Journal of Hazardous Materials 159 (2008) 72–80

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Reducing aluminum dust explosion hazards: Case study of dust inerting in an aluminum buffing operation

Timothy J. Myers*

Exponent, Inc., 21 Strathmore Road, Natick, MA 01760, USA

ARTICLE INFO

Article history:
Received 26 February 2008
Accepted 27 February 2008
Available online 6 March 2008

Keywords:
Dust explosion
Inert
Aluminum dust

ABSTRACT

Metal powders or dusts can represent significant dust explosion hazards in industry, due to their relatively low ignition energy and high explosivity. The hazard is well known in industries that produce or use aluminum powders, but is sometimes not recognized by facilities that produce aluminum dust as a byproduct of bulk aluminum processing. As demonstrated by the 2003 dust explosion at aluminum wheel manufacturer Hayes Lemmerz, facilities that process bulk metals are at risk due to dust generated during machining and finishing operations [U.S. Chemical Safety and Hazard Investigation Board, Investigation Report, Aluminum Dust Explosion Hayes Lemmerz International, Inc., Huntington, Indiana, Report No. 2004-01-I-IN, September 2005]. Previous studies have shown that aluminum dust explosions are more difficult to suppress with flame retardants or inerting agents than dust explosions fueled by other materials such as coal [A.G. Dastidar, P.R. Amyotte, J. Going, K. Chatrathi, Flammability limits of dust—minimum inerting concentrations, Proc. Saf. Progr., 18-1 (1999) 56–63]. In this paper, an inerting method is discussed to reduce the dust explosion hazard of residue created in an aluminum buffing operation as the residue is generated. This technique reduces the dust explosion hazard throughout the buffing process and within the dust collector systems making the process inherently safer. Dust explosion testing results are presented for process dusts produced during trials with varying amounts of flame retardant additives.

1. Background

The subject manufacturing plant produces extruded aluminum products for a variety of applications. In a portion of the facility some of the products are processed in buffing lines to remove die lines created during the extrusion process and to polish the surface by removing oxidized aluminum. Typical buffing lines are shown in Fig. 1 and Fig. 2. On the buffing lines, extruded aluminum is placed on a table that traverses underneath a cylindrical buffing wheel inside of a dust collection hood. The buffing wheels are approximately 3 ft. long and 1–0.5 ft. in diameter and made of many circular fabric pads. A thick liquid or paste-like buffing compound is applied to the extruded aluminum before it passes underneath the buffing wheel. According to its material safety data sheet (MSDS), the buffing compound historically used at the facility was an oil-in-water emulsion that contained silicon dioxide.

Each of the buffers at the facility generates residue that is collected by either wet or dry dust collection systems. The buffing residue consists largely of non-metal buffing pad material and buffing compound with a measured aluminum content of about 6% and a moisture content ranging from approximately 14 to 43%. As demonstrated by the 2003 dust explosion at aluminum wheel manufacturer Hayes Lemmerz, facilities that process bulk metals are at risk due to dust generated during machining and finishing operations [1].

Shortly after the 2003 dust explosion at West Pharmaceuticals in North Carolina [3], the North Carolina Occupational Safety and Health Administration (NCOSHA) visited the facility and collected samples of buffing residue at the facility. The residue was dried and sieved to remove the fraction that would pass through a 200-mesh (75-μm) sieve. Standard dust explosion tests performed on this dried fine fraction indicated that it is a Class II combustible dust as defined by the National Fire Protection Association (NFPA) [4], National Material Advisory Board (NMAB) [5,6], and the Occupational Safety and Health Administration (OSHA) [7] for purposes of electrical classification. The dust explosion hazard of the finest fraction of the sample is typically conservatively higher than the hazard of the as-collected sample and represents the expected dust explosion hazard if the fines were to segregate from the remainder of the residue in the facility. No analysis was performed on buffing residues in their as-collected condition at the facility.

The facility determined that it would be prohibitively expensive to comply with the electrical requirements for a Class II area for the buffing lines and sought to abate the hazard by other means. The electrical requirements for Class II areas are intended to prevent electrical equipment from serving as an ignition source for dust

* Tel.: +1 508 652 8500; fax: +1 508 647 1899.
E-mail address: tmyers@exponent.com.

0304-3894/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhazmat.2008.02.106

Fig. 1. Typical buffing line. Buffing wheel is located in the center of the hood. The extruded aluminum is placed on a table that traverses back and forth under the hood. Buffing compound is applied to the aluminum and the buffing wheel is then lowered against the surface of the material. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

fires or explosions in the area. The facility instead chose to improve the inherent safety of the process by changing the combustibility characteristics of the residue and dust created by the buffing process, so that the dust is no longer classified as a Class II combustible dust. This method decreases both the ignition sensitivity and explosion severity of the dust, reducing the overall hazard of the dust, rather than just removing electrical ignition sources from the area. As described in more detail below, the combustibility of the residue produced by the buffing process is reduced by using buffing wheels and buffing compound that have been impregnated with a flame retardant.

1.1. Definitions of ignition sensitivity and explosion severity

For electrical classification of areas, both OSHA regulations and NFPA standards classify potential combustible dusts based on two empirical parameters, the ignition sensitivity and explosion severity. These parameters were originally developed by the United States Bureau of Mines, and are based on comparisons to the dust explosion properties of Pittsburgh seam coal [8]. The Pittsburgh seam coal test results are used as a baseline for the definitions of the subject dust ignition sensitivity and explosion severity. Pittsburgh seam coal is a reference dust historically used in dust testing and often used as a calibration dust by laboratories. Some of the test equipment originally used by the Bureau of Mines is no longer in common use and so the ignition sensitivity and explosion severity are now commonly determined based on ASTM test methods in the United States [9].

Fig. 2. Photograph of extruded aluminum traversing from left to right under buffing wheel and hood. A portion of bluish-green buffing wheel is visible in center of the picture. Tan colored buffing compound can be seen to the left of the buffing wheel, and the luster of the buffed aluminum surfaces can be seen to the right of the buffing wheel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Table 1
Summary of ignition sensitivity and explosion severity hazard criteria [6]

Degree of hazard severity	Ignition sensitivity	Explosion severity	Dust classification
Weak	<0.2	<0.5	Not classified
Moderate	0.2–1.0	0.5–1.0	Class II combustible dust
Strong	1.0–5.0	1.0–2.0	Class II combustible dust
Severe	>5.0	>2.0	Class II combustible dust

The ignition sensitivity (IS) of a dust is defined as [4,5]:

$$\mathrm{IS} = \frac{(\mathrm{MIT} \times \mathrm{MIE} \times \mathrm{MEC})_{\text{Pittsburgh Seam Coal}}}{(\mathrm{MIT} \times \mathrm{MIE} \times \mathrm{MEC})_{\text{Test Dust}}},$$

where MIT is the minimum ignition temperature of a dust cloud (ASTM E1491), MIE is the minimum ignition energy of a dust cloud (ASTM E2019), and MEC is the minimum explosible concentration of a dust cloud (ASTM E1515). The ignition sensitivity is therefore defined as the ratio of the ignition properties of the Pittsburgh seam coal to the ignition properties of the test dust.

The explosion severity (ES) of a dust is defined as [4,5]:

$$\mathrm{ES} = \frac{\left[P_{\max} \times (\mathrm{d}P/\mathrm{d}t)_{\max}\right]_{\text{Test Dust}}}{\left[P_{\max} \times (\mathrm{d}P/\mathrm{d}t)_{\max}\right]_{\text{Pittsburgh Seam Coal}}},$$

where $P_{\max}$ is the maximum pressure rise and $(\mathrm{d}P/\mathrm{d}t)_{\max}$ is the maximum rate of pressure rise during testing in a closed chamber with high turbulence (ASTM E1226). The explosion severity is therefore defined as the ratio of the pressure rise properties of the test dust to the pressure rise properties of Pittsburgh seam coal.

Table 1 shows a qualitative summary of the severity of dust explosion hazards associated with dust with varying ignition sensitivity and explosion severity indices. As seen in the table, dusts with an ignition sensitivity of less than 0.2 and an explosion severity less than 0.5 are not classified as Class II Combustible Dusts and do not require Class II electrical equipment.

The ignition sensitivity and explosion severity parameters are not universally accepted as criteria for assessing dust explosion hazards. A 1987 US Bureau of Mines report criticized the indexes stating that they were outdated and should no longer be used [10]. However, they are still in common use and current OSHA regulations and NFPA guidelines use these parameters for electrical classification.

2. Addition of inert materials to combustible dusts

The approach employed by the subject facility to lessen the risk of an explosion was to add flame retardants to the buffing pads and/or buffing compound. The facility worked with two manufacturers who provided varying levels of flame retardant in their products and conducted a series of trials in order to determine the dust explosion hazards of the resulting buffing residue. The specific flame retardant used in the final formulation is proprietary, but is believed to be an aqueous halogenated compound.

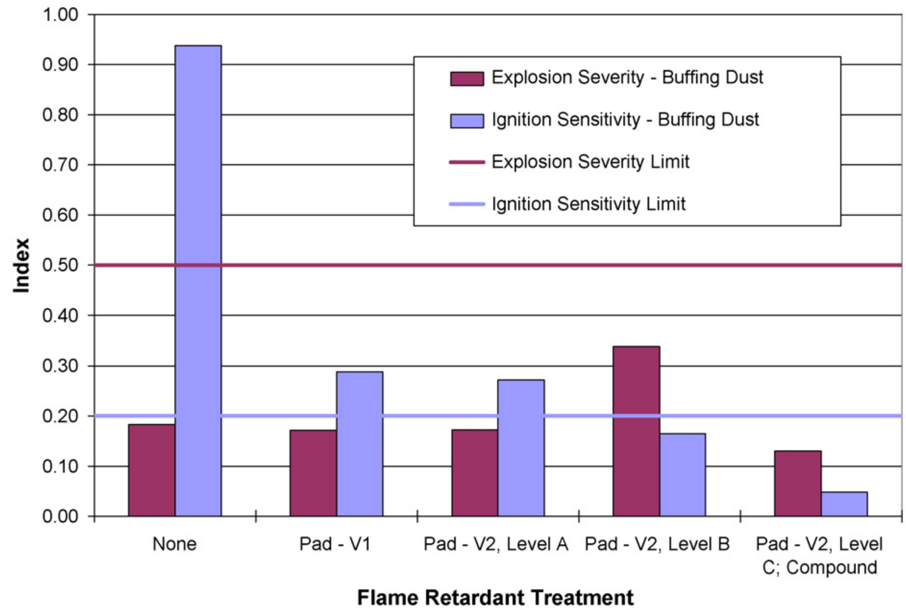

Fig. 3. Explosion severity and ignition sensitivity for sieved and dried samples of buffing residue with no flame retardant and varying levels of flame retardant added to buffing pads and buffing compound. The horizontal lines at 0.50 and 0.20 indicate the criteria for explosion severity and ignition sensitivity of Class II combustible dusts.

Adding inert or extinguishing materials to a potentially combustible dust is a recognized method to minimize or eliminate the fire and explosion hazards of a combustible dust described in the open literature [2,11–13], reference books [14–18], and generally accepted industrial standards [19,20]. Historically, this method has been most widely used in coal mines where rock dust is spread on surfaces of the mine to inert coal dust. Testing in the literature indicates that this approach can also be used to reduce or eliminate the dust explosion hazard of aluminum dusts. Dastidar et al. performed tests on 17-μm diameter aluminum dust where it was found that mixing the dust with 55–60% sodium bicarbonate or 60–65% monoammonium phosphate rendered the dust non-explosive (based on a criterion of an overpressure of 2 bar a, *i.e.* a pressure rise of 1 bar) at all dust cloud concentrations tested [2]. Sodium bicarbonate and monoammonium phosphate are commonly used as fire suppression agents.

Adding inert solids to combustible dusts sees limited use in industrial applications because of (1) the large amount of inert material required; (2) the contamination of the normally valuable combustible dust; (3) the requirement that the inert dust be intimately mixed with the combustible dust; and (4) the possibility of segregation of the combustible dust from the inert material.

While these issues limit the use of inerting materials in many industrial applications, they are not of concern at the subject buffing facility. The aluminum dust created by the buffing operation is a waste material and contamination of the dust with an extinguishing or inert material is not detrimental. In fact, as part of the buffing process the aluminum dust is always contaminated and diluted by

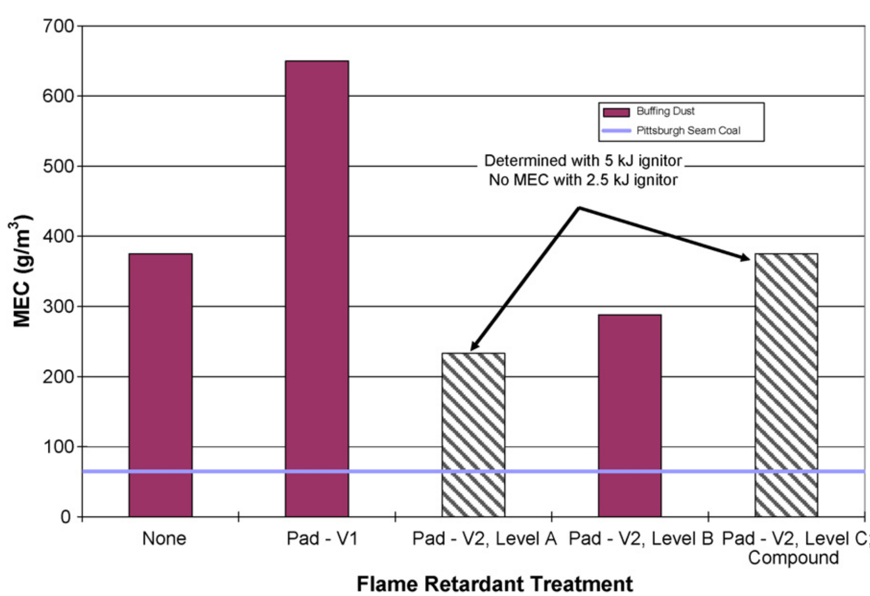

Fig. 4. Comparison of measured MEC for samples. The MEC of Pittsburgh seam coal measured on the same apparatus is shown by the blue line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

the buffing compound and material from the buffing wheels. Additionally, the buffing operation intimately mixes the aluminum dust with the buffing compound and buffing wheel material. As will be described later, the finest fraction of residues from the buffing process was tested to ensure that even if segregation of the dust occurred, the dust would be adequately inerted. Lastly, the explosion hazard of the original buffing residue was already significantly lower than that of pure aluminum dust, due to the presence of other materials within the residue. This makes the buffing residue dust easier to inert than pure aluminum dust.

3. Testing of dust from buffing residues

A series of trials were performed on a single buffing machine line using buffing pads and/or buffing compound containing flame retardant. Before running these trials, the buffing machine and dust collection system were both cleaned out. After cleaning, the buffing machine was operated for four or five days with buffing pads and/or buffing compound containing flame retardant. On the last day of operation a sample was collected from a hopper located below the dust collection cyclone and sent out for testing. Test results from these trials and original tests on samples collected by NCOSHA are shown in Table 2 and Fig. 3. Test results for the reference Pittsburgh Seam Coal are also shown in Table 2. All testing was performed at the Kidde Fenwal Combustion Research Center in Holliston, Massachusetts.

In the testing reported in Table 2 and Fig. 3, samples from the dust collector were first sieved and dried, and only the fraction of the sample that passed through a 200 mesh (75 μm) sieve was tested. Pittsburgh Seam Coal was tested in its as received state. The actual residue created by the process is moist and also contains larger particles, which would be expected to have a lower dust explosion hazard than the dried fine fraction that was tested. The samples ultimately tested therefore provide a conservatively high estimate of the dust explosion hazard present at the facility. This conservative testing procedure mimics the conditions that would be present if the finest particles of the residue became segregated from other components and became dried. Although the aluminum concentration was not measured in the tested fine fraction, it is expected to be higher than the measured value of 6% in the as-collected buffing residue. The dust testing laboratory indicated that a significant amount of fibrous material was separated from the residue during sieving, likely leaving particles of mostly aluminum and dried buffing compound.

The sample listed in the left most column of Fig. 3 and Table 2 was collected by NCOSHA and contained no flame retardant. These results serve as reference values for the fine component of the buffing residue while using traditional buffing pads and compound without flame retardant. Dust from this buffing residue is referred to as the original dust in this paper. For all samples represented in the table, the explosion severity is significantly below the 0.5 criterion for a Class II combustible dust, constituting a weak hazard severity. The ignition sensitivity value of 0.94 for the NCOSHA sample is above the 0.2 criterion for a Class II combustible dust. The measured ignition sensitivity represents a moderate dust explosion

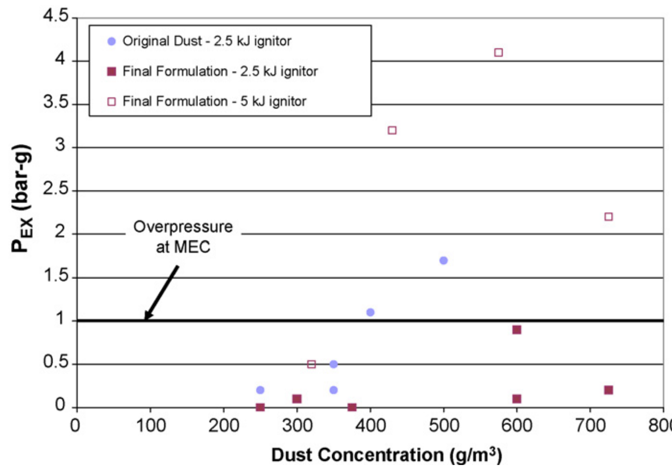

Fig. 5. Comparison of measured explosion pressure rise for the original dust and dust generated using the final formulation of buffing pad and compound. The pressure criterion for the MEC test is shown by the horizontal line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

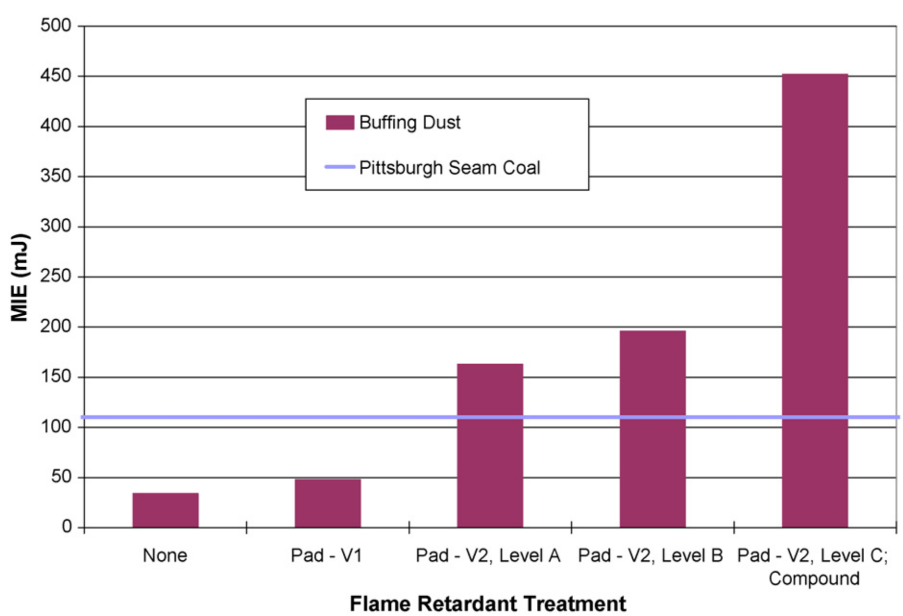

Fig. 6. Comparison of measured MIE for samples. The MIE of Pittsburgh seam coal measured on the same apparatus is shown by the blue line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Table 2
Summary of test results on sieved and dried samples of buffing residue

Buffing pad	Vendor 1, no flame retardant	Vendor 1, Flame Retardant	Vendor 2 Flame Retardant Level A	Vendor 2, Flame Retardant Level B	Vendor 2, Flame Retardant Level C	**Pittsburgh seam coal (reference dust)**
Buffing compound	Vendor 1, no flame retardant	Vendor 1, No Flame Retardant	Vendor 1, No Flame Retardant	Vendor 1, No Flame Retardant	Vendor 2, Flame Retardant	
Sample collection	NCOSHA	Trial	Trial	Trial	Trial	
P_{max} **(bar-g)**	4.9	4.6	4.7	5.6	4.7	7.3
$(dP/dt)_{max}$ **(bar/s)**	116	116	114	188	86	426
K_{St} **(bar-m/s)**	31	31	31	51	23	124
Explosion Severity	**0.18**	**0.17**	**0.17**	**0.34**	**0.13**	
MEC (g/m³)	375	650	233[a]	288	375[b]	65
MIT (°C)	350	465	405	450	513	585
MIE (mJ)	34	48	163	196	452	110
Ignition sensitivity	0.94	0.29	0.27	**0.16**	**0.05**	
Dust classification	Class II combustible	Class II Combustible	Class II Combustible	Not Classified	Not Classified	

Bold values are the calculated ignition sensitivity and explosion severity which are used to determine if the material is a Class II combustible dust.
[a] MEC measured with a 5-kJ ignitor. When tests were performed with a 2.5-kJ ignitor, the pressure rise was less than 1 bar in four tests at concentrations from 250 to 425 g/m^3, suggesting that the system may have been overdriven with the 5-kJ ignitor.
[b] MEC measured with a 5-kJ ignitor. When tests were performed with a 2.5-kJ ignitor, pressure rise was less than 1 bar in five tests at concentrations from 375 to 725 g/m^3, suggesting that the system may have been overdriven with the 5-kJ ignitor.

hazard and indicates that the fine fraction from the dust residue would represent a moderate ignition hazard if it became segregated from the bulk residue. In order to reduce the ignition sensitivity and avoid the Class II combustible dust classification, it is therefore necessary to raise the minimum ignition energy, dust cloud ignition temperature, or minimum explosible concentration.

The test results for the trial samples with flame retardant are listed in the four center columns of Table 2. The trial with Vendor 1 buffing pads containing flame retardant shown in the second column of test data significantly lowered the ignition sensitivity to 0.29 from the 0.94 value measured in the NCOSHA sample. However, this value is still slightly above the 0.20 criterion for Class II combustible dusts.

Three trials using Vendor 2 buffing wheels treated with a proprietary flame retardant are shown in the next three columns of Table 2. In the trial, increasing levels of flame retardant were used in the buffing pads (Levels A, B and C). The first trial, conducted using Vendor 2 buffing pads with the lowest level of flame retardant (Level A), reduced the ignition sensitivity of the fine fraction of the buffing residue to 0.27; slightly above the 0.2 criterion for Class II combustible dusts. In the second trial, an increased level of flame retardant (Level B) was used in the Vendor 2 buffing pads and the ignition sensitivity was reduced to 0.17; slightly below the 0.2 criterion for Class II combustible dusts.

In the last trial, the highest level of flame retardant (Level C) was used in the Vendor 2 buffing pads and a Vendor 2 buffing compound containing flame retardant was used in place of the Vendor 1 buffing compound. Tests of the fine fraction of that buffing residue showed an ignition sensitivity of 0.05, approximately four times lower than the 0.2 criterion. In this last trial and an earlier trial, the MEC was determined using 5-kJ ignitors rather than 2.5-kJ ignitors. When the testing was repeated with 2.5-kJ ignitors the pressure rise criterion of the ASTM E1515 test method for measuring MEC was not met even at dust concentrations almost double the MEC measured with 5-kJ ignitors [9]. As described in the test method, this indicates that the system may have been overdriven during the tests. The term 'overdriven explosion' refers to a condition that can occur with weakly explosible dusts in small test vessels like the 20-L sphere where the flame from high energy ignitors can occupy a significant fraction of the vessel and cause a dust cloud to combust, even though it would not normally self-propagate a flame. By similar arguments, the P_{max} and $(dP/dt)_{max}$ testing for this sample may also be overdriven by the 10-kJ ignitors used in the testing for explosion severity. This is discussed in more detail in the next section but suggests that the actual ignition sensitivity and explosion severity of the dust from the last trial may actually be lower than reported.

Ultimately, the Vendor 2/Level C formulation, containing the highest level of retardants, was chosen for use at the facility and is referred to as the final formulation throughout this paper. This material was selected so that it would ensure the ignition sensitivity and explosion severity values were well below the required limits. Under tests, the new formulation had the most significant effect on parameters in the ignition sensitivity, namely minimum ignition energy and dust cloud ignition temperature. The effect of flame retardant on minimum explosible concentration, maximum pressure rise, and maximum rate of pressure rise was minimal and may have been masked due to overdriving of the tests performed in 20-L vessels.

3.1. *Possible overdriving of testing*

With dusts that represent a greater dust explosion severity, a 20-L vessel and normally used ignitors produce results consistent with tests in the larger 1 m^3 vessel or larger scale testing. With some dust that are weakly explosive or near the flammability limits, a 20-L vessel and the normally used ignitors can overdrive the system [21]. When evaluating inerting of dusts, it is important to examine the effect of ignition energy.

In the ASTM E1515 test method, the MEC is determined by measuring the minimum dust concentration that when ignited will

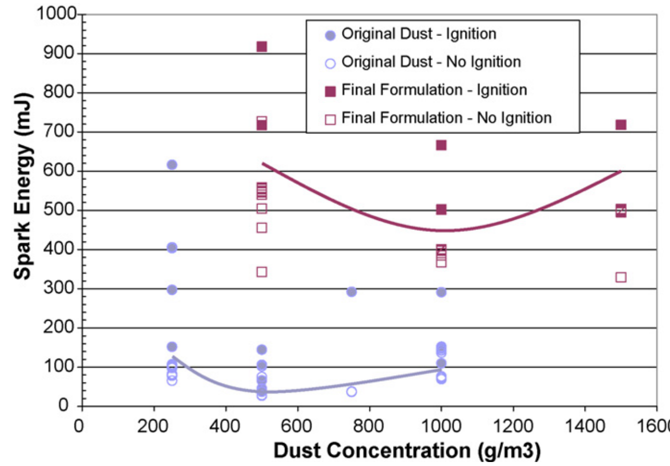

Fig. 7. Comparison of ignition energy data for the original dust and dust generated using the final formulation of buffing pad and compound. Tests that resulted in ignition are shown as solid symbols, tests that did not result in ignition are shown with open symbols. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

raise the pressure of the test chamber by a factor of 2 [9]. Typically this involves a 1 bar pressure rise from a 1 bar absolute initial pressure before ignition. The true MEC should be measured in conditions where it is independent of the energy of the ignition source. In the 20-L sphere MEC testing of dust from two of the trials, the MEC pressure criterion could not be met when using a 2.5-kJ ignitor even at dust concentrations almost double the MEC measured with 5-kJ ignitors, indicating that the system may have been overdriven.

With dust that represents a weak explosion hazard, the overdriven condition may preheat or burn dust within the flame of the ignitor, even though the dust would not normally burn due to propagation of a self-sustained flame through the dust cloud itself. The pressure rise measured in the tests with the higher energy 5-kJ ignitors may therefore be due to combustion taking place in the 20-L sphere because of the ignitor rather than due to self-propagation of a flame front through the dust cloud. In systems that are not

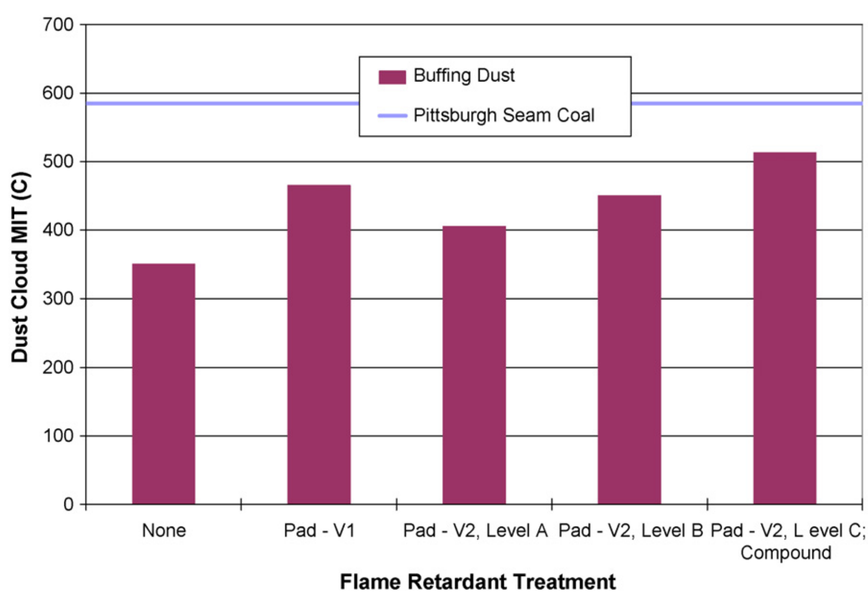

Fig. 8. Comparison of measured dust cloud ignition temperature for samples. The dust cloud ignition temperature of Pittsburgh seam coal measured on the same apparatus is shown by the blue line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

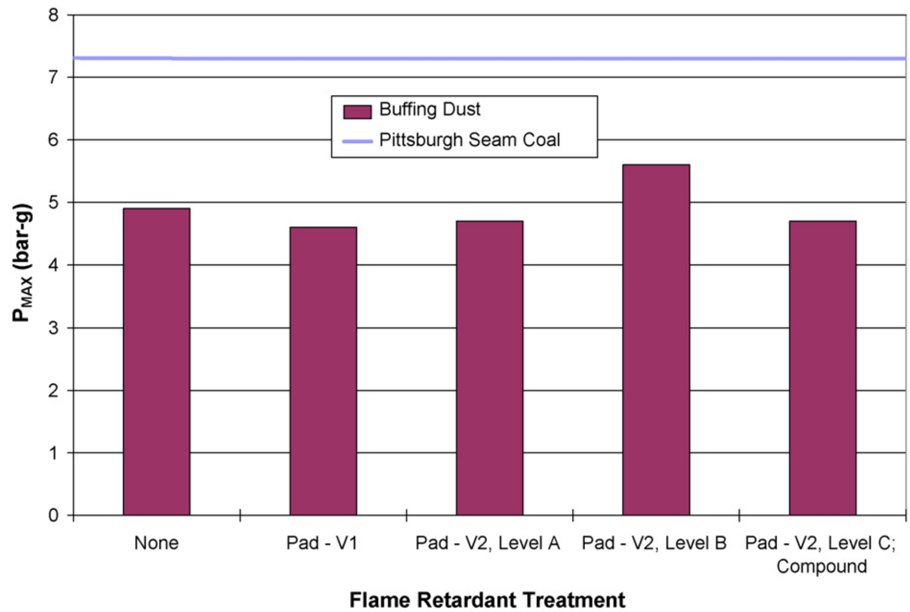

Fig. 9. Comparison of maximum explosion overpressure of different dust samples. The maximum overpressure of Pittsburgh seam coal measured on the same apparatus is shown by the blue line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

overdriven, the MEC is independent of the ignitor energy. Tests run in a larger vessel (such as a 1-m^3 (1000-L) vessel) with a larger dust cloud, where the igniter flame represents a smaller portion of the vessel, may indicate that the actual MEC of the dust is higher. A higher value of the MEC would result in even lower calculated ignition sensitivity. By similar arguments the P_{max} and $(dP/dt)_{max}$ testing for this sample may also be overdriven by the 10-kJ ignitors used in the testing for explosion severity. A portion of the dust, in this case, may again be combusting due to the ignitor flame, rather than due to propagation of a self-sustaining flame through the dust. If so, the true explosion severity would also be lower than reported.

The overdriving phenomenon is discussed in detail by Cashdollar and Chatrathi. Their conclusions are based on testing of three coals dust samples of varying volatility in both 20-L and 1-m^3 vessels [22]. In their tests, they found that a 2.5-kJ ignitor in a 20-L vessel produced results most similar to tests in a 1-m^3 vessel. Similar behavior may occur if dust from the final formulation buffing residue were tested in larger vessels. Another study of solid inerting of dusts found that for some dusts, a 0.5 kJ ignition energy in a 20-L vessel most closely matched test results in a 1-m^3 vessel [21].

For future research of the effectiveness of solid inerting, it would be beneficial to perform tests in larger vessels. However, testing in larger vessels requires larger dust samples and additional testing time and expense. Testing in a larger vessel was not required in this study as it would have only likely demonstrated that the dust explosion hazard was even weaker than determined in the 20-L vessel.

4. Detailed test results

The determination of the effectiveness of the flame retardants involves the comparison of the results of individual tests for each dust sample relative to the value for Pittsburgh seam coal. The following text provides a more detailed description of the tests performed and their results. Where appropriate a comparison of the test results as a function of concentration for both the original dust and dust created using the final formulation of buffing pads and compounds is also presented.

4.1. Minimum explosible concentration

The minimum explosible concentration (MEC) was measured in a 20-L sphere using 2.5-kJ ignitors. For two of the samples 2.5-kJ as well as 5-kJ ignitors were used. Results in Fig. 4 show that in all cases the MEC of the dust samples was significantly greater than the MEC of Pittsburgh seam coal (65 g/m^3). This indicates that a higher dust cloud concentration is required to create 1 bar pressure rise with the fine fraction of the buffing residue than with Pittsburgh seam coal. As discussed earlier, the use of larger ignitors may have influenced the results by 'overdriving' the explosion. The true MEC for the 5-kJ tests is therefore expected to be higher.

The explosion pressure rise as a function of dust cloud concentration is shown in Fig. 5 for the original dust sample created without flame retardant and the dust sample obtained from the final formulation buffing residue with flame retardant. For the

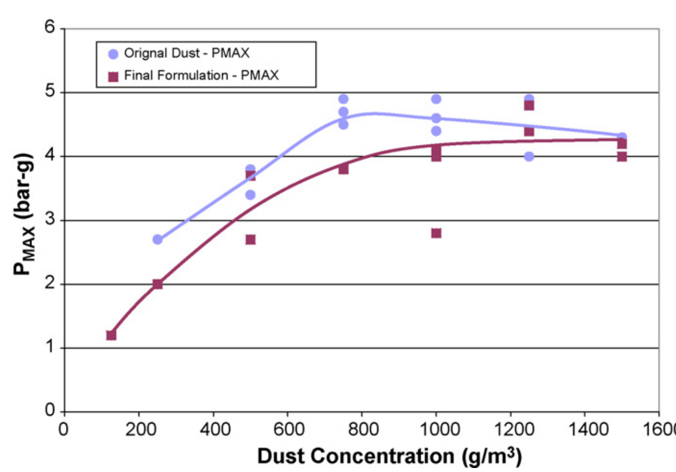

Fig. 10. Comparison of maximum explosion overpressure for the original dust and dust generated using the final formulation of buffing pad and compound. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

original dust, tests performed at 400 g/m^3 and higher resulted in pressure rises above 1 bar, reaching the criterion for the MEC. For dust with the final formulation a pressure rise above 1 bar is not reached with 2.5-kJ ignitors at the concentrations tested, but is reached with 5-kJ ignitors.

4.2. Minimum ignition energy

The Minimum Ignition Energy was measured in a modified Harman tube approximately 0.5-L in volume. As can be seen in Fig. 6, the minimum ignition energy greatly increased with the addition of flame retardant, from well below the 110-mJ MIE of Pittsburgh seam coal to significantly above it.

Data from individual ignition energy tests for the original dust sample created without flame retardant and the dust sample from the final formulation buffing residue with flame retardant are shown in Fig. 7. At each dust cloud concentration level, tests are run in order to determine the minimum spark energy at which ignition occurs. The maximum spark energy at which ignition does not occur is determined by performing ten repeat tests. As can be seen in the plot, the final formulation significantly increases the ignition energy over a range of dust cloud concentrations making it more difficult to ignite. However, the measured MIE of 452 mJ for the final formulation is quite low considering the difficulty of igniting the dust in the 20-L vessel with a 2.5-kJ ignitor. The difference in MIE test results which use an electric spark and MEC tests results which use a pyrotechnic ignitor was not investigated. The ignition criteria in the MIE testing is that a flame propagates a significant distance from the electrodes or a paper diaphragm on the top of the vessel bursts. Both criteria may be easier to meet than obtaining a 1 bar overpressure in the 20-L vessel, the criterion used in the MEC testing.

4.3. Dust cloud ignition temperature

Dust cloud ignition temperatures were determined in a Godbert–Greenwald furnace where a dust cloud is dispersed at the top of a cylindrical furnace at elevated temperatures and ignition is gauged by whether a visible flame is seen as the sample falls through the furnace. No ignition is deemed to occur if five successive tests at a temperature do not result in ignition. The resulting dust cloud ignition temperatures for the dust samples are shown in Fig. 8. The dust cloud ignition temperature for all samples is less than that of Pittsburgh seam coal (585 °C). The addition of flame retardant increased the ignition temperature of the dust making it more difficult to ignite. No data is presented as a function of dust cloud concentration as the testing was only performed at a few concentrations.

4.4. Maximum explosion overpressure

Maximum overpressures were measured in a 20-L spherical vessel with a 10-kJ ignitor. As described earlier, at least some of these test results may be conservatively high due to overdriving of the system by the ignitor. Nonetheless results in Fig. 9 demonstrate that both the original dust samples and samples containing flame retardant have maximum explosion overpressures less than those corresponding to Pittsburgh seam coal (7.3 bar g). In general, Fig. 9 shows that the presence of the flame retardant has minimal effect on the maximum explosion overpressure. The maximum overpressures recorded by these tests are typically not reached in industrial dust explosions, however, because most structures such as buildings fail at significantly lower overpressures.

Data from individual overpressure tests of the original dust sample created without flame retardant and the dust sample from the final formulation buffing residue with flame retardant are shown in Fig. 10. The maximum overpressure recorded with the dust generated with flame retardant is slightly lower than the original dust over most of the range of dust concentrations.

4.5. Maximum rate of pressure rise

The rate of pressure rise is also determined during overpressure tests. This is typically reported as the K_{St}, a volume normalized rate of pressure rise. The K_{St} characterizes the explosion violence and is an important parameter in determining explosion venting require-

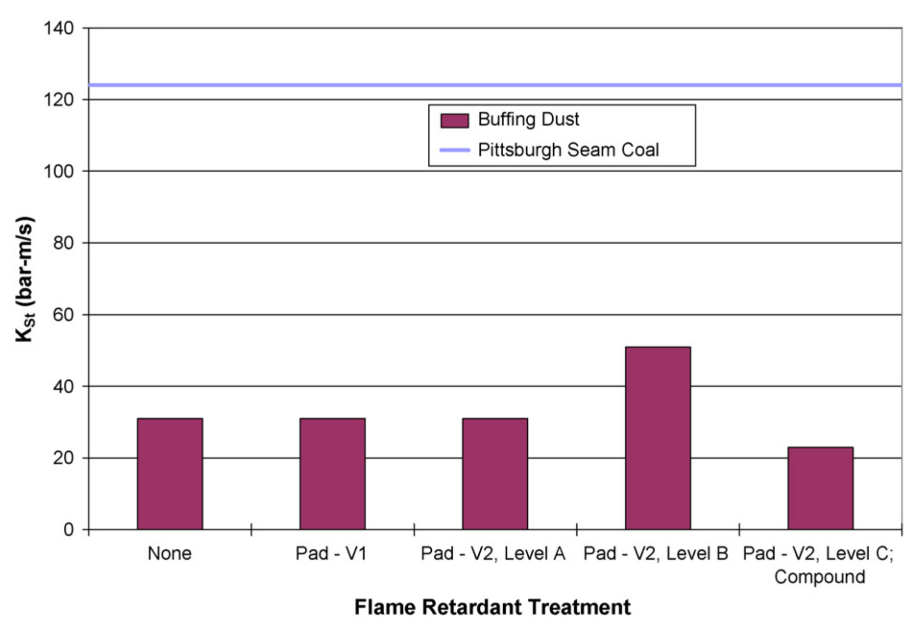

Fig. 11. Comparison of measured maximum KST for all samples over all concentrations. KST is a volume normalized rate of pressure rise. The KST of Pittsburgh seam coal measured on the same apparatus is shown by the blue line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

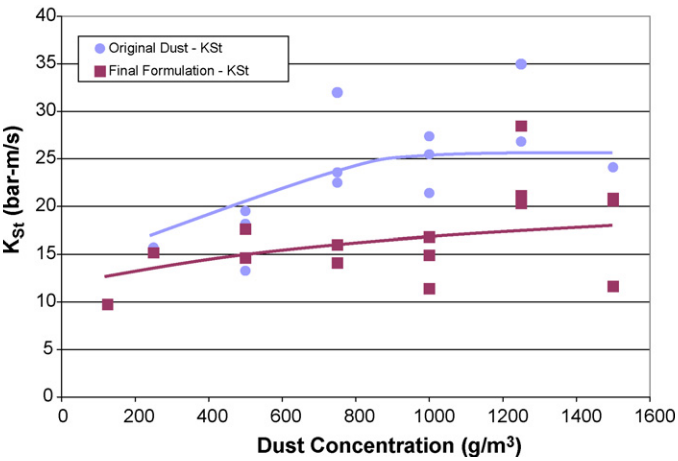

Fig. 12. Comparison of rate of pressure rise for the original dust and dust generated using the final formulation of buffing pad and compound.

ments. The K_{St} data for at least some of the samples shown in Fig. 11 may be conservatively high due to overdriving by the ignitors. The K_{St} for all samples is significantly below the K_{St} of Pittsburgh seam coal (124 bar g). While the presence of flame retardant had a small and inconsistent effect on the K_{St}, the dust from the final formulation has a lower K_{St} than other samples by more than 25%.

The measurements of rate of pressure rise obtained from separate dust samples are shown in Fig. 12. The K_{St} is lower for the new formulation of buffing pads over the concentration range tested.

5. Summary

The addition of flame retardant to buffing pads and compound provides an effective method to reduce the dust explosion hazard of the buffing residue created at the facility. Testing shows that even the finest fraction of the residue in its dried state has ignition sensitivity and explosion severity parameters significantly below those required to classify the area as a Class II combustible dust. This approach removes the need to use Class II electrical equipment in the buffing area and also reduces the hazard of the dust in the presence of other ignition sources, making the process inherently safer. The use of the flame retardant appeared to have the most significant effect on parameters related to the ignition sensitivity, namely minimum ignition energy and dust cloud ignition temperature. The effect of flame retardant on minimum explosible concentration, maximum pressure rise, and maximum rate of pressure rise was minimal. The effect of the flame retardant on these values may be masked due to overdriving of the tests performed in 20-L vessels. Use of larger test vessels such as 1-m^3 vessel is recommended for future research on inerting or when testing weakly explosible dusts.

Similar inerting techniques may be feasible in other industrial processes where dust is generated as a byproduct in processes and where flame retardants can be added as the dust is generated. While the current work focused on meeting the criteria for non-classified electrical locations, similar inerting techniques may sufficiently lower the dust explosion hazard of a material to eliminate the applicability of other standards. For instance, since the time of this study the 2006 edition of NFPA 484 *Standard for Combustible Metals* has incorporated specific testing methods to determine if a specific dust represents a sufficient hazard for the standard to be applicable to a facility.

References

[1] U.S. Chemical Safety and Hazard Investigation Board, Investigation Report, Aluminum Dust Explosion Hayes Lemmerz International, Inc., Huntington, Indiana, Report No. 2004-01-I-IN, September 2005.
[2] A.G. Dastidar, P.R. Amyotte, J. Going, K. Chatrathi, Flammability limits of dust - minimum inerting concentrations, Proc. Saf. Progr. 18-1 (1999) 56–63.
[3] U.S. Chemical Safety and Hazard Investigation Board, Investigation Report, Dust Explosion, West Pharmaceutical Services, Inc., Kinston, North Carolina, Report No. 2003-07-I-NC, September 2004.
[4] National Fire Protection Association, NFPA 499 Recommended Practice for the Classification of Combustible Dusts and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas, 2004 ed., Sections 5.7.2.5.2, 3.3.6, A-3.3.6, 3.3.9, A-3.3.9.
[5] National Materials Advisory Board, Classification of Dusts in Accordance with the National Electrical Code, Report of the Panel on Classification of Combustible Dusts of the Committee on Evaluation of Industrial Hazards, Publication NMAB 353-3, 1980.
[6] National Materials Advisory Board, Classification of Dusts Relative to Electrical Equipment in Class II Hazardous Locations, Report of the Committee on Evaluation of Industrial Hazards, Publication NMAB 353-4, 1982.
[7] U.S. Code of Federal Regulations, 29 CFR 1910.307 Hazardous (classified) locations, 29 CFR 1910.399 Definitions applicable to this subpart, 20 CFR 1910, Subpart S, Appendix A—Reference Documents.
[8] M. Jacobson, J. Nagy, A.R. Cooper, F.J. Ball, Explosibility of Agricultural Dusts, U.S. Bureau of Mines Report of Investigation 5753, 1961.
[9] ASTM, Annual Book of ASTM Standards, Volume 14.02, Conshocken, Pennsylvania, 2007.
[10] M. Herzberg, A critique of the dust explosibility index: an alternative for estimating explosion probabilities, U.S. Bureau of Mines Report of Investigations, 9095, 1987.
[11] P.R. Amyotte, Solid inertants and their use in dust explosion prevention and mitigation, J. Loss Prevent. Proc. Ind. 19 (2006) 161–173.
[12] P.R. Amyotte, M.J. Pegg, F.I. Khan, M. Nifuku, T. Yingxin, Moderation of dust explosions, J. Loss Prevent. Proc. Ind. 20 (2007) 675–687.
[13] P.R. Amyotte, M.J. Pegg, Dust explosion prevention by addition of thermal inhibitors, Proc. Saf. Progr. 11-3 (1992) 166–173.
[14] W. Bartnecht, Dust Explosions, Course, Prevention, Protection, Springer-Verlag, 1989, p. 141.
[15] R.K. Eckhoff, Dust Explosions in the Process Industries, Butterworth-Heinemann, 1997, pp. 56, 74.
[16] M. Hertzberg, K.L. Cashdollar, Introduction to dust explosions, in: K.L. Cashdollar, M. Hertzberg (Eds.), Industrial Dust Explosions, 958, ASTM Special Technical Publication, 1986, p. 29.
[17] W. Bartknecht, Preventive and design measures for protection against dust explosions, in: K.L. Cashdollar, M. Hertzberg (Eds.), Industrial Dust Explosions, 958, ASTM Special Technical Publication, 1986, p. 165.
[18] K.N. Palmer, Dust Explosions and Fires, Chapman & Hall, London, 1973, p. 77.
[19] National Fire Protection Association, NFPA 654 Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids, 2000, Section 3.1.1(5).
[20] FM Global Property Loss Prevention Data Sheet 7-76, Combustible Dust Explosions and Fire, Sections 2.3.4.2 and 2.4.3.2.
[21] A. Dastidar, P. Amyotte, Determination of minimum inerting concentrations for combustible dusts in a laboratory-scale chamber, Trans. IChemE 80-B (2002) 287–297.
[22] K.L. Cashdollar, K. Chatrathi, Minimum explosible dust concentrations measured in 20-L and 1-m^3 chambers, Combust. Sci. Technol. 87 (1992) 157–171.