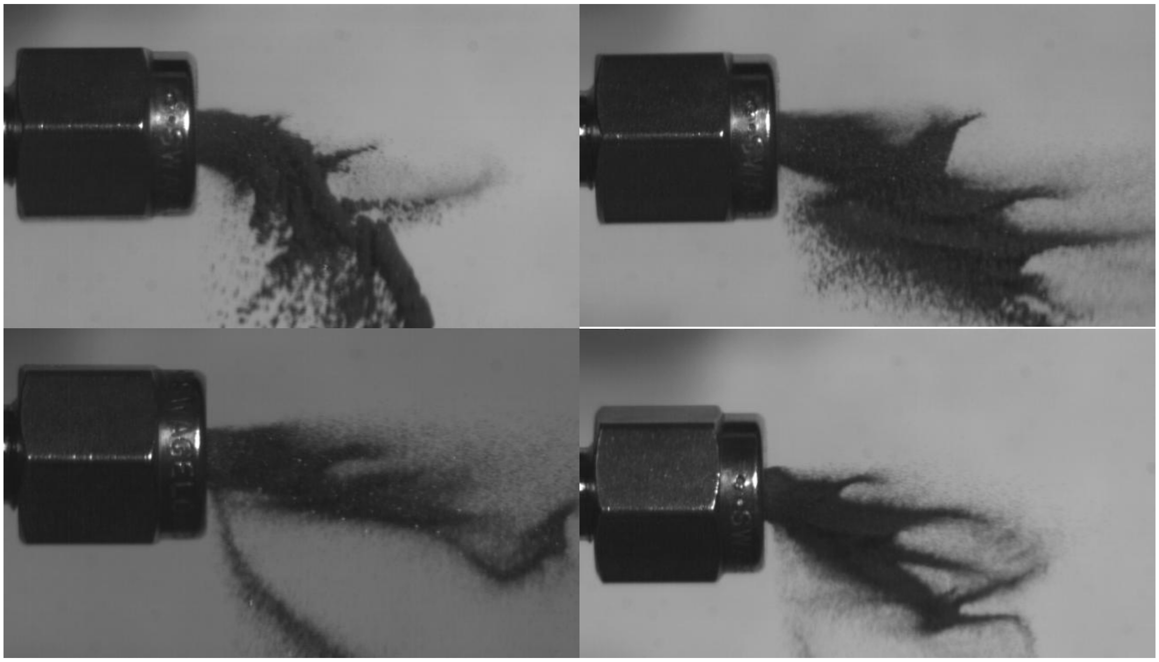


Figure 20: Image of particles during beginning of dispersion: (upper left) ST-371 (upper right) C100-3196 (lower left) C100-3186 (lower right) tungsten carbide spheres.

Elementary Observations of the Particles Exposed to Humid Air

In late December 2013, several grams of the tungsten and tungsten carbide powders were placed into separate small beakers. The uncovered beakers remained in an office until August 2014 just to see what happened. Generally, the office temperature ranged from 73-75° F, although there were some times when lack of heat allowed the temperature to drop into the 60s. The humidity was lower in winter and early spring, about 40%, and increased to above 45% when outside temperatures became summerlike in mid-May.

A small amount was selected to allow for more surface area relative to the total sample mass. Although micrographs are shown in Appendix 2, the eye could easily make some qualitative observations: The tungsten sparkles due to its highly irregular shape; whereas, the tungsten carbide is uniform in color due to its highly regular shape. After first tilting the small beaker about 45° and then rotating about the cylindrical axis, the tungsten sometimes stuck along the bottom of the beaker, which would easily fall when tapping the beaker. The tungsten carbide did not stick as much, hinting these spheres might be a better choice in packing aside from their orbital decay benefit of having uniform ballistic properties. The irregular tungsten particles might attach themselves to one another (clump) at times.

Using the expected visual indication of a tan or brown color as evidence that these powders rusted or oxidized, there is no indication of rust as both samples remained the same gray color. See Figure 21 and Figure 22. The office samples were weighed at the beginning and end of their seven-month exposure to room conditions and their weights increased within measurement error: tungsten gained 0.05% and tungsten carbide gained 0.07%.

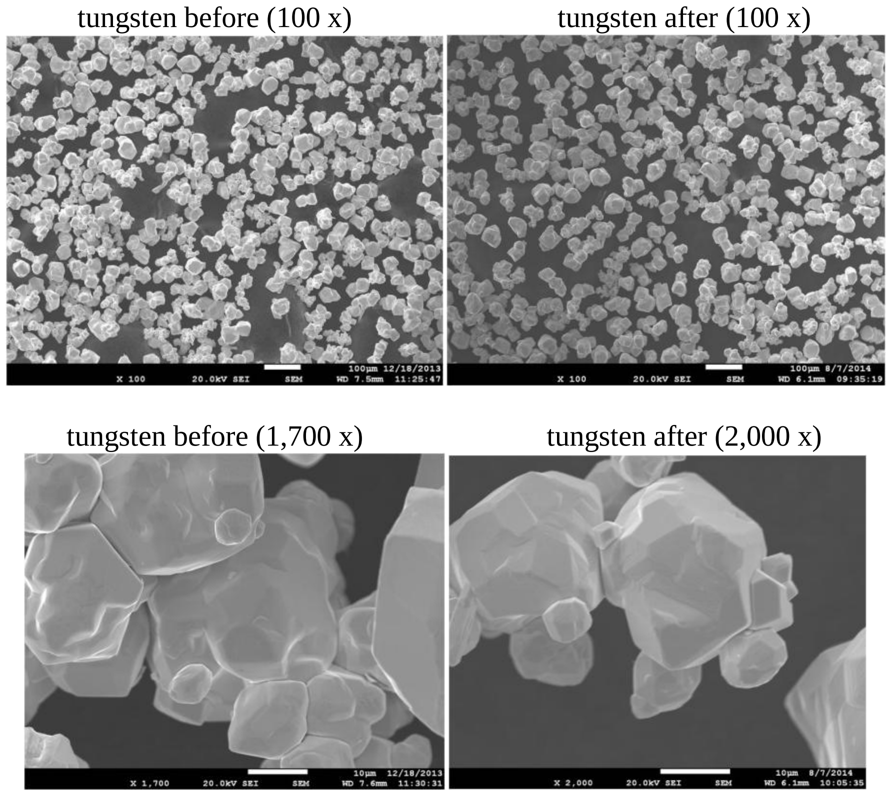


Figure 21: Micrographs of tungsten after seven months in an office environment with no signs of rust.

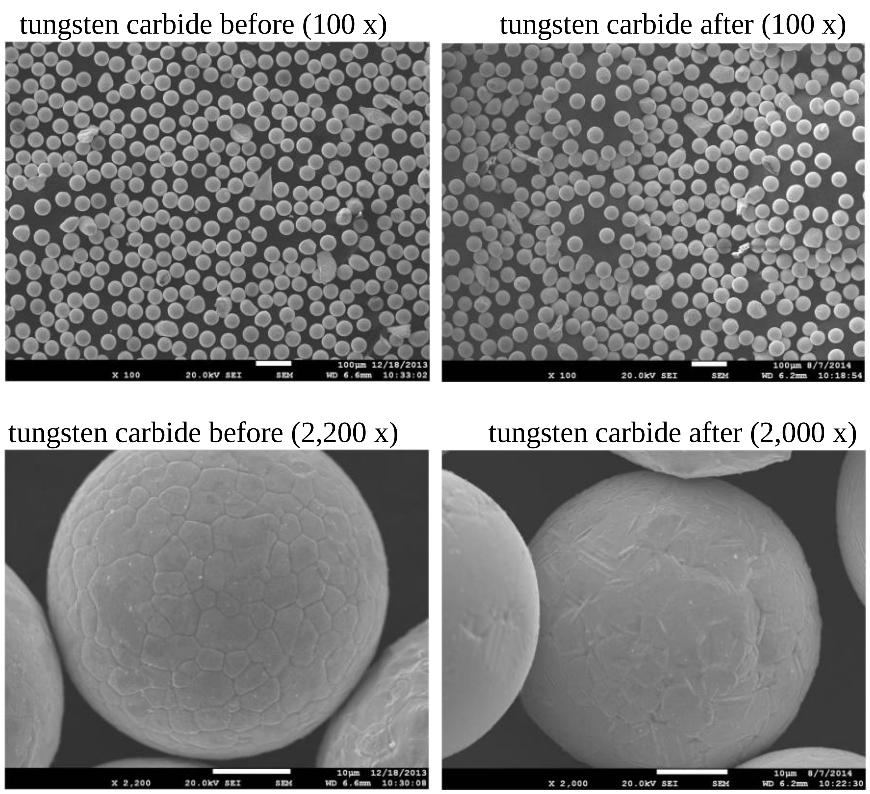


Figure 22: Micrographs of tungsten carbide after seven months in an office environment with no signs of rust.

In early June to early August 2014, a second sample group of the two materials was placed in the warehouse. There is no environmental control of either temperature or humidity. The warehouse protects against only wind and rain. We purposely took advantage of the Washington humidity to freely examine this extreme environment.

As with the office-stored samples, there is no indication of rust. See Figure 23 and Figure 24. Also, only the sample of tungsten increased a modest amount: tungsten gained 0.03% and tungsten carbide's weight did not change. Perhaps formal testing for humidity and temperature control, along with rigorous scientific testing for oxidation would have yielded different results.

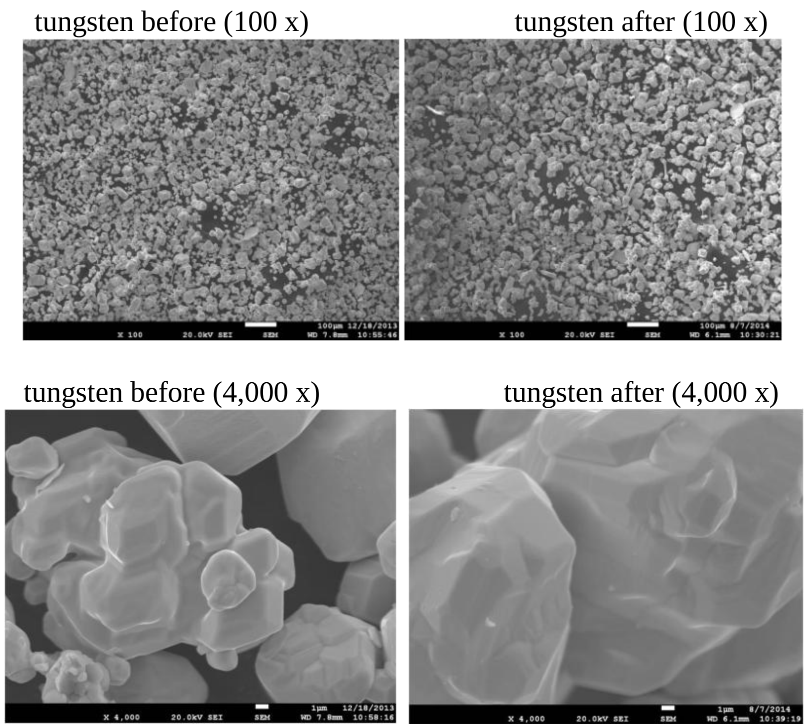
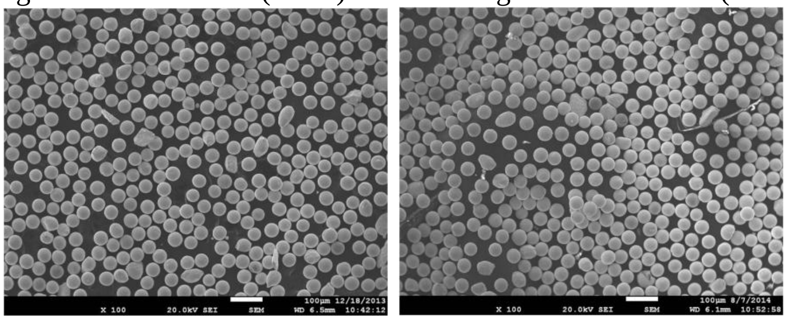


Figure 23: Micrographs of tungsten after two months in a warehouse environment with high humidity.

tungsten carbide before (100 x) tungsten carbide after (100 x)



tungsten carbide before (2,200 x) tungsten carbide after (2,000 x)

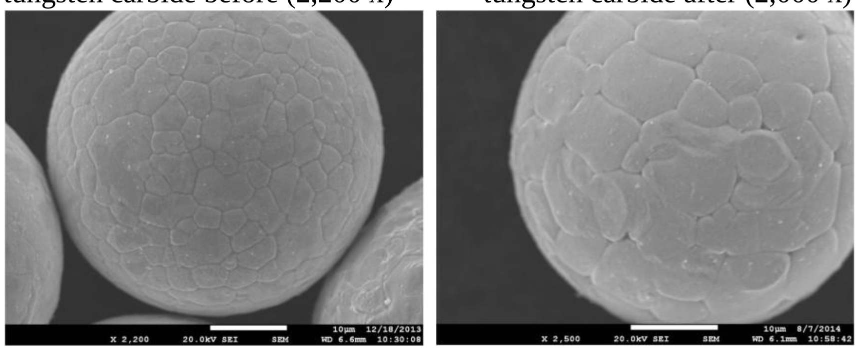


Figure 24: Micrographs of tungsten carbide after two months in warehouse environment with high humidity.

Placing several ounces of each product in a clear plastic bag easily showed the effects of clumping. The irregular tungsten falls in on itself as the sides of the bag are raised and forms rows or ridges. These are due to clumping. In contrast the spherical tungsten carbide seems to roll to a uniform flat surface. Figure 25 shows the appearance of these materials. The grinded tungsten on the left has more sparkles than the regular tungsten carbide spheres on the right.

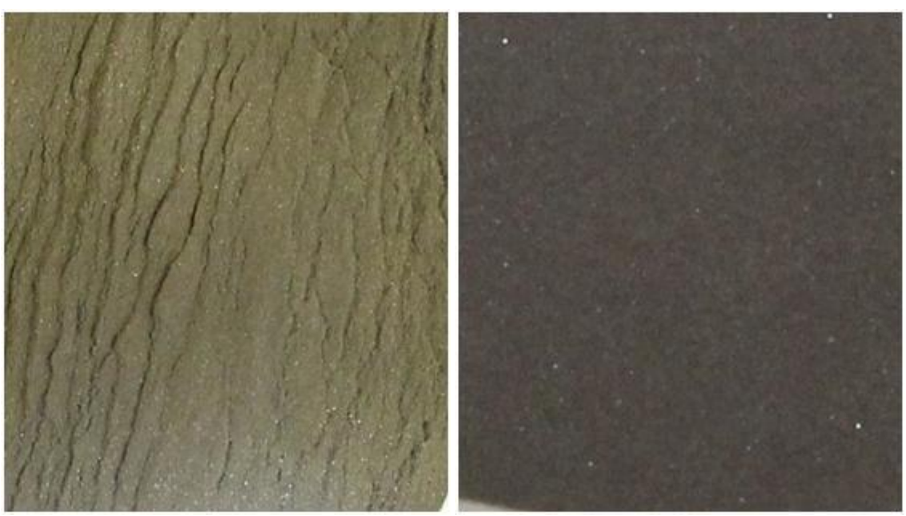


Figure 25: Clumping seen in tungsten grinds (left) and are not seen in spheres (right).

Summary of Trends Seen From Testing

As a summary of our results, we list some observed trends.

For the same inlet pressure and orifice size, the exit velocity in a vacuum is greater than in air.

Using pressurized gas alone to push out the particles, reduced orifice diameters improve controllability, while reducing mass flow rates; therefore, increasing dispensing times.

The piston, being driven by pressurized gas, showed improved controllability with larger orifice sizes and the corresponding increase in mass flow rate.

Orifice size and particle mass in the dispenser have the greatest impact – a larger quantity of particles has a greater ability to form a uniform stream before all particles are ejected.

At a given pressure, orifice size mattered little in terms of exit velocity.

There is a larger mass flow with increased supply pressure or increased orifice diameter.

The irregular shaped particles tend to clump relative to the spherical particles.

Gravity always bent the stream and made some estimates of speed difficult.

Start-up transients always exhibited as a smaller group of particles leaving the nozzle before the full stream developed (steady state). Ending transients were wisps of particles seen as the stream trailed off as the tungsten supply came to an end. Never did the stream begin and end as a solid group of particles. There were always tests where the particles fell away from the mainstream.

Sometimes the entire exit diameter is not filled at low velocities and with larger orifices.

In some tests, less than 1 second in duration, we were unsure if oscillations in the stream occurred in the transient or steady-state portion of the flow. This implies the need for larger test facilities and dispenser sizes.

The ability to develop a desired cone angle proved difficult given the low exit velocities and impact of gravity. The performance in a space application may be different, but could not be confirmed. The alternative design of an abrasive blaster did show some improved ability to control the exit geometry and mass flow rates.

In routine handling, the grinded particles clumped while the uniform spheres did not.

Neither tungsten or tungsten carbide appeared to oxidize in casual exposure to the environment of an office over several months and a warehouse over two months.

DESIGNS AND TOPICS FOR THE FUTURE

This project is a precursor in packaging and dispensing tungsten particles in space. We chose a small canister and dispenser to investigate handling and dispensing small volumes of particles. There are several avenues of further research. One of which considers the design of a full scale dispenser that can reliably dispense a given amount of dust based on the mission requirements. Perhaps there will be consideration of a low-altitude orbit for in-space testing.

Other Designs Based on the Preliminary Design

While a full scale dispenser was not built, there was still a lot of effort put into developing a future design concept. There was no specific mission identified at the time, so one of the main goals was to develop a modular concept that could be tailored as desired based on future requirements. In developing the concept the first step was to determine what driving force (rocket, detonation, pneumatic, etc) would be used to dispense the dust. Table 6 below shows a Pugh matrix that evaluates the dispensing forces that were considered with pneumatic force being the reference for evaluating the other concepts.

Table 6: Pugh matrix of dust dispensing forces.

Pugh Matrix for Evaluate Dust Dispensing Forces								
Criteria	**Description**	**Weighting**	**Rocket**	**Detonation**	**Pneumatic**	**Hydraulic**	**Spring**	**Linear Actuator**
Dust Velocity Control	Ability to control dust velocity from canister (0.5 to 5.0 m/s)	3	-1	-1	0	0	0	0
Cloud Repeatability	Repeatability of dust cloud cone angle and velocity distribution (0.5 to 5 /ms with half cone angle of 5°)	3	-1	-1	0	0	0	0
Testability	Ability for system to be tested reliably and safely	3	-1	-1	0	0	0	0
Dust Velocity Variability	System's ability to vary dust velocity	3	-1	-1	0	0	-1	1
Cone Angle Variability	System's ability to vary dust cone angle	3	0	0	0	0	0	0
Durability		3	-1	-1	0	-1	-1	-1
Packaging		3	-1	-1	0	-1	1	-1
Weight		3	-1	-1	0	-1	0	0
Cost		3	-1	-1	0	-1	1	1
Schedule	Rating based on whether the system can be designed, built, and tested within the time constraints of this project	3	-1	-1	0	0	0	0
Total			-27	-27	0	-12	0	0

From the above Pugh matrix pneumatic and spring actuation were the two best options to pursue. A linear actuator also looked appealing and did provide some benefits, but after some quick research it was determined that this option would put too many restrictions on the design and take away from the modularity, which is one of the main goals.

With the possible dispensing forces identified, a focus could be put on the specific mechanism that would be used to release the dust. Again a Pugh matrix was used to evaluate the possible options as shown in Table 7 and Table 8 below. For this matrix, the pneumatic solenoid with burst disc dispersion control was chosen as the reference as this was a design being considered in previous work.

Table 7: Pugh matrix of dust dispensing concepts. (1 of 2)

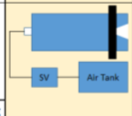
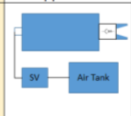
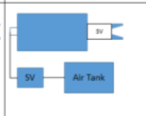
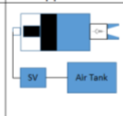
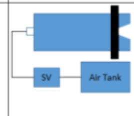
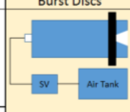
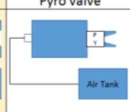
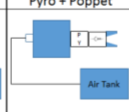
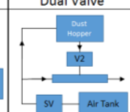
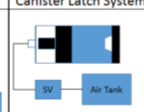
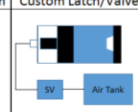
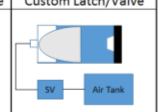
Pugh Matrix to Evaluate Dust Dispensing Mechanisms									
Actuating Force			Pneumatic	←	←	Pneumatic w/ Piston	Spring w/ Piston	Spring w/ Piston	Pneumatic
Force Control			Solenoid	←	←	←	←	←	←
Dispersion Control			Burst Discs	Poppet Valve	Solenoid Control Valve	Poppet Valve	Poppet	Burst Disc	Solenoid Gate Valve
Concept Image									
Criteria	Description	Weighting							
Dust Velocity Control	Ability to control dust velocity from canister (0.5 to 5.0 m/s)	3	0	0	2	1	-1	-1	1
Cloud Repeatability	Repeatability of dust cloud cone angle and velocity distribution (0.5 to 5 /ms with half cone angle of 5°)	3	0	0	0	1	1	1	0
Testability	Ability for system to be tested reliably and safely	3	0	0	0	0	0	0	0
Dust Velocity Variability	System's ability to vary dust velocity without changing hardware	3	0	0	2	1	-1	-1	1
Cone Angle Variability	System's ability to vary dust cone angle	3	0	0	0	0	0	0	0
Multiple Burst	Ability of system to perform multiple burst from one canister	3	0	1	2	1	1	0	1
Durability		3	0	-1	-2	-2	-2	-1	1
Packaging		3	0	0	-1	-1	1	0	-2
Weight		3	0	0	-2	-1	0	0	-1
Cost		3	0	1	-2	0	1	0	0
Schedule	Rating based on whether the system can be designed, built, and tested within the time constraints of this project	3	0	0	-2	0	-1	0	0
Launch capability	Ability to withstand 7g force	4	0	0	2	0	0	0	0
Total			0	3	-1	0	-3	-6	3

Table 8: Pugh matrix of dust dispensing concepts. (2 of 2)

Pugh Matrix to Evaluate Dust Dispensing Mechanisms									
Actuating Force			Pneumatic	Pneumatic	Pneumatic	Pneumatic	Pneumatic w/ Piston	Pneumatic w/ Piston	Pneumatic w/ Bladder
Force Control			Solenoid	←	←	←	←	←	←
Dispersion Control			Burst Discs	Pyro valve	Pyro + Poppet	Dual Valve	Canister Latch System	Custom Latch/Valve	Custom Latch/Valve
Concept Image									
Criteria	Description	Weighting							
Dust Velocity Control	Ability to control dust velocity from canister (0.5 to 5.0 m/s)	3	0	1	1	2	1	2	-1
Cloud Repeatability	Repeatability of dust cloud cone angle and velocity distribution (0.5 to 5 /ms with half cone angle of 5°)	3	0	0	0	1	1	1	1
Testability	Ability for system to be tested reliably and safely	3	0	-1	-1	0	0	0	0
Dust Velocity Variability	System's ability to vary dust velocity without changing hardware	3	0	1	0	1	0	1	1
Cone Angle Variability	System's ability to vary dust cone angle	3	0	0	0	0	0	1	1
Multiple Burst	Ability of system to perform multiple burst from one canister	3	0	0	1	1	0	1	0
Durability		3	0	2	-1	-1	0	-2	-1
Packaging		3	0	0	0	-1	-1	-1	-1
Weight		3	0	0	0	-1	0	0	0
Cost		3	0	-2	-2	-1	0	0	0
Schedule	Rating based on whether the system can be designed, built, and tested within the time constraints of this project	3	0	0	0	0	0	0	0
Launch capability	Ability to withstand 7g force	4	0	2	2	1	2	2	2
Total			0	11	2	7	11	17	8

As seen in the matrices above there were a large number of concepts considered. After much research into the possible options it became apparent that there was no product already in industry that could achieve our desired design goals for this specific application. They all came with considerable tradeoffs that made their application difficult. This led us to consider a design that incorporated attributes of the many different concepts considered.

First we needed a mechanism to release the tungsten particles when desired. We decided on a custom designed rotary gate/knife valve. The gate valve technology is already proven in industry and used for granular material, however all of the current designs are very large in size and difficult to package. To overcome the size and packaging issues the valve was put into a rotary design. This allows the technology to be incorporated into a small and lightweight package. An example of this concept can be seen in Figure 26.

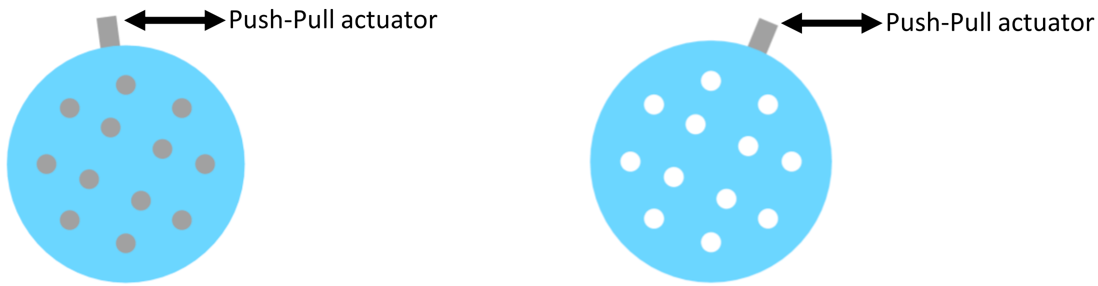


Figure 26: Rotary gate/knife valve concept. (Left) Closed position. (Right) Open position actuated by push-pull actuator.

The design provides a variety of benefits including a small package, lightweight, on-off control, multiple outlet orifices, and a valve technology already proven to handle this type of material. Another benefit to this design is it allows for a different number of orifices to be used with a different geometry if desired based on the valve position. Most importantly this design provides the modularity and versatility needed to tailor the design for different specifications.

In combination with the custom valve we selected a gas driven piston to move the tungsten out of the canister. The gas (pneumatic) system was chosen as it provides a high level of flexibility in the supply force and is relatively easy to package and control. The spring actuation was more compact in package, but gave a non-uniform supply force and limited stroke. The piston improves control as observed through our current testing. It also provided a support for the tungsten that prevented sloshing. As mentioned previously one of the main concerns observed with the piston concept is the ability for the particles to get trapped between the piston and cylinder walls, which may result in seizure. To prevent this from occurring a piston design concept that utilized both piston rings and a scrapper, as seen in Figure 27 below, was created. The piston rings act as a separation barrier between the gas and tungsten while the scrapper removes particles from the cylinder walls, thus preventing them from getting trapped between the piston and cylinder. This scrapper concept is the same as that used on both hydraulic and pneumatic rods to remove debris and fine particles.

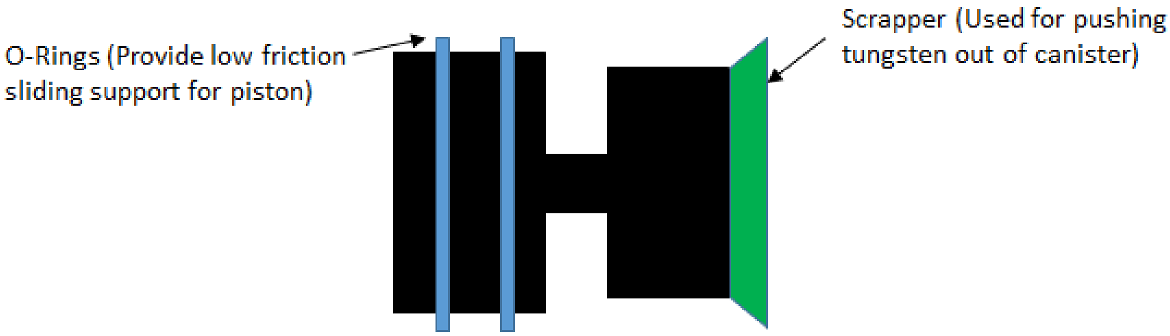


Figure 27: Piston concept for dispenser showing piston, O-rings, and scrapper.

By combining all the components outlined above a full system is created as seen in Figure 28 below. This concept can perform single or multiple burst, carry large or small quantities, as well as vary dust velocity, orifice size, and orifice geometry. This design can also be modified to perform as an abrasive blaster as outlined previously in this report. While not shown here, this can be accomplished by plumbing the outlets of the orifice plate to a separate air feed line where the particles would be introduced. The mixed stream would then flow to a single exit nozzle or multiple ones if desired. This achieves the goal of high modularity and can be tailored for a variety of missions.

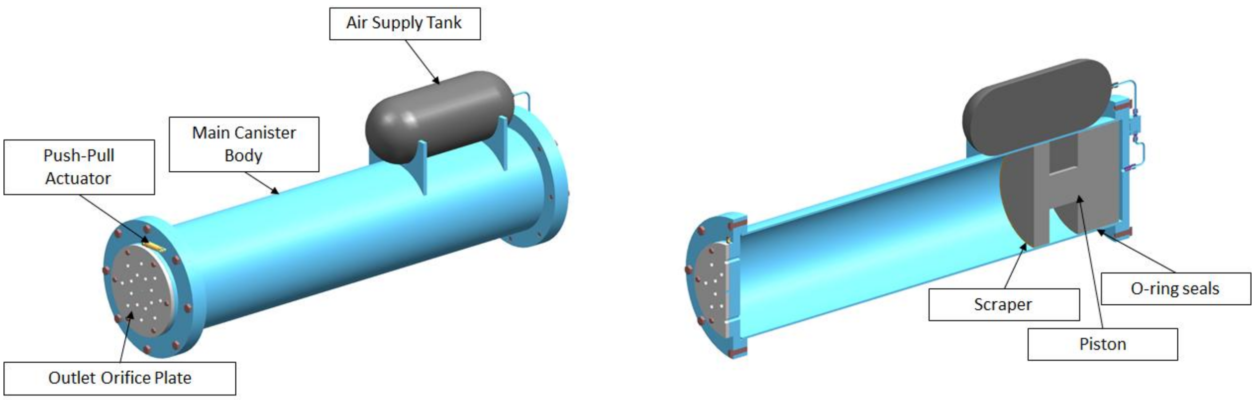
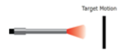


Figure 28: Dispenser concept including canister, valve, piston, solenoid, and gas supply tank.

Another goal of this design concept was to create a control strategy that gave us the ability to control and monitor the amount and velocity at which the dust is dispersed. To do this we need a system that can control the supply pressure (control velocity), monitor the piston position (monitor volume), and monitor the velocity of the dust particles exiting the canister. Controlling of the supply pressure is fairly easy as a simple proportionally controlled pressure regulator can be used. Monitoring the position of the piston becomes more difficult. Table 9 below shows some of the measuring concepts that were considered. The sting potentiometer proves to be the most effective with high accuracy in a compact design. It also can accommodate short and long strokes. The instantaneous velocity can be derived from the position data as well.

Table 9: Sensors for monitoring position of piston in canister.

Displacement and Speed Measurement Devices			
Option	**Image**	**Pros**	**Cons**
Non contact optical sensor		• Non-contact • Compact • High accuracy	• Complex • Not normal in space applications???? • Difficult in long stroke applications
Linear Variable Differential Transformer (LVDT) position sensor		• High accuracy	• Difficult to package • Limited stroke
Speed controlled linear actuator		• High accuracy • Actuator speed control • Simplifies control system • No pneumatics needed	• Difficult to package • Limited stroke • Limited speed
Draw wire (a.k.a cable transducer, string potentiometers, yo yo pots, string encoders)		• High accuracy • Compact design • Long stroke capable (up to 85")	• Contact sensor

There are at least two methods to determine exit velocity of the dust particles. The first is to mount a high speed camera to the canister and determine the velocity using the methods outlined in this paper. This however is not a very practical method for space application perhaps due to large volume and lighting conditions. The second method is to calibrate the system on the ground using the string potentiometer and high speed camera. Using these tools a map can be created of dust exit velocity vs. piston speed and supply pressure. The map can then be used to estimate dust exit velocity when the system is in operation. This eliminates the need for a camera and lighting considerations.

This gives a modular method for storing and controlling the dispersion of dust particles. The design has the versatility to be tailored to missions that are both big and small in scale, without significant changes to the design while accommodating different specifications. The concept also provides feedback to the amount and velocity of ejected particles

Design Concept Validation Methods

In addition to the design concept a test plan has also been outlined that can be used to validate the critical components of the dispenser. Those components include the custom valve, actuator, piston, and control system. The focus of the validation is to determine the failure limits of the hardware as well as the accuracy of the velocity control. Understanding the accuracy of the velocity control is crucial in order to have confidence in the velocity at which the dust is dispersed.

One of the questions that must be answered is what is the mechanical limit and cycle limit of the valve assembly, including the actuator? This is an important question to answer in an application where multiple bursts are occurring. We will be able to identify the maximum pressure at which the valve can operate as well as its cycle limit under that condition. This test will also help us to specify the actuator force needed. To find these answers, a test could be designed where the valve assembly is immersed in a column of tungsten. The column of tungsten is pressurized resulting in a force against the valve. Under the given condition the valve is cycled on and off until failure occurs. Failure is identified by either mechanical failure or if the valve fails to close and open completely. Judgment of the system would be based on the ratio of cycles achieved until failure to the desired dispersion events. An example of the setup can be seen in Figure 29 below.

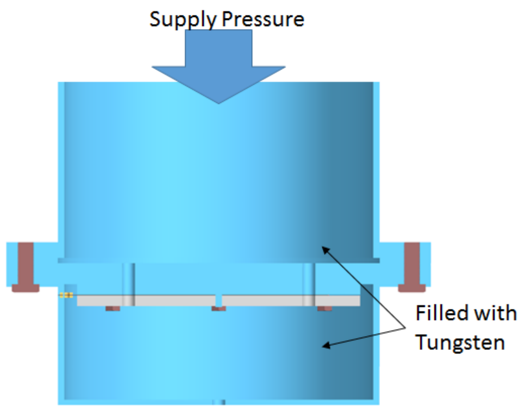


Figure 29: Test setup for valve assembly.

The next component that must be tested is the piston and cylinder assembly. The goal of this test is to determine the cycle limit of the piston and cylinder in the tungsten environment. It is important to ensure that seizure of the piston will not occur prior to all the dust being dispersed. An example of the test concept can be seen in Figure 30 below. In this test the canister is partially filled with tungsten. Gas is plumbed to both ends of the canister with a two-way valve controlling which end the gas is supplied to. The two-way valve is then cycled resulting in the piston moving back and forth while interacting with the tungsten particles. The test would be run until failure occurs or until the specified number of cycles is reached. Failure would be determine by disassembling and inspecting the piston, scrapper, O-rings, and cylinder. The amount of tungsten leakage past the piston can also be evaluated. The final judgment would be based from the cycles completed and condition of components. It must be considered that for this application the piston only needs to complete a half cycle to disperse all the particles.

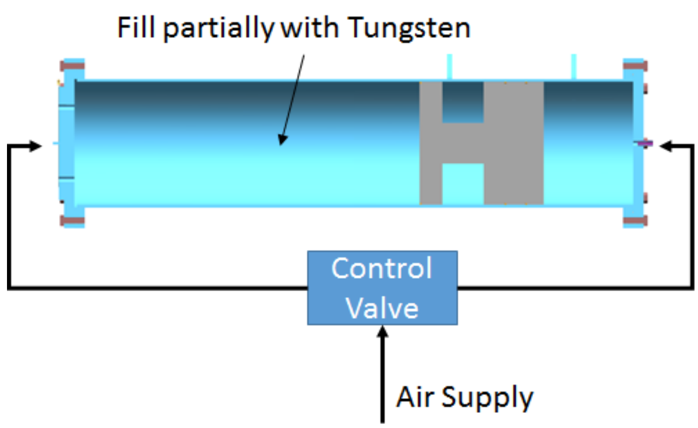


Figure 30: Test setup for validating piston and cylinder assembly.

The final step is to determine the accuracy and repeatability of the draw-wire sensor used to measure the volume and velocity of the dust ejected. A high-speed camera can be used to directly measure the dust velocities and then correlate to the draw-wire sensor. At the same time we can measure the change in displacement of the sensor to determine the volume ejected. The actual volume can be directly measured and the two correlated. By performing this test multiple times we can establish a statistical measure as to the accuracy and repeatability of the system.

The test program outlined provides a method that allows us to quantitatively evaluate the performance of the design. These tests will provide a measure of the durability of the system and give a statistical indication to the accuracy and repeatability.

These and earlier tabletop-sized experiments may not be scalable to flight-sized versions. Full-size models need to be tested.

Reduced orifice sizes yield better control; however, the dispensing time increases. At larger orifice sizes and higher speeds, controllability becomes more difficult. Today, there is no real requirement for the volume rate, speed, and angle of ejection. The goal is to uniformly fill the orbit ring. Only one case was suggested in Reference [3] that of six separate dispenses of 1,666 kg pure tungsten spheres.

Further Investigations

We clarify that tungsten carbide, a compound of tungsten and carbon, has density about 3.6 gm/cm^3 less than tungsten. The compound is harder than pure tungsten, which is hard itself. Because tungsten carbide spheres were readily available, having a range of 38-45 microns diameter, relative to grinded tungsten dust of irregular shape, we tested the spheres first. This does not mean that the tungsten carbide spheres are substitutes for tungsten in space for debris removal, it just means we used these spheres in the laboratory to begin to learn how to handle the granular material.

Future clumping experiments might investigate that during launch, the tungsten within the canister will be exposed to extreme loads. Perhaps some tests could be built to subject the tungsten particles to high compressive loads for perhaps several months and examine the product afterward. The micrograph may show particles have crushed or become stuck to adjacent particles. The ballistic property would be changed for that clump relative to other clumps or individual particles, thus causing the orbiting ring not to uniformly decay.

Be aware of unintended consequences that the tabletop-sized experiments may simply not be scalable to flight-sized versions. Full size models need to be tested. Be aware that ground-based tests may not work in space.

Several designs were listed and discussed for possible consideration. Developing and documenting there designs were invested to leave enough substance for the future designer to use when considering that the full dispensing scheme requires thousands of kilograms of tungsten particles released over a certain amount of time. In turn, there is likely to be the requirement to develop a full-scale system in vacuum and in orbit (to eliminate the effects of gravity) for testing to confirm the concept before the space mission. Perhaps this will be tested in a sounding rocket flight or very low earth orbit spacecraft mission, where the particles decay and enter the atmosphere in a few weeks. Whether the dispensing is of the pneumatic type, with just gas, or gas and piston, or the mixing of gas and tungsten particles in the blaster, or some other actuating force, the need to test the full-scale operation is necessary to gain confidence in the design and application.

Packaging of the particles is another area that needs further consideration. Assuming the particles are packaged months prior to the actual launch, a method would be needed to prevent oxidation. Oxidation may cause clumping and can change the physical properties of the particles. One method to mitigate this is to pack the material within a vacuum. One would also need to consider moisture control. As with all fine material, the additional of moisture can cause clumping: a concern that has been mentioned various times throughout this report.

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APPENDIX 1

Material and Chemical Properties of Tungsten and Tungsten Carbide

Property	Tungsten (W)	Tungsten Carbide (WC)
Color	• steel-gray to tin-white	• gray
Temperatures	• melting point: 3422° C • boiling point: 5555° C • liquid range: 2133° C	• melting point: 2870° C • boiling point: 6000° C • liquid range: 3130° C
Expansion and Conduction	• thermal conductivity: 174 W m^{-1} K^{-1} • coefficient of linear thermal expansion: 4.5 x 10^{-6} K^{-1}	• thermal conductivity: 84.2 W m^{-1} K^{-1} • coefficient of linear thermal expansion: 5.8 x 10^{-6} K^{-1}
Bulk	• density of solid: 19250 kg m^{-3} • tap density: ~10000 kg m^{-3}	• density of solid: 15800 kg m^{-3} • tap density: ~10000 kg m^{-3}
Elastic	• Young's modulus: 411 GPa • Bulk modulus: 310 GPa • Poisson's Ratio: 0.28	• Young's modulus: 550 GPa • Bulk modulus: 439 GPa • Poisson's Ratio: 0.18
Electrical	• resistivity: 5.4 x 1^{-8} Ω m	• resistivity: 2.7 x 1^{-7} Ω m

Some notes on oxidation:

Tungsten

- Does not react with air, oxygen, and water at room temperature [6]
- Strongly attacked by fluorine at room temperature [6]
- Oxidation of tungsten by oxygen or air starts at room temperature [7]
- Reacting agents increase with temperature [7]
  - Below 100°C: Dissolves in hydrofluoric-nitric acid mixtures, aqua regia, and alkali solutions containing oxidizing agents
  - At 250°C: Reacts with chlorine, phosphoric acid, potassium hydroxide, and sodium nitrate or nitrite
  - At 500°C: Attacks by oxygen or hydrogen chloride become vigorous
  - At 800°C: Reacts with ammonia
  - At 900°C: Reacts with carbon monoxide, bromine, iodine, and carbon disulfide
- Stable in dry and humid air only at moderate temperature [7]
- Oxidation starts at about 400°C and increases rapidly at about 700°C with sublimation of the oxide above 900° C [7]
- Oxidation strongly depends on temperature. A tungsten surface between room temperature and 370° C contains oxide. [7]
- Does not react with water, but will be oxidized by water vapor at elevated temperature. [7]
- Tungsten powder, of average grain size > 1µm, reacts like bulk tungsten [7]
- Oxidizes in air and must be protected at elevated temperatures [8]

Tungsten Carbide

- Oxidation starts at 500-600° C [9]
- Resistant to acids and is not attacked at room temperature by mixtures of HF and HNO3, but is attacked by these acids at elevated temperatures [9]
- Attacked by chlorine above 400° C and by fluorine at room temperature [9]

APPENDIX 2

Summaries of Powder Descriptions and Images

Several samples of dust particles were chosen to experiment with the characteristics of size, shape, and composition. Three separate samples of pure tungsten powder, or dust, were purchased with a high percentage of particles in the ranges of 10-20, 15-38, and 50-75 microns. The shapes of these particles are highly irregular, with great angularity and roughness. Another product, tungsten carbide spheres, was purchased because they are spherical. These diameters range between 38-45 microns. The variety of particles allowed us to investigate several configurations other than identical spheres of tungsten carbide.

Summary of Tungsten Powder Size Ranges

Type	Size Range (microns)		Type	Size Range (microns)	
	micron range	weight %		micron range	weight %
Tungsten Powder Lot No: ST-371	0-10	19	**Tungsten Powder Lot No: C110-3186**	0-10	0
	10-20	35		10-20	1
	20-30	19		20-30	3
	30-40	9		30-40	10
	40-50	6		40-50	23
	>50	12		50-75	51
				75-100	11
				>100	1
	micron range	weight %		micron range	weight %
Tungsten Powder Lot No: C100-3196	<15	10	**Tungsten Carbide Powder**	38-45	100
	15-38	80			
	>30	10			

The pure tungsten powders have a product density of 19.3 gm/cm^3 the tungsten carbide has a density of 15.6 gm/cm^3. Irrespective of type, the tap densities are all about 10 gm/cm^3. (Tap density is the mass of the many particles divided by the total volume they occupy. The total volume includes the particles, the void space in-between the particles, and the pores or absence of material within a particle. The tap density refers to a specified standard of compacting the material before measuring the volume, usually by vibrating the container.)

The three tungsten powders were obtained from Buffalo Tungsten and the tungsten carbide powder from TEKNA Advanced Materials.

Using the weight of product purchased and its tap density (estimated by the manufacturer), the total volume indicates the compactness of the product.

Summary of Tungsten Powder Volume

Type	Weight (lb)	Weight (kg)	Volume (assumes tap density of 10 gm/cm^3) (cm^3)
Tungsten Powder Lot No: ST-371	3	1.36	136 a cube 5.1 cm on a side
Tungsten Powder Lot No: C100-3196	6	2.72	272 a cube 6.5 cm on a side
Tungsten Powder Lot No: C110-3186	6	2.72	272 a cube 6.5 cm on a side
Tungsten Carbide Powder	55.1	25	2,500 a cube 13.6 cm on a side
totals	70.1	31.8	

These four samples were given to NRL's Materials Science and Technology Division to take micrographs for this report. The samples were prepared for the scanning electron microscope by placing special double-sided tape onto a stub. The stub is a disk, approximately the diameter of a dime, with a small rod attached perpendicular to the back to hold the stub in the microscope. The front side, with the tape, is placed into the sample bag to allow the particles to stick. In the micrographs below, the background is the sticky tape.

Typical Small Stub to Hold Powders for the Microscope (tape not shown)

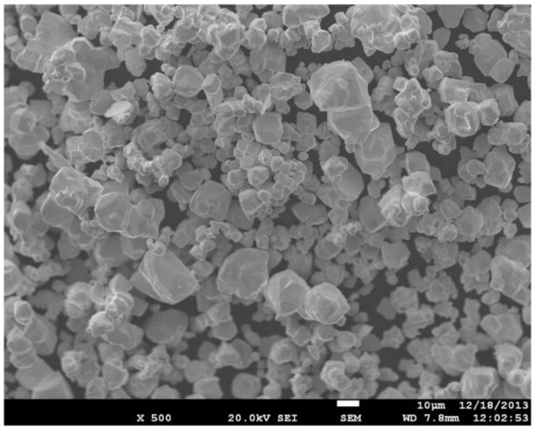
Magnification and Scale Sizes of the Micrographs Produced by the Scanning Electron Microscope

ST-371	C100-3196	C110-3186	WC-45
500x, 10 µm	100x, 100 µm	100x, 100 µm	100x, 100 µm
1,600x, 10 µm	4,000x, 1 µm	1,500x, 10 µm	2,200x, 10 µm
4,300x, 1 µm	1,900x, 10 µm	1,700x, 10 µm	100x, 100 µm
800x, 10 µm	350x, 10 µm	300x, 10 µm	100x, 100 µm
800x, 10 µm	350x, 10 µm	300x, 10 µm	1,800x, 10 µm
800x, 10 µm	350x, 10 µm	200x, 100 µm	1,800x, 10 µm
800x, 10 µm	350x, 10 µm	200x, 100 µm	100x, 100 µm
800x, 10 µm	350x, 10 µm	200x, 100 µm	100x, 100 µm
800x, 10 µm	350x, 10 µm	200x, 100 µm	100x, 100 µm
800x, 10 µm	350x, 10 µm	200x, 100 µm	100x, 100 µm
800x, 10 µm	350x, 10 µm	200x, 100 µm	100x, 100 µm
800x, 10 µm	350x, 10 µm	200x, 100 µm	100x, 100 µm
800x, 10 µm	350x, 10 µm	200x, 100 µm	100x, 100 µm

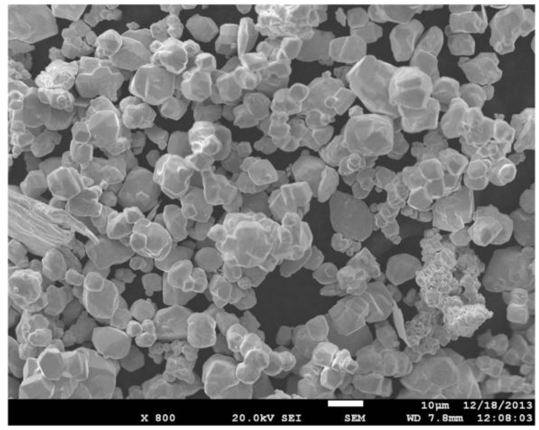
Some Micrographs and Observations (1 of 4)

ST-371 Tungsten Powder, Dust

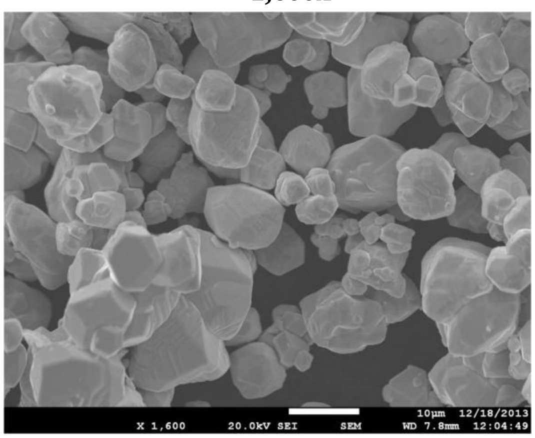
500x



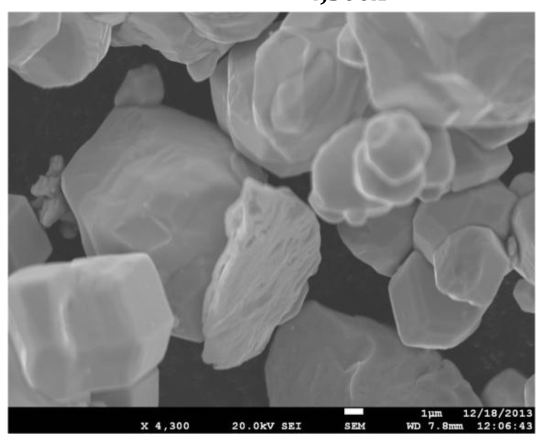
800x



1,600x



4,300x

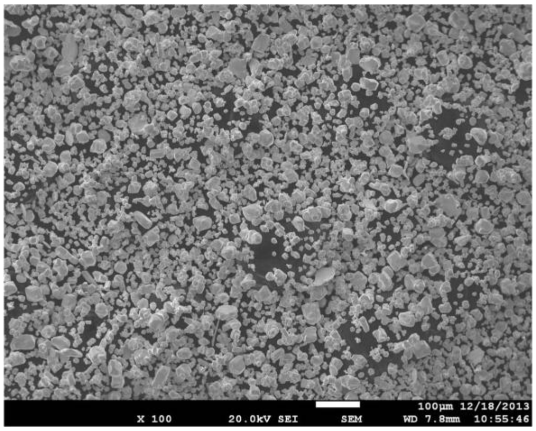


- Particles mostly range 1-40 microns, with about 1/3 in the 10-20 micron range
- Highly irregular shapes and sizes, quite rough and angular
- Appears that particles are not actually separated, but attached to one another so as to build-up closer to the microscope

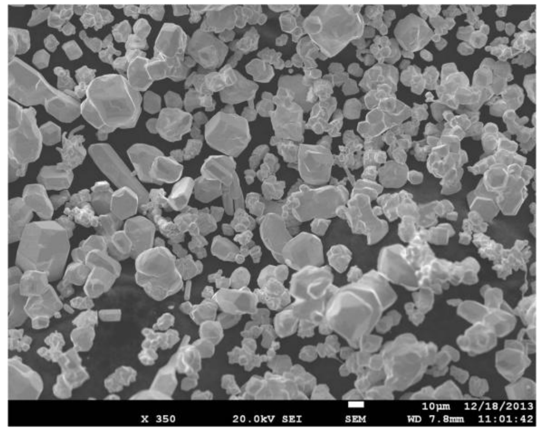
Some Micrographs and Observations (2 of 4)

C100-3196 Tungsten Powder, Dust

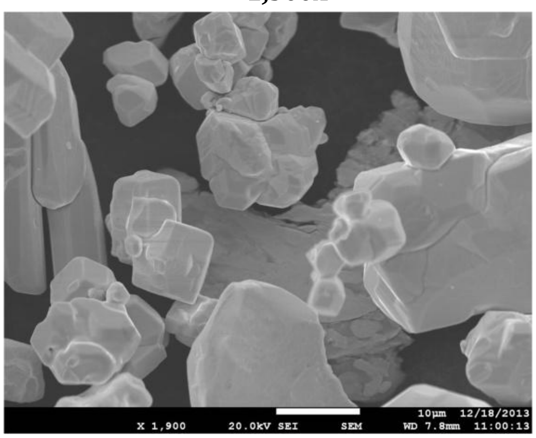
100x



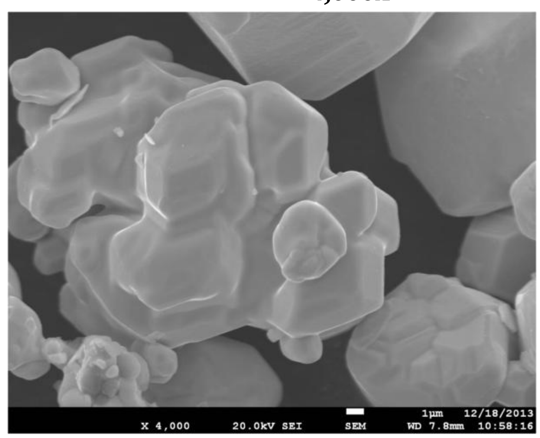
350x



1,900x



4,000x

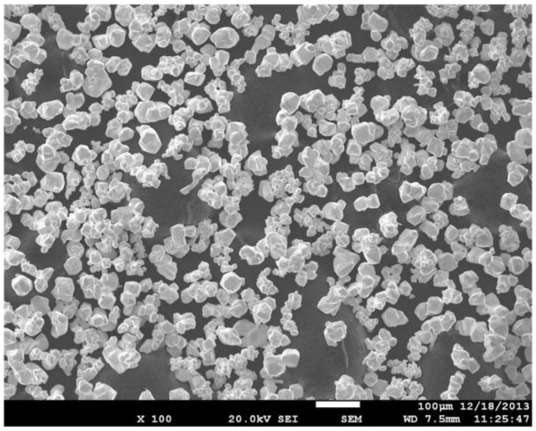


- Particles mostly range 15-38 microns
- Highly irregular shapes and sizes, quite rough and angular, elongated pieces in the mix
- Appears that particles are not actually separated, but attached to one another so as to build-up closer to the microscope

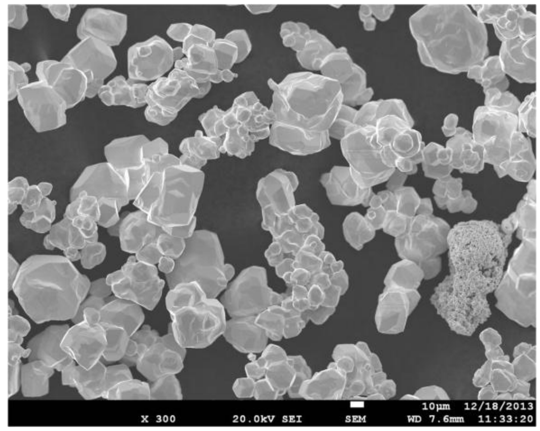
Some Micrographs and Observations (3 of 4)

C110-3186 Tungsten Powder, Dust

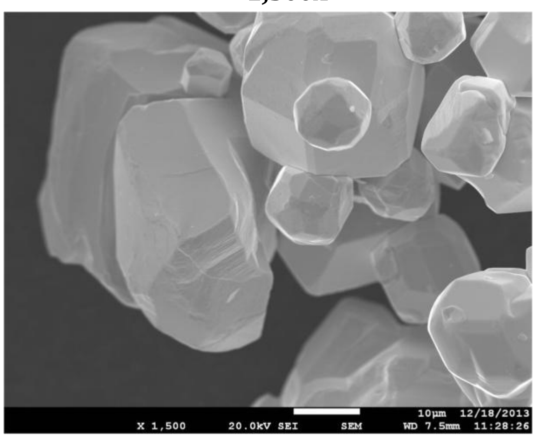
100x



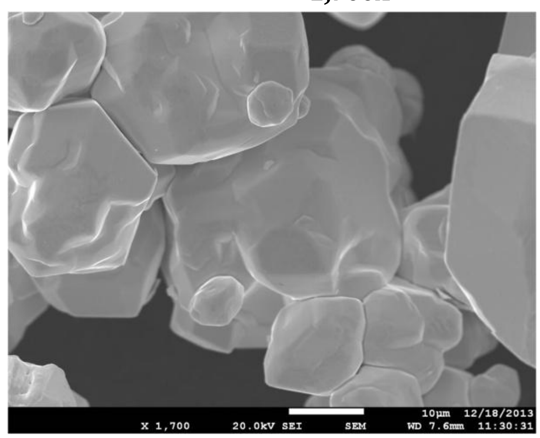
300x



1,500x



1,700x

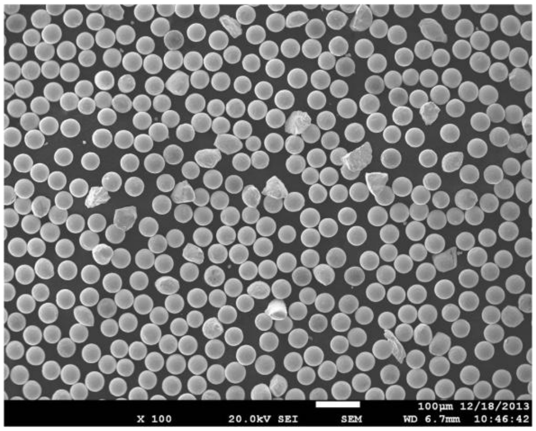


- Particles mostly range 30-75 microns, with about 1/2 in the 50-75 micron range
- Highly irregular shapes and sizes, quite rough and angular, appears that chains of materials and sponge-like cluster in the 300x micrograph
- Appears that particles are not actually separated, but attached to one another so as to build-up closer to the microscope

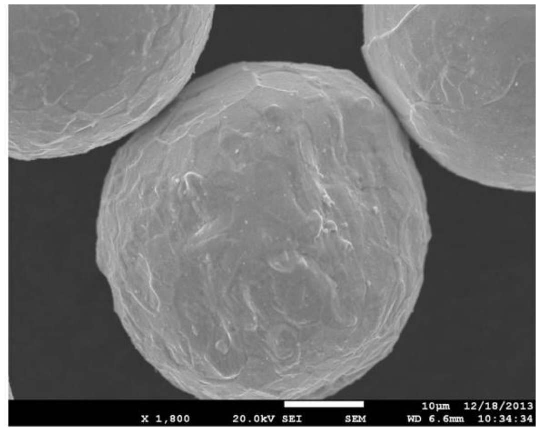
Some Micrographs and Observations (4 of 4)

WC-45 Tungsten Carbide Powder, Spheres

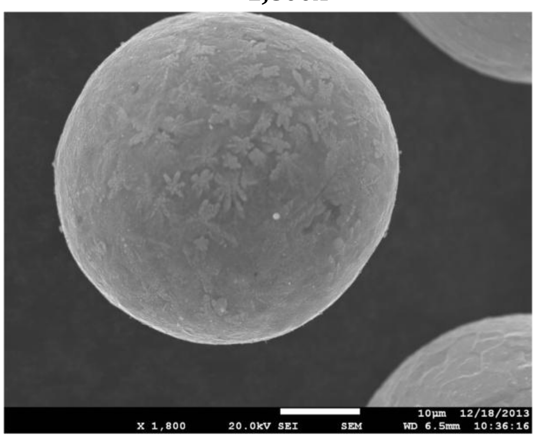
100x



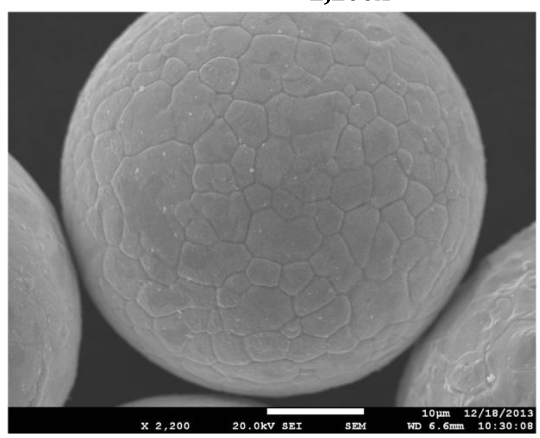
1,800x



1,800x



2,200x



- Particles range 38-45 microns
- Manufactured to be highly regular shapes and sizes, higher magnification micrographs show differences in cooling of the cast spheres
- Manufacturer states 10-20% could be angular

In all three sets of the tungsten dust micrographs, almost every particle is attached to many other particles. There are very few isolated particles in the micrographs. This uniting of mechanically separate particles is due to electrostatic forces allowing separate particles to attach to one another or preventing all the ground particles from falling off one another. Some particles do fall separate and some remain attached. Perhaps a device that can remove the electrostatic forces may be necessary somewhere in the dispenser chain. Perhaps the dispensing operation will separate all the particles so they leave as single particles. In the test chamber, they may fly separately but recombine due to electrostatics after landing on one another on the chamber's floor. Or, simply using pure tungsten spheres could eliminate these problems, which meets the requirements for uniform shape and size.

APPENDIX 3

Summaries of Safety Information Regarding Tungsten

Caution and care should be taken when handling the tungsten powders. All necessary personal protective devices are available within NRL and there should be no concerns with the testing as long as the tests are performed in an enclosed environment.

Pure Tungsten and Tungsten Carbide Dust

Physical and Chemical Data
- Odor: None
- Boiling Point: 5550-6000°C

Fire and Explosion Hazard Data
- Flash Point: N/A
- Autoignition Temperature: N/A
- Flammable Limits: Upper: N/A, Lower: N/A
- Extinguishing Media: Tungsten rod, wire and fabricated products are not a fire hazard. Fine dust may ignite if allowed to accumulate and subjected to an ignition source. Cover burning material with an inert powder.
- Unusual Fire and Explosion Hazards: Dust may present a fire or explosion hazard under favoring conditions of particle size, dispersion and strong ignition source. However is not expected to be a problem under normal handling conditions. Tungsten powder, particularly powder less than 1 micron, can be ignited in air by friction during blending, milling, or similar process. Ultra fine powders may ignite spontaneously in air.
- Special Fire Fighting Procedures: For a fire confined to a small area, use a respirator approved for toxic dusts and fumes.

Health Hazard Data
- Threshold Limit Value: 5 mg/m^3
- Skin Exposure: May cause irritation
- Skin First Aid: Remove contaminated clothing, brush material off skin, wash affected area well with soap and water. Seek medical attention if symptoms persist
- Eye Exposure: May cause irritation
- Eye First Aid: Flush eyes with clean, lukewarm water for 15 minutes. Obtain medical attention if irritation develops. Seek medical attention if symptoms persist
- Inhalation: Acute: May cause irritation to the respiratory Tract.
- Inhalation: Chronic: No chronic health effects recorded
- Inhalation First Aid: Removed victim to fresh air, keep arm and quiet, give oxygen if breather is difficult and seek medical attention if symptoms persist.
- Ingestion: Acute: No chronic health effects recorded
- Ingestion: Chronic: Large overdoses may cause nervous system disturbances, and diarrhea
- Ingestion First Aid: Give 1-2 glasses of milk or water and induce vomiting, seek medical attention if symptoms persist.

Health Hazard Data (Continued)
- Medical Conditions Generally Aggravated By Long Term Exposure: Pre-existing respiratory disorders.

Spill or Leak Procedures
- Steps To Be Taken In Case Material Is Released Or Spilled: Ventilate area of spill. Take care not to raise dust. Use non-sparking tools. Clean up using methods which avoid dust generation, such as vacuuming, west dust mop, or wet clean up. If airborne dust is generated use an appropriate NIOSH approved respirator.
- Waste Disposal Method: Dispose of in accordance with local, state, and federal regulations.

Exposure Controls/Personal Protection
- Use an appropriate NIOSH approved respirator when airborne dust consternations exceed the threshold limit value (TLV)
- Ventilation: Use local exhaust ventilation that are adequate and limit personal exposure to levels that do not exceed the TLV.
- Skin Protection: Rubber gloves should be worn.
- Eye Protection: Safety goggles or glasses are recommended

Handling and Storage

Handling: Maintain good housekeeping procedures to avoid accumulation of dust. Use clean-up methods that minimize dust generation. Wash thoroughly after handling and before eating. Do not shake clothing or other items to remove dust, use a vacuum.

Storage: Keep container closed

Stability and Reactivity
- Chemical Stability: Stable
- Incompatibility: Tungsten is slightly soluble in nitric acid, sulfuric acid and aqua regia. It is soluble in a mixture of HF acid and nitric acid. Vigorous reaction with bromine trifluoride. Tungsten becomes incandescent in cold fluorine, lad oxide, and iodine pentafluoride. Avoid oxidizers.
- Hazardous Decomposition Products: None