LABORATORY TESTING OF EXPLOSIBLE/COMBUSTIBLE DUST

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Abstract

The application of laboratory testing of dusts to determine whether the tested dust can serve as a fuel for a dust explosion has been blurred by terminology. The terminology in question is the use of the term “combustible” dust. Not all dust classified as combustible are explosible. Explosible dusts can serve as fuel for deflagrations and dust fires. Dusts that fuel dust explosions are “explosible” dusts. Not all combustible dusts are explosible but all explosible dusts are combustible. The ASTM protocol for laboratory testing of explosible (“combustible”) dust is flawed. Dust is dispersed in a 20 L chamber and ignited by a flame from a 10,000 J chemical igniter. Pressure is used as the only indicator of whether a deflagration occurred during tests. As a consequence, non-explosible dust such as cotton gin dust (CGD) can be tested in a commercial laboratory and be classified as a class A combustible dust. It is assumed that this classification is an indication that CGD is an explosible dust. CGD includes a fraction of organic dust that will burn when exposed to a flame from a 10,000 J energy source and the burning of dust will produce pressure. One approach to prevent a flawed test protocol from being promulgated by OSHA is to demonstrate with sound science that the threshold used with the ASTM dust testing protocol will be exceeded by burning dust with no self-propagating flame. The Center for Agricultural Air Quality Engineering and Science (CAAQES) method for determining whether a dust is explosible is to determine the minimum explosive concentration (MEC). If an MEC exists for a dust, it is an explosible dust. If an MEC does not exist, the dust is not an explosible dust. The ASTM E1515 standard describes the testing procedure for determining the minimum explosible concentration of any dust. In this paper, the accuracy and robustness of the ASTM methods for “combustible” dust testing are critically evaluated. The ASTM standard test method requires that dust testing be performed in a 20 L semi-spherical, totally enclosed chamber with 2500 or 5000 J pyrotechnic igniters. If the pressure rise exceeds one bar (14.5 psi), it is assumed that a deflagration had occurred in the chamber. Our research findings are that a one bar pressure rise can be a consequence of burning dust with no self-propagating flame and the total mass of oxygen in the chamber will be consumed by burning two grams of test dust. The main objective of this research was to evaluate the potential flaws in the current standard test protocol and to establish a new testing procedure that will prevent a dust from being classified as explosible when it is not.

Introduction

There are some changes taking place with OSHA Standards with regard to protecting workers in facilities that handle materials that are subject to dust explosions. It is the authors’ position that the ASTM standard for laboratory testing to determine whether a dust can serve as a fuel for a dust explosion is flawed. As a consequence of this flawed protocol, it is likely that cotton gins will be listed with those agricultural operations that handle combustible dust. There is some confusion as to what are the problems and why it is important to the cotton ginning industry that we find a way to correct this flawed protocol. The results of CAAQES testing of gin dust were that gin dust is not an explosible dust. It is not a dust that will fuel a dust explosion or dust fire. The success of our efforts to correct flaws in the ASTM laboratory testing protocol will be dependent upon sound science and technical arguments. The application of laboratory testing of dusts to determine whether the tested dust can serve as a fuel for a dust explosion has been blurred by terminology. The terminology in question is the use of the term “combustible” dust. Will all dust classified as combustible serve as fuel for a dust explosion? Dusts that fuel dust explosions are “explosible” dusts. Not all combustible dusts are explosible dusts. The ASTM test protocol consists of igniting a controlled concentration of a test dust in a 20 L chamber with a flame from a 10,000 J energy source and measuring the resulting pressure. If the resulting pressure exceeds one bar gage (14.5 psig), the dust is classified as a combustible dust and is perceived to be an explosible dust. The problem is that OSHA’s charge is to prevent dust explosions and fires. If the dust is combustible, but not an explosible dust, ineffective and costly enforcement actions would be taken to protect health and safety of employees as a consequence of the incorrect perception that this dust will fuel a deflagration.

The current philosophy of those supporting the existing protocol for laboratory testing is that all dusts that burn are fuel for either dust explosions of dust fires. According to Palmer (1973), “*Not all materials that will burn in air can cause dust explosions, even if finely divided and dry; that is, not all combustible dusts are explosible. All explosible dusts must be combustible.*”

The CAAQES method for determining whether a dust is explosible is to determine the minimum explosive concentration (MEC). If an MEC exists for a dust, it is an explosible dust. If an MEC does not exist, the dust is not an explosible dust. The ASTM protocol for determination of MEC’s uses pressure as the criterion for whether a deflagration occurred in the 20 L chamber when testing dusts. The CAAQES protocol uses multiple criteria for determining whether a deflagration occurred in the chamber when testing dusts. The CAAQES protocol for determining MEC’s is more accurate.

What is a deflagration?

The justifications for the increased emphasis by OSHA on safety in the work place are the incidences of dust explosions (deflagrations). It is possible that OSHA has the goal of preventing dust fires with the assumption that preventing dust fires will also prevent deflagrations. This assumption is incorrect. According to Palmer (1973), a dust fire is a consequence of ignition of an MEC with no containment. Without containment, the pressure produced by the burning dust does not result in an explosion. A deflagration is a consequence of an MEC being ignited with the subsequent pressure rupturing the initial containment (primary explosion) followed by multiple secondary explosions. Each explosion produces a pressure wave and fire front. The pressure wave may produce a secondary MEC which can be ignited by the relatively slow moving fire front. Most deflagrations include fire but the fire is a consequence of self-propagating flame of dust at or above the dust’s MEC. A dust fire does not result in the physical damage that is characteristic of deflagrations. It is illogical to assume that all combustible dust will have an MEC. An OSHA standard designed to prevent deflagrations and dust fires of all dusts deemed to be combustible dust using the ASTM protocol will impose explosion venting and housekeeping requirements with minimal improvement of worker safety. Dust fires are much more prevalent than deflagrations. To justify the determination of whether a dust is or is not combustible utilizing the ASTM protocol based upon prevention of dust fires is flawed. For a dust fire to occur, an MEC must exist. If an MEC does not exist, a dust fire will not occur. Hence, the ASTM protocol for determining whether a dust is combustible will not provide the necessary data needed to prevent either dust fires or explosions.

Gin Dust Testing

Samples of cotton gin dust (CGD) were sent to a commercial testing laboratory and to CAAQES for testing to determine whether CGD was an explosible dust. The CGD was obtained from cotton gins from across the cotton belt and screened to less than 75 μm. The testing laboratory results were that CGD was a class A combustible dust. This result was a consequence of measured pressure in a 20 L chamber in excess of 1 bar (14.5 psig). The CAAQES dust testing result was that CGD did not have an MEC and therefore was not an explosible dust. In addition, if the dust does not have an MEC, it cannot serve as fuel for a dust fire. Dust fires are similar to deflagrations in that a dust cloud at or above the MEC is ignited and a self-propagating flame results. The pressure is not contained so there is no rupture of the containment (explosion).

If the ignition of the dust cloud is a consequence of a stationary ignition source rather than flame passing through the cloud in a 20 L chamber, the burning is a consequence of a self- propagating flame and the dust has an MEC. If the flame does not self-propagate through the cloud, the dust does not have an MEC .The current ASTM protocol for testing of dusts to determine if they are explosible is in effect equivalent to a determination as to whether the dust will burn and produce pressure in a 20 L chamber and does not reflect whether the dust is explosible.

CAAQES Protocol

The indicator for a deflagration to occur in a CAAQES chamber is based on three criteria. They are: (a) the increase in pressure should burst the diaphragm; (b) the flame front should leave the chamber; and (c) a characteristic pressure vs. time curve. The only indicator for deflagration used by ASTM method is pressure rise; however, the pressure rise inside the chamber may not only result from combustion of the dust, but may also occur due to other factors like ignition source, burning of dust and gasification of unburned dust. The CAAQES protocol is illustrated in figure 1, which shows the explosion of corn starch with 50 g/m^3 concentration.

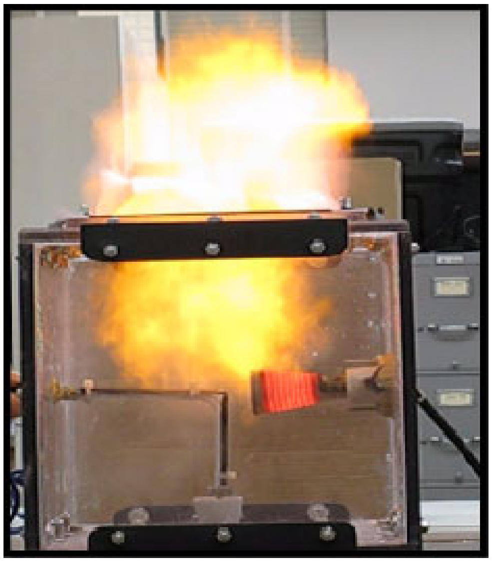

Figure 1. Cornstarch explosion with 50 g/m^3 concentration.

CAAQES Test Results

CGD and two additional dusts, corn starch and dust XX, were selected for the combustible dust testing. Dust XX was a dust with a very high level of non-combustibles. It was a dust that had been studied before and the MEC was determined to be approximately 75 g/m^3. The results for testing the dusts are shown in Table 1. Using the CAAQES method, the MEC for corn starch and dust XX were determined to be 43 g/m^3 and 73 g/m^3, respectively. Three replications were performed for each concentration tested. The explosions were indicated by the rupture of the paper diaphragm and the flame front leaving the chamber. For gin dust there were no deflagrations for any concentrations tested, including 500 g/m^3 and 1000 g/m^3. Several sparks were observed, but there were no ruptures of the diaphragm. CGD does not have an MEC; therefore, CGD is not an explosible dust.

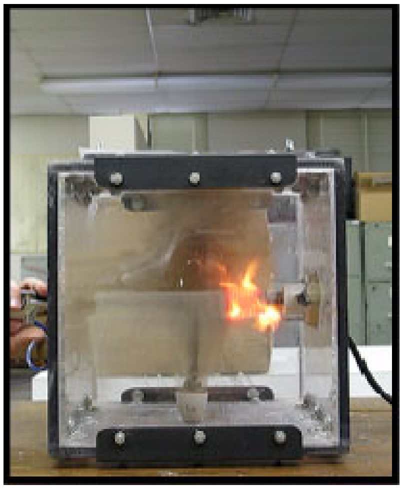

Figure 2. Gin dust burning at 500 g/m^3.

Figure 3. No explosion at 1000 g/m^3.

Table 1. Test results for determination of MEC's of corn starch, dust XX and CGD using the CAAQES protocol. The MEC's for corn starch and dust XX were determined to be 43 and 77 g/m^3, respectively. No concentration for CGD resulted in a deflagration. Therefore, CGD did not have an MEC.

Test	Conc. (g/m^3)	Def. (Y/N)	Test	Conc. (g/m^3)	Def. (Y/N)	Test	Conc. (g/m^3)	Def. (Y/N)
CS57_1	57	Y	XX93_1	93	Y	GD730_1	730	N
CS57_2	57	Y	XX93_2	93	Y	GD730_2	730	N
CS57_3	57	Y	XX93_3	93	Y	GD730_3	730	N
CS43_1	43	N	XX77_1	77	N	GD660_1	660	N
CS43_2	43	N	XX77_2	77	Y	GD660_2	660	N
CS43_3	43	Y	XX77_3	77	Y	GD660_3	660	N
CS40_1	40	Y	XX73_1	73	N	GD585_1	585	N
CS40_2	40	N	XX73_2	73	Y	GD585_2	585	N
CS40_3	40	N	XX73_3	73	N	GD585_3	585	N
CS37_1	37	N	XX70_1	70	N	GD440_1	440	N
CS37_2	37	N	XX70_2	70	N	GD440_2	440	N

The characteristic pressure versus time curves were obtained for three replications of each concentration of dust tested. Figure 4 shows the three pressures versus time curves for the three tests of cornstarch at 100 g/m^3. The pressure inside the chamber rose to 1.2 psi just prior to the diaphragm rupturing. This was followed by a rapid decrease in pressure to -0.8 psi. This phenomenon is typical of a primary dust explosion that may occur in any explosible dust handling facility.

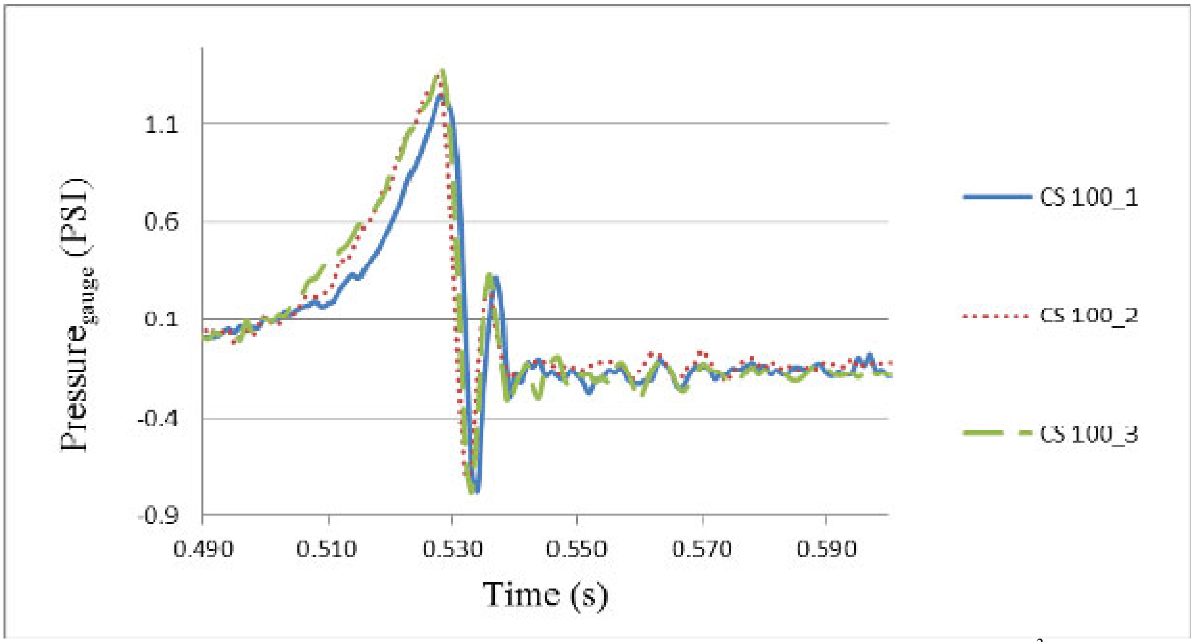

Figure 4. Pressure versus time curves for three replications of cornstarch at 100 g/m^3.

Figure 5 shows the pressure versus time curve for cotton gin dust at a concentration of 730 g/m3. For all three curves, there was no rise in pressure and no deflagration. **Thus cotton gin dust is not an explosible dust.**

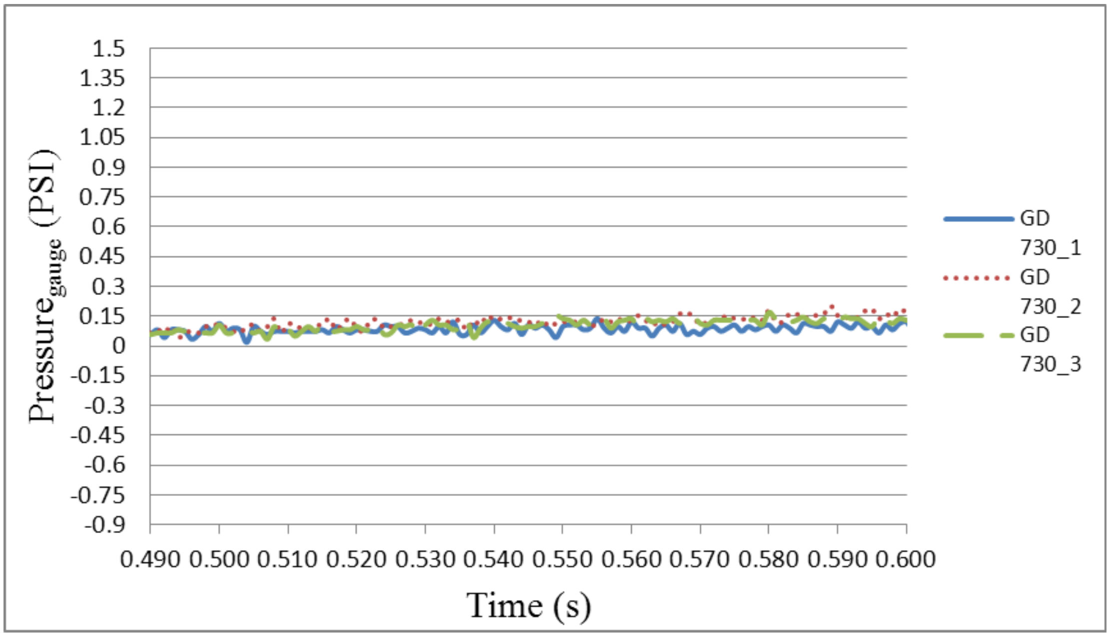

Figure 5.Pressure versus time curves for three replications of gin dust at 730 g/m^3.

Can sensing a deflagration in a 20 L chamber with pressure only be accomplished? The ASTM protocol specifies that measurement of a gage pressure increase of 1 bar (14.5 psig) from a test conducted on a dust in the 20 L chamber is an indication that a deflagration occurred in the chamber for that concentration.

How much dust burned in a 20 L chamber will result in a pressure rise in excess of 1 bar?

An approximation of the pressure produced in the 20 L chamber by burning 1 g of carbon was calculated using the ideal gas law and specific heat equations. The simple theoretical reaction for combustion of carbon (eq. 1) was used to simulate the reaction in combustible dust tests using the ASTM protocol.

Carbon was used as the surrogate for the combustible dust testing in the 20 L chamber. Equation 1 represents the chemical reaction for burning carbon dust. One mole of carbon (molecular weight [MW] = 12) reacts with 1 mol of oxygen (MW=32) with the requisite 3.76 mol of nitrogen (MW=28) contained in the air, producing 1 mol of carbon dioxide (MW=44). The carbon is solid prior to the reaction and does not impact the gas density.

$$C + O_2 + 3.76N_2 \rightarrow CO_2 + 3.76N_2 \tag{1}$$

Equation 1 can be used to determine the mass of O_2, N_2 and CO_2 for a reaction (burning) of 1 g of carbon. For carbon, 1 g equals 0.0833 mol. For the complete reaction of the 0.0833 mol of carbon, 0.0833 mol of O_2 (2.67 g) are required. Air consists of 3.76 mol of N_2 for every mol of O_2. Using air to provide the oxygen, 0.313 mol of N_2 are included before and after the reaction for each 0.0833 mol of O_2. The complete burning of 1 g of carbon will yield 0.0833 mol (3.67 g) of CO_2.

The following assumptions were used to calculate the pressure produced by burning dust in a totally enclosed 20 L chamber:

- The gas in the chamber prior to the reaction is at standard temperature and pressure (STP). (STP is a temperature of 25°C and barometric pressure of 1 atmosphere.)
- The molecular weights of the gases before and after the reaction are molar averages.
- The ideal gas equation can be used to calculate the gas density before and after the reaction.
- The mass of gas after the reaction is equal to the mass of gas prior to the reaction plus the mass of carbon that was burned based upon the conservation of mass.
- The change of temperature is defined by the specific heat equation.
- The energy in the enclosed chamber after the reaction is the sum of the ignition energy and the energy added by the combustion of carbon.

- The increase in pressure after the reaction is a consequence of increased mass of gas and the increased temperature.

Calculating the MW Before and After the Reaction

The MW before and after the reaction are molar averages. Equations 2 and 3 illustrate the MW calculations:

$$MW_{before} = (32+3.76*28)/4.76=28.8 \text{ g/mol} \tag{2}$$
$$MW_{after} = (44+3.76*28)/4.76=31.4 \text{ g/mol} \tag{3}$$

Calculating the Density of the Gases Before the Reaction in the 20 L Chamber Using the ASTM Protocol

Equation 4 illustrates the density calculation at STP prior to the burning of one gram of carbon. The density of gas in the 20 L chamber after the reaction is dependent upon temperature and pressure.

$$\rho_{before} = \frac{P_b * MW}{0.08206*(273+t)} = \frac{1*28.8}{0.08206*(273+25)} = 1.18\frac{g}{L} \tag{4}$$

where:

ρ_{before} = density of gases before reaction (g/L)
P_b = barometric pressure (atm)
t = chamber temperature (°C)

Calculating the Mass of Gas Before and After the Reaction

The mass of gas (at STP) in the 20L chamber before the reaction is 1.18 g/L *20 L = 23.6 g. The mass of gases in the 20L chamber after the reaction is 24.6 g. (The carbon is included in CO_2.)

Calculating Density and Chamber Pressure After the Reaction

Equation 5 gives the density of gas after the reaction and equation 6 is used to calculate the resulting pressure, given the temperature in the chamber:

$$\rho_{after} = \frac{P_c * MW}{0.08206*(273+t)} = \frac{P_c * 31.4}{0.08206*(273+t)} \tag{5}$$
$$P_c = 0.0032*(273+t) \tag{6}$$

where:

ρ_{after} = density of gases after reaction (g/L)
P_c = chamber pressure (atm),
t = chamber temperature (°C)

The temperature in the chamber after the reaction is a function of the energy released by burning of one gram of dust and the energy of the flame used as an ignition source. The temperatures range from 500-800 °C. Note that chamber temperatures of 500 °C and higher will result in pressures exceeding 1 bar suggesting a deflagration occurred in the chamber when in fact only 1 gram of dust had burned.

Table 2. Theoretical pressures for changes in chamber temperature using the ideal gas law.

Temperature (°C)	Absolute Pressure (atm)	Gage Pressure (atm)
500	2.5	1.5
600	2.8	1.8
700	3.1	2.1
800	3.5	2.5

Calculating Chamber Temperatures as the Result of Burning 1 g of Carbon and Igniting the Dust Cloud from 10,000 J Ignition Source

The specific heat at constant volume (C_V) is defined as amount of heat per unit mass (Δu) required to increase the temperature by 1°C. Equation 7 is used to calculate the change in temperature (ΔT) given the energy resulting from the ignition flame and the energy release from combustion.

$$C_v = \frac{\Delta u}{\Delta T} = 0.715 \frac{J}{g \cdot K} \tag{7}$$

The mass of gas in the chamber before the reaction is 23.6 g consisting of 5.5 g of O_2 and 18.1g of N_2. Burning 1 g of carbon will consume 2.7 g of O_2 in a stoichiometric reaction. Burning 2 grams of carbon will consume the available O_2. <u>There is enough O_2 in the chamber to burn only 2 grams of carbon (5.5/2.7)</u>.

Summary

The commercial testing laboratory reported no deflagrations with the totally enclosed Hartman tube for 110 tests for concentrations ranging from 208 to 16,700 g/m^3. ASTM and NFPA require that a more rigorous test using a 20-L chamber be performed prior to classifying the dust as non-combustible if no deflagrations resulted from the screening tests. The lab's test results from the 20 L chamber testing indicated that gin dust was a combustible dust. How can a non-combustible dust be classified as combustible? The answer is that the test protocol allows pressure from burning dust to be incorrectly interpreted as a deflagration when there is no self-propagating flame produced.

The commercial testing laboratory tested concentrations exceeding 1000g/m^3. 1000 g/m^3 is a test that requires dispersing 20 g of dust in the 20 L chamber. There is only sufficient oxygen to burn 2 of the 20 g inserted in the chamber. Why does the protocol require this testing when only a fraction of the dust can react in the chamber? The test should mimic what happens in the field and this test does not.

If we have 5.5 g of O_2 in the chamber prior to the reaction, the maximum amount of carbon that can react in the chamber is 5.5/2.67 = 2 g. (Note that no matter how much carbon is in the chamber, only 2 g can react because that is all of the oxygen available.)

If the insertion of the 10,000 J igniter flame into an empty chamber produces a gas temperature rise of 570°C, according to equation 6 the pressure would increase by 1.7 bars. The criterion for a deflagration in ASTM 1515 is a pressure increase of 1 bar. According to this result, the pressure increase resulting from the igniter energy would suggest that a deflagration occurred when there was no combustible dust in the chamber.

It is estimated that the internal energy of a combustible dust from an agricultural source is 16,000 J/g. The energy content of typical biomass is approximately 7,000 Btu/lb, which is 16,300 J/g. (Carbon has an energy content of 33,000 J/g.) If we assume that the energy content of the test dust is 16,000 J/g, we would be using approximately 50% of the energy in 1 g of carbon. The test used to determine the MEC of a suspected combustible dust must use a 2500 J, 5000 J, or 10,000 J pyrotechnic chemical igniter that produces a flame that according to ASTM (2008) "traverses the dust cloud to the opposite side of the chamber". The total energy in the chamber could range from 18,500 J to 26,000 J. The temperature rise using the specific heat equation (eq. 8) would range from 1060 to 1460K. This temperature rise would theoretically yield an absolute pressure of 3.4 to 4.6 atm. If the entire 2 g reacted instead of just 1 g, the pressure produced in the 20 L chamber would range from 6.8 to 9.2 atm.

Our findings were as follows:

- Cotton gin dust was incorrectly classified as an explosible dust.
- The ASTM protocol for determining if a dust is an explosible dust is flawed.
- The CAAQES method for determining whether a dust is an explosible dust is more accurate and is less likely to classify a dust as explosible when it is not.
- The terminology of testing to determine if a dust is combustible using the ASTM protocol implies that a combustible dust is an explosible dust. Not all combustible dusts are explosible.
- There are only 5.5 g of oxygen in the 20 L chamber. All oxygen will be consumed by only 2 g of dust. Why does the ASTM protocol require that 20 g be dispersed in the 20 L chamber to test a 1000 g/m^3 concentration? 18 g of the test dust are exposed to high temperatures but no oxygen.
- The ASTM test protocol does not mimic what happens in the field with a deflagration. Oxygen is never limited in a grain dust explosion.
- In the CAAQES method, only 10% of the chamber volume is needed to test for an MEC.

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