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A Critique of the Dust Explosibility Index: An Alternative for Estimating Explosion Probabilities

By M. Hertzberg



UNITED STATES DEPARTMENT OF THE INTERIOR

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CONTENTS

	<u>Page</u>
Abstract.....	1
Introduction.....	2
Rationale and critique.....	3
Dust dispersion, Pr(d).....	4
Flammability limits, Pr(f).....	5
Ignition probability, Pr(i).....	7
Critique of the explosibility index.....	9
Practical considerations.....	14
Actual evaluations.....	14
Examples A and B: Dust collector baghouse.....	14
Examples C and D: Pneumatic dust transport system.....	16
Example E: Grain storage facility.....	16
Correlation of events and randomness.....	18
Proposed method for evaluating Pr(i, thermal).....	20
Conclusions.....	21
References.....	22

ILLUSTRATIONS

1. Comparison of flammability limits for methane gas and polyethylene dust in air.....	6
2. Effectiveness of a pyrotechnic source of varying energy on the ignition of polyethylene, coal, and oil shale dusts.....	8
3. Domains of flammability and thermal autoignition for lycopodium dust in air.	8

TABLE

1. Flame propagation characteristics for CH ₄ -air explosions (7.55 pct) at Lake Lynn for various ignition locations compared with 20 L data.....	12
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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

atm	atmosphere, standard	K_{st}	size-normalized rate of pressure rise
bar m/s	bar meter per second	L	liter
bar/s	bar per second	m^3	cubic meter
$^{\circ}C$	degree Celsius	m/s	meter per second
ft	foot	min	minute
g	gram	μs	microsecond
g/m^3	gram per cubic meter	pct	percent
h	hour	psig	pound per square inch, gauge
J	joule	s	second
K	kelvin	yr	year

A CRITIQUE OF THE DUST EXPLOSIBILITY INDEX: AN ALTERNATIVE FOR ESTIMATING EXPLOSION PROBABILITIES

By M. Hertzberg¹

ABSTRACT

This Bureau of Mines report proposes a new methodology for estimating industrial dust explosion hazards in terms of three probabilities or cofactors: The dispersion of the dust, the existence of a flammable dust concentration, and the presence of an effective source of ignition. This method or rationale is proposed as a replacement for the "explosibility index" that was first suggested 25 yr ago, but which, by consensus among leading researchers in the field, is now outdated. This report presents a detailed critique of the deficiencies of that old, material-oriented index, and develops the logical rationale for its replacement by an approach that is better suited for quantitative hazard evaluations. A variety of such evaluations are illustrated, which show how a quantitative prediction of explosion frequencies can be obtained from laboratory measurements and operating conditions in a given industrial facility. The method has some pitfalls, particularly as they relate to the correlation of events or their randomness. These are discussed, as well as the method's other limitations and uncertainties. This work is intended to provide a beginning to a quantitative approach to explosion hazard assessment. To that end, a new method is proposed for estimating thermal ignition probabilities in terms of the measured laboratory autoignition temperature of a dust, its relationship to the operating temperature, and its distribution within a given industrial system.

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INTRODUCTION

It has been about 25 yr since the Bureau of Mines first proposed the use of an explosibility index for evaluation of the explosion potential of dusts (1-2).² Its original formulation was designed to provide approximate ratings that would be consistent with overall practical experience. It was not, however, based on a detailed theoretical analysis of the problem, or an exact study of accident statistics (3). The proposed explosibility index was the product of two parameters: The ignition sensitivity and the explosion severity. These parameters were determined by actual measurements made in laboratory-scale systems (4). The first parameter, the ignition sensitivity, was defined in terms of the product of three measured quantities for a given dust: The minimum cloud ignition temperature, T_{min} ; the minimum spark ignition energy, ϵ_{min} ; and the minimum explosive dust concentration, C_L . The product of those three measured quantities for Pittsburgh seam pulverized coal, divided by the product of those same three measured quantities for any given dust sample, defined that dust's ignition sensitivity. Thus

$$\text{Ignition Sensitivity} = \frac{(T_{min} \times \epsilon_{min} \times C_L) \text{ Pittsburgh coal dust}}{(T_{min} \times \epsilon_{min} \times C_L) \text{ sample dust}} \quad (1)$$

The second parameter, the explosion severity, was defined in terms of the product of two measured quantities: The maximum explosion pressure p_{max} and the maximum rate of pressure rise, $(dp/dt)_{max}$, at a dust concentration of 500 g/m³. The product of those two quantities for any given dust sample, divided by the product of those same two quantities for the "standard" or reference dust, Pittsburgh seam pulverized coal dust, defined the explosion severity. Thus,

$$\text{Explosion severity} = \frac{[p_{max} \times (dp/dt)_{max}] \text{ sample dust}}{[p_{max} \times (dp/dt)_{max}] \text{ Pittsburgh coal dust}} \quad (2)$$

Finely pulverized Pittsburgh seam coal dust was used as the standard of comparison because its explosivity behavior had already been extensively studied in both full-scale mine experiments (5) and in laboratory-scale systems (6).

The final product of the ignition sensitivity parameter, and the explosion severity parameter, defined the final explosibility index. Thus:

$$\text{Explosibility Index} = \text{Ignition Sensitivity} \times \text{Explosive Severity}. \quad (3)$$

Any given dust was then classified as being capable of generating weak, moderate, strong, or severe explosions, depending on its explosibility index (2). If the explosibility index was less than 0.1, the dust was rated as having a *weak* explosion hazard. For an index between 0.1 and 1.0, it was rated as *moderate*. For an index of 1.0 to 10, the dust was rated as having a *strong* explosion hazard. For an index of greater than 10, it was rated as *severe*.

In recent years, the index ratings based on equations 1, 2, and 3 have fallen out of favor. Current researchers in the field object to the use of such a combined index system, which mixes so many different parameters. Such a mixing confuses the issue of how to apply the laboratory measurements to a hazard evaluation for a given industrial system (7). Furthermore, the consensus is that the critical parameter in

²Underlined numbers in parentheses refer to items in the list of references at the end of this report.

obtaining a hazard evaluation is not the explosivity properties of a dust relative to some other dust (such as Pittsburgh seam coal), but rather, their values relative to the operating conditions within the industrial system being evaluated (8). At a recent symposium entitled "International Symposium on the Explosion Hazard Classification of Vapors, Gases and Dusts" (7), there was a virtually unanimous opinion that the index ratings based on equations 1 to 3 should no longer be used.

The major objections in previous years to the use of those index ratings were directed towards the older laboratory-scale test equipment and methods (4) that were used to measure the quantities T_{min} , ϵ_{min} , C_L , p_{max} , and $(dp/dt)_{max}$ (9-13). The criticisms were based in part on the fact that those earlier, laboratory-scale systems gave results that were in disagreement with larger-scale tests (14). These contradictions between laboratory-scale and full-scale experiments could lead to dangerous misapprehensions because they generally erred by underestimating the hazard. The older laboratory-scale tests gave low explosivity indices for dusts that were known to be capable of generating strong explosions in larger scale tests. The major cause of those discrepancies were the ignitability limitations of the older laboratory-scale systems. Those contradictions have been essentially resolved by the development of a new generation of laboratory-scale systems (10-11, 15-16). Those new systems and methods require that data be obtained in the asymptotic limit of high ignition energies, and they give

laboratory results that are in good agreement with mine tests (17-18). The developers of those older, laboratory-scale systems were aware of the conflicts with mine-scale results, and attempted to compensate for them (4). Nevertheless, the practical imperatives of their times seem to have required that some classification or rating scheme be available despite its limitations (19).

Although some feel a greater confidence in the newer experimental methods, there is no consensus for using the newer data in the old explosibility index (equations 1 to 3).

Just as there was a long recognized need for improved laboratory-scale tests and methods that would give results that are in agreement with the more costly and time-consuming full-scale tests, there is an equally compelling need to develop a new hazard evaluation method that is more realistic and in better agreement with real-world experience. The central purpose of this report is to support that emerging consensus and to provide the guidelines for obtaining such a realistic hazard assessment. The old index formulation of equations 1 to 3 has already served its purpose and should no longer be used; this report will document its major inadequacies. An alternative approach will be proposed, which is based on an overall analysis of the explosion hazard problem. The alternative provides for an evaluation of the hazard not just in terms of the intrinsic flammability properties of a dust, but also the relationship of those properties to the operating conditions in any given plant or facility in which the dust is present.

RATIONALE AND CRITIQUE

When considering any system of physical space, the following question arises: What is the probability of a dust explosion occurring in that region of space? Three conditions must be satisfied before a dust explosion can occur:

1. The dust contained within a system must be dispersed and mixed with the air,
2. The concentration of dispersed dust must be above the lean limit of

flammability (the minimum explosive concentration),

3. An ignition source must be present of sufficient power density and total energy to initiate the combustion wave, whose propagation generates the explosion.

For the initial consideration of this problem, it is implicitly assumed that the three conditions are mutually

independent of one another. Accordingly, the probability of a dust explosion occurring $Pr(\text{expl})$ can be quantified in terms of the product of the probabilities of each of those three conditions being satisfied. Thus

$$Pr(\text{expl}) = Pr(d) \times Pr(f) \times Pr(i) \quad (4)$$

where $Pr(d)$ is the probability of dispersing the dust that may have previously accumulated on surfaces within the system being considered; $Pr(f)$ is the probability of having a dispersed concentration that is above the lean limit of flammability; and $Pr(i)$ is the probability of having an adequate ignition source present in the system. Equation 4 will serve as the fundamental guideline for a basic, alternative approach to evaluating the dust explosion hazard.

DUST DISPERSION, $Pr(d)$

A major inadequacy of the explosibility index in equation 3 is that it does not include the first condition of equation 4, which deals with the dispersibility of the dust.

For a given dust loading on the interior surfaces of a mine, factory, or other facility, and in the presence of a given aerodynamic disturbance, the ease with which a dust can be dispersed into the air is a function of several factors: the individual density of the dust particles, their diameters, their shape, their cohesive properties with respect to each other, and their adhesive properties with respect to supporting surfaces. External factors also play a role in the dispersion process: the structure and intensity of aerodynamic disturbances, the location of the dust loading (roof, floor, walls, or shelves), the geometry of those surfaces, and other factors related to the operation of the mine or factory. The details of dust dispersion dynamics will not be considered in detail here; however, the problem becomes moot in systems in which the dust is dispersed by design, as in a pulverizer or in a pneumatic transport line whose function is to transport dust in an airstream. In the pulverized coal-firing system of a

power plant or a cement kiln using air as the transport medium, $Pr(d) = 1$. Furthermore, under normal operating conditions, for typical feed ratios of coal to air in such systems, $Pr(f) = 1$. In those systems, according to equation 4, the explosion probability is then determined exclusively by the probability of ignition, $Pr(i)$.

Equation 4 is equally valid for a fuel gas explosion and for a dust explosion. However, the dispersion and mixing problem for dusts is markedly different from that of gaseous fuels. The mass density of the solids from which the dusts are generated are typically factors of a thousand greater than the density of air into which they are dispersed. Accordingly, the everpresent gravitational force tends to segregate the dust from the air at a rate that is characterized by the settling velocity of the dust particles or their agglomerates. Intense airflows are usually required to disperse the dust against gravity and to maintain the dust-air mixture in a uniformly dispersed state. By contrast, for gaseous fuels, their molecular sizes and densities are comparable to that of the air, so that the airflows associated with the fuel's initial velocity, or even the everpresent natural convective eddies, are sufficient to mix the gas rather rapidly into the surrounding air. Furthermore, for the gas, once the flammable mixture is generated, the mixing is intimate on the molecular scale, and external forces of significant magnitude to cause the fuel to re-segregate are rare. A flammable, homogeneous gas-air mixture in a given isolated enclosure will remain explosive indefinitely. All that is then necessary to generate a gas explosion is an ignition source. For a dust-air mixture, on the other hand, if the dispersing flow is stopped, the dust will settle out rapidly depending on the particle settling velocities. The dust thus re-segregates rapidly on surfaces within the system. In such a system in which the dust has settled, the presence of an ignition source, by itself, will not generate an explosion unless the dust is redispersed into the ignition source. In view of the contrasting behavior between

dusts and gases, it can be argued that dust fuels are intrinsically less hazardous than gaseous fuels. The more difficult dispersion requirement for the solid dust is an additional limitation on the generation of a flammable volume, which might provide the dust system with an additional margin of safety.

The difference in the ease of dispersion of a gas, relative to that of a dust, is both advantageous and disadvantageous from a safety viewpoint. The same rapid and irreversible mixing process that facilitates the generation of a flammable volume from a gaseous fuel leak in air also facilitates the dilution of that fuel leak.

Consider a mine or factory through which air can flow at some fixed volumetric rate that is maintained by forced convection or even by natural convection. The ventilating air currents ensure the rapid mixing of gaseous fuel leaks with air. If the volume of the ventilating airflow rate is much larger than the volumetric flow of fuel, there will be adequate dilution of the gaseous fuel. The fuel concentration throughout the mine or factory will then remain well below the lean limit concentration and $Pr(f) = 0$. In that case, $Pr(expl) = 0$ regardless of the presence or absence of an ignition source. Once the fuel gas is diluted adequately, there normally is no opportunity for a dangerous accumulation. For the gaseous fuel, there is no subsequent demixing in the flow and the large ventilation flow will "dilute, carry away, and render harmless" whatever small fuel leaks may exist (20-21). Such dilution by adequate ventilation is clearly the most effective means of preventing gas explosions from a fuel source of small or moderate intensity.

However, in the case of a dust, the normal ventilation velocities in most regions of mines or factories are generally much too low to transport dust out of the system. For most dust sizes, gravitational settling velocities are too high relative to ventilation velocities and the ventilation flow is ineffective in removing the dust. Accordingly, the dust accumulates in time, and a loading density is eventually reached that

readily exceeds an explosive dust loading even if the rate of dust generation is rather mild.

In summary, for a gaseous fuel source or leaks into the system, adequate ventilation can ensure that $Pr(f)$ remains zero; however, for a dust source, the normal ventilation is generally not effective, and after some time interval $Pr(f)$ will inevitably become unity. For the dust, some countermeasure other than normal ventilation must be taken to remove the accumulation or to neutralize its presence. For the fuel gas leak, the hazard is a function only of the gas source intensity relative to the ventilation flow, and if these quantities are constant and the latter is strong enough to insure sufficient dilution to well below the lean limit, then $Pr(f)$ can be maintained at a zero level indefinitely. For the dust source, however, normal ventilation will not prevent its accumulation, and the hazard will increase in time as more regions of the system approach a flammable dust loading with $Pr(f) = 1$.

FLAMMABILITY LIMITS, $Pr(f)$

Whether the fuel being considered is a gas or a dust, an explosive reaction with air is possible only within a range of fuel concentrations. Those concentrations are defined as the limits of flammability (22-23). For gaseous fuels, there are usually both lean and rich limits; however, for dusts, a normal rich limit does not exist (10-11, 13, 17). The contrasting behavior between gases and dusts is illustrated in figure 1, which compares methane gas in air with polyethylene dust in air. Methane shows normal lean and rich limits beyond which explosions are impossible, whereas the dust shows only a normal lean limit. For all dust concentrations below the lean limit, $Pr(f) = 0$. For dust concentrations that exceed the lean limit, $Pr(f) = 1$. Accordingly, in order to obtain a realistic hazard evaluation, $Pr(f)$ may be simply quantified as the fraction of time the system exists in a state where its dust concentration is above the lean limit.

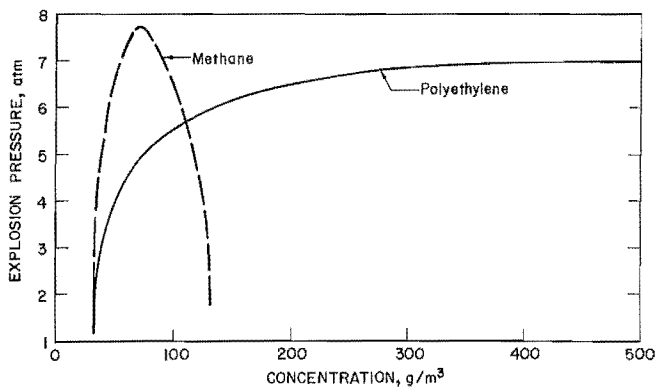


FIGURE 1.—Comparison of flammability limits for methane gas and polyethylene dust in air.

Although that definition of $Pr(f)$ appears simple, there is a hidden ambiguity that requires clarification. Is the dust concentration referred to above the actual dispersed dust concentration, or is it the potential dust concentration if all the dust accumulated on surfaces were dispersed? The dispersed dust concentration is readily expressed in normal volumetric concentration units of grams of dust per cubic meter of system volume (as in figure 1). If the dust is initially present on surfaces within that volume, then its distribution is more accurately described by surface loading density, which is the mass accumulation per unit surface area. The volumetric concentration that would be achieved if that surface loading of dust were distributed throughout the system volume can be calculated, but, that concentration is achieved only if there is perfect dispersion. If the dispersion is imperfect, higher concentrations are present in some regions and lower concentrations in others. In many industrial situations, that ambiguity is always present, and it plays an important role in the hazard evaluation.

Laboratory experiments designed to measure the flammability limits of a dust, such as those shown in figure 1, avoid such ambiguities. Great care is taken to effectively disperse a known mass of dust into a known volume, so that its concentration is uniform throughout the test volume (10, 16). In those cases, $Pr(d) = 1$. Furthermore, in such experiments, an effective ignition source

must be present so that $Pr(i) = 1$. In such laboratory experiments, according to equation 4, $Pr(expl) = Pr(f)$, and the occurrence or nonoccurrence of an explosion is determined uniquely by the existence or nonexistence of a flammable dust concentration. There are some industrial systems that clearly approximate those laboratory experiments: Pneumatic dust transport systems between a coal pulverizer and the burner of a coal-fired boiler; in the pulverized coal feed lines to a cement kiln; or in the case of a dust dryer, where the dust and the air are more or less uniformly mixed. In those industrial systems, $Pr(d) = 1$. The dust concentration in those systems is fairly uniform and is given approximately by the ratio of the mass flow rate of the dust divided by the volumetric flow rate of the air.

In other industrial systems, the dust accumulation is incidental so that it is present mainly on surfaces within the system. When attempts are made to evaluate the hazard associated with the dust's presence on surfaces, the ambiguity is inevitable. Even if it is known precisely what the surface loading density may be within the volumetric enclosure being studied, there is still an uncertainty as to whether that loading density can cause a lean limit concentration to be generated by an aerodynamic disturbance. Will the aerodynamic disturbance disperse the dust throughout the *entire* volume of the enclosure, or will the disturbance be more likely to disperse the dust through some fraction of the volume? The properties of the dispersion system can now play a role in determining whether a lean limit concentration is attained and the two probabilities, $Pr(d)$ and $Pr(f)$, are no longer mutually independent of one another.

Consider for example, a system of one cubic meter containing 60 g of Pittsburgh seam pulverized coal dust on the floor of the chamber. The lean limit concentration for that coal is 90 g/m³. What then is $Pr(f)$ for that system? If the dust is uniformly dispersed throughout the volume by a strong aerodynamic disturbance, the concentration would be 60 g/m³, which is below the lean limit. Thus, for a strong

disturbance, $Pr(f) = 0$. If, however, the aerodynamic disturbance were weaker so that dispersion were limited to the lower half of the chamber (but still strong enough to lift all the dust), then the concentration of dust in the lower half would be 120 g/m^3 , which is above the lean limit. For the weak disturbance in the lower half of the volume, $Pr(f) = 1$. An ignition source in the lower half of the chamber could then initiate an explosion in the system. Since in that instance, the flammable volume would only be half the chamber volume, the resultant explosion pressure would be halved. For the perfectly-dispersed dust, such an explosion would have been impossible.

Based on full-scale experiments conducted in the mine entries at Bruceton and the Lake Lynn Laboratory, there seems to be an uncertainty of approximately a factor of two, between the lean limit concentration of a predispersed dust cloud and the minimum surface loading required to propagate an explosion when the dust is not intentionally predispersed (24-26). For Pittsburgh seam coal dust, the lean limit concentration for the uniformly predispersed dust is about 90 g/m^3 (18), whereas the minimum surface loading required to propagate an explosion corresponds to about 35 to 60 g of dust per cubic meter of the dusted volume. The minimum surface loading is a function of where the dust is placed; with loading on roof shelves being more hazardous than the same loading on the floor (5). In such systems, $Pr(d)$ and $Pr(f)$ are not mutually independent of one another.

For practical evaluations, the uncertainty is probably best resolved by defining $Pr(f)$ in terms of the mass of dust contained in the smallest system volume that is realistically practical to consider, regardless of whether the dust is dispersed or whether it is accumulated on surfaces. A conservative estimate of $Pr(f)$ is obtained by assuming that for purposes of a hazard evaluation, a lean limit concentration will be chosen that is half of the true measured value. Thus, in those industrial systems where the dust is not predispersed by design, but is accumulating on surfaces, $Pr(f)$

will be given by the fraction of time that a surface loading density exists, which would generate a concentration equal to, or above, half the lean limit concentration if all the dust were dispersed throughout the volume of interest. Reasonable judgement must be exercised in choosing "the volume of interest."

IGNITION PROBABILITY, $Pr(i)$

Ignition sources are characterized according to the type of energy they introduce into the system. The most common types of sources are electrical, chemical, or purely thermal. In general, an ignition source can have a variety of geometric sizes and shapes, as well as a variety of time dependencies for its energy delivery rate or power density. The "effectiveness" of an ignition source is defined by whether or not it ignites a flammable volume, and that effectiveness will generally be a function of all of those factors: ignition source size, shape, and power density. As with the other probabilities, $Pr(i)$ may be simply defined as the fraction of time an effective ignition source is present within the system volume.

Examples of some of the data obtained on the effectiveness of chemical (pyrotechnic) sources for the ignition of polyethylene, coal dust, and oil shale dust are shown in figure 2. The effective source energy (12-13, 17) required for ignition is plotted as a function of fuel concentration. In these experiments, the effective source energy, by itself, is usually an adequate description of the source intensity so long as the energy is delivered rapidly enough and is sufficiently concentrated spatially. For a source which delivers its energy more slowly than the characteristic induction time for flame generation, or which is too extended in space, the power density, rather than the energy, will become the more important parameter. It is beyond the scope of this report to consider all possible complex geometries of various ignition sources or their infinite variety of time-dependent delivery rates. It will be simply assumed, hereafter, that the

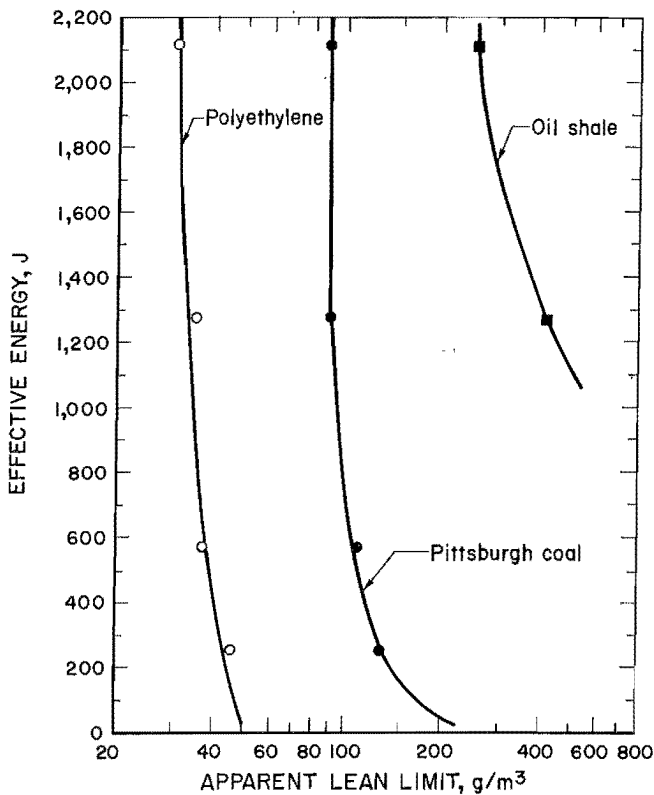


FIGURE 2.—Effectiveness of a pyrotechnic source of varying energy on the ignition of polyethylene, coal, and oil shale dusts.

effectiveness of a given ignition source is defined and determinable.

As indicated, the data in figure 2 are for a chemical ignition source that is concentrated spatially and temporarily. At the other end of the ignition source spectrum is a source that is spatially and temporally extended. The simplest such source is purely thermal and is geometrically uniform in spatial extension and steady state in time. Such a source is isothermal and its ignition behavior can, in principle, be reliably characterized solely by its temperature.

Consider a uniformly predispersed dust-air mixture in a large volume at a dust concentration above its lean limit of flammability so that $Pr(d) = 1$ and $Pr(f) = 1$. Then, ask the question: To what initial temperature must the entire volume of the system be raised in order for it to ignite spontaneously and generate an explosion? That initial temperature is referred to as the spontaneous "auto-ignition temperature" (AIT) of the dust.

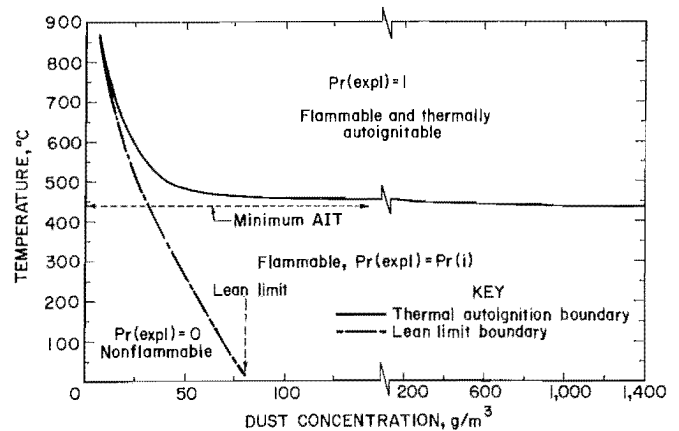


FIGURE 3. Domains of flammability and thermal autoignition for lycopodium dust in air.

An example of the kind of AIT data obtained with purely thermal ignition sources is shown in figure 3 for the case of lycopodium dust in air. The apparatus and method used were described elsewhere (8, 15). The data are for uniformly dispersed dusts so that $Pr(d) = 1$. The thermal autoignition boundary shown in the figure was measured in a region of dust concentrations that are above the lean limit of flammability, so that $Pr(f) = 1$. Thus, $Pr(expl) = Pr(d) Pr(f) = (1)(1) Pr(i) = Pr(i)$; and the explosion probability is equal to the ignition probability. The presence or absence of an explosion is then causally and uniquely related to the presence or absence of an adequate ignition source. The thermal autoignition boundary between ignition (explosion) and nonignition (no explosion) is plotted in temperature versus concentration space (at ambient pressure). Also shown is a lower dashed curve, which is the lean flammability limit boundary in the same concentration-temperature space. All states of the system below and to the left of the lean limit boundary are nonflammable or nonexplosive because $Pr(f) = 0$. For states above and to the right of that boundary, $Pr(f) = 1$, and the explosion probability is there equal to the ignition probability.

At still higher temperatures and concentrations in figure 3, the thermal autoignition boundary is encountered,

which is the innermost "core" or "heart" of all ignitability surfaces in the system's state space. Above that contour, explosion is *certain* because both $Pr(f)$ and $Pr(i)$ are unity. No external ignition source is necessary within that core because the system ignites spontaneously as soon as those dust concentrations are dispersed at those initial temperatures. The combination of dust concentrations and temperatures at or above that contour are therefore "pyrophoric" or "hypergolic," and the explosion probability is unity in that region of the system's state space.

Two quantities that characterize the lean limit boundary and the thermal auto-ignition boundary for any given dust are also shown in figure 3. The one is the lean limit of flammability at room temperature and ambient pressure. It is sometimes also referred to as the "minimum explosive concentration." The other is the minimum autoignition temperature, which is sometimes also called the "minimum cloud ignition temperature." Those two coordinates in temperature-concentration space characterize the two contours. The two contours are generally well-behaved with monotonic slopes as indicated, and the use of thermodynamic diagrams (similar to figure 3) is the simplest way to fully understand the relationships between the flammability limit and the ignitability behavior of any fuel. Elevated temperatures increase both the flammability and thermal auto-ignitability of the system; hence, with increasing temperature, the lean limit concentration decreases as does the concentration at which spontaneous auto-ignition occurs. At very high temperatures, the two contours generally converge.

CRITIQUE OF THE EXPLOSIBILITY INDEX

Now that an alternative approach to the problem of estimating explosion hazards has been sketched, it is appropriate to present a detailed analysis of the deficiencies in the old explosibility index (equations 1 to 3). The first deficiency has already been mentioned in the discussion of $Pr(d)$. The old index does not

contain an explicit measure of a dust's dispersibility. It is possible, however, that in the old experimental methods for measuring C_L , ϵ_{min} , and $(dp/dt)_{max}$, the uncontrollable dispersibility factor could actually play a role in determining the measured values of those parameters. In the case of a strongly agglomerating dust, or a dust whose material density is high, the dust might not disperse effectively, especially in the rather weak dispersion pulses used in the older systems. As a result, there could be large uncertainties in those C_L , ϵ_{min} , or $(dp/dt)_{max}$ values, and lack of reproducibility among the various investigators who used different dispersion methods (10). The current laboratory methods are designed to give complete dispersion so that the dispersion variable is no longer "hidden." Clearly, such a critical variable should not be hidden or confused with the intrinsic flammability or ignitability properties. Rather, the dispersibility should be measured directly so that its effect on the explosion hazard can be independently evaluated.

A variety of methods can be used to measure the effectiveness of a given aerodynamic source in dispersing a given dust configuration. Optical dust probe instrumentation for measuring the dispersion effectiveness of a given dust has already been developed by the Bureau, (24-25), and it should be a relatively simple matter to develop a test procedure for independently evaluating the dispersibility properties of a dust. That would be the first essential step in estimating $Pr(d)$ in a given industrial setting.

Another major problem with the old index involves the way in which it confuses flammability limits with ignitability factors. In any practical system, the safest mode of operation of a facility would be one which operates at a concentration of gaseous fuel or dust that is well below the lean limit of flammability. In that case, $Pr(f) = 0$ and the explosion probability will remain zero regardless of the dispersion probability or the strength of any ignition sources. Yet, in the old explosibility index, the only quantity that relates to $Pr(f)$, the minimum explosive concentration, C_L ,

appears in the ignition sensitivity parameter (equation 1). The old index does not contain independent evaluations for $Pr(f)$ and $Pr(i)$, but instead it mixes the two. While T_{min} and ϵ_{min} are important determinants of $Pr(i)$, the minimum explosive concentration, C_L , is not directly related to ignitability. Instead, it is the main determinant of $Pr(f)$. In fact, the quantities T_{min} and ϵ_{min} cannot even be measured unless the dust concentration is much larger than C_L , and those minima in autoignition temperature and spark ignition energy occur at dust concentrations that are much higher than C_L . The mixing of C_L with T_{min} and ϵ_{min} is logically immiscible. The one is a determinant of $Pr(f)$, the fraction of time the system exists as a flammable volume. The others are determinants of $Pr(i)$, the fraction of time an effective ignition source is present in the system. The intermixing of these two factors conceals them both from view and only serves to confuse the problem.

The objective above can be satisfied by simply removing C_L from the ignition sensitivity parameter, which leaves the product of T_{min} and ϵ_{min} , both of which are logical determinants of $Pr(i)$. There are, however, still serious problems with that approach. The first objection deals with the problem of reliably determining ϵ_{min} for a dust. While the concept of a minimum electrical ignition energy for homogeneous gas mixtures is well established, the concept does not appear to be particularly useful for dusts. A detailed consideration of the problem of reliably determining a ϵ_{min} for a dust is beyond the scope of this paper, but a recent analysis has appeared elsewhere (12-13). There are so many contradictory requirements involved in the experimental conditions needed, and such extraordinary complications, that a reliable determination of ϵ_{min} for a dust is dubious, even under the best of circumstances. Furthermore, there are very few well documented cases in industry of electrically initiated dust explosions. Yet, the tabulations of the old ignitability index show that it is determined mainly by the ϵ_{min} -value. The ϵ_{min} -value varies by orders of magnitude among the various

dusts, whereas T_{min} varies by factors of only two or three. While there are some important circumstances where the electrical ignitability properties of a dust can be significant in determining its explosion hazard, the current test methods for measuring ϵ_{min} are not reproducible or reliable enough to justify its use as the dominant factor in evaluating the overall ignitability of a dust. In cases where it is important, the probability of electric ignition, $Pr(i, \text{spark})$, requires a separate consideration. With the removal of C_L from the ignitability parameters, and a separate consideration for ϵ_{min} , one is left finally with T_{min} , the minimum autoignition temperature, which controls the purely thermal component of the ignition probability. Let us focus now on the purely thermal autoignition probability $Pr(i, \text{thermal})$.

The ratio $(T_{min})_{\text{Pittsburgh coal}} / (T_{min})_{\text{dust}}$ was previously used as the thermal component of the ignitability index; however, the choice of a simple linear function of temperature is quite arbitrary and cannot be justified. In addition, the use of centigrade degrees for T_{min} leads to absurdities for dusts that are hypergolic, with T_{min} values of 0°C or below. While such absurdities can be eliminated by expressing T_{min} in K rather than $^\circ\text{C}$, there is still no justifiable reason for choosing a linear temperature dependence for evaluating the thermal autoignitability of a dust. Using a *linear* scale means that a hypergolic dust with $T_{min} = 300 \text{ K}$ is only a factor of two more ignitable than a dust with a T_{min} of 600 K (327°C). A relatively unreactive dust with a T_{min} of 927°C is only a factor of four less ignitable than the hypergolic dust. Most practical dust-bearing systems operate either at room temperature or near $100\text{--}150^\circ \text{C}$ for drying, with occasional higher excursions in certain regions of the system, or during startup or shutdown transients, or under various emergency conditions. It is unreasonable to ascribe only a factor of two increase in ignition sensitivity or probability to a hypergolic dust in comparison to one that requires an ignition temperature of 327°C .

Similarly, the fraction of industrial dust-bearing systems that can even accidentally reach temperatures as high as 927°C is so trivial in comparison to those systems that can occasionally reach 327°C , that it is likewise unreasonable to ascribe only a factor of two differences between those two dusts. There should be orders of magnitude of difference between the $\text{Pr}(i, \text{thermal})$ values for those cases, yet the linear dependence gives only factors of two.

The linear relationship is thus not just arbitrary; it grossly underestimates the importance of the temperature variable. A more sensitive function of temperature is needed, and the logical choice is an exponential one. However, even with a more sensitive temperature function, an important point would still be missing if the T_{min} for Pittsburgh coal were retained as the standard by which other autoignition temperatures were evaluated. It is not the autoignition temperature relative to that of some other dust that is important in estimating the probability of thermal autoignition. The critical parameter in estimating $\text{Pr}(i, \text{thermal})$ is the autoignition temperature relative to the *operating* temperature of the dust-bearing system, or to the temperature *extremes* to which the system may be subjected. The critical factor in determining $\text{Pr}(i, \text{thermal})$ is the fraction of time the dust-bearing system operates at temperatures that approach or exceed the autoignition temperatures. If the time distribution function were known precisely, and if the system were spatially isothermal and contained dispersed dust at concentrations much higher than C_L , then $\text{Pr}(i, \text{thermal})$ could be determined quantitatively. The explosion frequency would then be equal to the ignition frequency, and would be given by the frequency at which the operating temperature, T_o , exceeded the autoignition temperature, T_{min} . Realistically, however, the operating dust-bearing systems are not isothermal, nor is the fraction of time that the system operates at or near T_{min} really known. Even with those uncertainties, the critical parameter is not the ratio, (T_{min}) Pittsburgh

coal/ (T_{min}) dust; instead, it is the temperature difference, $T_{\text{min}} - T_o$.

In the following section, a method will be proposed for using that temperature difference, $T_{\text{min}} - T_o$, for evaluating the probability of thermal autoignition.

In this section, the critique of the old index continues with a detailed consideration of the deficiencies in the second parameter, equation 2. The second parameter, the explosion severity, was defined in terms of the product of the maximum explosion pressure, p_{max} , with the maximum rate of pressure rise $(dp/dt)_{\text{max}}$. Those quantities were measured in the closed l-L Hartmann chamber at a fixed dust concentration (4). The major deficiency of the second parameter is the unjustified assumption that the "severity" of an actual explosion can realistically be related to measurements in small-scale laboratory systems that focus exclusively on the intrinsic spherical combustion rate of the dust under constant volume conditions. The overwhelming weight of evidence shows clearly that the real "severity" of an actual explosion cannot be predicted accurately by such simplified measurements. Other factors such as boundary constants, initial conditions, and the flow dynamics that develop during the course of an explosion are so critical that they can be overwhelming in determining the severity of an explosion (26). The data used to obtain an evaluation according to equation 2 ignore these critical factors. The intrinsic flammability properties of a dust play an important role in determining whether or not an explosion is possible and in determining the preliminary rate of flame propagation near the ignition source; however, once the process starts, the severity of the resultant explosion is controlled by other factors. These factors are the boundary constraint and initial conditions that determine the flow dynamics and the resultant turbulence interactions. They are controlled by the size and shape of the flammable volume; its size and shape relative to that of the enclosure, the location of the ignition point relative to the boundaries, the condition of the boundaries (open or closed), the

geometric structure of internal obstructions, and the initial turbulence intensity and the opportunity for the generation of turbulence by aerodynamic interactions developing during the course of the explosion (26).

A simple example of how such factors influence the severity of a real explosion is illustrated by some recent experiments performed at the Bruceton Lake Lynn Laboratory. A fixed volume of the mine entry was isolated with a plastic diaphragm at a distance of 27 ft from the mine face (closed end). The initial volume (so isolated) was 7 ft high by 22 ft wide by 27 ft long (118 m³) and was filled with a 7.55 pct methane-air mixture. The same volume and mixture were ignited at three different locations: at a closed end (the face), in the center of the flammable volume, and at the open end (near the plastic diaphragm, which ruptures readily after ignition). The three different results are shown in table 1, where they are also compared with laboratory scale data for spherical propagation for the same mixture in a fixed, 20-L volume. The maximum pressures measured in the mine experiments have no relationship to the p_{max} value measured in the 20-L system at constant volume. For the mine case, there is an outward expansion toward the open end that can relieve the developing pressure, and all the mine data show lower pressures than are observed at constant volume. However, the

three mine experiments show a marked sensitivity to the location of the ignition source. For ignition at the closed end, the explosion is much more severe than for ignition at the open end. For closed-end ignition, turbulence develops in the unburned gas motion ahead of the flame and causes a rapid flame acceleration. The maximum flame speed is almost two orders of magnitudes higher for closed-end ignition. The constant volume, 20-L data grossly overestimated the maximum pressure, grossly underestimated the flame speed, and gave no information on the sensitivity to ignition location, boundary constraints, and the dynamic effects of turbulence. If the flammable volume had been longer than 27 ft, and if periodic obstructions had been placed in the mine, flame velocities would have reached supersonic speeds and explosion pressures would have exceeded 7.2 bars, even if the system were free to expand. The 20-L measurements provide no information on those factors critical to the explosion's real severity.

Next, consider the p_{max} factor in equation 2. To what extent does p_{max} , by itself, measured in a constant volume system, control the severity of an explosion? For the more flammable dusts, p_{max} will generally be in the range of 6 to 10 bars; that is, if the system is initially at 1 bar (1 atm), explosions in a fixed volume will generate overpressures of from 5 to 9 bars (74 to 118 psig). For

TABLE 1. - Flame propagation characteristics for CH₄-air explosions (7.55 pct) at Lake Lynn for various ignition locations compared with 20 L data

Test system and ignition location	Maximum overpressure, bar	Flame speed, m/s		$(dp/dt)_{max}$, bar/s	K_{st} , bar m/s
		max	av		
Lake Lynn:					
Closed end or face..	0.48	168	34	3.3	15.7
Center.....	.27		32 ^a 3 ^b	1.7	8.1
Open end diaphragm...	.14	4	4	.02	.1
Constant volume, 20 L, center.....	7.2	3	1.5	129	35

K_{st} size-normalized rate of pressure rise.

^aOutward.

^bInward.

dusts that are barely flammable, explosion pressures will be in the 3 to 4 bar range. Those values are for concentrations of dust that are well within the domain of flammability. As the limits of flammability are approached, the explosion overpressures drop almost discontinuously to zero. Thus, nonexplosive dusts or explosive dusts at concentrations below their lean limits, show no explosion overpressures. Furthermore, for spherical flame propagation in a constant volume system that is ignited centrally, heat losses are low and measured explosion pressures generally approach those calculated on the basis of adiabatic equilibrium for constant volume combustion. Beyond the flammability limit, however, measured explosion overpressures are near zero even though adiabatic equilibrium conditions would generate overpressure in the 3 to 4 bar range. Therefore, the lean limit concentration, C_L , is a very important parameter since it is the dividing line between high explosion pressures at higher concentrations and insignificant overpressures at lower concentrations. But, when conducting experiments above C_L with explosive dust concentrations, is it important to distinguish between the case where the overpressure is 3 atm and where it is 8 atm? The answer depends on the purpose or use of the p_{max} factor. For the normal external structures of interest, such as the walls of a factory, the roof of a facility, the windows of a habitat, or even the concrete of a storage silo, the answer is that it makes little difference whether the overpressure is 3 or 8 atm. Structural failure will occur catastrophically in either case, and at much lower overpressures. Such structural failure opens the system to the surroundings and causes the venting of expanding explosion gases, both burned and unburned. In such cases, the p_{max} value measured in spherical, constant volume combustion, is generally not attained in reality. The severity of such a real-world explosion and the damage it causes is unrelated to the measured p_{max} value at constant volume, but it is determined by the rupture pressure of the structure, the vent area, the

dynamics of pressure development, and the flow dynamics of pressure relief. In fact, the strategy for explosion protection in such structures encourages their failure in a controlled manner at very low overpressures (27). That is achieved by using a large vent area, which opens at a relatively low overpressure. In such cases, the important parameter in determining the maximum pressure within the structure is $(dp/dt)_{max}$, as well as the vent area, and the aerodynamic and geometric factors mentioned earlier. In such cases, the p_{max} value measured in a constant volume sphere is virtually irrelevant.

On the other hand, if some of the internal plant equipment, pulverizers, dryers, reactors, or pneumatic feed lines can be designed to withstand and contain explosions, then clearly p_{max} is the critical factor. For that purpose p_{max} is critical; however, $(dp/dt)_{max}$ then becomes virtually irrelevant.

To summarize, while p_{max} is an important factor in the potential severity of an explosion since it measures the maximum explosion stress to which process equipment will be subjected, and is therefore, the critical factor in designing such equipment to contain or withstand explosions, the same p_{max} factor is not a realistic measure of the explosion severity or damage potential to external structures such as walls, silos, roofs, doors, or windows. In those latter cases, catastrophic failure results from even the mildest explosion pressures and the important factor is not p_{max} , but $(dp/dt)_{max}$. Thus, either the one parameter or the other is important depending on the purpose or use intended, and the mixing of the two quantities into a single severity index is inappropriate.

Furthermore, for the occupants of a plant or facility, if the flammable volume is a significant fraction of the plant volume, even the mildest explosion is not a survivable event. From their viewpoint, the absolute magnitude of p_{max} is irrelevant and even the value of $(dp/dt)_{max}$, which may be used to protect the external structure, may also be entirely irrelevant to their survival.

PRACTICAL CONSIDERATIONS

As indicated in the previous section, the intrinsic flammability properties of a dust do not by themselves uniquely determine the severity of an explosion. Nevertheless, previous considerations do indicate that intrinsic flammability properties have a profound influence on the probability of the occurrence of an explosion, quite apart from the question of its severity. How direct is the relationship between the intrinsic combustion behavior of the dust and the probability of the occurrence of an explosion in a dust-bearing system? A direct relationship is suggested because, if a dust is entirely noncombustible, the explosion probability is nil. If a dust cannot undergo an exothermic combustion reaction in air, then it does not have a finite lean limit concentration. In that case $Pr(f) = 0$, which means that the explosion probability is zero regardless of the dusts dispersibility or the presence of ignition sources. Examples of such dusts are limestone, fly ash, cement, alumina, silica, clay, or talc. For such dusts $C_L = \infty$, hence $Pr(f) = 0$, and $Pr(\text{expl}) = 0$. Dusts that are capable of undergoing an exothermic reaction in air (at a sufficiently rapid rate) such as coal, flour, wood, plastic, aluminum, or zirconium, have finite lean limit concentrations. Common sense thus suggests a simple inverse relationship between $Pr(f)$ and C_L . The lower the lean limit concentration, the easier it will be for a given source of dust to generate that minimum concentration, and the higher will be $Pr(f)$. In general, all dusts will have a finite dispersion probability, $Pr(d)$. Such flammable dusts also have finite auto-ignition temperatures and finite ignition probabilities. Accordingly, there is a finite hazard involved in their mining, manufacture, transport, storage, and use. This section will present some examples of actual evaluations of the hazard.

ACTUAL EVALUATIONS

The net explosion probability, equation 4, was previously expressed in terms of the product of three separate

probabilities; $Pr(d)$, $Pr(f)$, and $Pr(i)$. It was implicitly assumed that the events or conditions determining each of those probabilities were mutually independent of one another. In that case, the events or conditions that determine each probability are randomly distributed in time, with respect to one another. Each probability was defined in terms of the fraction of time the system existed in a state in which those separate events or conditions were present. $Pr(d)$ was the fraction of time the dust was dispersed; $Pr(f)$ was the fraction of time a flammable concentration was present, and $Pr(i)$ was the fraction of time an effective ignition source was present. The requirement of mutual independence for each of these probabilities does not mean that the events that determine any one probability must themselves be randomly distributed in time, but only that they have a random relationship to the events that determine the other two probabilities.

Examples A and B: Dust
Collector Baghouse

Consider a filter bag dust collector that is periodically cleaned every hour by a reverse pressure pulse, which generates a flammable dust cloud that is airborne for 3 min before the dust settles by gravity to the bottom of the system where it is removed by a rotary feeder. In that system, $Pr(d) = 3/60 = 0.05$. The cleaning pulses, which generate the finite value of $Pr(d)$, are quite periodic and not at all randomly distributed in time. But that, by itself, says nothing about its mutual independence with respect to either one of the other probabilities. If the events that may cause the presence of an ignition source in the baghouse volume are randomly distributed with respect to the pulse cleaning period, then $Pr(i)$ and $Pr(d)$ would be mutually independent of one another. Such would be the case, for example, if the only ignition source possible were hot embers from an upstream grinder. Assume that such an ignition source was present

only once a month, on the average. Furthermore, assume that these embers cooled rapidly so that they were hot enough to ignite the dispersed dust for a short time interval of only 10 s. In that case, $\text{Pr}(i) = 10/(60)(60)(24)(30) = 3.9 \times 10^{-6}$. The events governing those two probabilities are mutually independent of one another. As a result, the net probability of both dispersion and ignition occurring at the same time would be $\text{Pr}(d)\text{Pr}(i) = (0.05)(3.9 \times 10^{-6}) = 2 \times 10^{-7}$.

If, however, that same dust was easily ignited by an electrostatic spark discharge, which was always triggered by the reverse air pulse, then the two probabilities would no longer be mutually independent. If that spark discharge lasted only 10 μs , then at a cleaning rate of once per hour, it could be calculated that $\text{Pr}(i) = 10^{-5}/(60)(60) = 2.8 \times 10^{-9}$. However, since the dispersion and ignition events are now *not* mutually independent of one another, it would be incorrect to estimate the net probability of dispersion and ignition occurring at the same time as being $(.05)(2.8 \times 10^{-9}) = 1.4 \times 10^{-10}$. That would grossly underestimate the hazard because the ignition and dispersion events are not randomly distributed with respect to one another. According to our assumption, they are precisely correlated in time. Since the ignition source is present when dispersion occurs, the correct value for the product of the two probabilities is therefore $\text{Pr}(d)\text{Pr}(i) = \text{Pr}(d,i) = 0.05$.

To estimate $\text{Pr}(\text{expl})$ for the above two cases of the randomly present embers or the electrostatic spark associated with the cleaning pulse, it is necessary to know $\text{Pr}(f)$. Since $\text{Pr}(f)$ is defined in terms of the nominal loading and since it is assumed that a flammable dust concentration is present at each pulse cleaning event, $\text{Pr}(f) = 1$. In the case of the hot embers, therefore, $\text{Pr}(\text{expl}) = 2 \times 10^{-7}$. In the case of the electrostatic discharge, $\text{Pr}(\text{expl}) = 0.05$. The coupled electrostatic case is much more hazardous even though its individual, randomized ignition probability, $\text{Pr}(i)$, was much lower than for the hot embers ignition

source, since the spark lasted for a much shorter time period.

But, even after the calculation is made according to equation 4, the problem of interpretation remains. What is the practical meaning of an explosion probability of 2×10^{-7} ? Equation 4, as presented, does not yet have a clear-cut physical interpretation. From the viewpoint of predicting explosion hazards, it is not the dimensionless probability that is needed, but rather the predicted frequency of occurrence of an explosion. The explosion frequency quantifies the hazard in a physically meaningful form. For an explosion frequency prediction, only two of the three conditions should be expressed as probabilities, and the third should be expressed in terms of its frequency of occurrence. Thus, for the first case of ignition by hot embers: $f(\text{expl}) = \text{Pr}(f)\text{Pr}(d)f(i)$, where $f(i)$ is now the frequency of the presence of the hot ember ignition source within the dust collector. In this case, the presence of the ignition source was the least frequent of the three events that determine the three probabilities, and hence it was chosen as the third factor, which is expressed in terms of frequency. For the assumptions made earlier, $\text{Pr}(f) = 1$, and $\text{Pr}(d) = \tau_{\text{airborne}}/\tau_{\text{pulse}}$, where τ_{airborne} is the duration of the time the dust is airborne and τ_{pulse} is the period between dispersion pulses. Thus, for the hot ember case, $f(\text{expl}) = (1)(3 \text{ min}/60 \text{ min})$

$\frac{1}{1 \text{ month}} = 0.05 \text{ per month} = 0.60 \text{ per year}$.
The explosion frequency of 0.60 per year corresponds to a predicted period of one explosion every 1.7 years, on the average.

For the second case in which dispersion and ignition events are precisely correlated in time, the duration of the ignition source and the duration of time that the dust is airborne are both irrelevant. Since an affective ignition source is always present during the dispersion, $\text{Pr}(i) = 1$ and $f(\text{expl}) = \text{Pr}(f)\text{Pr}(d)f(d) = (1)(1)$

$\frac{1}{(1 \text{ hour})} = 1 \text{ per hour}$. An explosion will occur at each pulse cleaning operation, and the filter bag-house could never operate successfully in reality.

These specific examples were presented for illustrative purposes only. They should not be considered as real evaluations of a particular explosion hazard. With the exception of some special plastic and chemical dusts, the electrostatic ignition of most common dusts is highly improbable under most circumstances, so that the second case is somewhat fictitious. In the former case of hot embers, the real hazard has been underestimated by the above calculation because it has ignored the fire hazard and the potential for such a fire to lead to a subsequent explosion. The analysis assumed that for an explosion to occur, the presence of the random hot embers would have to overlap in time with the pulse cleaning duration during which the dust was airborne for only 3 min once every hour. However, regardless of when the embers appeared in the pulse cleaning cycle, they would still be collected on a filter bag, and could readily generate a smoldering fire in the accumulated dust even if that dust is not being dispersed. Such a fire could then lead to an explosion during the next cleaning cycle.

The above calculations were designed to illustrate some of the complexities and pitfalls involved in obtaining realistic hazard evaluations. A cautious approach must be taken: the complicated interrelationships between the various processes and events involved must be fully understood, and any evaluation should clearly emphasize the limitations and uncertainties involved in any hazard evaluation or forecast.

Examples C and D: Pneumatic Dust Transport System

In a simpler example, for a relatively dilute dust-bearing system in which a predispersed dust concentration above the lean limit concentration is present for only 1 pct of the time, $Pr(f) = 0.010$. Let the dispersion be continuous so that $Pr(d) = 1$. Consider, as before, an effective ignition source whose duration is very short compared to the duration of those concentration fluctuations or their

period. Let that ignition source be present at a frequency of once per year. For that system, the explosion frequency is simply: $f(\text{expl}) = Pr(d)Pr(f)f(i) = (1)(0.01) \frac{1}{1 \text{ yr}} = 10^{-2}$ per year. The explosion period is therefore one explosion every 100 yr. If, instead, the dust concentration were continuously maintained at a concentration above the lean limit, then $Pr(f) = 1$ and $f(\text{expl}) = (1)(1)f(i) = 1$ per year. The explosion frequency would be equal to the ignition frequency and would correspond to a period of one one explosion per year.

In these rather simplified examples, there appears to be some arbitrariness in the choice of the ignition event as the discrete event, which is expressed in terms of its frequency, $f(i)$. The other two conditions or events were expressed in terms of their fractional time duration, or probabilities $Pr(d)$ and $Pr(f)$. The choice is, however, not really arbitrary. The least frequent event, or the event with the smallest time duration, should be chosen as the discrete one. If, for example, in the system just considered the ignition probability was the larger one so that the ignition source was present for 1 pct of the time, then $Pr(i) = 0.01$. If the dust were predispersed but a lean limit concentration was randomly exceeded at a frequency of only once every 6 months, then $f(\text{expl}) = Pr(d)Pr(i)f(f) = (1)(0.01) \frac{1}{0.5 \text{ years}} = 2 \times 10^{-2}$ per year. The expected explosion period would then be the reciprocal of $f(\text{expl})$, or one explosion every 50 yr. Since the existence of the flammable volume is the rarer event, it was chosen to be expressed in terms of its frequency of occurrence. It is an implicit assumption in the calculation that the events in question must be random related to one another, as discussed earlier.

Example E: Grain Storage Facility

Let us consider still another specific example: a dusty grain storage facility containing a nominal dust loading on the

floor of the conveyor belt run that is sufficient to generate a flammable dust cloud if it were dispersed within the passageway containing the conveyor belt. If no care is taken to remove the accumulated dust, it would be present almost continuously, so that $\text{Pr}(f) = 1$. Consider an unshielded space-heater installed within the conveyor run passageway. The heater is usually operated only during the coldest months. Assume that the surface temperature of its heating elements reaches the hot surface ignition temperature of the grain dust cloud for, on the average, 5 pct of the time. The heater is not in direct contact with the dust accumulation on the floor, but is several feet above the floor. For that ignition source, $\text{Pr}(i) = 0.05$. In this case, it is the dispersion of the dust into the air that is the least probable event and hence it is treated as the discrete event that is "rate limiting." If some aerodynamic disturbance capable of dispersing the dust cloud into the heater is present, on the average of approximately once in 9 months, and if those disturbances are randomly distributed with respect to the operation of the space heater, then $f(\text{expl}) = \text{Pr}(f)\text{Pr}(i)f(d) = (1)(0.05)$

$$\frac{1}{0.75 \text{ year}} = 0.067 \text{ per year, and the average period of an explosion occurrence would be once every 15 yr. The offending aerodynamic disturbance could be an intense starting surge of the conveyor belt, a ruptured compressed air line, an object falling on the dusty floor, or an exceptionally strong wind gust through an open door or window.}$$

In such instances, conventional wisdom generally attributes the cause of the explosion to the event that has the lowest frequency. If the conveyor belt passageway just considered were continually observed, the explosion would not happen until the aerodynamic disturbance generates a dust cloud. Hence, conventional wisdom would attribute the "cause" of the explosion to that event which preceded it most directly in time. Even though an effective ignition source was present 5 pct of the time, and an explosive dust loading was present 100 pct of the time,

the explosion did not occur until the dust was dispersed. The instant the dust was dispersed, the explosion occurred; hence, it is considered by conventional wisdom to be the cause.

In the earlier cases considered, in which the ignition event was the least frequent one, conventional wisdom would say that the explosion was caused by the hot embers, or the electrostatic spark, or whatever else may have been determined to be the ignition source. However, in many accidents involving fuels that can be readily ignited, the offending ignition source may be impossible to find. Conventional wisdom thus overemphasizes the importance of the ignition source, and if this is done to the exclusion of the other factors, it often leads to the unproductive approach of trying to exclude all possible sources of ignition in a system, when, in fact, that may be the least productive approach to prevention.

Conventional wisdom is incorrect in emphasizing the least frequent of the events or conditions as the cause of the explosion. The least frequent event does indeed trigger the explosion, and because it immediately precedes the dramatic explosion event, there is inevitably a subjective temptation to say that it was therefore the cause of the explosion. But, if forced to choose a single cause for the explosion, it is more correct to attribute it to the offending condition or event with the highest frequency or probability, rather than to the one with the lowest. For the case of the grain storage facility just considered, it was the accumulation of a flammable dust loading that was the major cause, since $\text{Pr}(f)$ was unity. The ignition source was the next most significant cause since $\text{Pr}(i) = 0.05$. Although the aerodynamic disturbance triggered the explosion, its occurrence would have been of trivial significance in the absence of the other two conditions. It is more logical to consider the dust dispersion event as the least significant of the three factors. Conventional wisdom overemphasizes the final event at the expense of the entire chain of precipitating events.

CORRELATION OF EVENTS AND RANDOMNESS

As indicated earlier, in cases where the individual events that determine each of the three probabilities (or frequencies) are not randomly distributed with respect to one another, they cannot be considered mutually independent, and equation 4 cannot be used directly. If time correlations are present between the events involved, there may be a reinforcement of the hazard if the time correlations are such that the events tend to occur in phase. On the other hand, there may be a diminution of the hazard if the events occur out of phase. For example, in the case of the grain storage facility just considered, the space heater ignition source is more likely to be on during the winter months when the grain dust is drier. A drier grain dust has a lower lean limit concentration, a lower thermal ignition temperature, and a greater dispersibility in a given aerodynamic disturbance. A drier grain also has a higher rate of dust generation per unit mass of grain transported along the conveyor. Such correlations in these effects will tend to increase the hazard and give an explosion frequency higher than that estimated on the basis of randomness.

Proper safety practices will, in fact, attempt to reduce explosion hazards by a purposeful suppression of randomness. Consider, for example, a coal pulverizer and dust transport system to a coal dust burner or kiln in which air is used as the dust transport medium. For typical flows of coal and air, concentrations are well above the lean limit under normal operating conditions, and the dust is predispersed. Thus $Pr(d) = 1$ and $Pr(f) = 1$ in the pneumatic transport system that grinds the coal dust and feeds it to the burner. A welding torch is an effective ignition source for the coal dust-air mixture, and if it were known that such an effective ignition source would be present in the system once every 6 months, a slavish adherence to our previous formula would give the erroneous results that $f(\text{expl}) = Pr(d)Pr(f)f(i)$

$$= (1)(1) \frac{1}{0.5 \text{ year}} = 2 \text{ per year. Of}$$

course, the explosion frequency is not two explosions per year because the presence of the welding torch within the system is not a random event. The torch is used for internal repair and maintenance of the system and proper safety rules require that the system be shut down and the coal dust removed before any welding operations begin. Safe maintenance and repair require a purposeful ordering of events, so that $Pr(d) = 0$ and $Pr(f) = 0$ during the same time intervals that $Pr(i) = 1$. The events in the system are clearly not randomly distributed with respect to one another, and $Pr(\text{expl})$ will remain zero regardless of the repair frequency. If the events involved are not randomly distributed in time, then the probabilities must be considered in terms of the simultaneity of the events or their lack thereof. In the above case of welding, to obtain a correct estimate, $f(i)$ is not simply the average frequency of occurrence of an ignition source, but is its frequency of occurrence during the times that $Pr(d)Pr(f) = 1$. The simultaneous presence of all three conditions determine the explosion frequency. The system is safe as long as the "lockout" procedure is followed; namely, as long as there is never an overlap in the time intervals that $Pr(d)Pr(f)$ and $Pr(i)$ are simultaneously unity.

In the above welding case, the lack of randomness is purposeful; it is arranged by the system operator in order to minimize the explosion hazard. However, there are other instances where the events themselves are fortuitously and unfortunately "malevolent"; that is, they exhibit a time correlation or simultaneity that reinforces or magnifies the explosion hazard. A good example of such malevolent simultaneity is the "gas ignition" problem near the face of a coal mine. Consider a coal mine that contains a nominal loading of coal dust on the floor, ribs, and roof that would be flammable if it were dispersed within the mine entry. For that mine, $Pr(f) = 1$. Such a situation is now forbidden in coal mines by law (20-21); however, it was the rule, rather than the exception, near the turn of this century. Assume that the mine in question generates sufficient

methane so that it has a significant face ignition frequency. The term "face ignition" describes a smaller scale methane gas explosion that is limited to a small flammable volume near the mining machine. It is usually initiated by the frictional heating of hard inclusions when they are struck by the bits of a continuous miner (28). The source intensity of such an ignition is sufficient to ignite a dispersed coal dust-air mixture. Let the average frequency of occurrence of such a face ignition be $f(i) = 5$ per year. The dust in a coal mine is accumulated on surfaces and is not normally predisposed. It could logically be argued that the explosion frequency would then still be controlled by the dispersion probability $Pr(d)$, so that $f(\text{expl}) = Pr(f)Pr(d)f(i) = (1)Pr(d)(5 \text{ per year})$. Or, if dispersion were the least frequent event and the face ignition lasted for approximately 2 s, it could be argued that $f(\text{expl}) = Pr(f)Pr(i)f(d) = (1)[5 \times 2/(3,600)(24)(365)]f(d) = 3.2 \times 10^{-7}f(d)$, where $f(d)$ is the frequency of dust dispersion. However, in the case of face ignition, the ignition event is not randomly distributed with respect to the dispersion event. The same face ignition event that is capable of igniting a dispersed dust cloud also provides the aerodynamic disturbance that is usually sufficient to disperse the dust accumulations. Thus, ignition and dispersion occur at essentially the same instant in time. This simultaneity of dispersion and ignition means that the frequency of 5 per year is not just a measure of $f(i)$, but also of the products $Pr(d)f(i) = Pr(i)f(d)$. Hence, the explosion frequency is $f(\text{expl}) = 5$ per year, and is equal to the ignition (and dispersion) frequency. The hazard is thus markedly increased by the fact that the methane ignition process was also an effective dispersion process.

By contrast, some other ignition source that does not generate a simultaneous aerodynamic disturbance is far less hazardous; for example, a welder's torch or a trolley wire arc, either of which would be effective in igniting coal dust and might have the identical frequency of occurrence as the face ignition (5 per

year). If the welders torch were used for 1 h at a frequency of five times per year, then $Pr(i) = (5 \times 1 \text{ hour}/(24)(365) \text{ hours}) = 5.7 \times 10^{-4}$. Now consider an *independent* dispersion process, which is randomly distributed in time relative to the ignition source, but with the same frequency as before (5 aerodynamic disturbances per year). Now the predicted explosion frequency is $f(\text{expl}) = Pr(f)Pr(i)f(d) = (1)(5.7 \times 10^{-4}) 5 \text{ per year} = 0.0029 \text{ per year}$. For this case, where the same frequency of dispersion and ignition events are present, but where they are *randomly* distributed in time sequence, the explosion frequency has been reduced by over three orders of magnitude. From an unacceptable explosion period of one explosion every 2.4 months, it has been reduced to a less intolerable level of one every 350 yr!

Near the turn of the century, there was a misapprehension that coal dust by itself was not explosive. It was argued that the frequent disasters in coal mines were caused entirely by methane gas. So prevalent was that mistaken belief that loose coal dust in the mines was routinely used to pack or "stem" explosives in their boreholes. The explosives used at that time were readily capable of igniting coal dust, which explains the high explosion disaster rate in coal mines during that period. Those exceedingly hazardous blasting practices insured that $Pr(d)$, $Pr(f)$, and $Pr(i)$ were intimately coupled and correlated in phase so that they reached their peaks simultaneously in time.

The simultaneity of ignition and dispersion processes characterizes most accidental dust explosion processes. The burned gases generated by the dust explosion expand rapidly from the ignition source and push the still unburned gases outward. That aerodynamic disturbance disperses the dust ahead of the flame front and also markedly increases the Reynolds number of the flow ahead of the flame. The flow ahead of the flame becomes turbulent and as the flame propagates into the turbulent flow, it accelerates markedly. That turbulent flame front acceleration increases the unburned mixture flow velocity, which further

increases the turbulence intensity, thereby increasing the dust dispersion and further accelerating the flame. This self-accelerating process generates high pressures even in the absence of significant geometric confinement (26).

Such dust explosions are actually secondary explosions (29) that are quite common in mines, factories, grain storage facilities, or pulverized coal-firing systems. The secondary explosions are initiated by primary explosions of gas or dust. The primary explosion generates flows that vent into dusty spaces from adjacent regions or process equipment. Secondary explosion events are examples of a magnification of the hazard when ignition and dispersion processes are not randomly distributed in time, but are intimately coupled in the same process. For most secondary explosions, the additional turbulence, which further reinforces the dispersion and flame acceleration, magnifies the hazard. As previously indicated, it is the complex dynamics of such processes that ultimately determine the real severity of an industrial dust explosion. Such processes are not accurately simulated in laboratory-scale, spherical flames at constant volume.

PROPOSED METHOD FOR EVALUATING Pr(i, thermal)

As indicated in an earlier section, which enumerated the deficiencies of the old explosibility index (equation 3), the use of the linear ratio $(T_{min})_{\text{Pittsburgh coal}} / (T_{min})_{\text{dust}}$ in its ignition sensitivity parameter (equation 2) grossly underestimated the importance of the temperature variable. In addition, it was shown that the important variable in estimating the probability of thermal ignition was not the ratio of a dust's autoignition temperature T_{min} relative to that of some other dust, but rather the difference between its autoignition temperature and the operating temperature. The demonstrated need for a more sensitive, exponential function to relate Pr(i) to T_{min} , and the choice of $(T_{min} - T_o)$ as the important temperature

variable leads to a very familiar functional form for Pr(i, thermal). Safety engineers in a plant or factory will generally not have a precise knowledge of the fraction of time a dust-bearing system spends at each temperature. There are inevitable statistical and operational fluctuations in the system temperatures that are associated with startup and shutdown transients; for example, emergency trips of the system, variation in the properties of the material feed, and seasonal variations of ambient temperature and humidity. The problem of determining the fraction of time that the system's temperature (or internal energy) will exceed the critical level for ignition is mathematically analogous to the well-known problem of statistical mechanics: determining the fraction of particles in a gas, at a temperature T, whose energy exceeds some critical level ξ_1 . That fraction is given by the Boltzmann distribution function, $\exp(-\xi_1/kT)$, where the quantity, k, is a universal constant relating the kinetic energy or momentum of atomic particles (reflected in the pressure they exert on their surroundings) to the temperature of the system. Naturally, the statistics that determine the temperature fluctuations in a given apparatus or dust-bearing system are less predictable than those involved in the random motions of gas molecules exchanging kinetic energy by impact. Clearly, a different constant is required for the dust-bearing system, and its value cannot be predicted, a priori, nor would the constant determined for one dust-bearing system be applicable to another system of different structure or design. With that limitation, it seems plausible to estimate the small population of thermally autoignitable states by an analogous function:

$$\begin{aligned} \text{Pr}(i, \text{thermal}) \\ = \exp [-C (T_{min} - T_o(t))/T_o(t)] \quad (5), \end{aligned}$$

where C is some macroscopic facility constant to be determined by the operating characteristics of a given dust-bearing system.

The time-average operating temperature, $T_o(t)$, is naturally constrained to be less than the autoignition temperature, T_{min} . For those time intervals in which transient temperature excursions exceed T_{min} , $Pr(i, \text{thermal})$ becomes unity and explosion is certain if the dust is dispersed at a flammable concentration. Normally, $T_o(t) < T_{min}$, and the explosion probability is small. With the proper choice of the constant C , $Pr(i, \text{thermal})$ should represent the fraction of time that the system would accidentally experience a temperature excursion that would lead to ignition. The choice of a realistic proportionality constant would require a detailed measurement of the operating temperatures within the dust-bearing system. Once a particular dust is specified for the system, T_{min} is determined. The operator or designer of the equipment then has some control over $T_o(t)$ and the constant C . For safe operation, the constant C should be as large as possible, and $T_o(t)$ as low as possible.

One final point relates to the copresence of other types of energy sources in the system: electrical or chemical. As formulated, in the preceding development $Pr(i, \text{thermal})$ is the purely thermal autoignition probability. The copresence of other types of ignition sources would magnify the total ignition probability considerably. Increasing the operation temperature of a system markedly reduces the minimum spark ignition energy (12-13). For example, at a coal dust concentration of 400 g/m^3 , increasing the initial temperature from 25° to 200° C results in an order of magnitude reduction in the ϵ_{min} -value. That reduction

in the minimum spark ignition energy could take the system from a condition in which spark ignition is virtually impossible at 25° C to one in which the spark ignition probability $Pr(i, \text{spark})$ becomes significant during the operating life of the facility. The minimum AIT value for Pittsburgh coal is near 540° C , so that the difference, $T_{min} - T_o(t)$, would still be quite large even if the operating temperature is raised from 25° to 200° C .

Now if the dust-bearing system were well controlled at 200° C so that the temperature excursions about $T_o(t)$ were small in magnitude, the constant C would be large, and the purely thermal autoignition probability would be quite low even at $T_o(t) = 200^\circ \text{ C}$. However, if the spark ignition probability, $Pr(i, \text{spark})$ is enhanced by that temperature increase, the hazard is magnified. Thus, the thermal autoignition probability may still be trivial in going from 25° to 200° C , but that increase in operating temperature may have a profound effect on $Pr(i, \text{spark})$. There is a strong synergism between the thermal energy content and the spark ignition energy requirements, even at temperatures well below those required for autoignition. A similarly strong synergistic interaction may also exist for chemical ignition sources, such as those generated by the oxidation of tramp metal particles, the frictional "thermite" reaction between aluminum and steel, or even for unreacted explosives residues left in the fuel during its conventional mining. Those factors require special study, but their influence could, in principle, be incorporated into the proper choice of the constant C .

CONCLUSIONS

The major conclusions and recommendations of this study are as follows.

1. The use of the explosibility index (equation 3), which is comprised of the product of the ignition sensitivity (equation 1) and the explosion severity (equation 2), is not a realistic method of evaluating the explosion hazard of a dust, and should therefore no longer be

used. The justification for this recommendation has been presented in detail in the text.

2. If, for practical classification purposes, it is necessary to characterize the intrinsic explosion susceptibility of a dust in terms of one single parameter, the most meaningful parameter to use is the lean limit of flammability measured in the limit of fine particle sizes.

3. A more complete evaluation of the intrinsic explosion properties of a dust can be obtained from a delineation of its flammability and thermal autoignition domains, as shown in figure 3. Thermal, electrical, and chemical ignitability behavior are describable in terms of ignitability contours in that same temperature versus concentration space at constant pressure.

4. It is essential that a quantitative parameter be developed for evaluating the dispersibility of a dust and its dependence on particle size. (Such a parameter has not yet been proposed or developed.)

5. A quantitative hazard assessment for a dust involves both the intrinsic flammability properties of the dust and the operating conditions in the facility whose hazard is to be evaluated. Three conditions or cofactors are involved in the occurrence of a dust explosion. The first involves the dispersion of the dust; the second involves the concentration of the dust, which must exceed the lean limit; the third involves the presence of an adequate ignition source. Each of those conditions or cofactors are quantifiable in terms of their individual probabilities: $Pr(d)$, $Pr(f)$, and $Pr(i)$. Each probability may be defined in terms of the fraction of time the system or facility exists or operates in the hazardous state. $Pr(d)$ is the fraction of time the dust is dispersed; $Pr(f)$ is the fraction of time a lean limit concentration exists in the system; $Pr(i)$ is the fraction of time an effective ignition source is present.

6. In those instances where the three factors are mutually independent of one another; that is, where their presence or

absence are randomly distributed in time, the explosion frequency is predictable from the equation:

$$f(\text{expl}) = Pr(j) Pr(k) f(l),$$

where $Pr(j)$ and $Pr(k)$ are two of the aforementioned probabilities, and $f(l)$ is the frequency of occurrence of the third and least frequent of the cofactors.

7. In those instances where the cofactors are not mutually independent of one another but are correlated in time such that they can occur in phase, the cofactors cannot be used separately and the hazard is magnified markedly. A negative correlation among the cofactors, which causes them to occur out of phase, provides a margin of safety that diminishes the hazard.

8. The focus on a single one of those cofactors in a post-disaster investigation of an explosion does not provide for an adequate understanding of the causes of the explosion. Similarly, countermeasures that emphasize only one of those cofactors at the exclusion of the others will generally be less cost effective than a balanced set of countermeasures that includes all cofactors and their temporal dependencies with respect to one another.

9. If there is any single factor that provides the greatest margin of safety, it is the absence of a flammable dust concentration in which the condition $Pr(f) = 0$ is maintained throughout the system.

10. The factors that determine the occurrence of an explosion have, in general, little relationship to the severity of an explosion once it begins.

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