2017

Development of a Medium Scale Apparatus for Testing & Teaching Dispersed Dust Flame Effects

David Petrow

Eastern Kentucky University

Development of a Medium Scale Apparatus for Testing & Teaching Dispersed Dust Flame Effects

By

David J. Petrow

Thesis Approved:

Chair, Advisory Committee

Member, Advisory Committee

Member, Advisory Committee

Dean, Graduate School

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a Master of Science Degree in Safety, Security & Emergency Management at Eastern Kentucky University, I agree that the Library shall make it available to borrowers under rules of the Library. Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of the source is made.

Permission for extensive quotation from or reproduction of this thesis may be granted by my major professor, or in [his/her] absence, by the Head of Interlibrary Services when, in the opinion of either, the proposed use of the material is for scholarly purposes. Any copying or use of the material in this thesis for financial gain shall not be allowed without my written permission.

Signature ______________________

Date 3-30-17

Development of a Medium Scale Apparatus for Testing & Teaching
Dispersed Dust Flame Effects

By

David J. Petrow

Bachelor of Science
Eastern Kentucky University
Richmond, Kentucky
2012

Submitted to the faculty of the Graduate School
Eastern Kentucky University
in partial fulfillment of the requirements
for the degree of
Master of Science
May 2017

DEDICATION

This thesis is dedicated to my parents,
Kevin and Dawn,
and wife Sharla,
without their patience, love and support this would not have been possible.

ACKNOWLEDGEMENTS

I would like to express extreme gratitude to my thesis committee: Dr. Scott Rockwell, my committee chair; Dr. Scotty Dunlap; and Dr. Thomas Schneid.

I would also like to thank Corey Hanks, former Lab Coordinator and current Lecturer in the Fire Program at EKU. Serving as your Graduate Assistant during my tenure as a student in the Safety, Security, & Emergency Management program has been one of the best learning experiences I've had so far. I would like to thank you for your patience and guidance, without which this would have stayed just an idea.

Finally, I would like to thank Adam Coomes and Eric Curran for the long hours they sent helping to construct the apparatus that made this research possible.

ABSTRACT

Combustible dust explosions and flash fires are a leading cause of property damage, injuries, and death in industries around the world. An example of a disastrous dust explosion occurred at CTA Acoustics in Corbin, KY in 2003. This explosion cost the lives of seven workers and injured 37 more. A mobile inexpensive dust dispersion apparatus (DDA) was designed, built, and tested to reproduce medium scale dust flash fires. By using fuel amounts varying from 0.45kg to 4.54kg the DDA created dust clouds ranging from 2.5m to 7.5m in diameter. With these measurements, the characterization of dust hazards and validation of computer models is made possible. In addition to working as a testing platform, the DDA can be used to teach students and safety professionals about the dangers of combustible dusts.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

Dust explosions pose an often misunderstood and serious threat to a large portion of the manufacturing industries. Dust explosions, along with vapor cloud explosions (VCE) and boiling liquid expanding vapor explosions (BLEVE), are the most common explosion hazard in manufacturing today. When dust explosions do occur they often cause life threatening injuries and/or death to employees in addition to the serious financial losses for the company due to facility damage and down time loss (Joseph, 2007). There are a wide variety of industries that work with or create dusts in their manufacturing processes and many would not be viewed as hazardous without education and training in dust explosions. The US Chemical Safety and Hazard Investigation Board (CSB) identified 281 separate combustible dust incidents that injured 718 and killed 119 across 44 states between 1980 and 2005. Table 1 identifies some recent incidents involving combustible dust (CSB, 2017). A few common industries at risk are: agriculture, chemical processing, candy manufacturing, sugar refining, flour mills, grain elevators, tobacco processing, fertilizer, wood, plastic manufacturing, pharmaceuticals, textiles, tire manufacturing, coal mines, and industries that process metals such as aluminum, magnesium. or iron to name but few.

Table 1: Selected Industrial Dust Explosions

Year	Description	Location	Type of Dust	Fatalities	Injuries
2003	Hayes Lemmerz	Huntington, IN	Aluminum	1	2

Table 1: (continued)

Year	Description	Location	Type of Dust	Fatalities	Injuries
2003	CTA Acoustics	Corbin, KY	Resin	7	0
2009	Imperial Sugar Company	Port Wentworth, GA	Sugar	14	38
2010	AL Solutions, Inc.	New Cumberland, WV	Zirconium	3	1
2011	Hoeganaes Corp. (3 incidents)	Gallatin, TN	Iron	5	3
2012	US Ink/Sun Chemical Corp.	New Jersey, NJ	Ink	0	7

Source: CSB, U. Completed Investigations. Retrieved 2017. Available from: http://www.csb.gov/investigations/.

Researching dust flash fires and explosions is typically a difficult and expensive process. While there are several methods and testing apparatuses to study dust flash fires on a smaller scale it becomes exponentially more difficult and expensive to when the experiment moves to the medium and large scale. Results from various testing apparatus will vary due to the differing experimental procedures and parameters. This lack of uniformity between testing apparatuses makes comparing results difficult if not impossible unless a correlative study using the same dust sample has been performed (Cote, Grant, Hall, & Solomon, 2008). Due to the high cost of many of these apparatuses there is a need for a cost-efficient testing device such as the Dust Dispersion Apparatus (DDA).

In addition to working as a combustible dust research platform the DDA is also an excellent tool to educate and train people on the dangers presented by combustible dusts. The National Fire Protection Association (NFPA) recently published their first comprehensive *Standard on the Fundamentals of Combustible Dust,* NFPA 652, in 2016. While NFPA has recognized combustible dusts as a hazard as far back as the 1920's, NFPA 652 is the first standard that covers the fundamentals of combustible dust hazards and ensures that safeguards are met across all types of industry (National Fire Protection Association, 2016). Before this standard came into effect, NFPA produced several successful industry specific standards on the hazards associated with combustible dusts. A few of the more prominent standards are: NFPA 61, *Standard for the Prevention of Fires and Dust Explosions in Agricultural and Food Processing Facilities*; NFPA 484, *Standard for Combustible Metals*; and NFPA 654, *Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids*. NFPA 68, the *Standard on Explosion Protection by Deflagration Venting* covers the use, design, location, installation, and maintenance of devices that are used to vent pressure and the combustion gases that occur because of a deflagration. In this standard, values such as, minimum ignition temperature, dust concentration, maximum rate of pressure rise, and minimum ignition energy are used to design devices that protect enclosed structures from deflagrations, including dust explosions. With NFPA 652 a greater number of industries than these previous standards, the number of individuals who need to be educated and trained will also increase. The DDA can serve as an effective training tool to mimic combustible dust hazards in various industrial settings.

Through proper training and education, the hazards of combustible dusts will become better understood and hopefully this will lead to a reduction in the number of injuries and deaths caused as a result.

Chapter 2

Literature Review

Dust explosions occur when combustible particles become suspended in air and experience accelerated combustion after being exposed to an ignition source. As of 2006, more than 70% of dusts created in industry are considered combustible (Abbasi, 2007). The National Fire Protection Association (NFPA) defines a combustible dust as: A finely divided combustible particulate solid that presents a flash fire hazard or explosion hazard when suspended in air or the process-specific oxidizing medium over a range of concentrations (National Fire Protection Association, 2013). Many materials that are not commonly thought of as combustible in larger solid states can fuel a dust explosion when the particle is small enough. For example; corn, sugar, and wheat are not ordinarily thought of as combustible materials but when they are ground fine enough to be considered a dust they can have explosive results in the proper conditions. To be considered a dust a material must have a particle size smaller than 0.017 inches (Cote, Grant, Hall, & Solomon, 2008). Other common combustible dusts include: aluminum, magnesium, coal, non-fire retardant polyurethane foam, rice, titanium, polyvinyl chloride (PVC), synthetic rubber, and a whole host of others which can be seen on Table 2 (Cote, Grant, Hall, & Solomon, 2008). Given the wide variety of materials that can fuel dust explosions it can be expected that there are a great number of industries at risk.

Table 2: Selected List of Combustible Dusts

Material	Classification	Particle Size (m)	Min. Concentration for Ignition or C_{min} in 1 m^3 vessel (g/m^3)	K_{st} (BAR m/sec)
Aluminum Powder	Metal	<10	60	515
Ascorbic Acid	Pharmaceutical	39	60	111
Asphalt	Coal Product	29	15	117
Bituminous Coal	Coal	<10	60	55
Bronze Powder	Metal	18	750	31
Charcoal	Coal Product	19	60	117
Corn Starch	Food Product	16	60	158
Cotton	Cotton	44	100*	151
Epoxy Resin	Resin	26	30	129
Lycopodium	Organic Product	30	-	179
Magnesium	Metal	28	30	508
Milk Sugar	Food Product	27	60	82
Paper Dust	Wood	<10	-	18
Phenol Resin	Resin	<10	15	129

Table 2: (continued)

Material	Classification	Particle Size (m)	Min. Concentration for Ignition or C_{min} in 1 m^3 vessel (g/m^3)	K_{st} (BAR m/sec)
Polypropylene	Plastic	25	30*	101

* C_{min} data from Hartmann Tube

Source: Cote, A., Grant, C., Hall, J., & Solomon, R. (Eds.). (2008). Fire Protection Handbook Volume I & II (Twentieth). Quincy, Massachusetts: National Fire Protection Association.

For a dust explosion to occur there are very specific requirements and conditions that must be met as well as many factors that can impact the intensity of the explosion. The three basic elements that must be present for any particle flash fire appear on the fire triangle shown in Figure 1 fuel, oxygen, and heat or an ignition source (Cote, Grant, Hall, & Solomon, 2008). The fuel is simply the combustible dust that has been thrown into suspension. When the fuel is suspended in the air it mixes with the oxygen in the environment and creates the ideal fuel to air mixture that is necessary for ignition. The third element of the fire triangle that is necessary for a dust explosion to occur is an ignition source (Cashdollar, 2000).

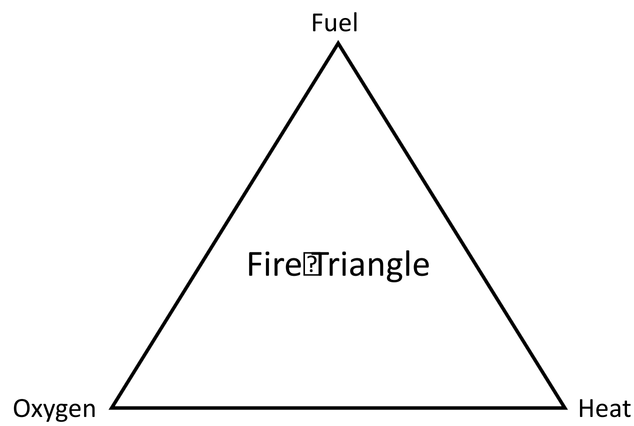


Figure 1: Fire Triangle

There are a wide variety of ignition sources in a manufacturing facility that could ignite a dust explosion. Manufacturers will often focus on eliminating all ignition sources in their hazard area to mitigate the possibility of a dust explosion but there are some factors that may be difficult if not impossible for them to control. The most obvious type of ignition source and easiest to remove from a facility is an open flame. An open flame could occur in a facility due to an employee lighting a cigarette, a pilot light, or using stoves or open flames to heat materials. Another common ignition source in manufacturing industries is hot work. Hot work is considered any operation such as cutting, grinding, or welding that produces heat and sparks. The hazard area must be thoroughly cleaned of any dust accumulation before any hot work can be done in the area. Hot surfaces such as electric lamps, machinery, and moving equipment are also possible methods of ignition. These surfaces need to be continuously monitored and cleared of accumulation to ensure that they do not become ignition hazards, particularly when surrounded by dusts with a low flashpoint. Electrical equipment that can discharge electrostatic sparks need to be kept out of the hazard area. Electrical sparks and electrostatic sparks are also potential ignition hazards. These sparks can happen in the normal operation of switches and relays or in electrical equipment that is malfunctioning. Electrostatic sparks transpire most frequently in malfunctioning electrical equipment as well as the normal operation of relays and switches. One of the most difficult ignition sources to protect against is the buildup of static electricity. Static electricity can ignite a dust cloud when the static charge turns into a spark. This occurs when an item moves rapidly into and out of the static field (Abbasi, 2007; Zalosh, 2011).

There are several dusts that can ignite spontaneously in the right circumstances, this is known as self-heating. Self-heating can result from various types of chemical reactions such as an exothermic reaction, oxidation reaction, or the reaction of a dust with another substance. These reactions can turn explosive when the smoldering self-heating dust is introduced into a screen or hopper and become suspended in air (Abassi, 2007; Cote et al, 2008; Zalosh, 2011). A fire has three requirements for ignition but a dust explosion has five requirements. In addition to fuel, heat, and oxygen; a dust explosion also need dispersion and confinement to ignite. Figure 2 shows the Dust Explosion Tetrahedron.

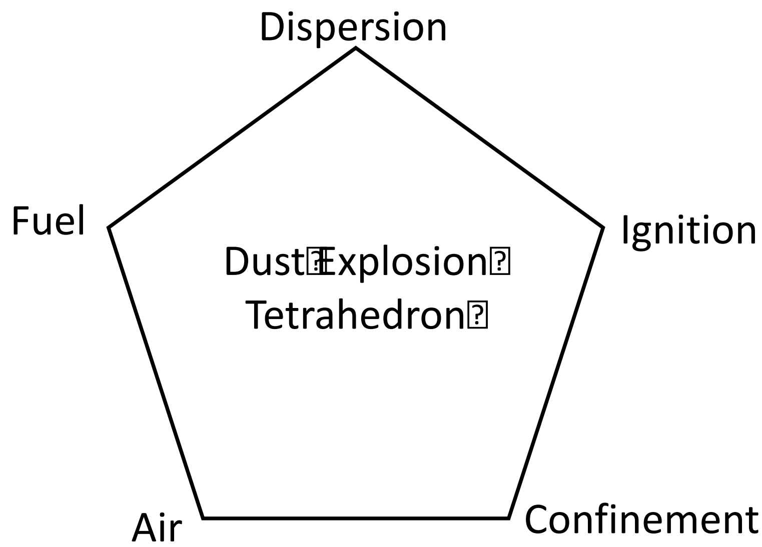


Figure 2: Dust Explosion Tetrahedron

There are many factors of the combustible dust that greatly influences its explosibility. The size of a dust particle is one of the first factors to consider when evaluating combustible dust hazards. During the combustion process, smaller particles are more apt to react quickly and efficiently compared to larger particles of the same material. This is a result of the smaller particles having a greater surface area per mass as well as their ease of dispersal in air (Abbasi, 2007).

The maximum rate of pressure rise is an important property when discussing to the explosibility of dust particles. The rate of pressure rise is the maximum change in pressure in time during the flame propagation of a dust explosion in a spherical vessel. If a substance has a drastic change in pressure in a very short amount of time then it would be considered more explosive and dangerous than a substance that has a small change in pressure in the same amount of time. This maximum rate of pressure rise value is defined as K_{st}

(Abbasi, 2007; Cashdollar, 2000; Cote et al, 2008; National Fire Protection Association, 2013).

While the three main requirements for a dust flash fire are oxygen, fuel, and heat there are many environmental factors that can influence the severity. The presence of a primary and secondary explosion will usually mean for a more severe dust explosion. Through the “domino effect” the primary explosion can then trigger a much larger secondary explosion. The primary dust explosion is a smaller explosion that generally occurs inside a piece of equipment such as a mill, screen, hopper, silo, transit system, or bucket elevator. The larger secondary explosion occurs when settled dust in the area is disturbed by the primary explosion and then suspended in air (Abbasi, 2007; Zalosh, 2011).

The concentration of the dust also influences the severity of a dust flash fire. If there is too little fuel in the dust cloud then it will fail to ignite, the same can also be said if there is too much fuel suspended in the cloud. Like gases, there is a range of concentration where ignition is possible. This range is defined by the lower explosive limit (LEL) and the upper explosive limit (UEL) (Cote, Grant, Hall, & Solomon, 2008).

Along with needing the proper mixture of fuel a dust flash fire also needs the proper amount of oxygen or air. An oxygen concentration of less than 21% will reduce the burning velocity of the dust while a concentration greater than 21% will increase the burning velocity. Without enough oxygen, the rate of combustion is reduced and reduce the severity of the explosion (Abbasi, 2007).

One of the most important circumstances influencing the destructiveness of particulate flash fires is confinement. During a dust flash fire gases and heat are released. As these gases expand when heated the pressures they produce is applied to the surrounding area. If the dust flash fire is in an enclosed space these pressures can reach dangerous levels unless proper ventilation is provided (Cote, Grant, Hall, & Solomon, 2008).

The presence of moisture in the dust can affect how the particles react to an ignition source. Dust particles containing moisture will have a higher ignition temperature than its dry counterpart. This is because the moisture will absorb heat away from the dust during the heating and vaporization process (Cote, Grant, Hall, & Solomon, 2008).

Turbulent mixing of the dust particles increases the danger of dust explosions. An extremely turbulent cloud will yield evenly distributed dust particles throughout. In addition, the turbulence will create a mixing effect and blend the cold unburnt sections with the hot burning sections of the cloud. This will cause the flame to propagate extremely quickly though the dust cloud (Abbasi, 2007; Cote et al, 2008).

The presence of a flammable gas in the dust cloud can increase the explosibility of the dust. With a flammable gas such as propane or methane present the minimum ignition temperature and minimum explosive concentration are decreased. This means that a dust cloud that would ordinarily be below the lower explosive limit would have the potential to ignite. Flammable gases could also make a large dust particle size that is not normally explosive more likely to ignite. The maximum rate of pressure rise of a dust particle is also increased in the presence of flammable gasses (Abbasi, 2007; Cote et al, 2008).

There are currently a variety of devices used to test combustible dusts on the small to medium scale. The Hartmann Tube and Spherical Explosion Vessels are two of the most common testing apparatuses but, they both have their unique pros and cons. The main issue with having several different testing apparatuses is the difficulty in comparing results between them. The lack of homogeneity between the testing procedures in each apparatus rules out any comparison unless an extensive correlative study is performed (Cote, Grant, Hall, & Solomon, 2008).

One of the apparatuses with the greatest amount of data collected so far is the Hartmann Tube. The Hartmann Tube is a vertical tube that can disperse dust by means of an air blast with a spark or hot wire serving as the igniter. While this apparatus was one of the first combustible dust test apparatuses and was used extensively by the U.S. Bureau of Mines it has many drawbacks. The Hartmann tube and its horizontal variants produce less than ideal conditions for studying combustible dusts. With this device, it is very difficult to produce consistent conditions for turbulence and dust dispersion. The walls of the tube also posed a significant problem after ignition. Once the flame goes through the beginning spherical expansion it then travels along the walls of the tube, which produces incorrect pressure rise and combustion rate data. This limitation makes tubular test apparatuses unsuitable for the design of explosion venting (Abbasi, 2007; Cote et al, 2008).

One of the most widely used dust explosion test apparatuses is the Spherical Explosion Vessel. The Spherical Explosion Vessel is a resilient spherical vessel that creates a dust explosion by sending dust into the apparatus by way of compressed air. Once the dust is in suspension it is ignited using a detonator or ignition device. There are several spherical apparatuses of various sized used to allow for the scaling of dust explosions. The most commonly used size is the 20-liter sphere, which has become an industry standard, and the $1m^3$ sphere (Cashdollar,1992). Many of the shortcomings of the tube apparatuses are overcome by using a spherical vessel. In an explosion sphere the flame can propagate in its natural spherical direction, which means it can better simulate a naturally occurring dust explosion and be used in the design of explosion venting (Abbasi, 2007; Cote et al, 2008). One of the drawbacks of the explosion spheres is the inability to control the turbulence as an independent variable. While the spheres are well received in industry and are efficient in studying combustible dusts they lack the ability to work as an effective visual training tool.

Chapter 3

Experimental Apparatus Construction and Procedure

The Dust Dispersion Apparatus was designed and built with mobility, cost, and ease of use in mind. Figure 3 shows an overview of the design. The base of the apparatus was constructed by connecting a standard 48”x40” pallet with a second pallet that was reduced in size to conserve weight. The two pallets were joined by using 2”x4” wooden studs and bolts. A ½” thick water resistant plywood was screwed to the pallets to create a flat working surface. Pallets were chosen as the base due to their ease of procurement, large size, and the added mobility of the apparatus using a forklift.

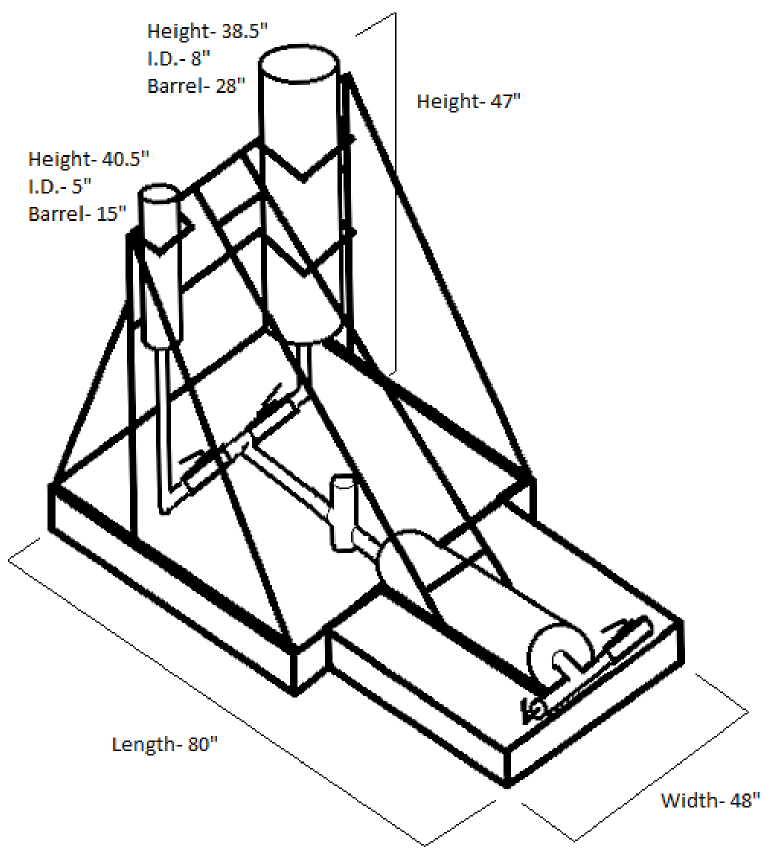


Figure 3: Dust Dispersion Apparatus Design

The frame used to attach the launch barrels to the pallets is made from 1.5" steel angle iron and 1" square steel tubing. An "A frame" design was chosen to eliminate the possibility of vertical and horizontal movement during operation. The frame is welded together using a Miller 180 MIG welder.

The DDA was designed to accommodate two different sized launch barrels constructed from two repurposed fire extinguishers. A larger barrel measuring 8" x 28" with an internal volume of 1408 in^3 was fitted to demonstrate a larger dust cloud. The smaller barrel, measuring 5" x 15" with a volume of 577.5 in^3, is used to produce a smaller diameter dust cloud when filling the larger barrel might be cost prohibitive. The barrels are connected to a fill tank, also constructed from an 8" repurposed fire extinguisher, using 2" schedule 40 steel piping. Two 2" high pressure ball valves are used to direct the air flow to the desired barrel. This ensures that the air is released out of only one barrel at a time when testing.

On the opposite end of the fill tank from the barrels is a pressure gauge, air compressor quick connection, and another 3" high pressure ball valve. The pressure gauge and quick connection allow the user to precisely fill the tank to a desired PSI and this high-pressure ball valve acts as a manual release for the fill tank in the event of an emergency or malfunction. Air is released from the fill tank using a 2" high-pressure, fast-opening electronic solenoid valve. The valve chosen is a bronze Magnatrol Valve rated to 500psi which gives the DDA a high-pressure capability. Manufacturer tests performed in the mid 1990's indicate that this particular valve should open on the order of milliseconds, which is more than adequate for use in the DDA.

The DDA is remotely operated by way of a “push button” switch connected to the solenoid valve via wires. The remote activation is essential to ensure that there is no danger to any of the test team members.

A propane ignition device consisting of a frame, torch, fuel lines, and tank is utilized to ignite the dust cloud when it has reached the proper fuel-air mixture. Figure 4 shows a diagram of the ignition device. The frame should be set several feet above the test barrels on the DDA. An adequate length of fuel lines should be used to ensure that the propane tank is not exposed to any flames or radiant heat. Placing the fuel tank out of the Hot Zone, seen in Appendix 2, also allows the test team members to remotely shutoff the torch should they see a need to.

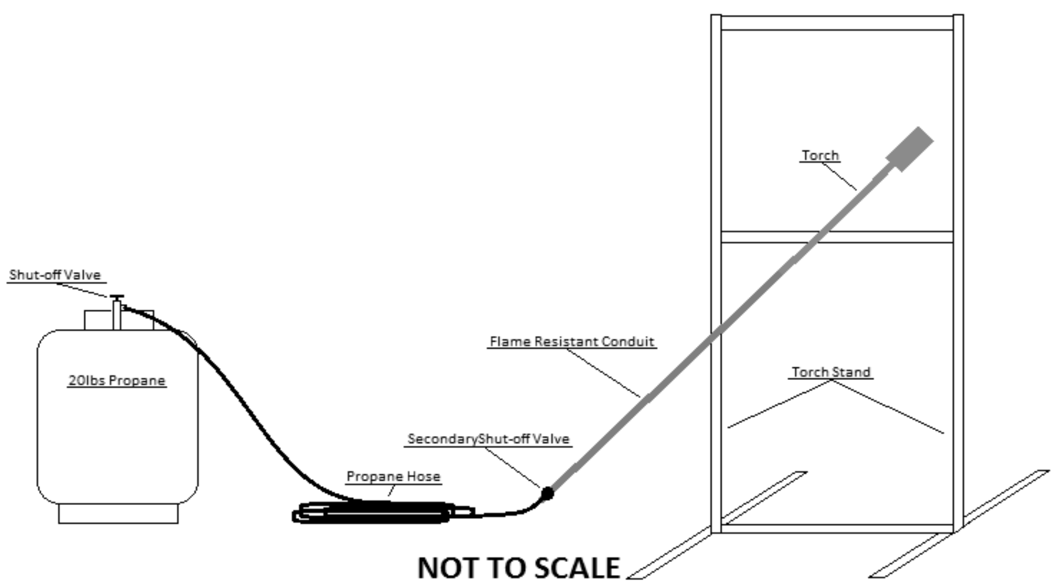


Figure 4: Propane Ignition Device

A user's manual and test procedure was created for the Dust Dispersion Apparatus. This section is included in Appendix E. In addition to the test procedure a Safety Standard Operating Procedure, included in Appendix B was created. These documents must be followed to ensure the safety of all test team members while the DDA is in operation. Failure to follow these procedures may result in serious injury or death. The DDA is inherently a dangerous testing apparatus and accidents may still occur even with proper use. If at any time, environmental conditions change, the DDA malfunctions, or you feel troubled immediately stop the tests and revaluate before deciding to continue.

Chapter 4

Results and Discussion

Testing on the DDA was completed using various weights of confectionary sugar and wood meal released at 100psi. 100psi was chosen for the initial tests to create an adequate baseline without nearing the 500psi limit of the DDA. The electric solenoid valve opened in approximately 66 milliseconds and was set to stay open rather than immediately shut. This would ensure all air in the storage tank would be released. The duration of each fire ball was measured by utilizing a high-speed video camera recording at 300 frames per second. To define the size and length of each fire ball an average maximum height and width was created for each test. A characteristic length was determined by averaging the maximum width and height of the fire ball for each test performed. Table 3 shows the results of the tests for woodmeal and sugar. The characteristic length for the woodmeal ranged from 3.7m/m to 6.9 m/m with a duration of 0.4s to 2.8s. In comparison, the sugar had a characteristic length of only 2.6m/m to 5.5m/m with a duration of 0.4s to 1.1s. These data indicate that as the mass of the dust fuel is increased the size and duration of the fire ball will also increase. Wood meal has a larger width, height, characteristic length, and duration than sugar at equivalent weights. Figure 5 shows an example of two identical tests with the only difference being the presence of an ignition device. (A) shows the release of 4.55 kg of woodmeal at 100 psi without ignition and (B) shows the release of the same mass of woodmeal at 100 psi with ignition.

Table 3: Flashfire Testing Results

Tube	Fuel type	Mass (kg)	Max Width (m)	Max Height (m)	Characteristic length	Duration (s)
Small	Woodmeal	0.450	3.2	4.1	3.7	0.4
	Woodmeal	0.680	3.0	4.9	4.0	0.8
	Woodmeal	0.910	3.1	5.1	4.1	0.9
	Sugar	0.680	2.6	2.7	2.6	0.4
	Sugar	1.36	2.9	4.6	3.8	0.4
	Sugar	1.82	3.2	5.3	4.2	0.5
Large	Woodmeal	2.27	3.4	7.5	5.5	1.4
	Sugar	2.27	2.6	4.6	3.6	0.9

Table 3: (continued)

Tube	Fuel type	Mass (kg)	Max Width (m)	Max Height (m)	Characteristic length
Woodmeal	4.55	6.1	7.2	6.7	2.8
Woodmeal	4.55	6.3	7.5	6.9	2.1
Sugar	4.55	3.6	7.4	5.5	1.1

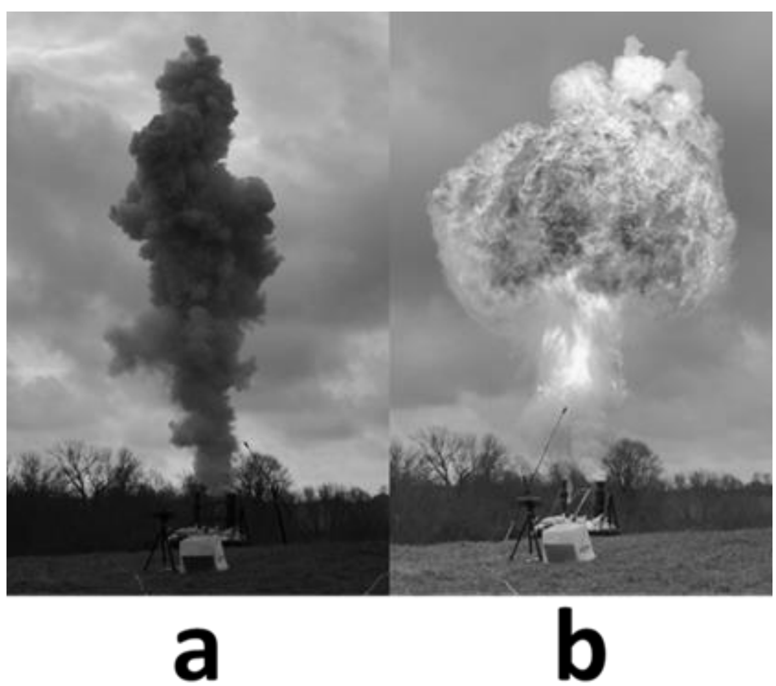


Figure 5: Test using 4.55kg of Woodmeal.

a: Dust Cloud with no ignition.

b: Ignition of dust cloud with the propane ignition system

One of the greatest drawbacks of the DDA are the rigid vertical barrels. Future variations of the DDA should include adjustable pipes so the barrel angle can be adjusted. This would be useful for studying dust deflagrations inside a compartment where the dust is not released vertically. Adjustable barrels could be used to direct the release of the dust cloud when wind conditions are unfavorable during outdoor tests.

Chapter 5

Conclusion

The DDA has much wider possibilities than the data in this paper indicate. In addition to studying various dusts at different weights and releasing them at different psi's the capabilities of the DDA can be increased with some minor modifications. By adding deflectors, like those found on a fire protection sprinkler head, above the barrels on the DDA various cloud shapes and sizes could be studied. The deflector would change the angle at which the dust exits each barrel and result in different cloud shapes. The DDA can also be adjusted to simulate various industrial settings. By adding pipes, hoppers, screens, or silos the DDA can easily reproduce any number of industrial processes.

The greatest use for the DDA is its use as an inexpensive training and education tool for students and professionals alike. There are many classes here at Eastern Kentucky University in the Occupational Safety & Health bachelors program and Safety, Security, & Emergency Management graduate program that could benefit from using the DDA as an educational platform. While all future safety professionals would benefit from learning the hazards of dust explosions first hand in a safe environment the classes that would benefit the most are SSE 826 Emergency Prep/Response, SSE 828 Industrial Safety Management, and SSE 845 Personal/Environmental Hazards.

With the implementation of NFPA 652, many more industries will now be required to protect against the dangers of combustible dusts than ever before. The DDA will help safety professionals and employees understand the dangers combustible dusts present and the importance of the prevention techniques they are now required to follow.

References

Abbasi, T., & Abbasi, S. A. (2007). Dust explosions–Cases, causes, consequences, and control. *Journal of Hazardous Materials*, *140*(1–2), 7–44. https://doi.org/10.1016/j.jhazmat.2006.11.007

Average Weather for Lexington Kentucky. (n.d.). Retrieved from https://weatherspark.com/averages/30718Lexington-Kentucky-United-States

Blair, A. S. (2007). Dust explosion incidents and regulations in the United States. *Journal of Loss Prevention in the Process Industries*, *20*(4–6), 523–529. https://doi.org/10.1016/j.jlp.2007.03.012

Cashdollar, K. L. (2000). Cashdollar_Overview of dust explosibility characteristics.pdf. *Journal of Loss Prevention in the Process Industries*, *13*(3–5), 183–199.

Cashdollar, K. L., Weiss, E. S., Greninger, N. B., & Chatrathi, K. (1992). Laboratory and large-scale dust explosion research. *Process Safety Progress*, *11*(4), 247–255.

Cote, A., Grant, C., Hall, J., & Solomon, R. (Eds.). (2008). *Fire Protection Handbook Volume I & II* (Twentieth). Quincy, Massachusetts: National Fire Protection Association.

CSB. (2006). Combustible Dust Hazard Study. Retrieved from https://pdfs.semanticscholar.org/84a1/aa0d0cc149c8b1f245de1dee421b5dd00c76.pdf

CSB, U. Completed Investigations. Retrieved 2017. Available from: http://www.csb.gov/investigations/.

Emergency Action Plan, Richmond Campus (2015), Eastern Kentucky University. Created: August 3, 2009. Revised: September 1, 2015.

Joseph, G. (2007). Combustible dusts: A serious industrial hazard. *Journal of Hazardous Materials*, *142*(3), 589–591. https://doi.org/10.1016/j.jhazmat.2006.06.127

National Fire Protection Association, & Explosion Protection Systems. (2013). *NFPA 68: standard on explosion protection by deflagration venting.*

National Fire Protection Association. (2016). *NFPA 652: Standard on the fundamentals of combustible dust*.

National Fire Protection Association. (2012), NFPA 1403: *Standard Live Fire Training Evolutions.*

National Fire Protection Association. (2012), NFPA 1971: *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting.*

Zalosh, R. (2011). Dust explosion fundamentals: Ignition criteria and pressure development. *Wellesley, ME*. Retrieved from https://set3.com/wp-content/uploads/2016/03/dust_explosion_fundamentals_ignition_criteria_and_pressure_d -1.pdf

Appendix A:

Maximum Diameter Test Images

Test 01- 1lb. Woodmeal

Test 02- 1.5 lbs. Woodmeal

Test 03- 2 lb. Woodmeal

Test 04- 1.5 lbs. Sugar

Test 05- 3 lbs. Sugar

Test 06- 4 lbs. Sugar

Test 07- 5 lbs. Woodmeal

Test 08- 8 lbs. Woodmeal, No Ignition

Test 09- 5 lbs. Sugar

Test 10- Dry Fire Ignition

Test 11- 10 lbs. Woodmeal

Test 12- 10 lbs. Woodmeal

Test 13- 10 lbs. Sugar

Appendix B:

Dust Dispersion Apparatus Safety SOP

PURPOSE: The purpose of this safety procedure exists to ensure proper safety measures are utilized during operation of the full scale condense phase flash fire experiment.

SCOPE: This procedure shall apply to all approved personnel assisting with the experiment. Failure to comply in accordance with this SOP in a manner not consistent with this procedure may result in dismissal from operations.

- The following requirements are national standards that shall be complied with:

- ❖ NFPA 1403 provides minimum requirements for conducting live fire training to ensure they are conducted in safe facilities and a safe manner for participants. (NFPA 1403)

- ❖ NFPA 1971 protects firefighting personnel by establishing minimum levels of protection from thermal, physical, environmental, and blood borne pathogen hazards encountered during structural and proximity firefighting operations. (NFPA 1971)

COMMUNICATION: All personnel participating in the experiment shall be provided a radio and required to use plain text to comply with federal regulations and to ensure clear communications and interoperability between users.

RADIO CHANNELS: All personnel participating in the experiment shall be provided a radio and required to use plain text to ensure clear communications and interoperability between users.

RESPONSE PERSONNEL: The personnel required for operations shall be no less than specified:

- 1 Person to serve as Test Coordinator (TC)
- 1 Person to serve as Safety Officer
- 2 Person(s) to prepare dust dispersion apparatus, ignite torch, prepare data acquisition, instrumentation, and cameras (Experiment Technician)
- 1 Person(s) to monitor readings from research equipment
- 2 Person(s) on standby to assist with flame suppression efforts
- 1 Person on standby to operate fire pump apparatus (Engine 5 Operator)

NOTE: All personnel shall be qualified individuals approved by the FSE Lab Coordinator.

POSITION DUTIES & REQUIRMENT CHART:

Position	**Job Description**	**Required PPE**	**Certification Requirements**
Test Coordinator	Has overall command of the experiment site	N/A	N/A
Safety Officer	Oversees safety of the experiment site	Full turnout gear & SCBA	Firefighter 150, SCBA Certified
DAQ Team	Oversees Data Acquisition Equipment	N/A	N/A
Experiment Tech.	Readies Dust Dispersion Apparatus and Propane Ignition Device	Full turnout gear & SCBA	SCBA Certified
Pump Operator	Oversees Operation of Engine 5	N/A	Firefighter 150
Firefighter	Ready hose lines and respond to any ignition of surrounding material	Full turnout gear & SCBA	Firefighter 150, SCBA Certified

PERSONAL PROTECTIVE EQUIPMENT: All personnel shall be required to wear proper personal protective equipment in accordance with NFPA 1971 guidelines to ensure protection from thermal exposure during experiment operations.

- The Safety Officer shall be required to be in full turn out PPE and SCBA equipment during the experiment.
- All suppression crew shall be required to be in full turn out PPE and SCBA equipment during the experiment.
- All personnel taking shelter in the research trailer shall be required to be in full turn out PPE and SCBA equipment during the experiment.
- All other bystanders and observers shall be required to stand 200 feet away from experiment in approved designated observation area in the COLD ZONE.

EMERGENCY TRANSMISSIONS: Any personnel in distress shall be identified by the standard “MAYDAY” format. Any other emergency transmission shall be identified as ‘Emergency Traffic.’ The Test Coordinator shall then acknowledge the message and respond accordingly.

WEATHER RELATED SHUT DOWN: In the event of an undesirable forecast or damaging weather, notably strong wind gusts, the Test Coordinator shall signal for termination of operations by utilizing the air horn from the Engine. The Test Coordinator shall utilize the emergency shut down procedure if the experiment is already being conducted. FIGURE 5 in the appendices shows the average wind speeds for the Lexington, Kentucky area (WeatherSpark.com). APPENDIX B is an ALOHA Software model that shows the effects of a 10 mile per hour wind on a 5 lbs. propane fuel fireball. Propane was used as an equivalent substitute for organic combustible powders.

EMERGENCY SHUT DOWN PROCEDURE: In the event of an emergency, Test Coordinator the shall signal for termination of operations by utilizing the air horn from the Engine, while the suppression team provides coverage for the Experiment Technician(s). The Test Coordinator shall utilize the following procedure in the event of an emergency:

1) **STEP ONE:** The Test Coordinator shall signal Experiment technicians to shut off fuel to the torch and kill power to the air compressor.

2) **STEP TWO:** Once the torch is extinguished the Test Coordinator shall then order the Experiment Technician’s to remotely open the manual emergency release ball valve on the dust dispersion apparatus.

3) **STEP THREE:** The Test Coordinator shall signal for all personnel to move to the COLD ZONE by utilizing the air horn from engine 5 and by issuing directions over the radios.

4) **STEP FOUR**: Once the Test Coordinator has determined that the scene is safe, they may allow for personnel in proper PPE to approach the scene and shut down cameras and other equipment.

NOTE: In the event of an emergency shut down procedure failure, all personnel shall evacuate to the predetermined location in the COLD ZONE. 911 Emergency

Response and Richmond Fire Department shall then take over operations and suppression duties if necessary.

EMERGENCY COMMUNICATION CONTACT:

- Dial for Emergency: 911
- EKU Police: (859) 622-1111
- Kentucky State Police: (859) 623-2404
- Baptist Health Hospital: (859) 625-3999
- U.K. Helicopter: (859) 323-5901

EVACUATION MESSAGE: If command orders the termination of operations, they shall transmit an alert message over the radio and by utilizing the air horn from Engine 5 followed by instructions for all personnel to shut off power, fuel, manually release compressed air, and safely evacuate the area to the predetermined evacuation area.

EVACUATION PROCEDURE: Before the initiation of the experiment, the Test Coordinator shall conduct a briefing that shall encompass a predetermined evacuation area for all bystanders and personnel in the event of an emergency. If the Test Coordinator has called for the initiation of evacuation procedures, all personnel shall move away from experimentation area into the designated Evacuation Point in the COLD ZONE. See FIGURE 4.

IGNITION OF SURROUNDING MATERIAL BY DUST Dispersion Apparatus: In the event of an ignition of surrounding areas by the dust dispersion apparatus, the suppression team shall suppress any combustion materials in the vicinity utilizing the hose line from the engine. Class A fire extinguishers shall be in place as a contingency strategy to the primary hose line from the Engine should they be needed.

COMPRESSED AIR TANK RUPTURE: In the event of a compressed air tank rupture the Test Coordinator will order the Experiment Tech.'s to shut down the fuel to the torch and kill power to the air compressor. The Test Coordinator will then order the suppression crew to use Class A fire extinguishers or a charged hose line to suppress any fires that may have been ignited due to a tank rupture. Covering the surface of the dust dispersion apparatus fill tank with multiple 30 – 50 lbs. sandbags shall mitigate the risk of a compressed air tank rupture.

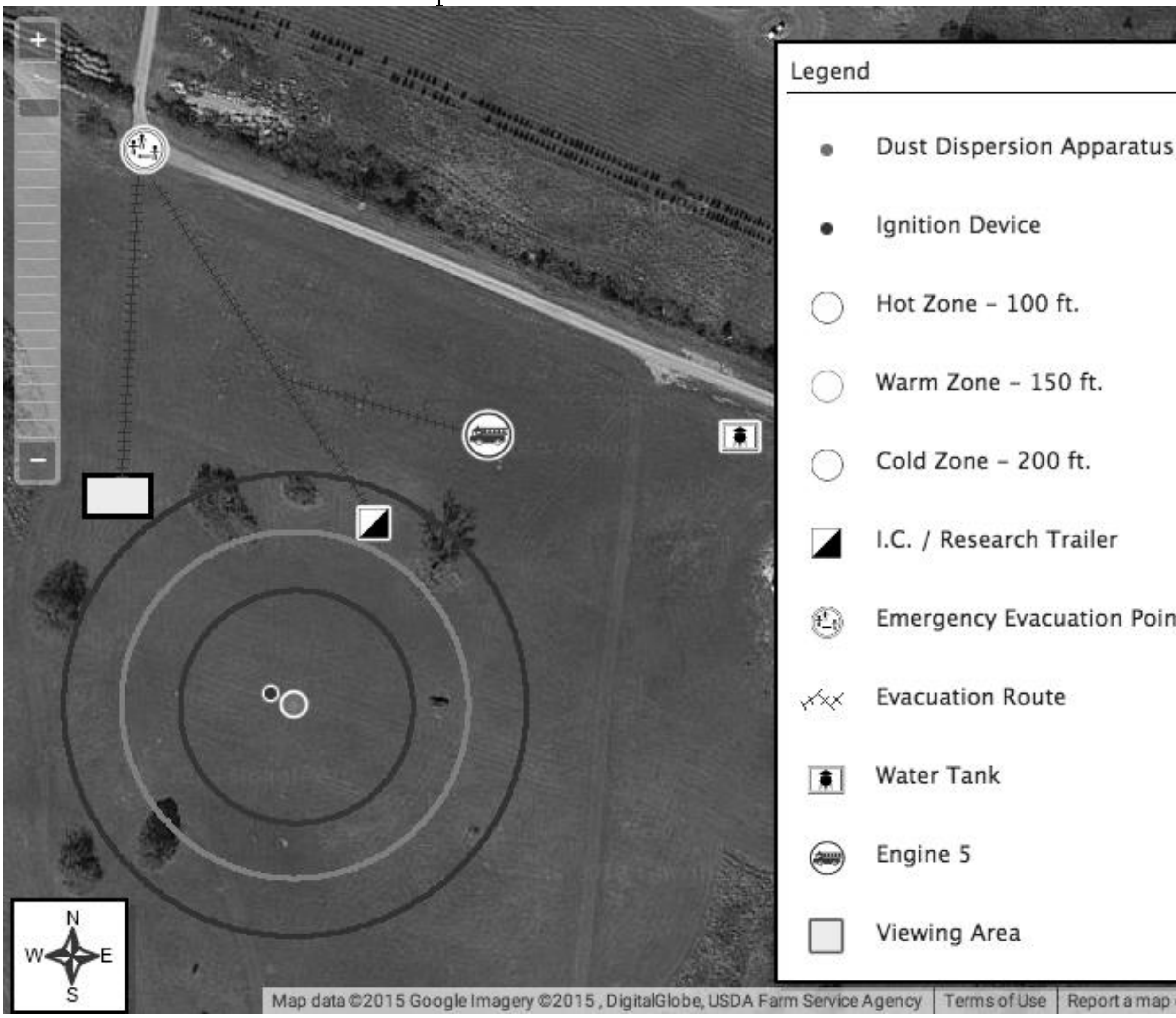
MEDICAL EMERGENCY: In the event of a medical emergency the Test Coordinator and Safety Officer shall be immediately notified so they may initiate the emergency shut down procedure and seek appropriate aid as outlined in Section 8 of the Emergency Action Plan, Richmond Campus.

LIVE FIRE EXPERIMENTATION: All personnel shall utilize procedures in accordance with NFPA 1403 guidelines prior to ignition of live fire operations. The person(s) in command shall review NFPA 1403.

VIOLATIONS: Any violations of this policy will be addressed by the appropriate Eastern Kentucky University faculty or staff member in accordance to the departmental discipline policy.

REVIEW: This policy shall be reviewed and amended as necessary prior to the condense phase flash fire experiment. A review will consist of a meeting of EKU faculty supervisors, and all other personnel involved in the experiment. Discussion of any experiment safety issues shall be addressed and this policy amended accordingly.

Experiment Site



NOTE: HOT, WARM, & COLD Zone distances determined by Hydrocarbon Fireball Calculations in APPENDIX 4.

Appendix C:

Thermal Radiation From Propane Fireballs

CHAPTER 5
ESTIMATING THERMAL RADIATION FROM HYDROCARBON FIREBALLS

Version 1805.1 (SI Units)

The following calculations estimate the thermal heat flux from hydrocarbon fuel vapors received by an object.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Type Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s). The chapter in the NUREG should be read before an analysis is made.

Project / Inspection Title:

INPUT PARAMETERS

Mass of Fuel Vapor (m_F)	2.27	kg
Distance at Ground Level from the Origin (L)	30.5	m
Fuel Vapor Density (ρ_F)	1.60	kg/m^3

Calculate

THERMAL PROPERTIES FOR

Vapor Densities of Hydrocarbon Fuels at Normal Temperature and Pressure

Fuel	Fuel Vapor Density (ρ_F) (kg/m^3)
Acetone	2.00
Acetylene	0.90
Benzene	2.80
Butane	2.00
Carbon Monoxide	1.00
Cyclohexane	29.00
Ethanol	1.50
Ethane	1.00
Ethylene	1.00
Gasoline	3.49
Heptane	3.50
Hexane	3.00
Hydrogen	0.10
Methane	0.60
Methanol	1.10
Octene	3.90
Propane	1.60
Propylene	1.50
Styrene	3.60
Toluene	3.10
Xylene	3.70
User Specified Value	Enter Value

Reference: NFPA 325, Fire Hazard Properties of Flammable Liquids, Gases, and Volatile Solids, 1994 Edition.

Select Fuel Type

Propane

Scroll to desired fuel type **then Click** on selection

ESTIMATING THERMAL RADIATION FROM HYDROCARBON FIREBALLS
METHOD OF HASEGAWA AND SATO

Reference: SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-306.

$$q''_r = 828\,(m_F)^{0.771} / R^2$$

Where,
q''_r = thermal radiation from fireball (kW/m²)
m_F = mass of fuel vapor (kg)
R = distance from the center of the fireball to the target (m)

Volume of the Fireball Fuel Calculation

$$V_F = m_F/\rho_F$$

Where,
V_F = volume of fuel vapor (m³)
m_F = mass of fuel vapor (kg)
ρ_F = fuel vapor density (kg/m³)

V_F = 1.42 m³

Fireball Flame Height Calculation

$$Z_p = 12.73\,(V_F)^{1/3}$$

Where,
Z_p = height of the maximum visible flame (m)
V_F = volume of fuel vapor (m³)

Z_p = 14.30 m

Distance from the Center of the Fireball to the Target Calculation

$$R = \sqrt{(Z_p^2 + L^2)}$$

Where,
R = distance from center of the fireball to the target (m)
Z_p = height of the maximum visible flame (m)
L = distance at ground level from the origin (m)

R = 33.69 m

MAXIMUM HEAT FLUX ON TARGET

$q''_r = 828\ (m_F)^{0.771} / R^2$

Answer	q''_r =	1.37 kW/m^2	0.12 Btu/ft^2-sec

DIAMETER OF THE FIREBALL

$D = 5.8\ (m_F)^{1/3}$

Where,
D = maximum fireball diameter (m)
m_F = mass of fuel vapor (kg)

Answer	D =	7.62 m	25.01 ft

DURATION OF THE FIREBALL

$t_p = 2.8\ (V_F)^{1/6}$

Where,
t_p = time of the fireball (sec)
V_F = volume of fuel vapor (m^3)

Answer	t_p =	2.97 sec	0.05 min

NOTE:

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation and should only be interpreted by an informed user. Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations. Any questions, comments, concerns and suggestions or to report an error(s) in the spreadsheets, please send an email to David.Stroup@nrc.gov or Naeem.Iqbal@nrc.gov.

Prepared by:		Date:		Organization:	
Checked by:		Date:		Organization:	

Additional Information:

Appendix D:

Thermal Radiation Threat Zone Output

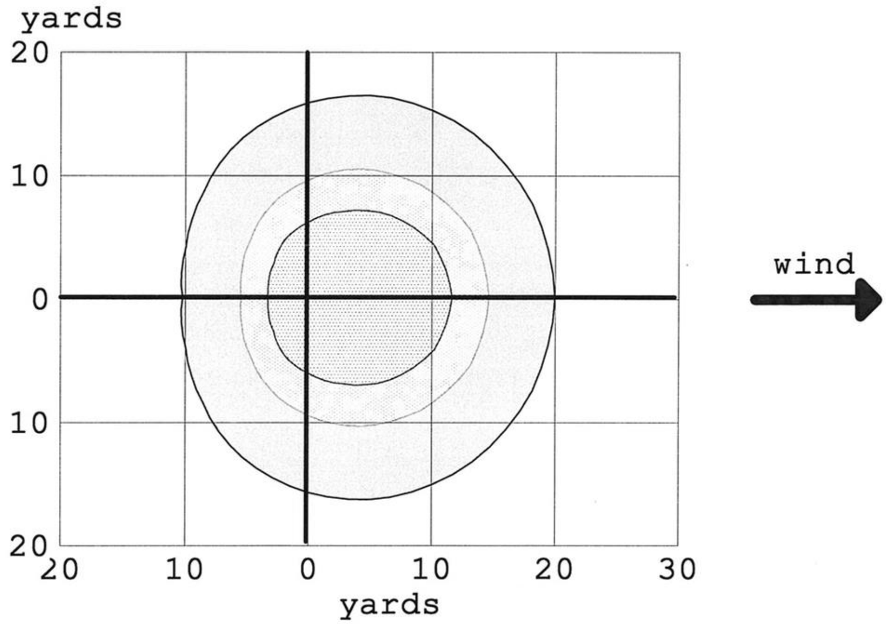
Thermal Radiation Threat Zone ALOHA® 5.4.5

```
Time: November 12, 2015  1711 hours EST (using computer's clock)

Chemical Name: PROPANE

Wind: 10 miles/hour from ne at 3 meters

THREAT ZONE:
  Threat Modeled: Thermal radiation from pool fire
  Red   : 12 yards --- (10.0 kW/(sq m) = potentially lethal within 60 sec)
  Orange: 15 yards --- (5.0 kW/(sq m) = 2nd degree burns within 60 sec)
  Yellow: 20 yards --- (2.0 kW/(sq m) = pain within 60 sec)
```



greater than 10.0 kW/(sq m) (potentially letha
greater than 5.0 kW/(sq m) (2nd degree burns w
greater than 2.0 kW/(sq m) (pain within 60 sec

Text Summary

ALOHA® 5.4.5

```
SITE DATA:
  Location: LEXINGTON, KENTUCKY
  Building Air Exchanges Per Hour: 1 (user specified)
  Time: November 12, 2015  1711 hours EST (using computer's clock)

CHEMICAL DATA:
  Chemical Name: PROPANE                    Molecular Weight: 44.10 g/mol
  AEGL-1 (60 min): 5500 ppm   AEGL-2 (60 min): 17000 ppm   AEGL-3 (60 min):
33000 ppm
  IDLH: 2100 ppm     LEL: 21000 ppm      UEL: 95000 ppm
  Ambient Boiling Point: -45.1° F
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 10 miles/hour from ne at 3 meters
  Ground Roughness: open country            Cloud Cover: 5 tenths
  Air Temperature: 50° F                    Stability Class: D
  No Inversion Height                       Relative Humidity: 50%

SOURCE STRENGTH:
  Burning Puddle / Pool Fire
  Puddle Area: 5 square meters              Puddle Volume: 20 gallons
  Initial Puddle Temperature: -45.1° F
  Flame Length: 8 yards                     Burn Duration: 1 minute
  Burn Rate: 72 pounds/min
  Total Amount Burned: 97.4 pounds

THREAT ZONE:
  Threat Modeled: Thermal radiation from pool fire
  Red   : 12 yards --- (10.0 kW/(sq m) = potentially lethal within 60 sec)
  Orange: 15 yards --- (5.0 kW/(sq m) = 2nd degree burns within 60 sec)
  Yellow: 20 yards --- (2.0 kW/(sq m) = pain within 60 sec)
```

Text Summary

ALOHA® 5.4.5

```
SITE DATA:
  Location: LEXINGTON, KENTUCKY
  Building Air Exchanges Per Hour: 1 (user specified)
  Time: November 12, 2015  1711 hours EST (using computer's clock)

CHEMICAL DATA:
  Chemical Name: PROPANE                     Molecular Weight: 44.10 g/mol
  AEGL-1 (60 min): 5500 ppm   AEGL-2 (60 min): 17000 ppm   AEGL-3 (60 min):
33000 ppm
  IDLH: 2100 ppm     LEL: 21000 ppm      UEL: 95000 ppm
  Ambient Boiling Point: -45.1° F
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 10 miles/hour from ne at 3 meters
  Ground Roughness: open country             Cloud Cover: 5 tenths
  Air Temperature: 50° F                     Stability Class: D
  No Inversion Height                        Relative Humidity: 50%

SOURCE STRENGTH:
  Burning Puddle / Pool Fire
  Puddle Area: 5 square meters               Puddle Volume: 20 gallons
  Initial Puddle Temperature: -45.1° F
  Flame Length: 8 yards                      Burn Duration: 1 minute
  Burn Rate: 72 pounds/min
  Total Amount Burned: 97.4 pounds

THREAT ZONE:
  Threat Modeled: Thermal radiation from pool fire
  Red   : 12 yards --- (10.0 kW/(sq m) = potentially lethal within 60 sec)
  Orange: 15 yards --- (5.0 kW/(sq m) = 2nd degree burns within 60 sec)
  Yellow: 20 yards --- (2.0 kW/(sq m) = pain within 60 sec)
```

Appendix E:

Dust Dispersion Apparatus Experiment Procedure

INTIAL PROCEDURE: The designated Test Coordinator shall brief all personnel involved in assisting with the tests on proper safety precautions as well as experiment procedure. The Test Coordinator shall also address bystanders to make sure that all observers are a safe distance away from experiment in a designated viewing area.

1) **STEP ONE:** All personnel shall be in proper PPE before taking their position as designated by the Test Coordinator.
2) **STEP TWO:** Research team shall turn on all data acquisition equipment.
3) **STEP THREE:** Test Coordinator shall signal the experiment technicians to fill the dust dispersion apparatus with the appropriate powder.
4) **STEP FOUR:** On the Test Coordinators signal the experiment technicians will ignite the propane ignition device.
5) **STEP FIVE:** Experiment technicians will charge the dust dispersion apparatus to a predetermined PSI and ensure the air compressor is switched off and unplugged when the predetermined PSI has been reached.
6) **STEP SIX:** All personnel will vacate the hot zone and seek refuge.
7) **STEP SEVEN:** Test Coordinator shall ensure the scene is safe and give confirmation to the DAC team that the area is secure and the dust dispersion apparatus is ready for launch.
8) **STEP EIGHT:** DAC team will conduct a countdown audible to all bystanders and personnel before initiating the dust dispersion apparatus.
9) **STEP NINE:** When the flash fire has dissipated the Test Coordinator will ensure the scene is safe.
10) **STEP TEN:** Before reentering the hot zone the experiment technicians will shut off fuel to the propane ignition device and wait for the lines to completely bleed off and de-energize the remote ignition device.
11) **STEP ELEVEN:** Experiment technicians will clean any remaining powders out of the dust dispersion apparatus.
12) **STEP TWELVE:** Repeat until all ignitable powder weight and dust dispersion apparatus PSI variables have been accounted for.

PROPANE IGNITION DEVICE SETUP:

The propane ignition device shall consist of the following:

- 20lb Propane Tank
- 100 ft. Propane Hose
- Secondary Shut-off Valve
- Flame Resistant Conduit
- Torch
- Clamp/ zip ties
- Metal Stand

Setup Procedures:

1) Place the torch stand adjacent to the dust dispersion apparatus
2) Attach the torch to the stand using the clamp or zip ties
3) Connect the hose to the conduit and propane tank
4) Move the propane tank into the warm zone

Ignition Procedures:

1) Open the shut-off valve on the propane tank
2) Open the secondary shut-off valve on the conduit
3) Ignite the propane torch with a long-stemmed lighter

Shut-off Procedure:

1) Wait for the Test Coordinator to give the “all clear” signal
2) Shut off propane flow at the tank
3) Allow remaining propane to bleed from the line and burn off
4) Shut the secondary shut-off valve on the conduit

BREAK DOWN PROCEDURE: Once completion of the flash fire data has been recorded and saved, the Test Coordinator shall signal for initiation of break down procedure.

Note: All PPE gear shall remain in place until break down procedure is completed.

1) **STEP ONE:** Test Coordinator shall ensure that the fuel to the propane ignition device is shut off and all lines are bled.
2) **STEP TWO:** Test Coordinator shall ensure that there is no remaining pressure in the dust launching apparatus.
3) **STEP THREE:** Once the Test Coordinator has determined that the scene is safe they may allow for personnel to approach scene and turn off cameras and any other equipment.

POST EXPERIMENT: It shall be the duty of the Test Coordinator and FSE Lab Coordinator to check scene after break down of the Condense Phase Flash Fire Experiment to ensure that the equipment is adequately stored and secured. Power needs