COMBUSTIBLE DUST TESTS

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Abstract

The sugar dust explosion in Georgia on February 7, 2008 killed 14 workers and injured many others (OSHA, 2009). As a consequence of this explosion, OSHA revised its Combustible Dust National Emphasis (NEP) program. The NEP targets 64 industries with more than 1,000 inspections and has found more than 4,000 combustible dust related violations. Many agricultural operations handle products such as grain and sugar that results in concentrations of combustible dust that can fuel deflagrations (explosions). It has been alleged that dust found in cotton gins is a combustible dust. Tests were conducted by the Center for Agricultural Air Quality Engineering and Science (CAAQES) and by a commercial laboratory to determine if gin dust was combustible. CAAQES reported that gin dust was not a combustible dust. The commercial laboratory reported that gin dust was a class "A" combustible dust. The justification of classifying gin dust as combustible dust was based upon a requirement that the dust be tested in 20 L spherical chamber with a 10,000 J chemical igniter sprayed through the dust cloud. Using a bench mark of 2 bars pressure rise as an indicator that an explosion occurred in the test chamber, it was determined that gin dust was combustible. The authors of this paper point out that burning of dust will result in a rise of pressure sufficient to exceed that benchmark of 2 bars resulting in an incorrect classification for gin dust. The CAAQES method uses tests for determining the minimum explosive concentration (MEC) as the criterion for determining whether a dust is a combustible dust or not. Numerous tests were conducted on corn starch, dust XX, and gin dust to determine MECs. The MECs of corn starch and dust XX were 43 g/m^3 and 73 g/m^3. There were no deflagrations for any concentration of gin dust tested. It was concluded that gin dust did not have an MEC and therefore was not a combustible dust.

Introduction

It is important that the determination of whether an unknown dust is a combustible dusts be accurate. It has been alleged that dust found in cotton gins is a combustible dust. Tests were conducted by faculty in the biological and Agricultural Engineering Department (BAEN), Center for Agricultural Air Quality Engineering and Science (CAAQES) and by a commercial laboratory to determine if gin dust was combustible. In other words, did testing of different concentrations of gin dust indicate a minimum explosive concentration (MEC) existed? If a dust has an MEC, it is a combustible dust. CAAQES reported that gin dust was not a combustible dust. The commercial laboratory reported that gin dust was a class "A" combustible dust. If gin dust meets OSHA's definition of a "combustible dust", cotton gins will be subject to regulation, either under the general duty clause, or through regulations similar to those associated with grain elevators, feed mills, and sugar processing facilities. OSHA inspectors will likely cite gins for combustible dust related violations such as dust accumulations on surfaces and a lack of explosion venting. Cotton gins do not have a history of dust explosions as do grain processing facilities and it is likely that no cotton gin has ever had a dust explosions. The authors believe the testing protocol of spraying a chemical igniter of 10,000 J through the dust cloud and using a pressure of 2 bars as the indicator of a deflagration will result in a false indication of a combustible dust.

The authors of this paper believe that, to be classified as combustible, the testing of the dust in the laboratory should include a requirement that the flame propagate through the dust cloud. Spraying a chemical igniter of 10,000 J through the dust cloud will result increased pressure as a consequence of burning dust particles. The pressure criterion as the indicator of a deflagration dust not reflect whether the flame propagated through the dust cloud as required for a deflagration. The problem with challenging the protocol used by the commercial laboratory to classify gin dust as a combustible dust is that the laboratory used the protocol specified by ASTM 789 (2001), ASTM 1226 (2005), ASTM 1515 (2007) and NFPA 68 (2007). The argument that gin dust is not a combustible dust is in effect an argument that the protocols specified by ASTM and NFPA are flawed. <u>The objective of this paper is to document the problems associated with the required ASTM and NFPA laboratory tests before a dust can be classified as "noncombustible" including the following:</u>

1. The protocol specified by ASTM and NFPA requires testing dusts in a 20L totally enclosed spherical chamber with ignition energies as high as 10,000J when no deflagrations are detected from multiple tests using the previous standard of the 1.2L Hartman tube with ignition energy of 10J. *This requirement results in dust being incorrectly classified as combustible. Spraying 10,000J into a 20L chamber of air only can theoretically result in a temperature in excess of 1000 degrees F.*
2. Using measured pressure in excess of 2 bars from a totally enclosed chamber (ASTM 1515) to determine whether a deflagration occurred for a specific dust concentration is problematic. Burning of volatiles in a dust cloud will result in increased temperatures and gases (products of combustion). Increased temperatures and gases from combustion of solid particles in a totally enclosed chamber will increase the pressure suggesting a deflagration occurred when it did not. *It would be more accurate to use the Hartman tube (with diaphragm) or the CAAQES method to determine the MEC of dusts. It is proposed that the "signature" pressure-versus-time data for a deflagration plus rupture of the diaphragm and observing flame leaving the test chamber would be more accurate indicators for determining whether deflagrations occurred than a pressure rise of 2 bars. (Raising the temperature of the air in a 20 L chamber to 1000 degrees Fahrenheit (F) will result in a gage pressure of 1.7 bars. If 4 gram of carbon burns and the temperature increases to 1000F the gage pressure will theoretically increase to 3.5 bars.*
3. Ideally, the laboratory testing for determining whether a dust is combustible should mimic what occurs in a combustible dust explosion. *Using a totally enclosed 20L chamber and spraying 10,000J of a chemical ignition source through the cloud for laboratory testing to determine whether an MEC exists does not mimic a dust explosion.*

<u>What is a dust explosion?</u>

In simple terms, combustible dust provides the fuel for a dust explosion. A dust explosion is a consequence of a "deflagration". Deflagrations and detonations are different. Explosions as a result of "detonating" dynamite or C4 with a shockwave (blasting cap) have characteristic pressure waves and fire fronts leaving the initial location at or above the speed of sound. The sound of a detonation is a single loud explosion. In contrast, a deflagration is the result of a dust **cloud in a contained volume being ignited followed by <u>a rapid propagation of flame throughout the dust cloud</u>.** The burning of solid particles in the cloud produces gases that occupy much larger volumes than the solid particles. This increased volume of combustion gases and increased temperatures in a totally enclosed chamber results in a rapid increase in pressure. The increased pressure results in a rupture of the initial containment releasing the pressure wave into another, larger containment volume. (The rupture of the containment is the explosion.) A fire front follows the pressure wave of the dust explosion fueled by the unburned dust from the initial deflagration and is often the ignition source for the dust cloud in the new containment volume. The pressure wave of a deflagration moves away from the ignition site at a speed equal to or less than the speed of sound (330 m/s). The fire front follows at a speed of from 1 to 10 m/s (Palmer, 1973).

A dust explosion (deflagration) is often a series of explosions. The first is referred as the "primary explosion". All subsequent explosions following the primary are referred to as secondary explosions. Primary dust explosions will typically result in pressures less than 2 psi. Secondary dust explosions can result in pressures in excess of 100 psi. Often, witnesses describe hearing a grain elevator explosion as a "rumble" rather than a single loud noise. A primary followed by multiple secondary explosions will result in a noise that can accurately be described as a "rumble".

In order for a primary explosion to occur, fuel, oxygen, ignition source, and containment are required. The fuel for a primary dust explosion is a concentration of combustible dust at or above the minimum explosive concentration (MEC). For grain dust, the MEC is approximately 50 g/m^3. This concentration is so heavy that one cannot see their fingers moving one foot away. Containment is required in order to achieve the MEC of grain dust of 50 g/m^3.

Collapsed ducts attached to the chamber where either a primary or a secondary explosion occurred have been observed and reported. Collapsed ducts are a consequence of the significant vacuum in the chamber as an immediate result of the pressure wave leaving the chamber where the dust cloud was ignited.

Figure 1illustrates 3 replications of results of laboratory testing using the CAAQES method for corn starch at 100 g/m^3. Note the pressure versus time curves rise to 1.2 psi followed by a rapid decrease in pressure to negative 0.8 psi corresponding to the rupture and release of the pressure wave. The pressure-versus-time curve in Figure1 exactly mimics the primary explosion of a primary dust explosion. The ruptured diaphragm indicates that the flame propagated through the dust cloud resulting in a pressure exceeding that needed to indicate an explosion. The fire front followed the pressure wave fueled by unburned dust. This pressure-versus-time curve along with rupture of the diaphragm and flame leaving the chamber are the criteria used to define a deflagration using the CAAQES method.

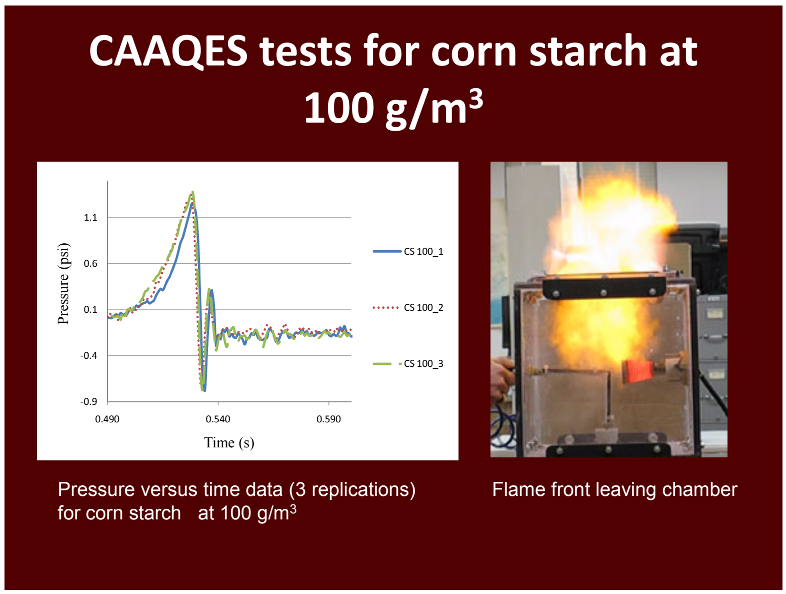

Figure 1.Pressure-versus-time curves for three replications of corn starch deflagrations at 100 g/m^3 and visual data showing the flame leaving the chamber.

In December, 2009, the National Cotton Ginners Association (NCGA) made a special request for CAAQES faculty to perform testing of dust found in cotton gins to determine if gin dust was a combustible dust. In previous years, faculty and their graduate students in the BAEN department had performed a number of research efforts related to combustible dust explosions resulting in the following references: Goforth, 1985; Jones, 1986; Lesikar, 1987 and 1989; Lesikar et al., 1991; Wardlaw, 1987 and 1989; Parnell et.al, 1986 and 1987; Parnell, 1978, 1980, and 1993; Plemons, 1981; Schulman, 1983). Lesikar et al. (1991) developed a relatively simple method to determine the MEC of unknown dusts. It consisted of two connected chambers with two diaphragms that allowed the explosion to vent from one chamber to the other and ultimately to the laboratory. The smaller chamber (1 ft^3) simulated the initial or primary explosion and the larger chamber (2 ft^3) was the chamber that contained dust that could fuel a secondary dust explosion. Pressure sensors were installed in both chambers in order to obtain pressure versus time data. The chambers were constructed of Plexiglas to facilitate high speed photography for visual data of the tests.

A modified version of the MEC testing system consisting of 28.3L (1 ft^3) chamber with a diaphragm has been used by the instructors of the BAEN 365 “Processing” laboratory when lecturing on grain dust explosions for more than 20 years. The students are required to determine the MEC of an unknown dust with multiple tests using different concentrations. The method used to entrain the dust sample into a dust cloud consists of placing a known quantity of dust in a crucible and using a short blast of compressed air. The ignition source is a 600 Joule (J) coil with a surface temperature in excess of 1,500 degrees F. When the dust cloud contacts the ignition source, there is an immediate propagation of flame through the cloud. The paper diaphragm is ruptured as a consequence of the over-pressure allowing the pressure wave to leave. A flame front follows the pressure wave fueled by the unburned dust carried by the pressure wave. (See figure 1.)

Figure 2 shows results of a CAAQES test for gin dust at 1,000 g/m^3. Note that there was no rupture of the diaphragm. It was concluded that the flame front did not propagate through the cloud to produce the pressure needed to rupture the diaphragm. Note the flame at the ignition source. This stationary ignition source did not produce enough pressure to rupture the diaphragm.

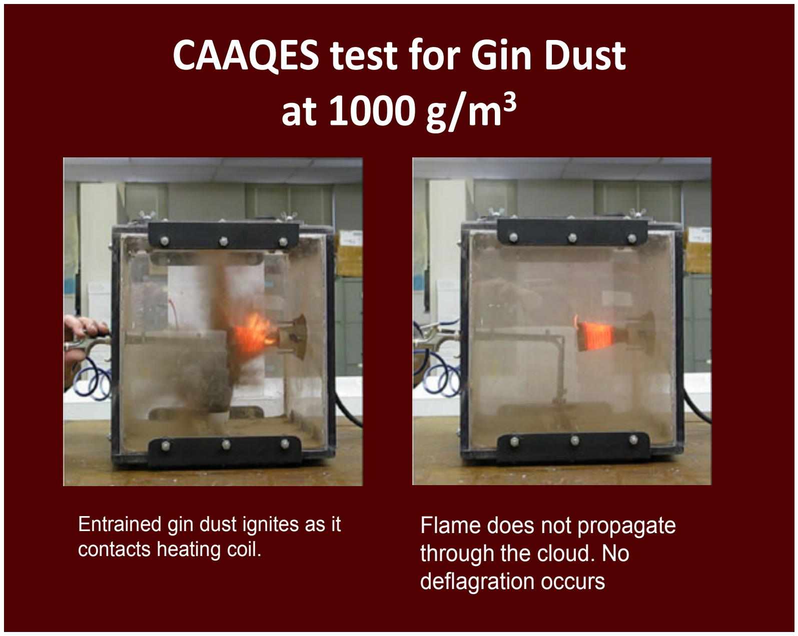

Figure 2.Visual data for gin dust test run at 1000 g/m^3. No deflagration occurred for any gin dust concentration tested.

Combustible dusts have an upper concentration limit where the concentration is so high that the flame is unable to propagate through the cloud. Additional tests were conducted at 500 g/m^3 and 250 g/m^3 with similar results. There were no deflagrations for any of the gin dust concentrations tested using the CAAQES method.

Test Methods

Three laboratory tests were used to determine the MEC of gin dust in order to determine if gin dust was combustible. Test #1was the CAAQES method. Tests #2 and #3 were performed by the commercial laboratory (SCE, 2010) using protocols specified in ASTM 789 and ASTM 1515. All of the tests for combustibility were designed to determine the MEC by varying dust concentrations and selecting the least concentration that yielded a deflagration. **If no MEC could be determined from the results of testing, the dust was considered non-combustible.**

More detailed descriptions of the tests are as follows: Test method #1 is the CAAQES method which consists of using a 28.3L (1 ft^3) chamber with a diaphragm. The CAAQES chamber is constructed of Plexiglas which allows for visual confirmation of a dust explosion. The MEC was defined as the least concentration tested that resulted in a rupture of the diaphragm and flame leaving the chamber. The pressure-versus-time result shown in figure 1 is a characteristic of any dust deflagration (explosion). The primary dust explosion occurs when the dust cloud contacts the ignition source producing a flame that propagates through the cloud fueled by dust particles. The increased pressure is a consequence of flame propagation and not a consequence of burning volatiles by the ignition source.
Test method #2 consisted of using a totally enclosed 1.2L Hartman tube. In the 1970's, the 1.2L Hartman tube with diaphragm was the standard for determining MECs. Figure 2 illustrates the Hartman tube with the flame exiting the tube similar to method #1. This was the standard method developed by the Federal Bureau of Mines for determining MECs (Palmer, 1973). At that time, the totally enclosed Hartman tube was used to determine the "Explosion Indices".

Test method #3 consisted of using a 20L, totally enclosed, spherical chamber. Both methods #2 and #3 were used to determine "Explosion Indices" including maximum explosion pressure, (P_{max}), maximum rate of pressure rise $(dP/dt)_{max}$, and product specific constant (K_{max}) as specified by ASTM 1226. These indices are parameters needed to design and implement explosion venting (NFPA 68, 2011).

The least concentration that would result in a pressure rise in excess of 2 bars was the criterion used to determine the MEC. One of the difficulties with pressure being used to determine whether or not a deflagration occurred for a specific concentration tested in totally enclosed the 1.2 L or 20 L chambers is that rising temperatures and increased gas (products of combustion) will result in significant pressure with no propagation of the flame through the dust cloud. Increased pressure will result as a consequence of burning dust when 5,000 and/or 10,000 J chemical igniter is sprayed through the gin dust cloud in the test chamber. It is likely that an increased pressure could be miss-interpreted as a deflagration. (We believe that this is what happened with gin dust.)

In general, all three methods use compressed air to entrain dust into a dust cloud in the chamber. The differences in the methods are significant. Method #1 uses a stationary 600J coil for ignition. Method #2 uses a 10J continuous electric spark or coil. Method #3 uses a 2,500 to 10,000J chemical igniter sprayed through the dust cloud. (SCE used 5,000J chemical igniter to determine the MEC of gin dust and 10,000J chemical igniter in the screening test.) Method #1 uses rupture of the diaphragm by overpressure as a consequence of the rapid propagation of the flame through the dust cloud, flame leaving the chamber, and a signature pressure-versus-time curve as criteria for deflagrations in the test chamber and ultimately MECs. Methods #2 and #3 use a maximum pressure in excess of 2 bars as the criterion for a deflagration and for determining MEC.

Test Results

No deflagrations were detected by CAAQES personnel using method #1 for the initial series of tests for 1,000g/m^3, 500g/m^3, and 250g/m^3 concentrations. It was concluded that gin dust was not a combustible dust (Parnell, 2010). A decision was made to contract a commercial laboratory (SCE) to test gin dust. The plan was to have SCE conduct the screening tests ($700) before proceeding to the more detailed, and expensive tests. It was anticipated that SCE would have the same findings as reported by CAAQES. On May 25, SCE reported orally to Mr. Hughes that they had a deflagration with gin dust. After conferring with Messrs. Green, Hughes, Findley, and Ashley, it was decided to proceed with the additional testing.

Mr. Ed Hughs, Director of the USDA, ARS, Cotton Ginning Research Laboratory at Mesilla Park, N.M. served as the point person. He collected gin dust from cotton gins across the cotton belt, screened the dust to less than 75 micrometers, forwarded the screened dust to SCE. He served as the contact for SCE. Mr. Hughes sent seven pounds of this same dust to the CAAQES laboratory for testing.

From March 23 to April 15, 2010, CAAQES personnel tested 3 replications for 18 different concentrations of the gin dust supplied by Mr. Hughs using method #1 for concentrations ranging from 73 to 730 g/m^3. No deflagrations were detected.

Included in the CAAQES protocol were tests using corn starch and an unknown dust labeled XX. We determined the MEC for corn starch using method #1 to be 43 g/m^3 which was very close to the published value of 40g/m^3 (Palmer, 1973). The MEC of dust XX was unknown. Table 1 is a partial list of the data for corn starch and dust XX. The MEC for dust XX was 73 g/m^3. Figures 3 and 4 illustrate results of the pressure-versus-time curves for concentrations near the MECs for corn starch and dust XX. Figure 5 shows the method #1 pressure-versus-time results for three replications of gin dust at 730 g/m^3. The test results for all other concentrations of gin dust were similar.

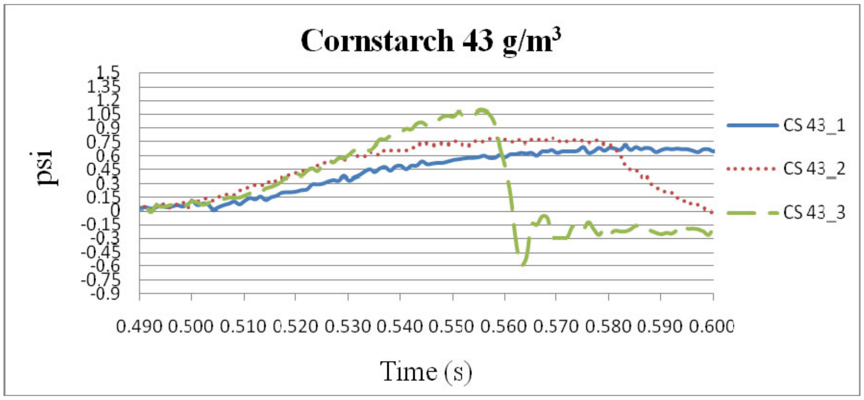

Figure 3. Pressure-versus-time curves for 3 replications of corn starch at 43 g/m^3. Note, pressures above atmosphric were detected for two replications (CS43_1 and CS43_2) with no deflagrations.The diaphragm was not ruptured. For CS43_3, the diaphragm was ruptured.

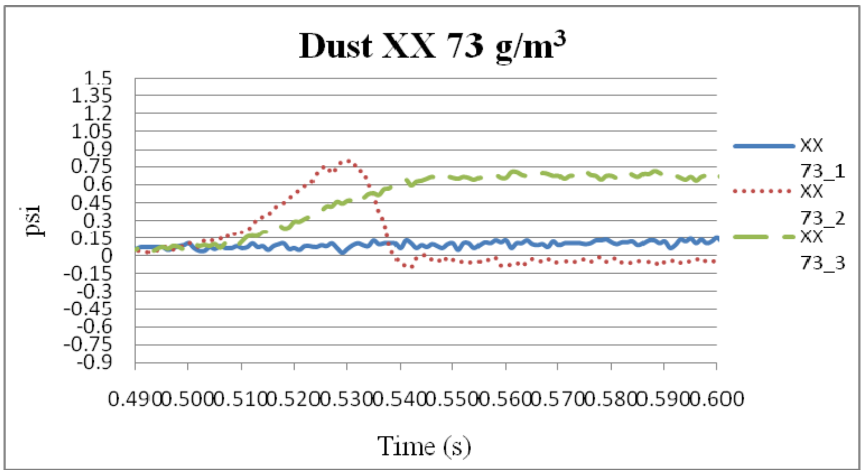

Figure 4. Pressure-versus-time curves for 3 replications of dust XX 73 g/m^3. Note, a pressure above atmosphric was detected for XX 73_3. No pressure was detected above atmospheric for XX73_1. Results for XX 73_2 shows a deflegration occurred.

Table 1. Results of method #1 tests to determine MEC for corn starch (CS) and dust XX. This table does not include results for concentrations higher or lower than those listed in the table. All of CS concentrations larger than 57 g/m^3 resulted in a deflagration. All concentrations of dust XX greater than 93 g/m^3 resulted in a deflagration. All concentrations less than 37 g/m^3 for CS and 70 g/m^3 for dust XX did not have a deflagration.

Test	Conc. (g/m^3)	Deflagration? (Y/N)	Test	Conc. (g/m^3)	Deflagration?(Y /N)
CS 57_1	57	Y	XX 93_1	93	Y
CS 57_2	57	Y	XX 93_2	93	Y
CS 57_3	57	Y	XX 93_3	93	Y
CS 43_1	43	N	XX 77_1	77	N
CS 43_2	43	N	XX 77_2	77	Y

CS 43_3	43	Y	XX 77_3	77	Y
CS 40_1	40	N	XX 73_1	73	N
CS 40_2	40	N	XX 73_2	73	Y
CS 40_3	40	N	XX 73_3	73	N
CS 37_1	37	N	XX 70_1	70	N
CS 37_2	37	N	XX 70_2	70	N
CS 37_3	37	N	XX 70_3	70	N

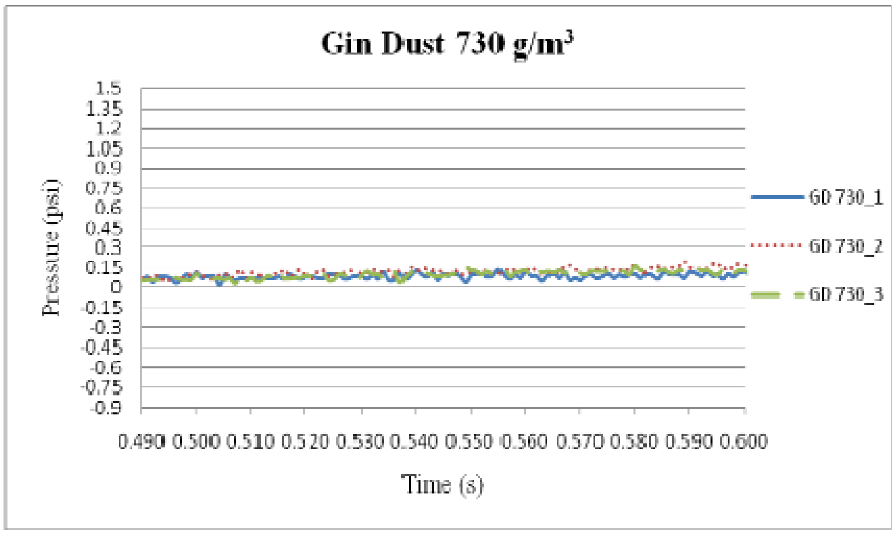

Figure 5. Pressure-versus-time curves for 3 replications of gin dust at 730 g/m^3. No rise in pressure was detected above atmospheric for any of the three replecations. No deflegration occurred for any of the tests of gin dust concentrations.

Results of ash analyses for the three dusts tested by CAAQES using method #1 are shown in Table 1. The protocol consisted of pre-weighing samples and post-weighing following four hours in a furnace at 575^o F. Ash analyses are used to determine the mass fraction of inert dust. Increased fractions of inert dust will increase the MEC or prevent the flame from propagating through the dust cloud. Gin dust will typically have high ash contents.

Table 2. Results of ash analysis of the three dust types tested using the CAAQES method. Note that the average ash content of gin dust was 87%. Only 13% of the gin dust was combustible.

Dust Type	**Ash% ± 95% CI**	**Std Dev(s)**
CS	0.98 ± 0.02	0.01
XX	61.6 ± 0.01	0.01
GD	87.2 ± 1.13	0.15

The particle size distributions (PSD) of the dusts tested by CAAQES were performed on the Malvern instrument in the BAEN department at Texas A&M University and the results are shown in Table 3. Dust samples typically have a lognormal distribution. The lognormal distributions are defined by mass median diameters (d_{50}) and geometric standard deviations ($d_{84.1}/d_{50}$) (Cooper and Alley, 2002).

Table 3. Results of particle size analysis of the three dust types tested using the CAAQES method. The mass median diameter (MMD) and the geometric standard deviation (GSD) are used to mathematically represent lognormal distributions of particulate matter (Cooper and Alley, 2010). The MMD is reported as aerodynamic equivalent diameter in micrometers (µm). A minimum of three replications were performed for each dust type. T he 95% confidence interval (CI) was calculated.

Dust Type	MMD ± 95% CI	GSD ± 95% CI
CS	15.5 ± 0.29	1.6 ± 0.08
XX	13.7 ± 0.06	2.1 ± 0.03
GD	23.7 ± 0.88	1.9 ± 0.01

Results of combustible dust testing by Safety Consulting Engineers Inc. (SCE)

SCE ran 10 replications for 11 different concentrations of gin dust for a total of 110 screening tests to determine if gin dust was a combustible dust. The initial screening used procedures prescribed by ASTM E 789 – 95 (2001). These tests were conducted using a 1.2L totally enclosed cylindrical vessel commonly known as the "Hartmann tube". The ignition source was a "constant arc ignition source" with ignition energy equal to 10J. The concentrations tested ranged from 208 to 16,700 g/m^3. The results for this series of tests were no deflagrations.

Figure 6 illustrates the Hartman tube with a diaphragm which is ruptured when a deflagration occurs and a totally enclosed 20L chamber. SCE used a Hartman tube that was similar but was totally enclosed for their screening tests with a criterion of a pressure rise of more than 0.5 bar (7.5 psi) used as the indicator for a deflagration.

The screening protocol required a second test be conducted using a 20 L test chamber, if the first series of tests using the totally enclosed Hartman tube yielded no deflagrations. SCE tested gin dust at a 1,000 g/m^3 in the 20 L spherical chamber with a 10,000 J chemical igniter. The results were interpreted as a deflagration with a maximum pressure of 5.5 bars, a max rate of pressure rise equal to 7 bar/s and a K_{st}=26 bar-m/s. They estimated the MEC equal to 300 to 350 g/m^3. SCE concluded that **gin dust should be classified as a "Group A: Explosive dust".**

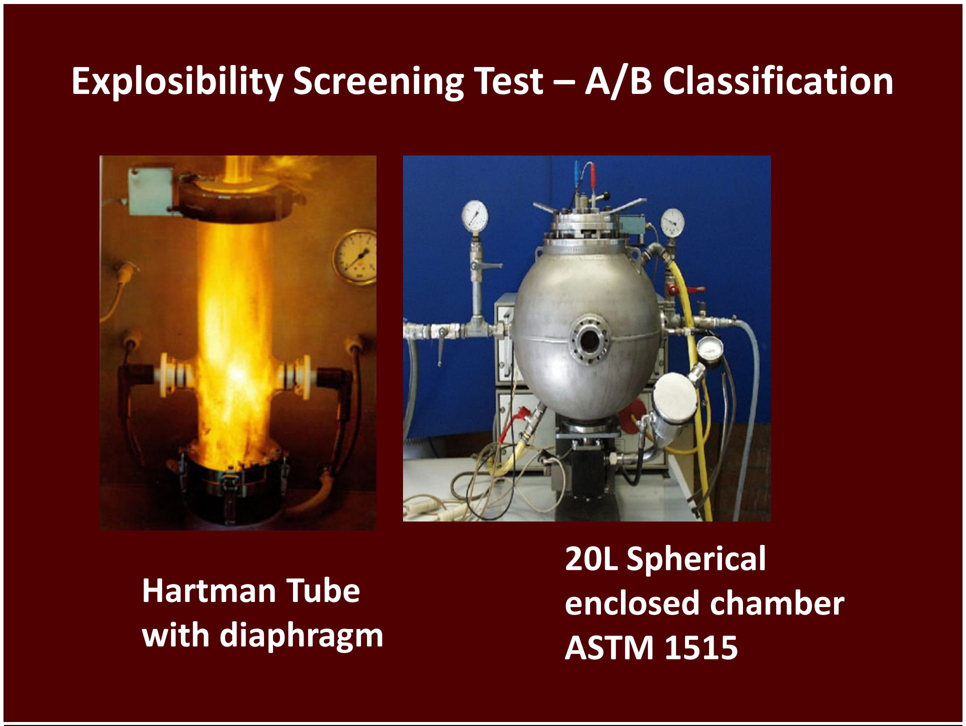

Figure 6. Illustration of Hartman Tube with diaphragm and 20L enclosed Spherical Chamber.

Summary and Analysis

Laboratory testing to determine the MEC of a combustible dust should be a system that simulates what happens when a deflagration occurs. The final test used by the commercial laboratory does not represent what happens when a deflagration occurs! Palmer (1973) describes explosibility classification tests as follows:
“Group (a) Dusts which ignite and propagate flame in the test apparatus.”
“Group (b) Dusts which do not propagate flame in the test apparatus.”
He goes on to say, “Group (a) dusts should be regarded as explosible, and liable to give rise to a dust explosion hazard, whereas Group (b) dusts are non-explosible…”

The 110 tests using the enclosed Hartman tube for concentrations ranging from 208 to 16,700 g/m^3 did not “propagate flame in the test apparatus” and as a consequence did not have a gage pressure in excess of 2 bars indicating a deflagration. The subsequent required testing with the 20L spherical chamber and spraying 10,000 J of a chemical igniter through the dust cloud resulted in products of combustion and high temperatures. It is likely that the gage pressure measured as a consequence of increased gases (products of combustion) and high temperatures yielded a false indicator of a deflagration. This is a consequence of using totally enclosed chambers and pressure as the indicator. The flame must propagate through the cloud for a deflagration to occur and as indicated in the 110 tests without a reaction in the Hartman tube, the flame did not. Hence, the protocol specified by ASTM and NFPA is flawed.

This NFPA 68 and ASTM 1515 protocols requiring tests results using the 20L chamber and spraying 10,000J through the dust cloud should be revisited. It is recommended that the protocol for determining MEC use a chamber with a diaphragm as in the CAAQES method or the Hartman tube with diaphragm. This procedure mimics dust explosions and has more than one indicator for whether a deflagration occurred in laboratory tests. It is essential that protocols for determining if a dust is or is not a combustible dust be accurate. For the purpose of determining whether an unknown dust is a combustible dust, an MEC must result from laboratory testing at some concentration. The definition of a deflagration requires that the flame front propagate through the cloud. The “false positive” result in enclosed test chamber tests by spraying 10,000 J through the cloud resulting in pressures that are perceived as deflagrations is flawed. OSHA combustible dust regulations must be based upon correct combustible dust classifications.

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