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BYOE: Hands-on Experiments for Teaching Process Safety: Exploring Dust Explosions

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Professional Skills and Safety are my main pedagogical interests. I use the Chemical Engineering laboratory to implement safety training to improve safety culture, and to adapt assessment methods to enhance development of students' professional skills. I am an Assistant Professor of Chemical Engineering at the University of Virginia and I hold a B.Sc. (University of Saskatchewan) and Ph.D. in Chemical Engineering (Queen's University). Complimenting my pedagogical research is an interest in bioprocess engineering, environmental engineering, environmental risk management, and I have authored >40 peer reviewed publications in these fields. I'm also active in developing workforce development initiatives, specifically within the biopharmaceutical manufacturing space. Beyond academia, I have 7+ years of international consulting experience working with the U.K. government, European Union, and the United Nations.

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BYOE: Hands-on Experiments for Teaching Process Safety: Exploring Dust Explosions

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Abstract

Process safety is a critical component of an undergraduate chemical engineering curriculum and is increasingly recognized as a key competency in the hiring process. Teaching of process safety is often limited to the classroom as there are few hands-on educational tools for instructing students on the practical aspects of safety. In this paper we describe the design and development of a hands-on process safety experiment for a Chemical Engineering Unit Operations Laboratory that is used to assess the explosion risk posed by dust. We constructed a custom Hartman Tube, a device commonly used in industry for explosion risk analysis, at a fraction of the commercial cost–under $1,000 compared to the typical $30,000–using 3D printing and affordable pressure monitoring components. Protocols were established for dust sample preparation, including considerations for particle size and moisture content, as well as standardized testing and data collection procedures. We demonstrate how the device can be used to collect quantitative explosivity data and observational data helping students understand how factors such as humidity and material type can influence a combustion event.

Introduction and Motivation

Process safety is a cornerstone of chemical engineering education, equipping students with the skills to identify and mitigate hazards while maintaining rigorous safety standards in professional practice. Despite its critical importance, the integration of process safety into undergraduate curricula remains inconsistent. A survey of process safety education revealed that more than 70% of institutions incorporate process safety into core courses while 49% of programs require at least one dedicated safety course[1]. Most curricula emphasize theoretical instruction, often relying on chemistry-centric approaches that integrate safety concepts. However, these methods frequently lack the depth and practical context necessary to fully prepare students for industry demands. Overall, there is limited availability of hands-on safety training within academic settings and few institutions have implemented process safety demonstrations, with notable exceptions being the University of Iowa.

In this paper we develop a low-cost Hartmann tube for the study of dust explosions. This device, widely used in industrial safety testing, has been designed and developed for educational purposes providing students opportunity to gain deeper understanding and appreciation of dust explosions using a hands-on device. This Hartmann tube can be constructed using readily available materials, making it a viable option for most universities. Integrating process safety training tools into undergraduate laboratories can enhance student understanding of process safety education and equip students with the skills and experience necessary to prioritize safety in their future careers.

Background

Dust is a frequently underestimated industrial hazard. Despite its seemingly benign nature, dust can ignite, leading to fires and explosions that cause significant injury, loss of life, and industrial destruction. In 2022, the United States experienced 26 dust explosions, resulting in 21 injuries and one fatality[2]. A notable example occurred at the Imperial Sugar plant in Wentworth, Georgia, in 2008, where a powdered sugar dust cloud explosion killed 14 individuals and injured 38[3].

Dust explosions typically manifest as deflagrations—combustion events where the flame propagates through a fuel/oxidizer mixture at subsonic speeds. This differs from detonations, where reaction fronts move at supersonic speeds, generating shockwaves. Although dust explosions are primarily deflagrations, ignition near equipment or combustible materials can trigger secondary explosions or fires, potentially escalating into a deflagration-to-detonation transition (DDT).

The "fire triangle," composed of fuel, oxygen, and an ignition source, illustrates the conditions for combustion. Similarly, the "dust explosion pentagon" extends this framework to include dust dispersion and confinement, which are critical for dust explosions. Dispersion increases the surface area of particles, accelerating the combustion rate. Confinement leads to pressure buildup, creating the conditions necessary for an explosive event.

Several factors influence the intensity of a dust explosion, including dust type, particle size, dispersion, confinement, concentration, humidity, and ignition energy. Organic materials such as wood, polymers, and sugar are inherently combustible. Fine particles, typically under 400 μm, are more prone to ignition and produce more severe explosions. Uniform dispersion of the dust is critical to forming a combustible cloud, while confinement affects the pressure generated during the explosion. The dust concentration must fall within a specific range to sustain combustion: concentrations that are too low lack sufficient fuel, while concentrations that are too high limit oxygen availability. Humidity and moisture significantly reduce ignition potential, and in some cases, prevent explosions entirely. Additionally, each dust type has a specific minimum ignition energy (MIE) required to trigger an explosion[4].

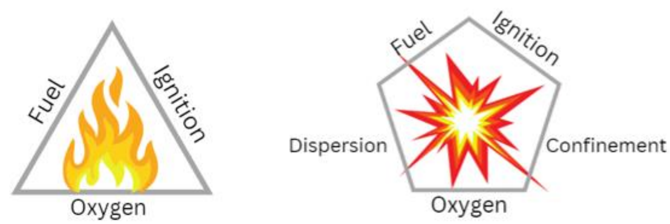

Figure 1. Graphical illustration of the fire triangle and the dust explosion pentagon.

Understanding these factors is essential for preventing and mitigating dust explosions. The Hartmann tube, a cylindrical apparatus, is commonly used to simulate dust ignition conditions to evaluate hazards posed by different types of dust under different environmental conditions. The minimum ignition energy (MIE), minimum explosible concentration (MEC), and the dust deflagration index (K_{st}), are common metrics used to evaluate the explosive severity of the dust.

The Dust Deflagration Index (K_{st})[5] expressed as [bar*m/s] is defined as:

$$K_{st} = \left(\frac{dP}{dt}\right)_{MAX} * V^{\frac{1}{3}} = \left[\frac{bar}{s}\right] * [m]$$

where K_{st} represents the explosion potential of a dust and the specific conditions under which dust becomes hazardous. To calculate K_{st} data about the maximum pressure change resulting from an explosion and the confinement volume are needed. For our Hartmann tube, evaluating the K_{st} was straightforward, as the pressure changes are measured with sensors and software while the volume of the confinement space remained constant. This setup provided an optimal platform for students to investigate and analyze dust explosivity.

K_{st} values are globally recognized and used in industry for measuring dust's explosivity. Table 1 provides K_{st} values for common combustible dust illustrating the wide variance in explosivity across materials. The Occupational Safety and Health Administration (OSHA) organizes this information into explosion classes that range from St 0 (no explosion) to St 3 (very strong explosion)[4].

Table 1: K_{st} Values for Different Materials [bar*m/s] [6]

Material	K_{st} Value [bar*m/s]
Cornstarch	128-158
Wheat Flour	87
Powdered Sugar	26.18-139
Aluminum Dust	400-1100
Saw Dust	102
Wheat Grain Dust	112

The American Society for Testing Materials (ASTM) International is a globally recognized organization for developing and publishing voluntary consensus standards, has established numerous protocols for evaluating the combustibility and explosibility of dust. We located a now-withdrawn standard for a 1.2-liter cylindrical apparatus, (Hartmann tube) retired in 2007 due to its inability to conclusively determine a material's flammability[12]. The current standard for testing explosibility of dust uses a 20 L spherical closed steel combustion chamber[13], a highly effective tool that produces accurate industry and research data, but is a prohibitively expensive education device. This became the impetus for our work. We sought to create an affordable alternative to the expensive commercial models available. Building our Hartmann tube based on ASTM standards, we could provide students an experiential activity that demonstrates dust explosion fundamentals in a reliable and memorable way.

Design Methods and Physical Components

Our device used a 1.2 L working volume, 100 psi inlet air pressure, 50 mL air dispersion volume, and an ignition height of 100 mm. Use of a weighted metal lid was borrowed from the design of commercial devices. We combusted only non-toxic materials. The Hartmann tube assembly is organized into six main components: the tube, base, air supply and nozzle, ignition source, pressure sensor, lid options, and materials. Each component contributes to the controlled environment needed to initiate and study dust explosivity.

The Tube

The containment tube is an 18-inch-long (457mm), 3-inch-diameter (76.2mm), 1/8-inch-thick (3.175mm) transparent polycarbonate tube that provides confinement necessary to initiate, contain and observe the dust explosion. Polycarbonate was chosen over acrylic due to its durability as acrylic can become brittle over time, presenting a potential shatter risk. Though polycarbonate was a cheap and safe alternative to metal or glass, we observed that plastic tends to hold a static charge causing dust to cling to the inner walls of the tube.

Figure 2. 3D renderings of the Hartmann Tube completed using Autodesk Fusion.

The Base

A 3D-printed polyethylene terephthalate glycol (PETG) plastic base was used to mount the tube (Figure 3). The base comprised a parabolic cavity. The base also served to connect the air supply. The tube was secured to the base using bale clips which prevented the tube from detaching due to the pressure of the explosion. A PETG collar, adjustable to a fixed height, was tightened around the tube. The collar was lined with silicone tape to prevent sliding and was tightened with two square nuts and a screw, while two bale clips clamped onto the collar’s appendages, providing additional stability during ignition and enabled quick and easy removal. The base and collar were printed using a 2024 Prusa MK4 3D printer, requiring 9.5 hours for the base, and another hour for the collar. Bale clips were glued and then secured to the base using screws.

Figure 3. PETG printed Hartmann Tube base, collar, and bale clips used to secure the tube.

The Ignition Source

The ignition source was contained within a 30.0 mm long and 25.4 mm diameter solid Teflon cylinder threaded into the polycarbonate tube (Figure 4). The electrode was positioned approximately 100 mm above the dust sample. Two zinc-plated steel slotted spring pins were inserted through the plug with a 0.25-ohm resistance electrode inserted into the ends of the pins. A WANPTEK DC Power Supply Variable was connected to the other end of the pins using alligator clips. The variable power unit supplied up to 40 Watts of power to the resistance electrode causing it to glow red hot and creating an ignition source. The electrodes were low-cost and easy to replace in the event they became contaminated with combustion residue.

Air Supply and Nozzle

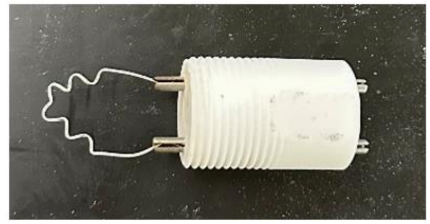

Figure 4. Teflon ignition plug with zinc plated steel spring pins inserted lengthwise and 0.25 ohm electrode attached to pins.

Air was used to disperse the dust sample with 50 mL of air introduced at 100 psi via a gas cylinder. The base was connected to a gas cylinder via clear rubber tubing, which linked to a ¼-inch (6.35mm) diameter air nozzle housed in the base. The nozzle featured 16 holes, each 1/16 inch (1.58mm) in diameter, arranged in two rows—8 at the top and 8 at the bottom. These holes were oriented downward, perpendicular to the concave walls of the dust cavity, ensuring efficient dust dispersion up the cavity walls and into the tube void. Airflow was controlled using two ball valves: one located near the pressure regulator on the air tank and another near the base of the Hartmann tube. This configuration allowed precise regulation of pressurization and air release into the tube to achieve consistent dust dispersion.

Pressure change across the tube was measured using a Vernier Go Direct Wide-Range Pressure Sensor. The sensor was inserted through a hole in the side of the polycarbonate tube and secured using a grommet. Pressure readings were recorded using Vernier's supplied software. The maximum change in pressure $\left(\frac{dP}{dt}\right)_{MAX}$ was used to calculate the K_{st} values. The pressure sensor collected samples at a rate of 80 per second.

Lid Options

We learned that to measure pressure change, the Hartmann tube required a sealed top lid. Without the lid, the Vernier pressure sensors were not sensitive enough to register pressure change. We settled on using a tractor exhaust rain cap for the lid, which provided a durable and reusable solution. Magnets (100g) were used to add weight the lid.

Dust Samples

We studied a series of non-toxic organic materials, which were chosen for their ease of use, ease of cleaning, non-toxic character, convenience and affordability, particle size, and reliable ignitability. Particle size is also a significant factor in dust ignitability with a smaller particle size generally being more explosive. Table 2 provides the particle sizes of the different materials. Samples were dried using an oven at a temperature of 60°C for 24 hours.

Table 2. Materials used in combustion studies and associated particle sizes.

Material	**Particle Size**
Cornstarch	(16 µm)
Flour	(135 µm)
Powdered Sugar	(50 µm)
Sugar Free Coffee Creamer	(99 µm)

Maintenance and Cleaning

The Hartmann tube requires thorough cleaning between runs to remove dust and combustion residue. Cleaning tools included dryer balls, Swiffer dust wipes, a test tube brush, and an organic fiber brush. Wet wipes were used sparingly and only if sufficient time was available to ensure complete drying. A dryer ball attached to a 0.5m threaded rod was used to remove particulate matter from the tube's inner surface, which would become statically charged after use. Sandpaper (120 grit and greater) was used to clean charred residue from the base and electrical connections, including spring pins, ensuring consistent electrode contact.

Laboratory Safety

Several safety hazards are present when operating the Hartmann tube including electrical shock from the power supply, burns from the electrode, accidental ignition, and smoke inhalation. We mitigate these risks by conducting all experiments in a fume hood with the sash lowered, having the ignition source be contained within the Hartmann tube, and maintaining strict adherence to documented lab safety protocols. Though the Hartmann tube and all 3D printed components have proven safe for use with low K_{st} value materials (St < 1), we strictly prohibit the use of high K_{st} materials such as metal dusts, which could melt components or generate secondary fires. We also limit the sample mass to 1 gram to similarly prevent secondary fires or explosions. Finally, we make explicit that the Hartmann tube must never be ignited outside the fume hood or near other flammable materials to prevent secondary fires, explosions, or burns.

Manufacturing Requirements and Cost

The construction and operation of the Hartmann tube require a workshop with basic tools, a 3D printer, a fume hood, a compressed air tank with a regulator, and an oven capable of maintaining 60°C for drying materials. These resources are necessary for safe and effective operation of the Hartmann tube but are not included in the cost estimate. Our primary objective was to build a Hartmann tube for under $1,000. The total cost, including all building materials and cleaning components, amounted to $629.80. A comprehensive list of all components, vendor information, part numbers (when available), and quantities, are provided in Table 5 of the Appendix.

Results and Discussion

The Design Process

Design of the Hartmann tube was iterative, with many steps taken to improve functionality and reliability. Early designs of the base featured a square structure that used hex key screws to secure the tube. We quickly learned through use of the device that this configuration was unstable and cumbersome during operation, but more importantly was time consuming to setup requiring all four screws to be tightened or removed during sample replacement, cleaning, or troubleshooting. As a laboratory experiment, we required shorter operational turnaround times to enable a larger number of experiments to be completed, and a sturdier base to account for the inexperience of the users. Other iterative design changes include the ignition source. Initial designs simply connected a heating element to opposing welding rods, which created an unreliable electrical connection. This design hindered cleaning and contributed to inconsistent ignition performance.

Development of Experimental Procedures

We wanted to use the Hartmann tube to study the explosivity of dust in an undergraduate laboratory and to do so we needed to design an experimental procedure that students would understand and could implement during a four-hour class time. The experiments should include some quantitative data collection and analysis, but also include observational data related to practical implications of dust hazards.

We developed two Hartmann tube experiments (described in Table 3) that enable students to investigate the effects of humidity and material type on the explosivity of dust. By observing these experiments, students develop a foundational understanding about why and how dust explosions occur. For a dust explosion to occur, several conditions must be present (Figure 1) and given this complexity the phenomenon is not a given. We believe that the difficulty igniting a dust cloud is just as impactful for the learner as is an explosion itself. The concept of uncertainty and whether or not a hazard might become harmful are difficult to convey in the classroom but become salient when observed in the laboratory. We believe that this captures the true value of the Hartmann tube as an educational tool.

Table 3. Summary of experiments and desired results to be implemented in a chemical engineering undergraduate laboratory course.

Experiments	Description	Desired results
Experiment 1 Dried vs Undried samples	Students measure the effects of moisture to explosivity by attempting to ignite a one dried and one un-dried sample of the same material of dust *Flour is recommended	Students observe a clear distinction between the dried and undried sample, either by the undried sample having a lower Kst, or not igniting at all.
Experiment 2 Multi-material testing	Students measure the difference between all materials by attempting to ignite each one (dried) approximately 3 times and averaging the Kst value for each material	Students obtain 4 unique average Kst values that can be compared to literature values Students observe differences in Kst values due to variable dust particle size Students observe and qualitatively assess differences in explosion characteristics for each sample (e.g., different rates of explosion, secondary explosions, etc.)

Demonstration of concept

We tested the efficacy of the Hartmann tube by combusting four different types of materials. Pressure readings from each experiment were used to calculate experimental K_{st} values that were compared to K_{st} values taken from the literature. Results of the study are presented in Table 4.

Table 4: Comparison of experimental and literature material dust deflagration index (Kst) values for preliminary study of dust materials.

Material	Literature K_{st} value (bar-m/s)	Experimental K_{st} value (bar-m/s)
Cornstarch	128-158	125
Flour	87	83
Powdered Sugar	26.18-139	128
Sugar Free Coffee Creamer	No reliable data	51

Our study confirmed that the device was able to generate K_{st} values that reflected trends in data taken from literature and reinforced the inverse relationship between particle size and explosion intensity. Qualitatively, we observed differences in the character of each type of dust explosion including differences in the rates of ignition and explosion, delays in some material igniting, effects of different dispersion profiles on ignition, and the potential for multiple ignitions (Figure 5).

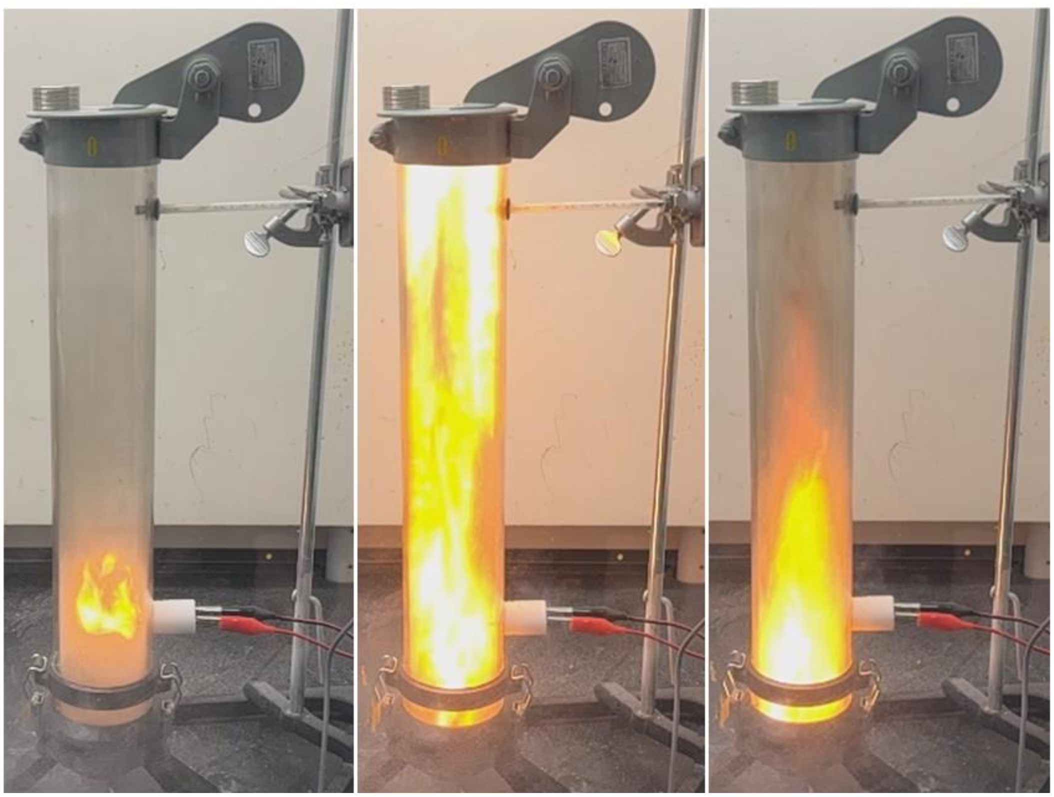

Figure 5. Experimental setup of the Hartmann tube and a montage illustrating the combustion of coffee creamer.

From this study we learned that the combustibility of dust is greatly affected by the humidity of the sample and the air. In low-humidity conditions, ignition occurred with as little as 20 watts of power, whereas high-humidity conditions (>60% RH) required upwards of 30–40 watts of energy and necessitated sample drying for consistency. Though a failed ignition can be frustrating for students, we contend that this feature of the experiment remains useful for communicating the complex and uncertain nature of solid hazards. We intend to integrate the Hartmann tube into the Chemical Engineering Laboratory I course during the Spring 2025 term.

Conclusion

In conclusion, we successfully developed and built a low-cost, user-friendly Hartmann tube capable of providing reliable semi-quantitative data for investigating dust explosions. The hands-on nature of this device offers students a unique and memorable experience in understanding the hazards associated with commonly used non-toxic dust materials. The device consistently delivers meaningful data to support experimentation in engineering laboratories while empowering students to actively engage with critical process safety concepts, such as hazard mitigation and risk assessment. We believe that the Hartmann tube provides students that rare opportunity to engage with, study, and observe a hazardous event, thus enhancing their understanding of and commitment to process safety in engineering contexts.

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Appendix

Table 5. Summary of specific parts and associated costs for all elements of the Hartmann tube.

Items for the Hartmann tube	Vendor	Part #	Unit Price	Quantity	Price per Quantity
General Purpose Polycarbonate Tubes ID:2-3/4", OD: 3", 2'	Grainger	55PF84	$50.24	18”	$37.68
PETG filament	Amazon		$14.99		$3.00
Items for Air Supply					
Manual Two-Way Ball Valve: 1/4 in	Grainger	56DK23	$ 19.92	2	$39.90
PARKER Tubing: MicroWeld, Polyether Polyurethane, ID 1/8 in, OD 1/4 in, 25 ft Lg, Black	Grainger	819V89	$ 126.73	25 ft	
Items for Ignition Source					
Zinc-Plated 1050-1095 Steel Slotted Spring Pins 1/8" Diameter, 2" Long (pack of 100)	McMaster-Carr	90692A705	$ 26.59	2 pins	$0.53
WANPTEK DC Power Supply Variable	Amazon	N/A	$ 69.99	1	
Hot Heating Wire - Versatile Resistance Wire-Coil 316L 28x2+38ga	Amazon	N/A	$ 20.99	1 pack	
Plastic Rod: 1 ft 1” diameter	Grainger	30GC03	$ 64.01	3”	$16.00
Items for Pressure Reading and Lids					
Vernier Go Direct Wide-Range Pressure Sensor	Vernier	GDX-WRP	$ 219.00	1	
70409 Double Loop Quick Release Hose Clamp, 3 Inch, 2 PK	Power Tech Products	843441131939	$ 11.68	1	$5.84

3-1/16 in. Steel Rain Cap for 3 in. to 3-1/16 in. Pipes	Tractor Supply Co	SKU: 23538899	$ 12.99	1	
LOVIMAG Strong Neodymium Disc Magnets with Double-Sided Adhesive Powerful Rare Earth Magnets - 1.26 inch x 0.08 inch - Pack of 20	Amazon	N/A	$ 16.99	10	$8.50
pre-cut tin foil squares	Product Club	AL-66-50	$ 11.95	1 pack. Resupply as needed	
Grommet: Rubber, 0.19 in Inside Dia, 0.5 in Outside Dia	Grainger	3MRT7	$17.54	1	$0.18
Items for Collar					
M4 hex cap Screw 35 mm	Amazon		$7.96	1	$0.63
M4x7mmx2mm Square nut	Amazon		$8.99	2	$0.45
HJ Garden 4pcs Spring Loaded Toggle Latch Hasp,304 Stainless Steel Box Cabinet Latch Catch Locks Hasps 73mm/2.88 in	Amazon	N/A	$ 9.58	2	$4.79
Items for Cleaning	**Vendor**		**Unit Price**		**Qty**
Wool Dryer Balls	Amazon	N/A	$ 6.99	1 pack of 6. Resupply as needed	
Swiffer Dry Cloths	Amazon	N/A	$ 14.10	1 box. Resupply as needed	
Test Tube Cleaning Bristle Brush	North Spore	N/A	$5.50	1	
Natural Bristle Flat Trim Brush	Lowes	285872	$14.74	1	
3ft Threaded Rod	Lowes	215915	$ 3.48	1	
Gator Red Resin Multi-Surface Clamp-on 1/4	Walmart	N/A	$ 5.84	1	

Sanding Sheets Assorted Grit					
		Purchase quantity total	$760.79	**Total**	$629.80

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