Laboratory and Large-Scale Dust Explosion Research

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This paper describes dust explosibility research in full-scale experimental mines and a 20-L laboratory chamber at the U.S. Bureau of Mines and in a 1-m³ laboratory chamber at Fike Corporation. The purpose of this research is to improve safety in mining and other industries that manufacture, process, or use combustible dusts. As part of this work, carbonaceous dusts with a wide range of volatilities and various particle size distributions were studied. Laboratory data on the minimum explosible concentrations of predispersed dusts were comparable to mine data for nominal dust loadings that were dispersed by the aerodynamic disturbance from a gas ignition zone. Recommendations are given on the limitations of small-scale testing such as "overdriving" by too strong of an ignitor. The effect of dust particle size on explosibility data is illustrated for coal and aluminum dusts. For both dusts, the finest sizes were the most hazardous. The inerting requirements for preventing explosions were also measured in both laboratory and large-scale systems. All the data show relatively good agreement between the laboratory and the large-scale tests.

Introduction

An accurate knowledge of the explosibility behavior of materials is essential for a realistic safety evaluation of their use in manufacturing and processing. Various books such as references *1* through *6* have been published on the subject of dust and gas explosion hazards. This paper will concentrate on the hazards of dust and hybrid mixture explosions as measured in both laboratory chambers and in full-scale experimental mines. Explosion characteristics studied include minimum explosible concentrations or lean flammable limits, maximum explosion pressures, amounts of various inhibitors necessary to inert dusts, the effects of dust particle size, and the effects of the addition of a few percent methane to the air. These are some examples of the various explosion characteristics of dusts. Other characteristics such as minimum ignition energy and minimum autoignition temperature will not be discussed here. In this paper, the terms "flammability" and "explosibility" are used interchangeably to refer to the ability of an airborne dust cloud to propagate a flame after it has been initiated by a sufficiently strong ignition source. The terms refer to a rapid deflagration and not a detonation.

The laboratory data in this paper were obtained in the Bureau of Mines 20-L chamber [*7–8*] located near Pittsburgh, PA and in the Fike Corporation 1-m³ chamber [*8*] located at Blue Springs, MO. The 20-L chamber is the standard laboratory test chamber used at the Bureau for studying the explosibility and inerting of fuel dusts and gases. Some data on the explosibility of coals and other carbonaceous dusts as measured in the Bureau's 20-L chamber have been reported previously. Those previous papers have discussed the ignition energy requirements for accurate measurements of flammability limits of dusts and gases [*9*], a volatility model for coal dust flame propagation [*10*], comparisons of laboratory and mine research on lean explosibility limits and rock dust inerting of various coals [*11–12*], the effect of volatility on the explosibility limits of coals and other carbonaceous dusts [*13–15*], and the effects of particle size [*14–15*]. The Fike Corporation also has a 20-L chamber of somewhat different design, but it was not used as part of the current test program. There is a third 20-L design [*1, 5, 16–17*] that is in wide use in Europe. Also in use in Europe is a 1-m³ chamber [*1, 5*] of somewhat different design than the Fike 1-m³ sphere.

*Reference to trade names does not imply endorsement by the Bureau of Mines.

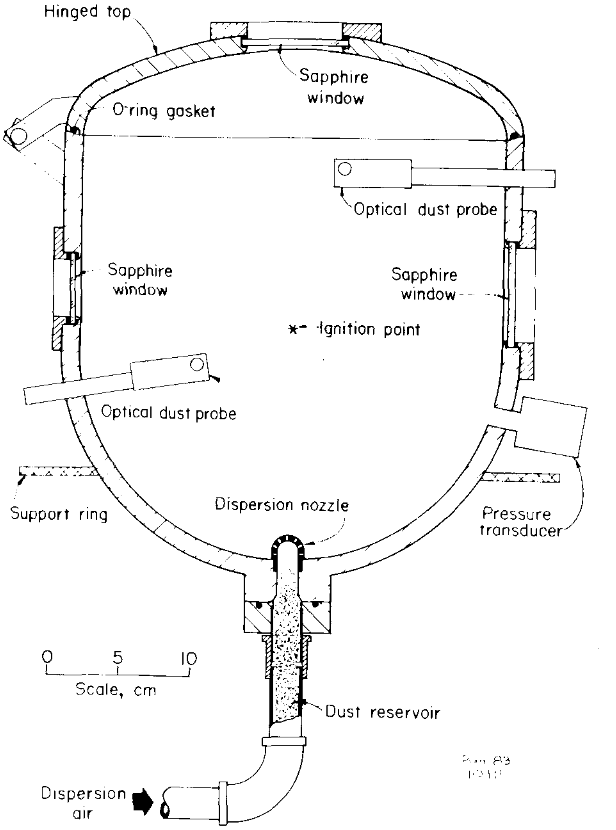

FIGURE 1. Vertical cross section of 20-L laboratory explosibility test chamber.

From 1910 until the mid 1980's, the Bureau conducted full-scale explosion testing in the Bruceton experimental mine (BEM) near Pittsburgh, PA [*18-23*]. In 1982, the Bureau completed a new experimental mine [*24-25*] at Lake Lynn, about 60 miles south of Pittsburgh. Full-scale explosion tests are now conducted in the Lake Lynn experimental mine (LLEM), which is more representative of modern mining geometries. Recent full-scale coal dust explosion research at the Bureau has included the measurement of minimum coal dust loadings and rock dust inerting amounts [*12, 26*], the problems of float coal dust [*27*], the effects of pulverized versus coarse particle size [*11, 26*], and triggered barriers for explosion suppression [*28-30*]. The Bureau has also made comparisons of explosion data from different sized mine entries [*26, 31*].

In the United States, regulations for the mining industry are based on the results of full-scale experimental mine testing. The data from the 20-L laboratory chamber are, however, in reasonably good agreement with the full-scale results. Therefore, the 20-L chamber can be used for preliminary screening tests in order to improve the cost effectiveness of the full-scale tests. Because the laboratory tests require much less time than the full-scale tests, many more types and sizes of dusts can be tested in the laboratory chamber. The 20-L and 1-m^3 laboratory chambers are also useful for the evaluation of explosion hazards in various other industries.

Experimental Facilities and Test Procedures

Some of the dust explosibility data in this paper were obtained in the 20-L laboratory chamber [*7*] shown in Figures 1 and 2. The near-spherical chamber is made of stainless steel and has a gauge pressure rating of 21 bar, g. The hinged top is attached with six 19-mm-diameter bolts which are not shown on the drawings. Two optical dust probes [*32-34*] are used to measure the uniformity of the dust dispersion at the positions shown in the drawings. The optical probes measure the transmission over a 38-mm path length through the dust cloud. Thin jets of air keep the windows of the probes clean. References [*7, 8*] and [*11*] contain examples of dust probe transmission measurements showing the dispersion uniformity in the 20-L chamber. The strain gauge pressure transducer measures the explosion pressure. Multichannel infrared pyrometers [*35-36*] can be used to measure the explosion temperature. The data from the various instruments are collected by a high speed personal computer (PC) based data acquisition system. It can sample data from 16 channels at a maximum rate of 9 kHz if all channels are used or at faster rates if fewer channels are used. Data are displayed on a color monitor immediately after each test. The dust to be tested can be placed either in the dust reservoir or on top of the dispersion nozzle at the bottom of the chamber (Figure 1). After the dust and ignitor have been placed in the chamber, the top is bolted on and the chamber is partially evacuated to an absolute pressure of 0.14 bar, a. Then a short blast of dry air (0.3 s duration at 9 bar, g from a 16-L reserve tank) disperses the dust and raises the chamber pressure to about 1 bar, a. The ignitor is activated after an additional delay of 0.1 s. This results in a total ignition delay of 0.4 s from the start of dispersion until ignition. The experimental dust concentration reported for both laboratory chambers is the mass of dust divided by the chamber volume.

The 1-m^3 chamber [*8*] shown in Figure 3 was also used to measure the explosion hazards of dusts. This 1-m^3 chamber is spherical with an internal diameter of 122 cm and a wall thickness of 0.95 cm. It has a pressure rating of 21 bar, g. The two halves of the sphere are connected by twelve 51-mm-diameter bolts (not shown). Two variable-reluctance pressure transducers are used to measure the explosion pressure. For the tests described in this paper, two Bureau of Mines optical dust probes were installed in the 1-m^3 chamber to monitor the dust dispersion uniformity at the positions shown in Figure 3. Data from the various instruments are collected by a high speed PC based data acquisition system.

The dust injection system for the 1-m^3 chamber consists of a 5-L dispersion reservoir, a 19-mm pneumatically-activated ball valve, and a circular dispersion ring (Figure 3). To create a dust cloud, a weighed sample of dust is placed in the dispersion reservoir. The reservoir is pressurized with dry air to 32 bar, g and the 1-m^3 chamber is partially evacuated to 0.88

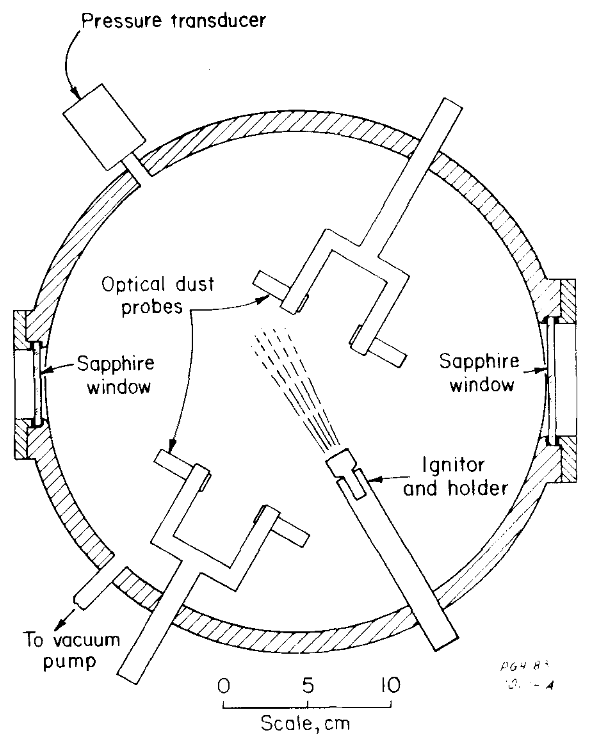

FIGURE 2. Horizontal cross section of 20-L laboratory explosibility test chamber.

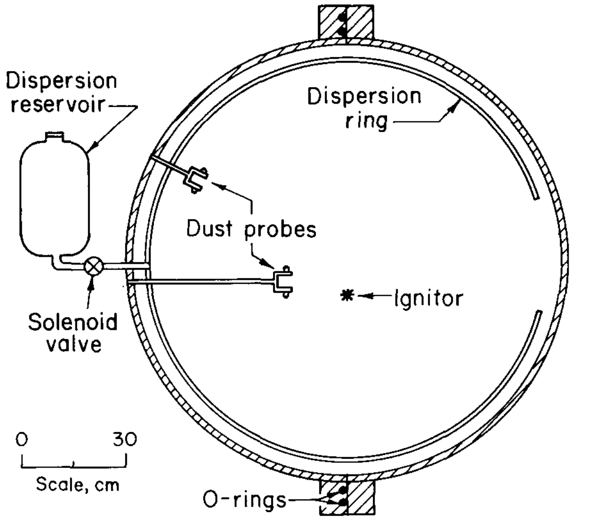

FIGURE 3. Vertical cross section schematic of 1-m^3 explosibility test sphere.

bar, a. Activation of the ball valve disperses the dust and air into the 1-m^3 chamber through the dispersion ring and raises the chamber pressure to about 1 bar, a. The ignitor is activated 0.55 s after activation of the ball valve.

The dispersion time and turbulence level in the Fike 1-m^3 chamber are comparable to those in the European 1-m^3 chambers [*1, 5*]. This is the turbulence level in ASTM Standard E1226, ISO Standard 6184/1, NFPA Guide 68, and VDI Standard 3673 to determine the maximum rate of pressure rise for a dust explosion in order to determine vent sizes. Because it is not possible to vent mine explosions, the Bureau has historically placed more emphasis on the measurement of minimum explosible concentrations and rock dust inerting amounts rather than on the measurement of rates of pressure rise. Therefore, the standard turbulence level in the Bureau's 20-L chamber is lower. This should mainly affect the rates of pressure rise (at high concentrations) and should not affect measurements of the minimum explosible concentrations [*8*] or inerting amounts.

The ignition sources used for the 20-L and 1-m^3 tests were electrically activated, pyrotechnic ignitors manufactured by Fr. Sobbe* of Germany. These ignitors are composed of 40% zirconium, 30% barium nitrate, and 30% barium peroxide. They are activated electrically with an internal fuse wire and deliver their energy in about 10 ms. The Sobbe ignitors are available in energies of 250, 500, 1,000, 2,500, 5,000, and 10,000 J. These are nominal calorimetric energies based on the mass of pyrotechnic powder in each ignitor. The 5,000-J ignitor by itself produces a pressure rise of about 540 mbar in the 20-L chamber but only 11 mbar in the 1-m^3 chamber. The pressure rises from the other ignitors in the two chambers can be estimated based on their relative energies. The Sobbe ignitors for these tests are the new type that are sealed with plastic end caps. The older type were sealed with paper end caps and tended to lose some of the powder, resulting in lower effective energies. Additional information on the Sobbe ignitors (older type) is in reference [*9*].

At the Bureau of Mines, full-scale explosion tests are now conducted in the Lake Lynn experimental mine (LLEM) shown in Figure 4. There are similar underground experimental mines in China [*37*], Germany [*38*] and Poland [*39-40*]. The LLEM is a former limestone mine, and five new drifts (horizontal passageways) were developed to simulate the geometries of modern U.S. coal mines. Drifts A, B, and C and their interconnections simulate a room and pillar mining configuration. Drifts C and D are connected by drift E, a 152-m long entry which simulates a longwall mining face. The dust explosion tests described in this paper were conducted in the single entry

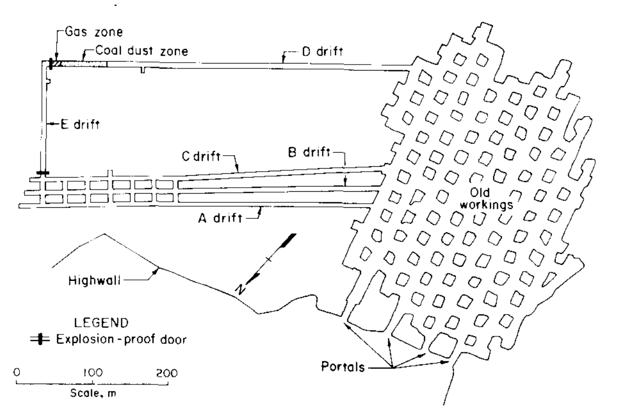

FIGURE 4. Plan view of the Lake Lynn experimental mine.

drift D (Figure 5), which was isolated from drift E by means of an explosion-proof movable bulkhead. Drift D is 520 m long with a cross-sectional area ranging from 11.2 to 13.0 m^2 (average 12.8 m^2). The average height in drift D is 2.1 m, and the average width is 6.0 m. Drift D is instrumented (Figure 5) with pressure transducers located at the face and at 10, 15, 31, 46, 61, 91, 119, 153, 183, and 229 m from the face. Optical flame sensors are located at 5, 10, 15, 23, 31, 38, 46, 53, 61, 76, 91, 105, 119, 136, 153, 168, 183, 198, 213, and 229 m from the face. Data from over 60 channels can be sampled by a high speed computer system at a frequency of 1500 Hz per channel. For some explosion tests in the LLEM, a rapid sampling system was used to collect gas and dust samples as the flame front passed [*41-43*].

The ignitor for all of these full-scale dust explosibility tests was a 12-m long zone of a 10% methane in air mixture at the face (closed end) of drift D. This methane-air zone was ignited near the center of the face using electric matches grouped in a single-point configuration. In tests involving a pure fuel dust such as coal, all the dust was placed on roof shelves. This simulates an accumulation of dust on overhead timbers, etc. in mines. In the rock dust inerting tests, the mixtures of fuel dust and limestone rock dust were placed half on roof shelves and half on the floor. The nominal dust loading reported for the LLEM tests assumes that all of the dust is dispersed uniformly throughout the cross section. The dust test zone extended from the end of the methane zone (12 m) out to 76, 94, 152, or 195 m from the face. The length of the total test zone listed in the remainder of this paper is the total distance from the face, including the 12-m-long methane ignitor zone.

Experimental Data

Examples of absolute pressure versus time traces for typical explosions of dusts in the 20-L chamber are shown in Figure 6. Aluminum, polyethylene, high volatile bituminous (hvb) coal, and low volatile bituminous (lvb) coal were tested at a

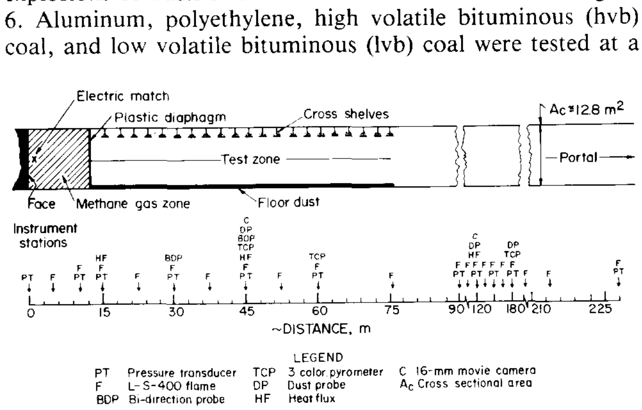

FIGURE 5. Side view of drift D in the Lake Lynn experimental mine, showing instrumentation.

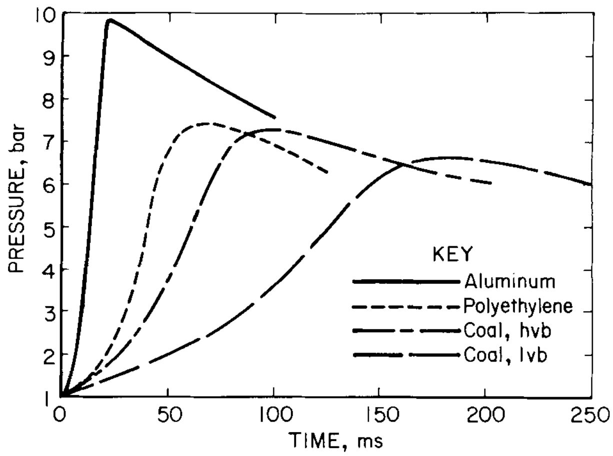

FIGURE 6. Pressure-time traces for explosions of four dusts in 20-L chamber.

concentration of 600 g/m^3. The relative reactivity of the dusts can be estimated from either the maximum rate of pressure rise, the time to peak pressure, or the absolute magnitude of the peak pressure. Whichever parameter is used, one obtains the same order of reactivity: aluminum > polyethylene > hvb coal > lvb coal.

In order to study the overall explosibility characteristics of dusts, tests are made over a range of concentrations. Figure 7 shows a summary of 20-L explosibility data with 2,500-J ignitors for the high volatile bituminous coal dust from the Pittsburgh seam. In the bottom part of the figure, the pressure ratio (PR) is the maximum absolute explosion pressure (with the pressure rise of the ignitor subtracted) divided by the pressure at ignition (about 1 bar, a). Therefore, the pressure ratio corresponds approximately to the absolute explosion pressure in atmospheres or bars. In the top part of the figure, $(dP/dt)\,V^{1/3}$ is the size normalized maximum rate of pressure rise for each explosion test. Note again that the turbulence level is lower in the Bureau's 20-L chamber, and therefore the $(dP/dt)\,V^{1/3}$ data are not recommended for the sizing of vents. The data are, however, useful as a relative measure of explosion hazard. At the higher turbulence level recommended in ASTM Standard E1226, the maximum $(dP/dt)\,V^{1/3}$ data for this Pittsburgh coal would be roughly three times higher.

The data in Figure 7 show a minimum explosible concentration (MEC) or lean flammable limit (LFL), but there is no evidence of a rich limit. At the higher concentrations in Figure 7, the maximum pressures and rates of pressure rise level off as all of the oxygen in the chamber is consumed. Additional tests at even higher concentrations have shown no evidence of a rich limit out to a concentration of 4000 g/m^3. This agrees with older full-scale data from the BEM [*20*].

A summary of 20-L chamber explosibility data for three dusts (using 2500 J ignitors) is shown in Figure 8. Only the average data curves are shown and not the individual data points for each test. The dusts include polyethylene and low volatile bituminous coal in addition to the high volatile bituminous coal data from Figure 7. The data for each dust show that below a certain dust concentration, explosions are not observed. That minimum concentration is the MEC or LFL. As in Figure 7, the explosion pressure data level off at high dust concentrations. The reason is that all of the oxygen in the chamber is consumed at a dust concentration of 300 to 500 g/m^3, depending on the particular dust. At even higher dust concentrations, although the mixture is nominally fuel rich, the pressures nevertheless remain constant or decline only slightly. The normal rich limit observed for hydrocarbon gases is not observed for the dusts. An explanation of this effect, at least for many dusts, is that the solid phase fuel must first devolatilize before it can mix with the air [*10*]. As soon as sufficient volatiles are generated to form a stoichiometric concentration of volatiles in air, the flame front propagates rapidly through the mixture before excess fuel volatiles can be generated.

One question about laboratory data, and in particular the 20-L data, is whether a strong ignition source can "overdrive" the system. Dust clouds are intrinsically more difficult to ignite than gases and therefore require stronger ignition energies to measure the MEC or LFL. A "true" MEC is one that is independent of ignition energy. If too weak an ignition source is used, one measures an apparent MEC that is higher than the true value. This is an ignitability limit rather than a flam-

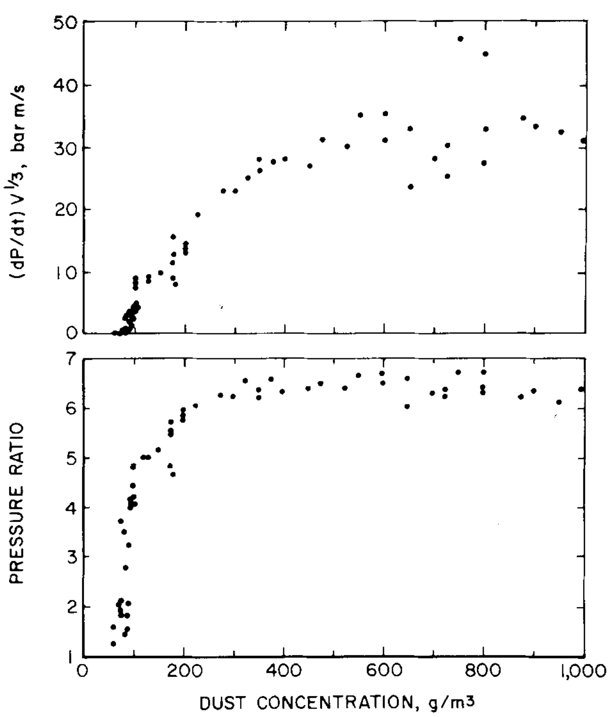

FIGURE 7. Explosibility data for bituminous coal in 20-L chamber.

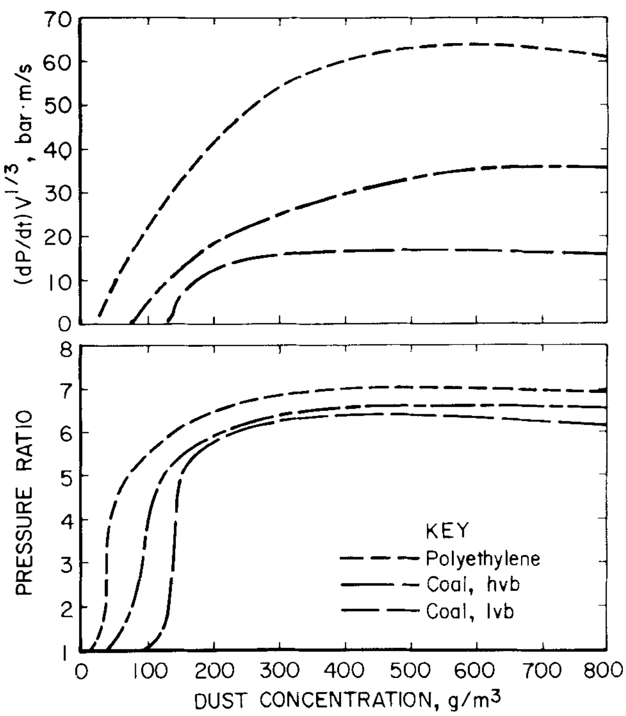

FIGURE 8. Explosibility data for three dusts in 20-L chamber.

mability limit, and the test could be described as "underdriven." Ideally, one increases the ignition energy until the MEC-value becomes independent of ignition energy. However, at some point the ignition energy becomes too strong for the size of the test chamber, and the system becomes "overdriven." When the ignitor flame becomes too large relative to the chamber volume, a test could appear to result in an explosion, while it is actually just dust burning in the ignitor flame with no real propagation beyond the ignitor. Alternatively, too strong of an ignitor energy could sufficiently change the initial test conditions, such as raising the initial temperature of the dust cloud, so that a nonexplosible mixture becomes explosible.

To evaluate the effect of overdriving in a 20-L chamber, comparison tests must be made in a larger chamber such as a 1-m^3 chamber. A given ignitor that overdrives a 20-L chamber would not overdrive the much larger 1-m^3 chamber. Therefore, it is easier in principle to determine an ignition energy independent MEC-value in a 1-m^3 chamber. The extent to which strong chemical ignitors overdrive the 20-L chamber for LFL measurements of gases was discussed in a previous paper [*9*] in which 20-L data were compared to data from a 120-L chamber. Bartknecht [*5*] also reported some data on the overdriving of a 20-L chamber with 10,000-J ignitors when measuring the minimum oxygen concentration for a dust explosion.

The possible overdriving in the 20-L chamber was investigated by measuring the MEC values as a function of ignitor energy for gilsonite dust and Pittsburgh coal dust in the 20-L and 1-m^3 chambers. The details are in reference [*8*], and a summary is presented here. Gilsonite is a natural bitumen or asphaltum that is mined in Utah; it has a volatility of 84%. It was pulverized and had a surface weighted mean diameter of 19 μm, a mass weighted mean diameter of 37 μm, and 91% by weight minus 200 mesh (<75 μm). (Note that these size data are revised somewhat from those in reference [*12*] based on new, more accurate size analyses.) The Pittsburgh coal dust had a standard volatility of 36%, a surface mean diameter of 30 μm, a mass mean diameter of 50 μm, and 80% by weight minus 200 mesh.

As part of the explosibility testing, the effectiveness of the dust dispersion in the 20-L and 1-m^3 chambers was studied by using the optical dust probes to measure the transmission through the dust cloud at various positions in the two chambers. As described in reference [*33*], the transmission T is related to the mass concentration C_m by Bouguer's law: $T = \exp(-3QC_m l/2\rho\overline{D}_s)$, where Q is a dimensionless extinction coefficient, l is the path length, ρ is the density of a particle, and $\overline{D}_s$ is the surface mean particle diameter. An example of the dust probe data for gilsonite dust dispersed in the 20-L and 1-m^3 chambers is shown in Figure 9. The data generally follow the expected linear relationship on this semilogarithmic plot. Due to agglomeration, the $\overline{D}_s$ mean particle size in the dust cloud is usually larger than the intrinsic size. The scatter in the data in Figure 9 is probably due to variations in the agglomerated particle size of the air dispersed dust. At the lower concentrations, the 1-m^3 transmission data are slightly lower than the 20-L data, possibly because there is more agglomeration of the dust in the 20-L chamber. This may be due to the lower level of turbulence in the 20-L chamber. Additional comparison dust dispersion data for the 20-L and 1-m^3 chambers are in reference [*8*]. The general conclusion was that the dispersion in the 1-m^3 chamber was at least as good as that in the 20-L chamber.

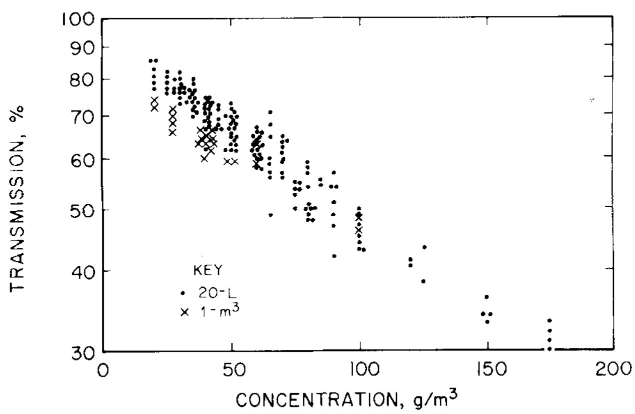

FIGURE 9. Dust probe transmission data for gilsonite dust dispersed in 20-L and 1-m^3 chambers.

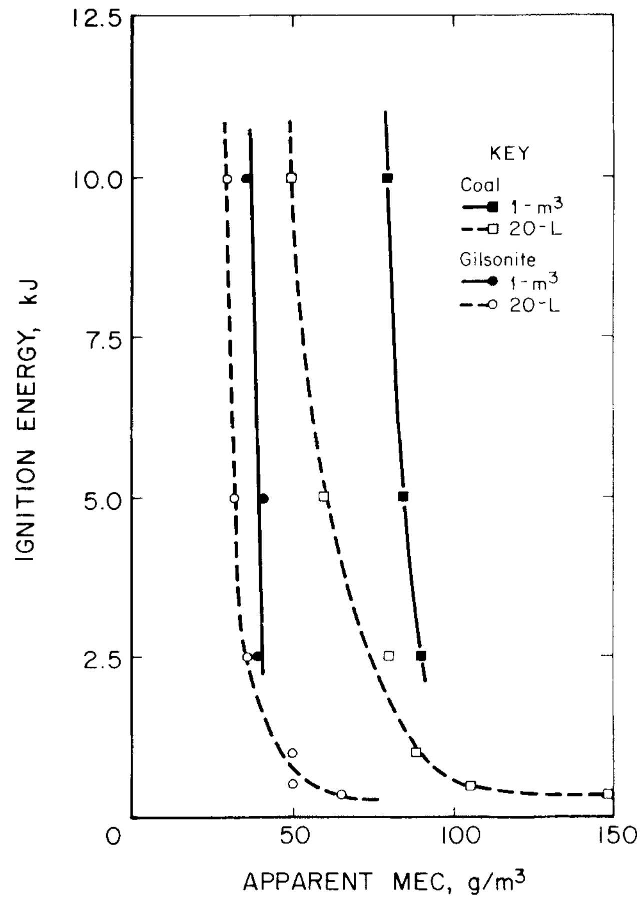

FIGURE 10. Effect of ignition energy on the apparent minimum explosible concentration (MEC) for gilsonite and Pittsburgh bituminous coal dusts.

As discussed earlier in this section, the "true" minimum explosible concentration for a dust is that value that is independent of ignition energy. To evaluate this for the gilsonite and bituminous coal dusts, the apparent or measured MEC data in the 20-L and 1-m^3 chambers [*8*] are plotted versus ignition energy in Figure 10. In the 1-m^3 chamber, the measured MEC data for each of the two dusts are relatively independent of ignition energy over the range studied. The vertical asymptotes for the 1-m^3 data yield a MEC of 35 to 40 g/m^3 for the gilsonite and a MEC of 80 $\pm$ 5 g/m^3 for the Pittsburgh bituminous coal. The 20-L MEC-values were measured over a wider range of ignition energies. Sobbe ignitors were used for all the data except for the lowest energy, which corresponds to two electric matches. The measured MEC-values increase at the lowest energies where the ignition energy is insufficient to measure a true limit. At the highest energies studied, the apparent MEC-values from the 20-L chamber are lower than those from the 1-m^3 chamber. This is evidence of overdriving in the 20-L chamber when the strongest ignitors are used. The measured MEC-values at 2,500 J in the 20-L chamber are about 35 to 40 g/m^3 for the gilsonite and about 80 $\pm$ 10 g/m^3 for the bituminous coal. These values are comparable to the asymptotic values at high ignition energy in the 1-m^3 chamber. Therefore, for these dusts, the 2,500-J ignitor appears to be appropriate for measuring the MEC in the 20-L chamber without overdriving the system.

The MEC data for gilsonite and Pittsburgh bituminous coal in the 20-L and 1-m³ laboratory chambers can also be compared to minimum nominal loading data from large-scale experimental mine tests [*12*]. In the LLEM tests, there is a 12-m long methane-air ignition zone at the face (closed end) of the mine entry. The dust is placed on roof shelves. The methane-air explosion both entrains and ignites the dust. The dust concentration data reported are the nominal values, assuming uniform dispersion throughout the cross section. However, the dust does not necessarily disperse as uniformly in the mine entry as it does in the laboratory chambers. The flame from the methane-air ignition zone travels about 70 m, even in the absence of any fuel dust in the test zone. For a dust explosibility test, if the flame does not reach the end of the test zone, the result is considered a nonpropagation. If the flame just reaches the end of the test zone or slightly beyond, the result is considered a marginal propagation. If the flame travels significantly beyond the test zone, the result is considered a propagation. Measurement of the flame travel distance is, of course, limited by the number and locations of the flame sensors. For most tests, the flame sensors were located at intervals of about 15 m. The estimated flame travel distance is interpolated between flame sensors, based on the strengths of the signals at the sensors.

Even in the large-scale experimental mine tests there was a question whether or not a particular ignition source could "overdrive" the system. To evaluate the possibility of overdriving for the LLEM studies, some tests were made with longer test zones (152 m) in addition to tests with 76- or 94-m lengths. Details of the individual tests are in reference [*12*], and the results are summarized here. For gilsonite dust, the minimum nominal loading for flame propagation in the LLEM was measured using test zones of 94 and 152 m in length. The data [*12*] showed that the flame from the methane-air ignition zone could overdrive the results somewhat for the minimum loading tests when the shorter test zone was used. The best value for the minimum nominal concentration for flame propagation in the LLEM was about 35 g/m³ for the gilsonite dust, based on the data from the longer test zone. This agrees well with the laboratory data.

The minimum nominal dust loading for the Pittsburgh coal in the LLEM was studied using test zones of 76 and 152 m in length. Again, the data [*12*] showed that the flame from the methane-air ignition zone could overdrive the results somewhat for the minimum loading tests when the shorter test zone was used. The best value for the minimum nominal loading for the Pittsburgh coal dust in the LLEM was about 60 g/m³, based on the data from the longer test zone. This value is somewhat lower than the 80-g/m³ value measured in the 20-L chamber with 2,500-J ignitors and in the 1-m³ chamber with 10,000-J ignitors. However, the agreement is still rather good, considering the differences in dispersion methods and the uncertainties involved.

As another test of possible overdriving in the 20-L chamber, anthracite coal was tested in both laboratory chambers [*8*]. The anthracite had a standard volatility of 8%, a surface mean diameter of 24 μm, a mass mean diameter of 45 μm, and 85% minus 200 mesh. Using 5,000-J ignitors, the anthracite produced explosions at dust concentrations above 600 g/m³ in the 20-L chamber. Using 2,500-J ignitors in the 20-L chamber, the anthracite produced only a slight pressure rise and no evidence of flame propagation. The anthracite was also tested in the 1-m³ chamber with 30,000-J ignition sources, and no ignitions were observed. Since the anthracite did not ignite even with the 30,000-J ignitor in the 1-m³ chamber, the apparent ignitions with 5,000 J in the 20-L chamber are evidence of overdriving. The 1-m³ data are also consistent with those from older full-scale experimental mine tests in which similar pulverized anthracite dusts did not produce explosions [*18*, *20*].

The data from the laboratory chambers show that useful MEC data may be obtained in a 20-L chamber, but that more accurate data may be obtained in a 1-m³ chamber. For the gilsonite, bituminous coal, and anthracite coal dusts tested, the 2,500-J ignitor appears to be the most appropriate energy for MEC-testing in the 20-L chamber in order to obtain data that are comparable to those obtained in the 1-m³ chamber with 10,000 J. At higher ignitor energies, there is evidence of overdriving in the 20-L chamber. Ignitor energies below 2,500 J are not recommended for MEC dust explosion testing because they usually give values that are larger than the "true" MEC values. The conclusions reached here apply to the particular dusts tested, and one must be cautious in generalizing or in extrapolating to other dusts or other sizes of these dusts. These comparison data from 20-L and 1-m³ chambers are the basis for a proposed ASTM standard test method for measuring the MEC of a dust cloud.

For other types of explosibility data from 20-L chambers, a different ignitor energy may be more appropriate. Bartknecht [*1*, *5*] and Siwek [*16–17*] recommend a 10,000-J ignitor for measuring the size-normalized maximum rate of pressure rise in their 20-L chamber. For most of the dusts they studied, 10,000 J in the 20-L chamber gave the best agreement with 10,000 J in a 1-m³ chamber. However, our data for anthracite dust show that 10,000 or even 5,000 J in a 20-L chamber is inappropriate for some materials because the dusts appear to deflagrate in the 20-L with 5,000 J but do not ignite in a 1-m³ chamber even with much stronger ignitors. A general recommendation for dust testing [either MEC or $(dP/dt)\,V^{1/3}$] is that if a dust appears to deflagrate with a 5,000- or 10,000-J ignitor but does not ignite with a 2,500-J ignitor in a 20-L chamber, the final determination should be made in a larger system, such as a 1-m³ chamber. For dusts that ignite with 2,500-J or lower energy, useful data may be obtained in 20-L chambers.

The previous explosibility data were measured for dusts with rather broad size distributions. The Bureau has also studied the effect of particle size on the explosibility of dusts by using narrow size distributions. Some preliminary data from the Bureau's earlier 8-L chamber were presented previously [*44–45*]. Figure 11 shows new explosibility data from the 20-L chamber for Pittsburgh bituminous coal dust as a function of mass median particle diameter, using 2,500-J ignitors. The larger sizes were sieve classified and the smaller sizes were centrifugally classified. The MEC-values in the bottom section of the figure are relatively independent of particle size for the finer sizes. At the larger sizes, above 100 μm, the MEC-values increase with particle size until a size is reached that can not be ignited. The top two sections of Figure 11 show that the maximum pressures and rates of pressure rise are found at the finest sizes tested. The pressures decline slowly and the pressure rise rates decrease faster with increasing particle size. At some size above 200 μm, the dust can no longer be ignited by the 2,500-J ignitor. These data are typical for narrow size distributions of carbonaceous fuel dusts. A broad size distribution is just a combination of narrow distributions, and these data show that it is the finer particles in a broad distribution that contribute the most to its hazard.

Data for three sizes of aluminum dust are shown in Figure 12. The data are shown as bars rather than points because the particle sizes are more uncertain than those for the Pittsburgh coal. Also, the aluminum size distributions were not as narrow as for the coal. The explosion data are similar to those for the coal. The maximum values for pressure and rate of pressure rise are found at the finest particle size. The MEC values are relatively size-independent at the finer sizes and increase slightly at the largest size tested.

In addition to the minimum concentration, maximum pressure, and maximum rate of pressure rise measurements, the inerting of various fuel dusts was studied. In the mining industry, inert rock dust is mixed with the fugitive coal dust in

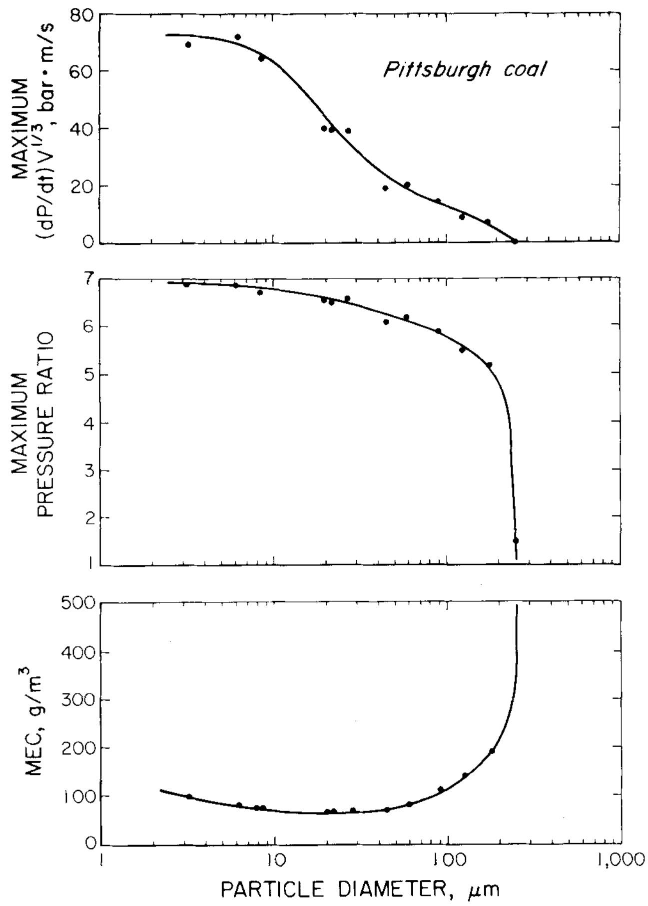

FIGURE 11. Explosibility data for Pittsburgh bituminous coal dust as function of mass median particle diameter.

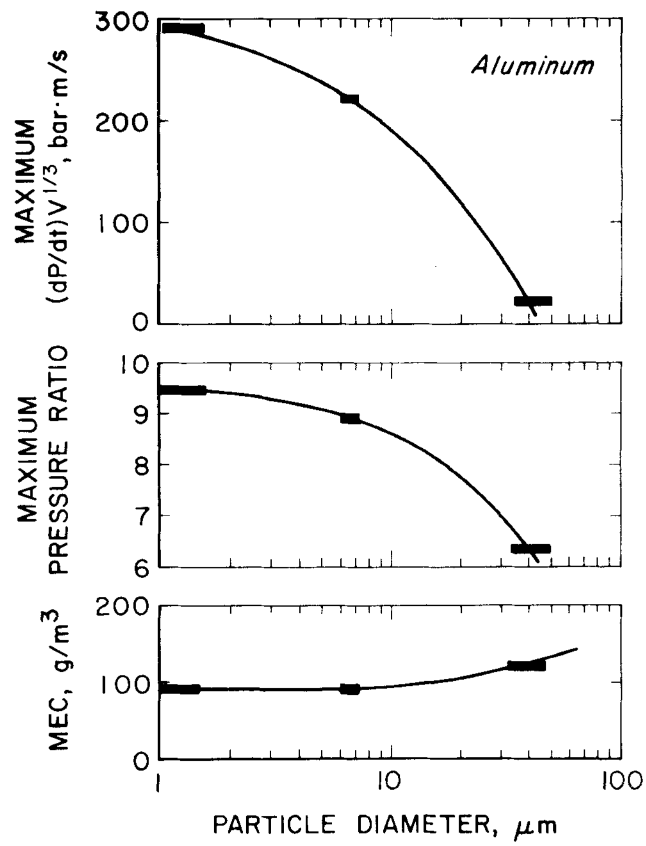

FIGURE 12. Explosibility data for aluminum dust as function of mass median particle diameter.

order to prevent flame propagation. The amount of limestone rock dust necessary to inert coal dust was measured in the Lake Lynn experimental mine [*12, 26*] and the 20-L laboratory chamber [*12–15*]. For the limestone rock dust inerting tests in the LLEM, the results were based on tests at the most hazardous fuel dust concentration. Test zones of 76 to 195 m were used, and the results were independent of length of zone. The rock dust content necessary to prevent an explosion of the Pittsburgh coal dust in the single entry of the LLEM was about 78 to 81%. The rock dust content necessary to inert the gilsonite dust in the LLEM was about 87 to 90%.

The amounts of limestone rock dust necessary to inert the Pittsburgh coal dust and gilsonite dust were also measured in the 20-L chamber. The stronger 5,000-J ignitors were used for these tests because the heavily inhibited, high dust concentrations were intrinsically more difficult to ignite. The tests were conducted over a wide range of fuel dust concentrations to determine the worst case. Examples of the tests are shown in Figure 13. These are absolute pressure versus time traces for various coal-rock mixtures. All of the tests in the figure were made at a fixed Pittsburgh coal dust concentration of 400 g/m^3. The weight percent of limestone rock dust in each mixture is listed in the figure with its respective pressure-time trace. The data in the figure show that, as more rock dust is added to the mixture, the maximum pressure and rate of pressure rise decrease. At 75% rock dust in the mixture, there is still an obvious explosion. At 80% rock dust, only the initial pressure rise of the ignitor is observed, and there is no flame propagation through the coal-rock mixture. Therefore, for the Pittsburgh coal, the limestone rock dust content necessary to inert the mixture is between 75 and 80%. For the gilsonite dust, the rock dust content necessary to inert the mixture was about 90%. These laboratory data show reasonably good agreement with the full-scale experimental mine data. Rock dust inerting tests were not made in the 1-m^3 chamber.

A summary of experimental mine and 20-L laboratory limestone rock dust inerting data for various fuel dusts is shown in Figure 14. The vertical axis shows the amount of rock dust in the mixture necessary to inert the various fuel dusts. The horizontal axis is the moisture-ash-free volatility of the fuel dusts. The data at low volatilities are for various coal dusts and the data at high volatility are based on the gilsonite tests. The dotted line is a summary of previous inerting tests of

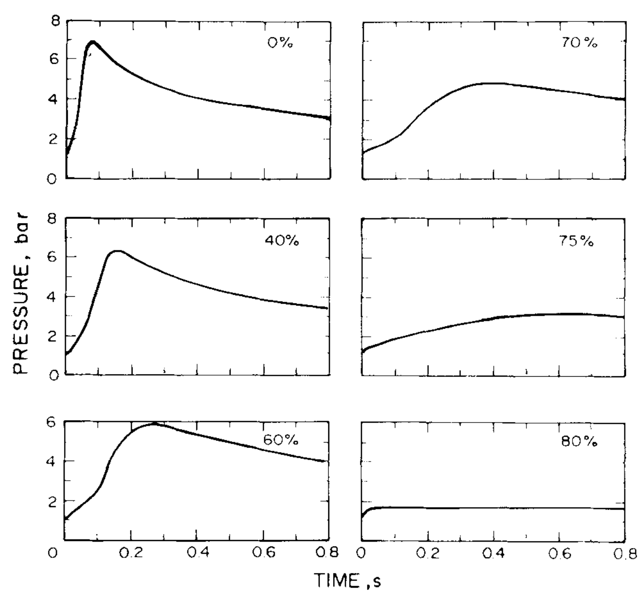

FIGURE 13. Pressure-time traces for tests of coal dust in 20-L chamber with the listed amounts of added limestone rock dust as an inhibitor.

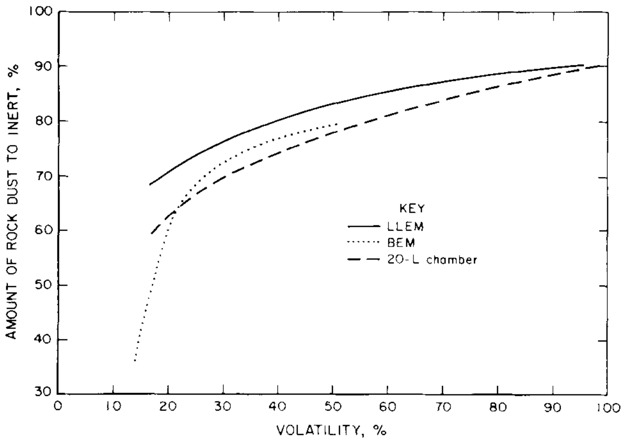

FIGURE 14. Rock dust inerting requirements for dusts of different volatilities, showing comparison among Lake Lynn experimental mine (LLEM) data, Bruceton experimental mine (BEM) data, and 20-L laboratory data.

various coals in the BEM using a strong ignition source [*18, 20-21*]. The LLEM data [*12, 26*] are shown as the solid line. The 20-L laboratory data [*12-15*] for the same dusts are represented by the dashed line. The uncertainties in the mine and laboratory data are of the order of $\pm 3\%$ rock dust content. There is a general trend that the mine tests show a somewhat higher rock dust inerting requirement than the laboratory chamber, especially for the lower volatile coals. However, the laboratory data do show sufficiently good agreement with the mine data that the 20-L chamber can be used for preliminary testing before full-scale mine testing.

In previous laboratory [*46-47*] and full-scale tests [*48*] of other inhibitor dusts, the Bureau determined that ammonium phosphate was the most effective inhibitor powder against coal dust and/or methane gas explosions. Ammonium phosphate is not cost effective as a replacement in general rock dusting, but it has been tested and found to be feasible in explosion suppression systems such as triggered barriers [*28*]. Water has also been shown to be an effective inhibitor in barrier type suppression systems against both coal dust and methane gas explosions [*30*].

Hybrid mixtures of coal dust and methane gas are also a common hazard in the mining industry. The minimum explosible concentrations or lean flammable limits of Pittsburgh coal and methane mixtures were measured in the 20-L chamber and compared to large-scale data from the BEM [*11*]. In the BEM, the coal dust was predispersed into a 45 m^3 test zone containing various methane-air mixtures. In both the laboratory and mine tests, the ignitor was initiated after the dust was dispersed. In both cases, the data followed a linear relationship for the lean limits of the mixtures, as predicted by Le Chatelier's law, which was originally proposed for flammable gas mixtures [*49*]. In additional laboratory tests with other carbonaceous dusts, the MEC values for dust and methane gas mixtures also followed a linear relationship [*50*].

The data in this paper show that useful dust explosibility information may be obtained in laboratory test chambers and that the data are in reasonably good agreement with large-scale data. These comparison data will be useful to the various standards writing organizations in formulating laboratory test methods. The purpose of this and future research is to improve the safety in mining and other industries.

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This paper (72c) was presented at the AIChE Spring National Meeting in New Orleans, March 29th through April 2, 1992.