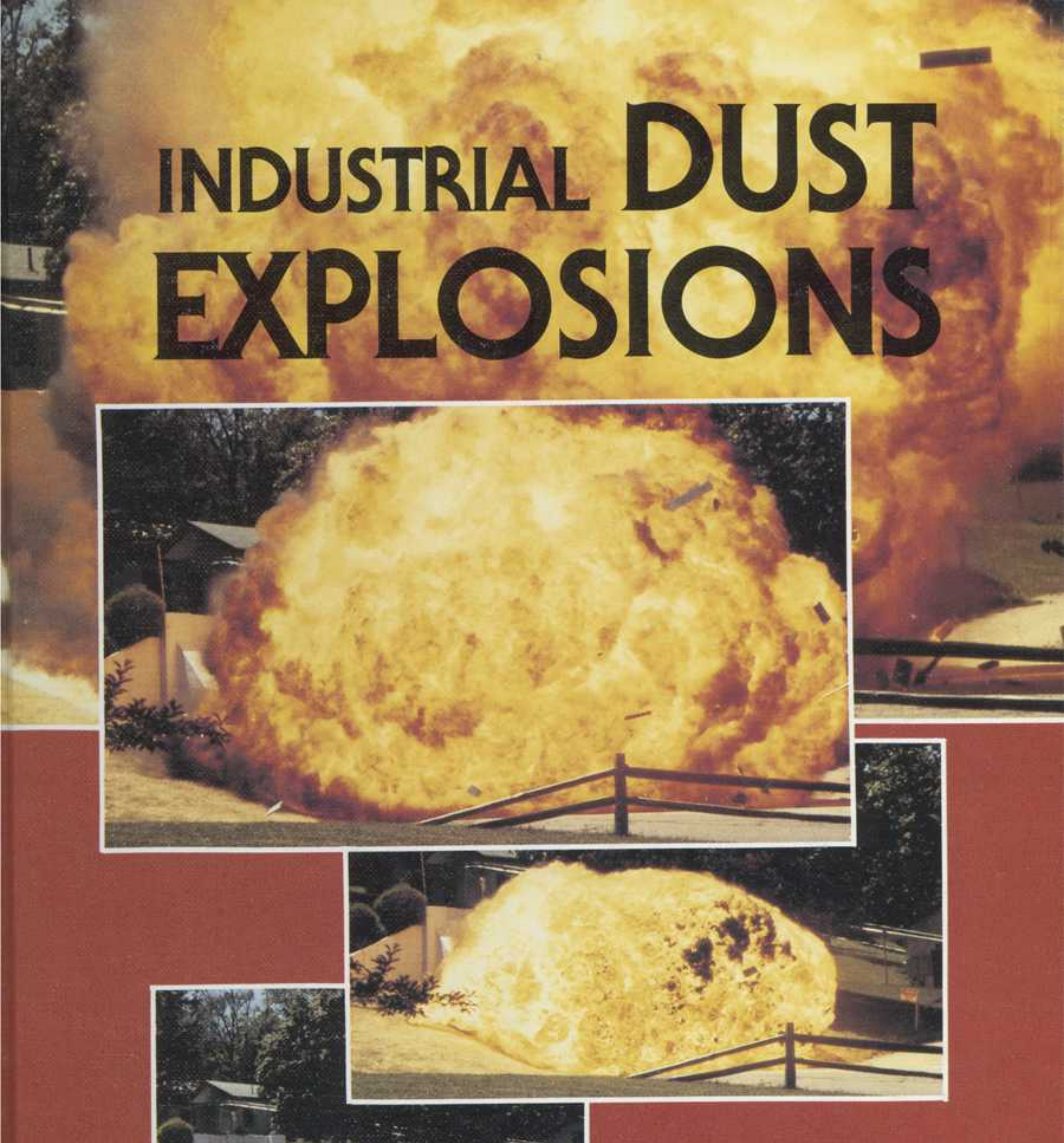
INDUSTRIAL DUST EXPLOSIONS



Cashdollar/Hertzberg, editors

ASTM STP 958

On the cover:

(Bottom) Entrance portal of the Experimental Mine at Bruceton, Pennsylvania. Research on the explosion hazards of coal dust and methane gas has been conducted at this Bureau of Mines facility continuously since 1910 and it is now a National Historical Site.

(Second from bottom) Coal dust explosion propagating outward from the mine portal. This demonstration was conducted for the attendees of the Symposium on Industrial Dust Explosions in June 1986.

(Second from top) Explosion propagation is essentially complete as the hot fireball of combustion products expands and begins to cool.

(Top) Explosion fireball rises as a result of buoyancy forces and continues to cool.

(Photographer: K. L. Cashdollar)

INDUSTRIAL DUST EXPLOSIONS

Symposium on
Industrial Dust Explosions
sponsored by
ASTM Committee E-27 on
Hazard Potential of Chemicals

Bureau of Mines, U.S. Department
of the Interior

NFPA®
National Fire Protection
Association—Committee on
Explosion Protection Systems

Pittsburgh, Pennsylvania, 10–13 June 1986

ASTM SPECIAL TECHNICAL PUBLICATION 958
Kenneth L. Cashdollar, Bureau of Mines,
and Martin Hertzberg, Bureau of Mines,
editors

ASTM Publication Code Number (PCN)
04-958000-31

1916 Race Street, Philadelphia, PA 19103

Library of Congress Cataloging-in-Publication Data

Symposium on Industrial Dust Explosions (1986:
Pittsburgh, Pa.)
Industrial dust explosions.

(ASTM special technical publication; 958)
"ASTM publication code number (PCN) 04-958-000-31."
Includes bibliographies and index.
1. Dust explosions—Congresses. 2. Dust control—Congresses. I. Cashdollar, Kenneth L. II. Hertzberg, Martin. III. ASTM Committee E-27 on Hazard Potential of Chemicals. IV. United States. Bureau of Mines. V. National Fire Protection Association. Committee on Explosion Protection Systems. VI. Title. VII. Series.
TH9446.D86S96 1986 604.7 87-27066
ISBN 0-8031-0957-1

Library of Congress Catalog Card Number: 87-27066

Printed in Baltimore, MD
October 1987

Foreword

The Symposium on Industrial Dust Explosions was held in Pittsburgh, Pennsylvania on 10–13 June 1986. ASTM Committee E-27 on Hazard Potential of Chemicals, the Bureau of Mines, and the National Fire Protection Association—Committee on Explosion Protection Systems were the sponsors. Kenneth L. Cashdollar and Martin Hertzberg, both with the Bureau of Mines, served as symposium chairman and co-chairman, respectively, and have edited this publication. Robert P. Benedetti, National Fire Protection Association, and Thomas F. Hoppe, Ciba-Geigy Corp., were also symposium co-chairmen.

Related
ASTM Publication

Fire Safety: Science and Engineering, STP 882 (1985), 04-882000-31

A Note of Appreciation to Reviewers

The quality of the papers that appear in this publication reflects not only the obvious efforts of the authors but also the unheralded, though essential, work of the reviewers. On behalf of ASTM we acknowledge with appreciation their dedication to high professional standards and their sacrifice of time and effort.

ASTM Committee on Publications

ASTM Editorial Staff

Contents

OVERVIEW

The purpose of the Symposium on Industrial Dust Explosions was to provide a forum for the discussion of dust explosion hazards. In the coal mining, electric power generation, grain handling, plastics, chemicals, wood products, and metal powders industries, dust explosions and fires have been a continuing problem. Various preventive and protective measures must be taken to ensure safety. The papers presented at the symposium provided new data from laboratory and large-scale dust explosibility testing, data from recent accident investigations in industry, and information on the practical design of preventive and protective measures for industrial equipment.

The symposium was successful in increasing the communication among the various scientists and engineers in the field of dust explosibility hazards. In addition to the papers by U.S. researchers, there were eight papers from Europe, one from China, and one from Canada. The Europeans have several standard laboratory test methods for measuring the explosibility characteristics of dusts. The Dusts Subcommittee of ASTM Committee E27 on the Hazard Potential of Chemicals has as its purpose the development and standardization of test methods, equipment, and nomenclature relating to research on the deflagration characteristics of dusts. Another symposium cosponsor, NFPA Committee on Explosion Protection Systems, is involved in the development of guides for the sizing of vents for the protection of industrial equipment from accidental dust deflagrations. The papers presented at the symposium and the resulting discussions have increased the dissemination of knowledge regarding dust explosion hazards and may also help to bring about a consensus regarding standard test methods for measuring dust deflagration characteristics.

This STP resulting from the symposium should be of interest to researchers in the dust explosibility field and to safety engineers in the various industries that produce or handle combustible dusts.

Acknowledgments

As coeditors of this STP, we would like to thank the other symposium Chairmen, Robert P. Benedetti of NFPA and Thomas F. Hoppe of Ciba-Geigy, for their assistance in the planning and execution of the symposium. We also acknowledge the valuable advice and assistance of E. Dale Weir, ASTM E27 Committee Chairman, from the symposium planning to the review of the revised papers for the STP. We would also like to thank the Program Committee, which was responsible for the review and selection of the abstracts of the papers presented at the symposium and which assisted in symposium organization and execution. In addition to the symposium Cochairmen and the E27 Chairman, the Program Committee members were: Ronald S. Conti of the Bureau of Mines; Thomas E. Frank of Factory Mutual Engineering; Joseph P. Gillis of Fenwal; Steven J. Luzik of the Mine Safety and Health Administration; J. Bruce Powers of Dow Chemical; John E. Rogerson, consultant; Michael J. Sapko of the Bureau of Mines; and Richard Siwek of Ciba-Geigy.

In addition to the papers and discussion at the symposium, there were tours of the Bureau of Mines research facilities at the Pittsburgh Research Center and at the Lake Lynn Laboratory. We would like to express our appreciation to John N. Murphy, Research Director; Richard W. Watson, Research Supervisor of the Fires and Explosions Group; and other Bureau personnel for organizing these tours and otherwise assisting with the symposium. An example of the large-scale dust explosibility research at the Bureau of Mines is the series of photographs on the front cover showing a demonstration dust explosion exiting from the portal of the Bureau's Experimental Mine. Bureau research was also described in four papers at the symposium.

Technical Summary

The papers at the symposium and in the STP can be divided into two main groups. The first deals with laboratory and large-scale explosibility testing of dusts. The second deals with accident investigations of dust explosions in industry and the design of measures to prevent dust explosions or to protect equipment and personnel from the results of accidental dust explosions. The papers presented at the symposium were revised for the STP based on audience discussion at the symposium and on a detailed peer review process.

The first paper in the STP is an Introduction to Dust Explosions by Hertzberg and Cashdollar. This invited paper describes the phenomena of dust explosions in general terms. The topics discussed include flame propagation, rapid pressure rise, turbulence, flammability limits, ignitability characteristics, chemical reactions, effects of initial temperature and pressure, particle size effects, hybrid mixtures, and inerting and extinguishment.

The next series of papers describe the results of laboratory and large-scale testing of dusts.

The paper by Wiemann entitled Influence of Temperature and Pressure on the Explosion Characteristics of Dust/Air and Dust/Air/Inert Gas Mixtures describes the results of tests in a 1-m^3 chamber. He measured the maximum explosion pressures, rates of pressure rise, and limiting oxygen concentrations as a function of initial pressure and temperature for various dusts.

Conti and Hertzberg discuss the temperatures at which dust clouds autoignite in a 1.2-L furnace. They present minimum autoignition temperatures for a variety of dusts and gases and discuss the relevance of these temperatures to the evaluation of the ignition probability of dusts and gases in an industrial situation.

Abrahamsen discusses the various dust explosibility and ignitability testing procedures used in the United Kingdom and their relevance to explosion prevention and protection in industry.

Pineau and Ronchail describe large scale tests in their invited paper entitled Propagation of Coal Dust Explosions in Pipes. The test facilities included a 1-m^3 chamber and pipes with diameters of 0.15, 0.25, and 0.44 m and lengths of 10, 20, 30, and 40 m. Flame propagation in the pipes was monitored with pressure transducers, flame sensors, and high-speed movies.

Srinath, Kauffman, Nicholls, and Sichel also studied flame propagation in pipes in their paper entitled Secondary Dust Explosions. A primary explosion disperses and ignites a nominal loading of dust placed on the floor and/or walls of their 0.3-m-diameter by 37-m-long tube, thus generating the secondary explosions.

Cashdollar, Sapko, Weiss, and Hertzberg report on dust explosion research at the U.S. Bureau of Mines. They compare laboratory tests in a 20-L chamber with full-scale tests in two experimental mines. This is the first of four papers dealing with underground coal mines.

Michelis, Margenburg, Müller, and Kleine report the results of coal dust explosion tests in a German underground experimental mine. In particular, they studied the buildup and development of the propagating explosions.

Ng, Sapko, Furno, and Pro describe U.S. Bureau of Mines research on the suppression of coal dust and methane gas explosions by both passive and triggered barriers. The tests were conducted in an underground experimental mine.

Zhou and Lu describe Chinese research on the suppression of coal dust explosions by water barriers. Their tests were conducted in both an aboveground gallery and an underground experimental mine in China. This paper was presented at the symposium by Lung Cheng of the U.S. Bureau of Mines at the request of the authors, who were unable to attend.

The invited paper by Bartknecht is entitled Preventive and Design Measures for Protection Against the Danger of Dust Explosions. It introduces a series of papers on the practical topic of dust explosion hazards in industry. Bartknecht's paper discusses the prevention of dust explosions by avoiding explosible dust-air mixtures, by inerting, or by elimination of ignition sources. If explosions cannot be prevented, various equipment design measures such as pressure resistant design, venting, or explosion suppression can be used.

The next paper, by Zalosh, is a Review of Coal Pulverizer Fire and Explosion Incidents. Overall statistics and individual accidents are reviewed to learn causes and prevention measures.

Carini and Hules also report on the statistics of coal pulverizer explosions. In addition to the statistical data, they report on a series of experimental tests relating to coal dust explosions in pulverizers and pipes.

Alameddin and Luzik report case histories of accidents at coal fired cement kilns. The coal firing systems are described, and the individual accidents are studied to learn causes and preventive measures

Geysen, Belman, and Scheys investigated a dust explosion in the Belgian sugar processing industry and discuss recommended preventive measures. This paper was presented at the symposium by Reinhard Bruderer of Ciba-Geigy at the request of the authors, who were unable to attend.

The next four papers deal with the grain industry. Kauffman presents statistics and individual case histories of dust explosion incidents in the U.S. grain industry.

The invited paper by Eckhoff describes a Differentiated Approach to the Sizing of Dust Explosion Vents. In particular, he discusses the effects of turbulence and ignition source location on the venting of large, slender silos up to 236 m^3 in volume.

Moore describes the Suppression of Maize Dust Explosions. These were intermediate and large scale tests in 6- to 25-m^3 vessels. Various media were used in triggered suppressant systems to extinguish developing grain dust explosions.

Rajendran describes the calibration and performance of several types of dust probes that he used to measure dust concentrations in bucket elevators in the grain handling industry.

The next three papers deal with the problems of electrical and mechanical ignition sources. The paper by Napier and Roopchand on the Ignition Probability of Hybrid Mixtures could not be presented at the symposium but has been included in the STP. They discuss the effect of added small amounts of flammable gases on the electrical ignitability of dusts.

Dahn and Reyes studied the characteristics of metal grinding sparks as ignition sources for dust explosions.

Vaicauski reports on the testing of Electrical Equipment for Use in Class II Hazardous Locations. The equipment must be dust ignition proof, dust tight, or intrinsically safe to prevent electrical ignition of the dust.

The last paper, by Verakis and Nagy, is a Brief Historical Summary of Dust Explosions. They describe early accidental dust explosions in industry in the eighteenth and nineteenth centuries. They also discuss the early research on the explosibility of dusts in the nineteenth and early twentieth centuries.

The papers in this STP present the current state of knowledge on the subject of dust explosions. Areas for future research include the ignitability and explosibility characteristics of hybrid mixtures of combustible dusts and gases, the conditions for transition from deflagration to detonation, and the measurement of the turbulence levels in laboratory test chambers and industrial equipment. Scientists and engineers also need to reach a consensus on the best laboratory test methods for measuring the ignitability and explosibility characteristics of dusts and the applicability to industrial situations.

Kenneth L. Cashdollar
Martin Hertzberg
Pittsburgh Research Center, Bureau of Mines, U.S. Department of the Interior, Pittsburgh, PA; Symposium cochairmen and coeditors

Martin Hertzberg[1] *and Kenneth L. Cashdollar*[1]

Introduction to Dust Explosions

REFERENCE: Hertzberg, M. and Cashdollar, K. L., "**Introduction to Dust Explosions,**" *Industrial Dust Explosions, ASTM STP 958,* Kenneth L. Cashdollar and Martin Hertzberg, Eds., American Society for Testing and Materials, Philadelphia, 1987, pp. 5–32.

ABSTRACT: This Bureau of Mines paper is an introduction to the subject of dust explosions. The phenomena associated with the occurrence of dust explosions are described in general terms, with several specific examples of dusts that react so rapidly and exothermically with air that destructive pressures are generated when they are dispersed and ignited. The accompanying gas-dynamic phenomena are also considered in some detail in terms of rates of pressure rise, speed of flame propagation, confinement, turbulence, and propagation dynamics. The explosion probabilities in any given plant or facility can be quantified in terms of the state of dispersion of the dust, its lean limit concentration, and its ignitability characteristics (thermal, electrical, and chemical). Dust explosions are contrasted with gas explosions in terms of those factors. Other variables considered for the dusts include volatility, particle size, oxygen content of the dispersing "air," initial temperature, initial pressure, the presence of added fuel gases, and inerting or extinguishing requirements. Data to be discussed include laboratory measurements and full-scale test results; phenomena to be considered include both the fundamental and the practical.

KEY WORDS: dust explosions, flame propagation dynamics, flammability limits, ignitability, inhibitors

This paper will first define an explosion in general terms and then describe some of the phenomena associated with its occurrence. Several simplified examples of fuel dust explosions that were studied in laboratory-scale systems will be presented and the basic variables that influence the characteristics of explosions will be discussed in detail. The basic variables will be discussed in general terms without specific reference to practical systems, a task that is left to other papers in this Symposium volume. A logical framework for the practical assessment of explosion probabilities is presented in terms of the three critical processes involved: the dispersion of the dust in air, the existence of a dust concentration above the lean limit, and the presence of an adequate ignition source. Nevertheless, a specific assessment of risks in any given industrial setting is beyond the scope of these generalizations. In a similar way, a simplified treatment of the relevant gas-dynamic phenomena associated with flame-driven explosions will also be presented, but the application to practical systems will be left to others.

The data presented in this paper are only examples of the various factors affecting dust explosibility. Therefore, only the general data curves are shown and not the individual, measured data points. The data are from several laboratory chambers of different volumes with various ignition sources. The detailed data and test conditions are found in the papers referred to in the text.

Definition of an Explosion

An explosion is a gas-dynamic phenomenon characterized by such a rapid increase in system pressure that destructive forces are generated. These destructive pressure forces can damage or

---

[1] Supervisory research chemist and research physicist, respectively, U.S. Department of the Interior, Bureau of Mines, Pittsburgh Research Center, Cochrans Mill Rd., P.O. Box 18070, Pittsburgh, Pa 15236.

destroy structures and endanger nearby personnel. For a dust explosion, specifically, it is usually the rapid chemical oxidation of dust particles dispersed in air that leads to a rapid energy release which increases the temperature of the system so rapidly that a pressure increase follows. Whether the reacting fuel is a dust or a gas, the combustion products are normally gases so that the explosion process is most simply understood by reference to the ideal gas law:

$$pV_o = (m/M)RT = nRT \tag{1}$$

where the system volume is V_o, the system absolute pressure is p, and that pressure is proportional to the absolute temperature, T. The proportionality constants are the number of moles of gas, n, and the universal gas constant, R. The number of moles, n, is equal to the mass of gas, m, divided by the average molecule weight, M. For typical accidental explosions, air is the oxidant while the fuel is either a gas, a dust, or a liquid fuel spray. Because air consists mostly of nitrogen, there is usually little change in M as the exothermic combustion reaction proceeds, and, as a result, n also remains essentially constant. The reactions proceed so rapidly that most of the internal chemical energy is released as heat, which is retained by the nitrogen and the burned gas products within the system volume, V_o. As a result, the system temperature increases rapidly from its initial value, T_o, to a much higher, burned gas temperature, T_b. According to Eq 1, the pressure will increase proportionately, from its initial value p_o to the explosion pressure, $p_{\max}$:

$$p_{\max}/p_o \simeq T_b/T_0 \tag{2}$$

An example of the pressure–time history for such an explosion occurring in a 20-L volume is shown in Fig. 1*a*. Coal dust, at a concentration of 500 g/m^3, is initially dispersed uniformly in air at atmospheric pressure. When ignited, the exothermic reaction propagates through the dust–air mixture as a spherical combustion wave [*1*]. The combustion reaction is completed in about 0.14 s as the reaction wave reaches the wall. A burned gas fireball is generated in the wake of the wave at a temperature of about T_b = 2100 K [*2*]. Since the initial temperature was ambient at T_o = 300 K, the ratio T_b/T_o is about 7. As Fig. 1*a* indicates, the measured maximum explosion pressure (absolute) is about 7 atm, as predicted by Eq 2. For comparison, the pressure trace of a methane–air explosion is shown in Fig. 1*b*. A detailed discussion of the comparison between dust and gas explosions will be found in the later section entitled "Rate of Pressure Rise and Speed of Flame Propagation."

Because the 20-L chamber is made of thick steel, it easily withstands the pressure, and the explosion force is contained within the chamber volume, V_o. If, however, the chamber had been made of glass, thin metal, or even concrete (unsupported), it would have ruptured. Such structural failure would not only destroy the functional integrity of the system, but would be a threat to nearby personnel as well. If the system volume had not been fixed at V_o by a confining structure, the pressure forces generated by the combustion reaction would have been determined by gas-dynamic motions—the velocity of the expanding flow that can relieve the internal pressure relative to the velocity of the combustion wave that generates it. Even if the volume of the system is not fixed and the burned gases are not confined but are free to expand toward a vent or the open end of a tube, the reaction rate during the explosion can be so rapid that gas motions may be too slow to relieve the developing pressure, and structural failure may still result. Explosions can occur even if the initial flammable volume is completely unconfined. As indicated in the definition, an explosion is a gas-dynamic phenomenon, and as will be shown shortly, the degree of confinement is not entirely determined by geometric boundary constraints such as confining walls. As combustion wave velocities approach (or exceed) the speed of sound in the unburned mixture, expanding gas motions become too slow to provide for pressure relief, and the system becomes confined by its own dynamic state quite apart from the initial geometric structure of its boundaries [*3–6*].

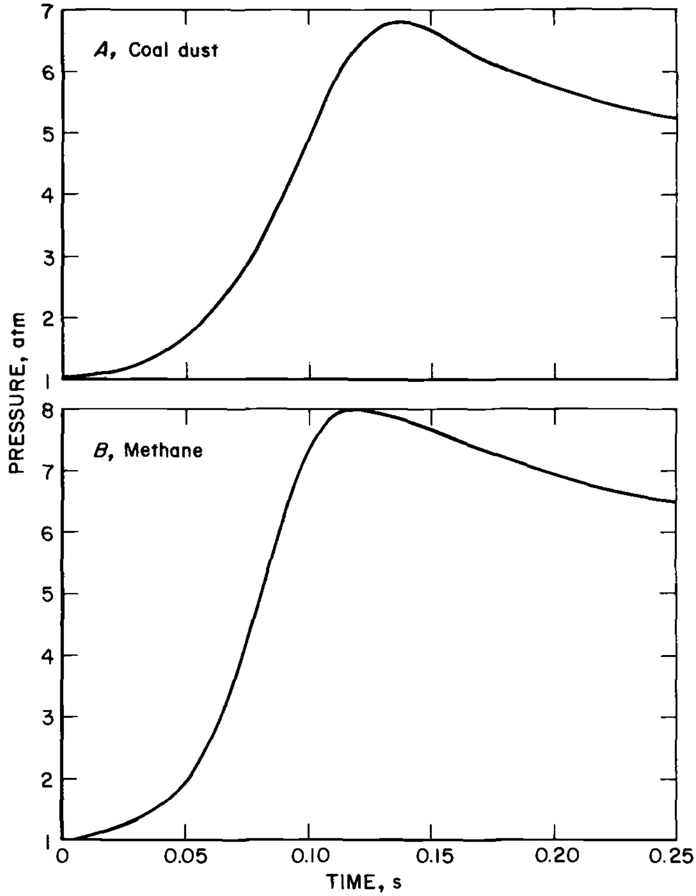


FIG. 1—*Comparison of the pressure–time traces for a coal dust explosion* (a) *and a methane gas explosion* (b).

Exothermic Reactions

Three examples of exothermic chemical reactions of dusts with air that can generate explosions are shown below:

$$16\,\mathrm{Al}(s) + 12\,\mathrm{O_2}(g) + 45\,\mathrm{N_2}(g) \rightarrow 8\,\mathrm{Al_2O_3}(s) + 45\,\mathrm{N_2}(g) + 1540\ \mathrm{cal/g}$$

$$8\,[\text{–}\mathrm{CH_2}\text{–}]_n(s) + 12n\,\mathrm{O_2}(g) + 45n\,\mathrm{N_2}(g) \rightarrow 8n\,\mathrm{CO_2}(g) + 8n\,\mathrm{H_2O}(g) + 45n\,\mathrm{N_2}(g) + 712\ \mathrm{cal/g}$$

$$16\,\mathrm{FeS_2}(s) + 44\,\mathrm{O_2}(g) + 165\,\mathrm{N_2}(g) \rightarrow 8\,\mathrm{Fe_2O_3}(s) + 32\,\mathrm{SO_2}(g) + 165\,\mathrm{N_2}(g) + 402\ \mathrm{cal/g}$$

where (s) denotes a solid and (g) denotes a gas-phase component. These reactions approximate those that occur during explosions of aluminum dust, polyethylene powder, and pulverized iron sulfide ore when they are dispersed in air and ignited.

The reaction exothermicities are indicated in calories per gram of total reacting mixture. Those energies are sufficiently large that the dusts react explosively in certain concentration ranges.

Examples of explosions obtained with these dusts are shown in Fig. 2. As can be seen there, the measured peak explosion pressures scale with the reaction energies, as expected from Eq 2.

The above examples all involve dust fuels that react explosively with the gaseous oxidant, air. This paper also considers reactions of fuel dusts with air mixtures that have either been enriched in oxygen or reduced in oxygen content by dilution with an inert gas. Explosions are also possible in propellants or high explosives that contain solid fuel and *condensed phase* oxidants mixed intimately as dusts or even intramolecularly within the same chemical structure. Such highly explosive dusts or solids are excluded from consideration in this paper. Attention is confined here to fuel dusts dispersed in a gaseous, oxidizing medium which is usually air (containing 21% oxygen).

Rate of Pressure Rise and Speed of Flame Propagation

As indicated earlier, an explosion is a gas-dynamic phenomenon. In this section and the following one, the complexities associated with the flows generated by explosions will be considered in more detail. In its simplest form, the dust explosion process appears in the form of the pressure–time traces shown in Figs. 1*a* and 2, which are for dusts ignited centrally in a constant volume, 20-L chamber. There is some initial turbulence in those mixtures that is associated with the dispersion of the dust cloud, but the turbulence level is only moderate and the propagation is approximately spherical. The pressure–time trace for a gas explosion in an initially quiescent mixture of stoichiometric methane–air is shown in Fig. 1*b*, and that trace is not much different than the coal dust explosion trace shown in Fig. 1*a*. Both pressure–time histories are typical of explosions generated by spherical combustion waves. They are generated by flame fronts that propagate outward from a central ignition point at subsonic burning velocities. Both are rapid flames or deflagrations. The pressure evolution in such systems at constant volume is predicted by classical combustion theory [*1*]. For the ideal case, the pressure–time evolution, $p(t)$, in a

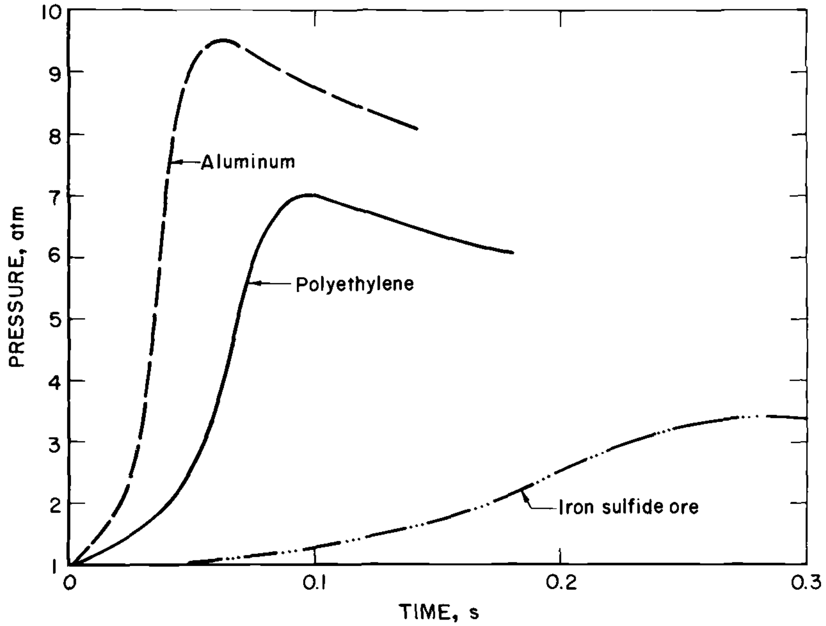


FIG. 2—*Explosion pressure traces for three dusts of different reactivities.*

constant volume, spherical explosion is related to the fractional volume, $V(t)$, occupied by the fireball during the time of propagation, t. Thus

$$[p(t) - p_o]/(p_{\max} - p_o) = kV(t)/V_o \tag{3}$$

where k is a correction factor related to the difference in compressibility between burned and unburned gases. For spherical propagation from a point source

$$V(t)/V_o = [r(t)/r_o]^3 = [S_b t/r_o]^3 \tag{4}$$

where $r(t)$ is the radius, and S_b is the flame speed given by

$$S_b = \mathrm{d}r(t)/dt = (\rho_u/\rho_b)S_u. \tag{5}$$

The burning velocity is S_u, and ρ_u/ρ_b is the density ratio of unburned to burned gases (at constant pressure). The maximum pressure, $p_{\max}$, is reached at the instant the last fraction of unburned gas adjacent to the wall of the chamber is overtaken by the spherical combustion wave and transformed into combustion products; that is, as $r(t) \rightarrow r_o$. At that instant the proportionality factor, k, is unity. Differentiating Eq 3 with respect to time and substituting Eq 4 and 5 into the results gives

$$dp(t)/dt = 3(p_{\max} - p_o)\ (\rho_u/\rho_b)\ S_u r(t)^2/r_o{}^3. \tag{6}$$

Equation 6 shows that the maximum rate of pressure rise should also occur at the instant the wave front contacts the wall. Setting $r(t) = r_o = (3V_o/4\pi)^{1/3}$ and letting $\rho_u/\rho_b \simeq T_b/T_o \simeq p_{\max}/p_o$, gives

$$[dp(t)/dt]_{\max} V_o{}^{1/3} = K = 4.84\ (p_{\max}/p_o{}^{-1})\ p_{\max}S_u. \tag{7}$$

Equation 7 is the "cubic law" used to generate K_G values for gases and K_{St} values for dusts. (The *St* subscript refers to *staub*, which is German for "dust.") Because they are size normalized, the K parameters are useful in the practical design of venting systems for the relief of explosion pressures in containers of various sizes [7].

As Eq 7 shows, the driving force behind the size normalized rate of pressure rise is the burning velocity, S_u, which determines the combustion rate. For a laminar system, the burning velocity is a unique value or ***eigenvalue*** that characterizes the rate of release of internal energy during the explosion. The burning velocity determines the magnitude of the combustion force that drives the gas-dynamic motions associated with the explosion. But as indicated earlier, it is a unique ***eigenvalue*** for a given fuel–air mixture only when the propagation is laminar. Its value is altered dramatically by turbulence, as shown in Fig. 3. The data are the maximum rates of pressure rise for dust explosions as a function of the time delay in a 20-L laboratory chamber. The delay is measured from the end of the dust dispersion until the initiation of the chemical ignitor. For dusts dispersed by an air blast, the initial turbulence level is high but then decays to a more quiescent condition as the time delay between dispersion and ignition is increased. As the data in Fig. 3 show, with little or no time delay, the maximum rate of pressure rise, $(dp/dt)_{\max}$, is high because S_u is high in the turbulent flow associated with the dispersion air blast. With increasing time delay, the turbulence level decays and the rate of pressure rise decreases markedly as S_u begins to approach its laminar value.

Turbulence, Partial Confinement, and Propagation Dynamics

Although the laminar burning velocity is precisely determined by the thermostatic state of a fuel–air mixture (its composition, T_o, and p_o), the actual burning velocity is not invariant with respect to flow dynamics. A detailed consideration of turbulence phenomena and a precise description of the flow fields associated with combustion driven explosions is beyond the scope of this introductory paper. However, the effect of flow dynamics on the explosion process can be

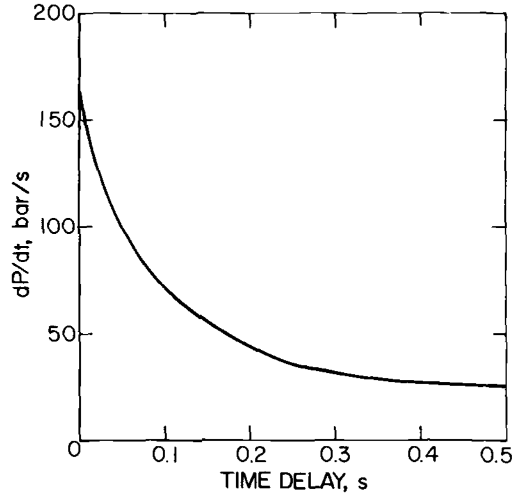


FIG. 3—*Effect of turbulence decay on the maximum rate of pressure rise for coal dust explosions.*

so critical that it requires further clarification. Turbulence causes a dramatic increase in S_u, which drastically accelerates the rate at which an explosion develops. In the absence of turbulence, flame propagation is laminar, and the reaction rate driving the explosion is limited to a two-dimensional flame front surface that propagates at a constant speed from the ignition source. However, turbulent flows are characterized by eddies which move randomly in all directions. As the eddies are overtaken by a flame front and transformed into burned products, they will maintain their initial random motions. Those burned gas eddies that project well ahead of the average flow serve as multiple ignition sources which accelerate the combustion rate. In turbulent propagation, the reaction rate thus becomes volumetric or three-dimensional and is no longer confined to a two-dimensional surface propagating at a constant speed. The number of eddies, their length scale, and the perturbation velocities with which they project outward into the reactants is clearly a function of the turbulence intensity. In addition, other aerodynamic phenomena provide mechanisms for the volumetric acceleration of the combustion rate. Those other phenomena involve acoustic wave interactions with the flame front [*8*] and the generation of Rayleigh-Taylor instabilities [*9*]. A detailed consideration of such phenomena, like a precise consideration of turbulent flow dynamics, is beyond the scope of this paper. Their effects can nevertheless be critical.

The effect of preexisting turbulence in accelerating the development of an explosion, such as indicated in Fig. 3, is one manifestation of the turbulence effect. The effects can be even more dramatic if the turbulence is generated by the flow dynamics of the combustion process itself. In fact, the marked difference in behavior between laminar waves and turbulent ones has been known since the earliest studies of combustion waves. Fuel gas burning velocities in a tube were observed to be near "normal" (laminar and stable) only for open end ignition. For closed end ignition, a rapid flame front acceleration that transited into a detonation propagating at supersonic speed was observed [*3,4*]. This sensitivity to initial conditions is associated with the interplay of fluid dynamics and the flame propagation process which continues to be a determining factor for many practical problems: rapid extinguishing systems [*10*], prevention measures used against explosions in pneumatic feed lines of coal fired powerplants [*11*], and proper sizing of explosion vents in grain silos [*7,12*].

The effect of turbulence is pronounced and devastating when the flammable volume is partially confined in a tube or corridor, with one end open and ignition at the other closed end (Fig. 4*a*).

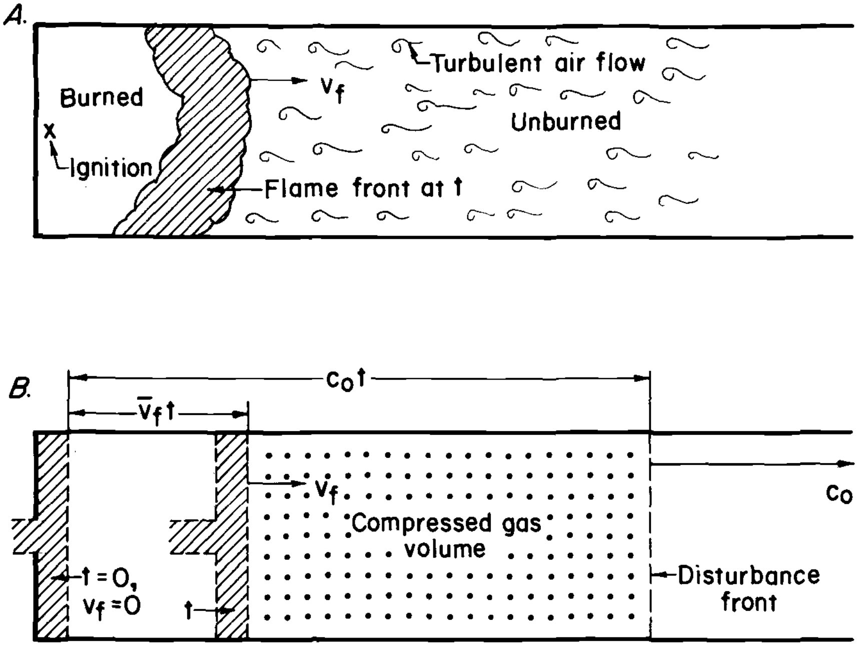


FIG. 4—*Propagation of a dust flame from the closed end of a tube (a) and the idealization of that process as an accelerating piston* (b).

The flame front is depicted at some time, t, propagating toward the open end as the burned gases generated behind the flame front expand and push the still unburned mixture outward toward the open end. For typical flame speeds and tube diameters beyond a few centimetres, the Reynolds number of the unburned mixture flow in the tube or corridor rapidly exceeds the critical value for the generation of turbulence. A turbulent flow appears ahead of the wave, and as the flame propagates into that turbulent flow, it accelerates. This increases the flow velocity ahead of the wave, which increases the turbulence level, which further accelerates the flame front, and so forth. The process is self-accelerating and if the tube is long enough and wide enough, it eventually leads to a supersonic detonation [*3*,*4*]. Using the notation of Ref *6*, the gas volumes of interest are idealized in Fig. 4*b*, where the combustion wave acts as an accelerating piston exerting a pressure force on the unburned gas in the tube, accelerating it toward the open end. The flow disturbance associated with the piston motion is transmitted to the gas ahead of it at the finite velocity of sound, C_o. Only a finite volume of gas ahead of the piston is compressed by its motion during the finite time, t. The region of gas ahead of the disturbance front cannot "sense" or "feel" the motion of the piston. Only the gas volume in the space between the piston and the leading edge of the sonic disturbance is compressed in the time, t, and that volume is A_oC_ot, where A_o is the cross-sectional area of the tube or corridor and t is the time during which the piston has moved. If ρ_o is the initial cold gas density, during the time, t, the mass of gas accelerated by the piston is $m = \rho_oA_oC_oT$. That mass of gas, which was initially at rest, is accelerated to the piston velocity, v_f.

From Newton's law, the product of that mass and its change in velocity, Δv, must equal the impulse, which is the product of the pressure force, $F = \Delta pA_o$, times the time, t, during which the acceleration occurs. Thus,

$$m\Delta v = F\Delta t = \Delta p\, A_o t \tag{8}$$

$$\rho_o A_o C_o t\, (v_f - 0) = (p_{\max} - p_o)\, A_o t \tag{9}$$

which gives:

$$p_{\max} - p_o = \rho_o C_o v_f \tag{10}$$

where v_f is the flame speed (or piston velocity), and $p_{\max}$ is the explosion pressure. The pressure generated by the explosion thus is linearly proportional to the flame speed. The constant of proportionality is the speed of sound, C_o, and hence this equation is called the acoustic approximation [*13*]. It is simply a reflection of Newton's law of motion and the fact that the combustion force disturbance can propagate into the unburned gas no faster than the speed of sound, C_o. The general validity of this acoustic approximation and its more exact refinements have been amply demonstrated in many gas and dust explosion tests at the Bureau's Experimental Mine at Bruceton, PA [*13*] and in studies conducted elsewhere [*14*].

Such turbulent flame acceleration is magnified whenever a flame propagates from a large diameter tube into a smaller diameter tube or when a flame propagates from a large container into a smaller cross-sectional area tube or side arm [*11,15*]. The flame acceleration associated with such flow convergence is magnified markedly if it is caused by periodic obstructions in a tube or corridor, especially if the obstructions have a large blockage ratio [*16*]. The acceleration process for the converging flow is understood most readily in terms of the mass conservation equation for the flow in a tube whose radius decreases from r_i to r_f. Mass conservation gives

$$\rho_i v_i \pi r_i^2 = \rho_f v_f \pi r_f^2 \tag{11}$$

The average flow velocity necessarily increases from v_i to v_f as the radius decreases. For incompressible flow in the subsonic regime, $\rho_i = \rho_f$. The final Reynolds number for the flow is, therefore,

$$R_f = v_f r_f/\nu = (v_i r_i/\nu)(r_i/r_f) = R_i(r_i/r_f) \tag{12}$$

where ν is the kinematic viscosity. Consequently,

$$R_f/R_i = r_i/r_f \tag{13}$$

and the Reynolds number of the flow increases as the radius decreases from r_i to r_f. With an increasing Reynolds number, the converging flow becomes more turbulent and the adiabatic flame inevitably will accelerate as it propagates into the converging section of a tube. The acceleration is even more severe if a flame propagates from a larger volume into a side arm or tube of smaller cross-sectional area. If there is a marked reduction in the cross-sectional area, v_f can approach sonic speed even though v_i is quite low and is driven by a subsonic combustion wave. The flow ahead of the combustion wave is then both turbulent and precompressed in the converging region, and, as the combustion wave accelerates into that precompressed turbulent flow, explosion pressures can be magnified even further. This phenomenon is referred to as "pressure piling."

The acoustic approximation (Eq 10) shows quite clearly that the higher the flame speed driving an explosion in a tube, the higher is the explosion pressure. The gas motions driven by a flame front, and the burned gas expansion in its wake, can be communicated to adjacent volumes no faster than the speed of sound, C_o. If the flame propagates slowly enough, the compressive force can be transmitted throughout larger volumes of unburned gas ahead of the flame, and the gas can expand through the open end to relieve the pressure. The faster the flame speed, however, the smaller is the compressed gas volume ahead of the wave and the more difficult it is for the compressive force to be relieved by the gas motion, and the higher is the pressure generated by the propagating flame front or explosion wave. Although the derivation of the acoustic approximation has been presented for a tube of constant cross-sectional area, it is readily extended to other configurations, and the above generalizations are valid regardless of the geometric shape of the boundary.

If the combustion wave accelerates to sound velocity in the unburned mixture (or exceeds it), there can be no gas motion ahead of the combustion wave, and there can be no motion to relieve the pressure. In that case, even if the system is completely open or unconfined, pressures are generated behind the wave front that are comparable to or even exceed those observed in a geometrically confined volume. The question of confinement is not simply a matter of the geometric structure of the system's enclosure. Confinement is also related to the dynamics of the explosion process—to the magnitude of the flame speed relative to the speed of sound in the unburned mixture, that is, the Mach number of the propagating flame. The ratio of the burning velocity to the sound speed is controlled not only by the composition of the fuel–air mixture, but by its aerodynamic state. Once the turbulence level of its aerodynamic state exceeds the level required for the burning velocity to exceed the speed of sound, the system is dynamically confined regardless of the existence of any vent area and regardless of the shape of its boundaries. As the Mach number of the flame front exceeds unity and it propagates supersonically with respect to the unburned medium, there can be no motion to relieve the combustion force; the gas is compressed by its dynamic state regardless of the size, shape, or configuration of its container.

In this process of turbulent flame acceleration, the flame speed is not even limited by the speed of sound in the unburned mixture, C_o. The combustion process can transit into a detonation when the combustion wave front becomes supersonic and overtakes the leading edge of the pressure disturbance. The flame front and pressure front are then merged. The wave velocity of such a detonation approaches sound speed in the *burned* mixture which is higher than C_o by the ratio $(T_b/T_u)^{1/2}$. In such a detonation, the dynamic confinement is even more severe, and the pressures within the reaction front exceed the maximum explosion pressures observed in subsonic, constant volume deflagrations [*6*]. There are also marked spatial gradients in the pressures within such a detonating system, and the temporal pressure changes are much more rapid than those observed in deflagrations. Clearly, turbulence effects in explosions can be devastating because they magnify the flame speeds and their associated pressure forces. The process also transforms the normally isotropic pressure force into a nonisotropic tensor with large spatial and temporal gradients in its destructive force field.

Flammability Limits—Effect of Varying Dust Concentration

Now that the term explosion has been defined and its associated gas-dynamic phenomena have been described in some detail, it is appropriate to consider the conditions that can lead to an explosion. For the specific examples presented earlier—aluminum dust, polyethylene powder, and iron sulfide powder—the equations given and their exothermicities were for fuel concentrations that reacted stoichiometrically with air. If the ratio of fuel dust to air is diminished, the reaction energies decrease until, at some limiting concentration corresponding to some limiting exothermicity, the mixture is no longer capable of reacting explosively. The existence of such limiting exothermicities for homogeneous, gaseous fuel–air mixtures is well established [*17–20*]. Such gaseous mixtures are capable of reacting explosively only within a range of fuel concentrations, and those concentration boundaries are defined as the flammability limits [*21–23*]. In Fig. 5 data for methane–air are compared with the data for polyethylene dust in air. The methane data are plotted as mass concentration of fuel per unit volume of air so that they can be compared directly with the data for the polyethylene dust. The methane data show well-defined lean and rich limits [*24*]. The data for polyethylene dust show that its lean limit occurs at the same mass concentration as for methane. It is no coincidence that the lean limit concentrations for polyethylene dust and methane are nearly identical. The polyethylene volatilizes completely during combustion and its gas-phase combustion chemistry is virtually identical to that of other saturated hydrocarbons. It

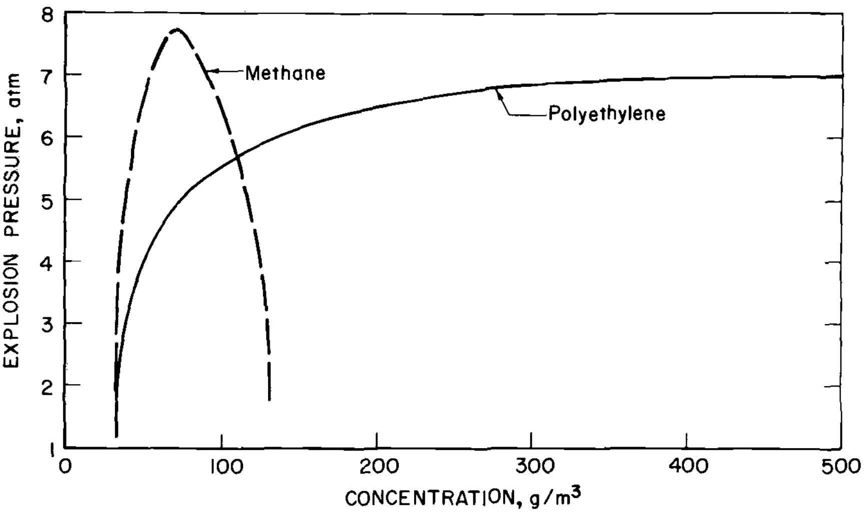


FIG. 5—*Comparison of flammability limits for methane gas and polyethylene dust in air.*

has been shown that the extinction mechanism for dust flames at their lean limits is essentially identical to that for homogeneous gases.[2] The data support that observation by showing quite clearly, as reported earlier [*25*], that the combustible volatile content of the lean limit concentration is essentially invariant for a wide variety of carbonaceous dusts.

The polyethylene dust, however, differs significantly from the methane gas in that it does not show the "normal" rich limit behavior, as can be seen from the data in Fig. 5. The polyethylene curve is typical of the data obtained for all dusts at higher concentrations. The absence of a "normal" rich limit is characteristic of all dusts, and it is a reflection of the phase heterogeneity of the reacting system. 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. Devolatilization is the pyrolysis or thermal decomposition of the particles and the resulting generation of volatiles. Only after devolatilization can the normal, homogeneous, gas-phase combustion reactions proceed [*26*]. As dust concentrations increase, the devolatilization rate becomes a limiting condition; it becomes too slow relative to the rate of the combustion reactions in the gas phase. The flame front then propagates rapidly through a near stoichiometric concentration of volatiles as soon as that concentration is generated and before it can be diluted with excess fuel. The flame front "rides the crest" of a near stoichiometric concentration, leaving the partially devolatilized dust in its wake. A near stoichiometric concentration is thus reacting in the flame front regardless of the initial dust loading; hence the absence of a "normal" rich limit. Eventually, at very heavy dust loadings corresponding to concentrations of several thousand grams per cubic metre, the large mass of excess unreacting dust will provide a sufficient heat sink for the flame to be quenched.

For lean concentrations, however, the burning velocity is low and the gas-phase reaction rates are slower, so that if the dust particles are fine enough, their devolatilization rates are not limiting [*26*]. The dust particles can then devolatilize fully at those lean concentrations, and the lean limit for the totally volatile, solid paraffin hydrocarbon (polyethylene) is about the same as for methane and the other paraffin hydrocarbons.

---

[2] R. Klemens and P. Wolanski, "Flame Structure in Dust and Hybrid Mixtures Near the Lean Flammability Limit," private communication, *1984*.

From the preceding discussion, it is clear that the explosion behavior of most of the carbonaceous dusts is quite consistent with the well established mechanisms of flame propagation that apply to homogeneous gas flames provided that one additional process is added: the heating and devolatilization of the solid dust particles [*20*]. That process most clearly distinguishes dust explosions from homogeneous gas explosions, and it can become rate controlling at high burning velocities, at high dust concentrations, and for large particle sizes.

The data for several other dusts tested in a 20-L chamber are shown in Fig. 6. The maximum explosion pressures and the normalized pressure rise rates (K_{St} values) are plotted as a function of concentration. The dusts display a wide range of lean limit concentrations, corresponding to their

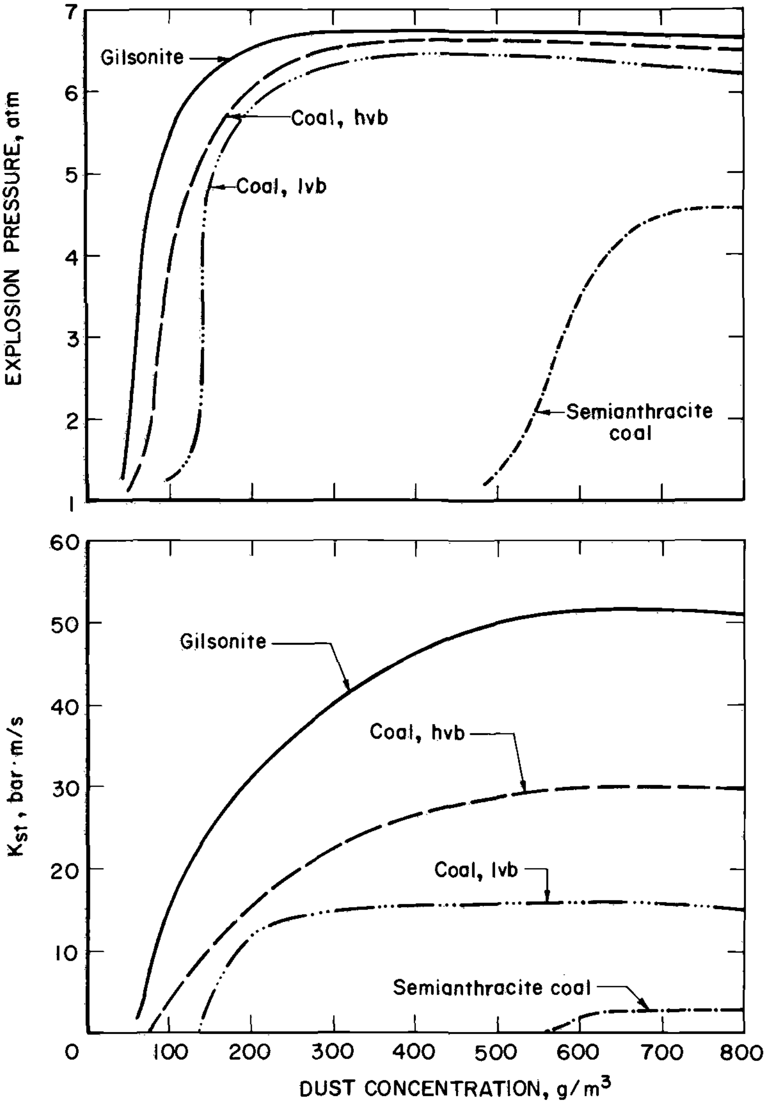
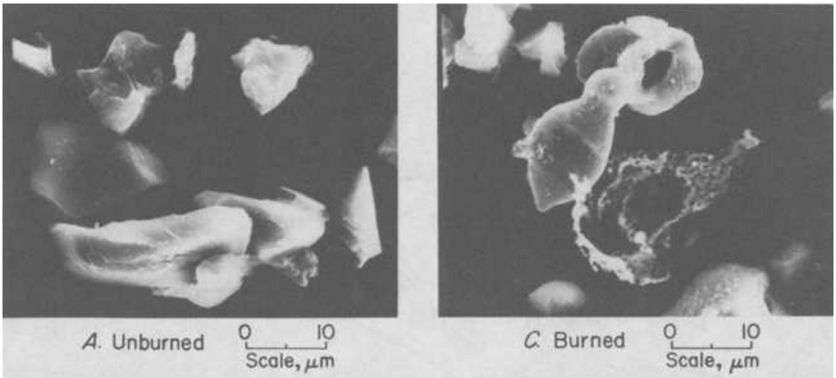


FIG. 6—*Flammability data for gilsonite, high volatile bituminous (hvb) coal, low volatile bituminous (lvb) coal, and anthracite coal in air.*

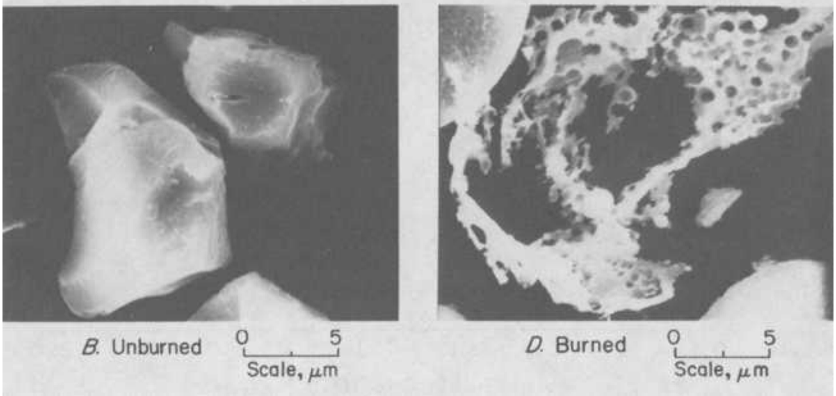
range of volatilities and intrinsic devolatilization rates. Each dust is characterized by its own lean limit concentration, but as indicated earlier, none of the dusts display the "normal" rich limit of flammability typical of gases. The burning velocities reflected in the K_{St} values increase rapidly as concentrations rise above the lean limits. The K_{St} values reach their maxima at concentrations that correspond to the burning of near stoichiometric concentrations of volatiles. As concentrations continue to increase for the dusts, the K_{St} values slowly decline. Eventually, of course, it is expected that a limiting rich concentration will be reached but only at extraordinarily high concentrations of several thousand grams per cubic metre. Such rich limit concentrations may be so high that the exact value becomes irrelevant since the dispersion of the dust at such extraordinarily high dust loadings becomes improbable.

Photomicrographs of Dust Particles

Scanning electron photomicrographs of original bituminous coal particles are shown at two different magnifications in Fig. 7*a* and *b*. They are compared with the "burned" or postexplosion particle residues in Fig. 7*c* and *d*. The burned particles are mainly char residues whose sizes are comparable to the original coal particles. The photomicrographs strongly suggest that only the volatile fraction of the coal particles has reacted during the explosion. The original coal particles become molten when they are heated by the advancing flame front. They devolatilize, emitting



A. Unburned *C*. Burned



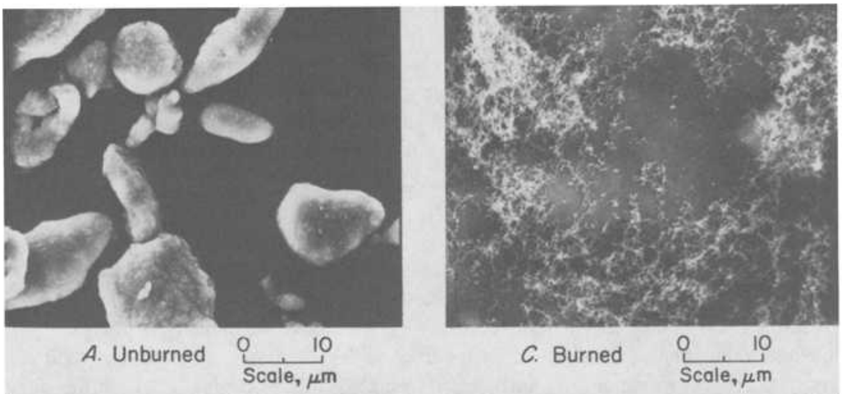
B. Unburned *D*. Burned

FIG. 7—*Scanning electron microscope photographs of bituminous coal particles before and after an explosion.*

their volatile content through "blow holes," whose remnants can still be seen in the char residues. The flame propagates rapidly through the volatiles–air mixture leaving the char residue in its wake. The char remains in the fireball for a relatively long time before it cools, but the oxygen has already been consumed by the flame front. As a result, there is no significant oxidation of the char residue and no evidence that char oxidation plays any role in the flame propagation process for this coal.

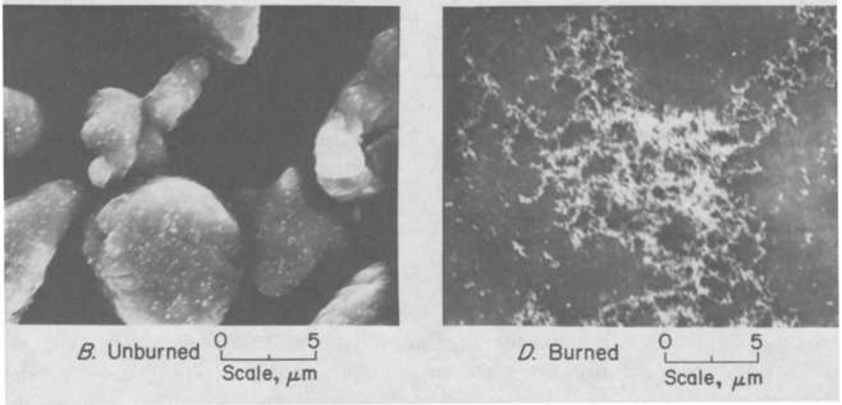
Photomicrographs of original aluminum dust particles are shown at two different magnifications in Fig. 8*a* and *b*. They are compared with "burned" or postexplosion residues in Fig. 8*c* and *d*. Clearly, the original aluminum particles were all completely vaporized by their exposure in the flame front and the fireball in its wake. From the evidence in Fig. 8, one cannot determine how much vaporized during flame front passage and how much vaporized during the much longer exposure time within the fireball. The burned residues in Fig. 8*c* and *d* consist of fine particles of aluminum oxide product and unreacted aluminum that recondensed into fine particles after the fireball cooled.

It should be pointed out that the flame propagation mechanism which involves devolatilization followed by gas-phase combustion adequately accounts for most of the data for the dusts studied. There are some instances, however, involving some metal dusts with exceedingly high boiling points [*27*], or graphite, or even diamond dust, which is flammable at enriched oxygen levels [*28*], where an alternative explanation in terms of heterogeneous, diffusion limited surface oxidation may become plausible.



A. Unburned

C. Burned



B. Unburned

D. Burned

FIG. 8—*Scanning electron microscope photographs of aluminum dust particles before and after an explosion.*

Explosion Probabilities

Having defined and described the lean limit concentrations for dusts, one must realize that the existence of a flammable dust concentration that exceeds the lean limit is only one of three conditions that must be satisfied before a dust explosion can occur. The three conditions that must be met are as follows:

1. The combustible dust contained within a volume must be dispersed and mixed with 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.

The probability of having an explosion is therefore the product of the separate probabilities for each of these conditions being met. Thus,

$$Pr(expl) = Pr(d)\,Pr(f)\,Pr(i) \tag{14}$$

It is only the second of those probabilities, *Pr(f)*, that is determined by the lean limit concentration. That probability of the existence of a flammable volume, *Pr(f)*, is simply quantified for gases or dusts as the fraction of time that the system exists in a composition domain that is between its lean and rich limits. For fuel substances in air, the wider the domain of flammability the more hazardous the substance. For dusts, which have essentially no practical rich limit, only the lean limit is determining, and the lower the lean limit concentration the more hazardous the dust. It is obvious from the definitions that *Pr(f)* and *Pr(d)* are not entirely independent because the dispersion process affects the concentration of dispersed dust. A complete quantitative risk assessment for a given facility is clearly beyond the scope of this paper; however, such an assessment is an integral part of any rational approach to the problem of explosion prevention and mitigation [*12*]. Equation 14 provides the logical starting point for such an assessment, and it also acknowledges the uncertainties and limitations of the evaluation process.

Dust Dispersion

For a given flammable 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 shapes, 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; however, it should be clear that the problem is 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 air stream. In the pulverized, coal firing system of a powerplant 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 Eq 14, the explosion probability is then determined exclusively by the probability of ignition, *Pr(i)*.

Before considering the ignition factor, one further point requires clarification. The dispersion and mixing problem for dusts is markedly different from that of gaseous fuels. The mass densities of the solids from which the dusts are generated are typically factors of a thousand greater than the density of air into which the dusts are dispersed. Accordingly, the ever-present gravitational force segregates the dust from the air at a rate that is characterized by the settling velocities of the dust particles or their agglomerates. Intense air flows 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 densities are comparable to that of the air, and the air flows associated with the initial velocity of the fuels, or even the ever-present natural convective eddies, are sufficient to mix the gas rather rapidly in the surrounding air. Furthermore, for the gas, once the flammable mixture is generated, the mixing is intimate on the molecular scale; and there are normally no external forces of significant magnitude to cause the fuel to resegregate. A flammable, homogeneous gas–air mixture in a given enclosure will remain flammable 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 and resegregate on surfaces within the system. In such a system, the presence of a ignition source, by itself, will not generate an explosion unless the dust is redispersed into the ignition source. In view of that contrasting behavior between dusts and gases, one is tempted to argue that dust fuels are intrinsically less hazardous than gaseous fuels. The more difficult dispersion requirements 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.

In reality, however, that difference in the ease of dispersion is a "double-edged sword." 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 the leaking fuel. Consider a mine or factory through which air can flow as 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 (such as the methane released from coal seams in mines) with air. If the volume of the ventilating air flow rate is much larger than the volumetric flow of fuel, there will be adequate dilution of the 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. For the fuel gas, there is no possibility of demixing in the flow and the ventilation will "dilute, carry away, and render harmless" that fuel leak, as required in coal mines by the Federal Mine Health and Safety Act [*29*]. Once the fuel gas is diluted adequately, there is no opportunity for a dangerous accumulation. Such dilution by adequate ventilation is clearly the most effective means of preventing gas explosions for a given fuel source.

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 on surfaces within the system, and a loading density is eventually reached that would exceed the lean flammable limit if the dust were dispersed into the air. For the dust, some countermeasure other than normal ventilation must be taken to remove the accumulation or to neutralize its presence.

Point Source Ignition and Thermal Autoignition

Ignition sources can be characterized according to the type of energy they introduce into the system. The most common types of ignition 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 is capable of initiating a freely propagating combustion wave in a flammable volume. Its effectiveness will generally be a function of 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 in a 20-L chamber on the effectiveness of chemical (pyrotechnic) sources for the ignition of polyethylene, coal, and oil shale dusts are shown in Fig. 9. Details of the test conditions and the pyrotechnic ignitors are described elsewhere [*24*]. The measured, apparent limits are plotted as a function of effective ignition energy. These effective energies [*24,30*] are related to the rapid heat input into the ignition volume and are lower than the calorimetric energies of the various ignitors. The curves approach the energy-independent, asymptotic limits of flammability only at high energies. The lower volatility dusts require higher ignition energy to attain these asymptotic limits. The medium grade oil shale does not even reach an asymptotic limit for the energies tested. The data in Fig. 9 show that the only way one can be certain that the ignition source is strong enough in any given system is for one to reach the energy-independent, asymptotic value at high energies.

Data on the electrical spark ignitability of dusts are presented elsewhere [*30–32*]. Those data correspond to the lowest energy region at the bottom of the energy scale in Fig. 9. Only the more reactive dusts can be ignited by electrical sparks.

In these experiments, the effective source energy, by itself, is usually an adequate description of the ignition source intensity as long as the energy is delivered rapidly enough and is sufficiently concentrated spatially. That is indeed the case for the pyrotechnic sources used to obtain the data in Fig. 9. For a source that delivers its energy more slowly than the characteristic induction time for flame generation, or that is too extended in space, the power density rather than the source energy will be the parameter which determines the ignition effectiveness of the source. It is clearly beyond the scope of this paper to consider all possible complex geometries or the infinite variety of time-dependent delivery rates.

At the other end of the spectrum of possible ignition sources is one that is extended in space and time. The simplest of such sources is a purely thermal one that is geometrically uniform in spatial extension and steady-state in time. Such a source is isothermal, and its ignition behavior can, in principle, be uniquely characterized solely by its temperature. The autoignition probabilities for such thermal sources have been studied [*26,30*] and are also described in detail in another paper [*33*] in this Symposium volume. An example of the thermal autoignition data is shown in Fig. *10*. The (*i,t*) curve is the autoignition boundary. At temperatures above the boundary, the dust cloud will autoignite. Below the boundary, the dust will not autoignite even though the concentration may be above the flammable limit. The minimum autoignition temperature (AIT) or

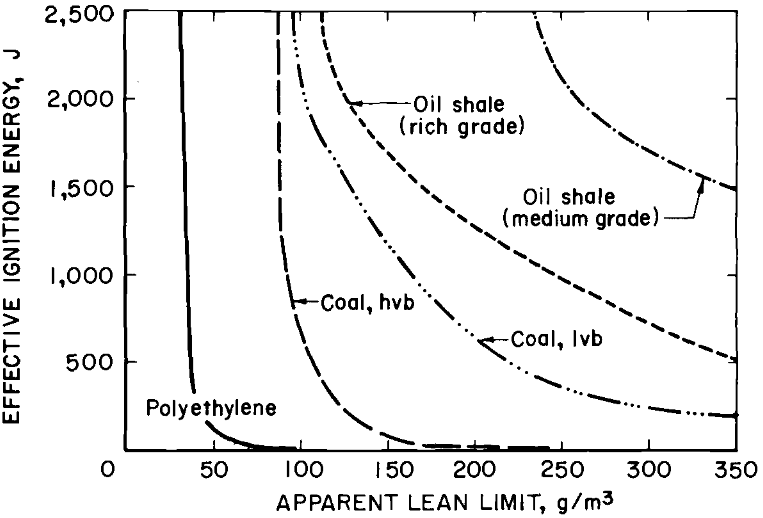


FIG. 9—*Apparent or measured lean flammable limits for five dusts as a function of effective ignition energy.*

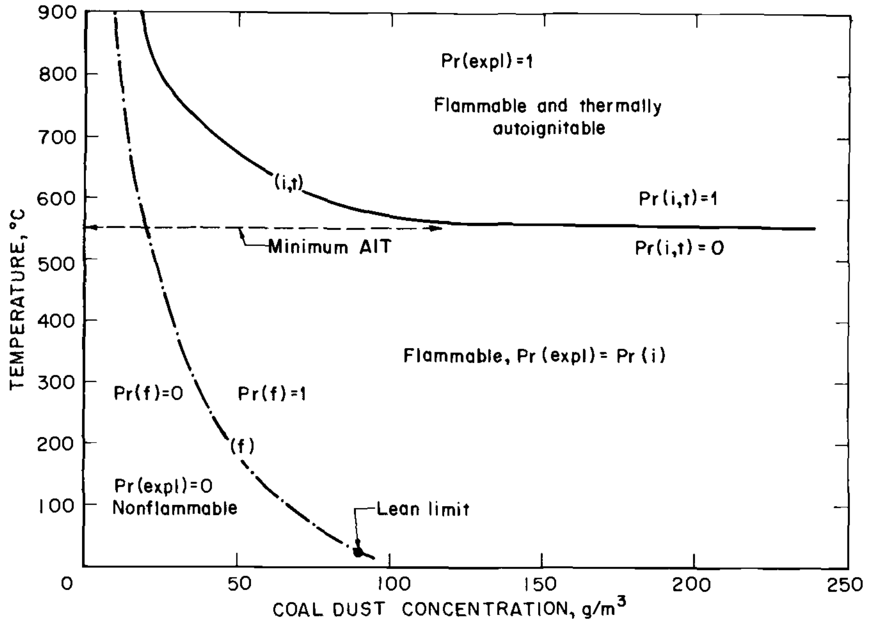


FIG. 10—*Domains of flammability and thermal autoignitability for a coal dust dispersed in air at varying temperatures.*

cloud ignition temperature is the lowest temperature at which dust will autoignite and is generally found at fairly high dust concentrations. The variation of the lean flammability limit with temperature, curve (f) in Fig. 10, will be discussed in the next section.

Effect of Initial Temperature and Pressure

Generally, both dusts and gases become more flammable as the initial temperature of the unburned mixture is increased. The behavior is illustrated by curve (f) in Fig. 10, where the lean limit concentration decreases with increasing temperature. For homogeneous gas mixtures, the temperature dependence is predicted by the modified Burgess-Wheeler law, which is derivable from the established concept of a constant limit flame temperature for a given class of fuels [*17–22*]. The same concept applies to the lean limit behavior of dusts, and the Burgess-Wheeler law, if expressed in terms of the mass concentration of fuel, becomes

$$C_T/C_{25} = [1 - \beta(T - 25)]\left[\frac{298}{T + 273}\right] \tag{15}$$

where the lean limit concentration at any temperature T is C_T, its value at 25°C is C_{25}, and β is a constant for a given class of fuels. For carbonaceous fuels $\beta \simeq 6$ to 7×10^{-4} °C^{-1}. Equation 15 has been shown to be reasonably valid for lycopodium [*30*], for sulfur and benzoic acid dusts [*34*], and for a variety of coals, agricultural dusts, and chemical dusts [*35*]. The (f) curve drawn in Fig. 10 was obtained using Eq 15 and the measured lean limit at room temperature.

Another important factor that influences the lean limit concentration is the operating pressure of a system. Data obtained in a 20-L chamber for the effect of initial pressure on the lean limits for coal dust and polyethylene are shown in Fig. 11, where they are compared with the data for methane gas [*24*]. Essentially the same linear dependence with initial pressure is observed for the

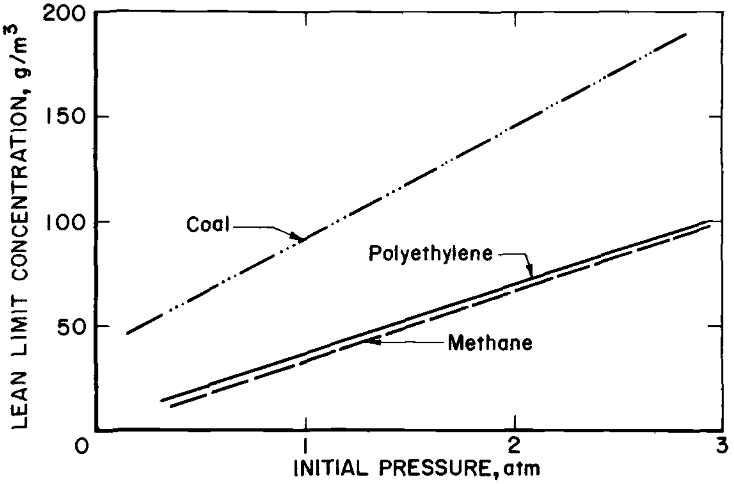


FIG. 11—*Effect of initial pressure on the lean flammable limits for coal and polyethylene dusts and methane gas.*

lean limits of both dusts and gases when these limits are expressed as mass concentration of fuel per unit of volume of air. The same linear pressure dependence was measured independently by another researcher for a lower rank of coal dust [*35*]. The identical pressure dependence for both hydrocarbon gases and carbonaceous dusts shown in Fig. 11 and the virtual identity of the absolute lean limit concentration measured for methane and polyethylene are consistent with the dust flame propagation mechanism [*26*] previously discussed in this paper for carbonaceous dusts. This mechanism involves the devolatilization of the dusts and the gas-phase combustion of the volatiles with air.

Aside from the question of flammability limits, the effect of initial temperature on ignitability is also an important consideration in assessing explosion hazards. The available data show quite clearly that the ignitability behavior of a dust is even more sensitive to an increase in ambient temperature than is its lean limit. For example, at a coal dust concentration of 400 g/m³, an increase in initial temperature from 75 to 200°C results in an order of magnitude reduction in its spark ignition energy [*30*]. The lean limit decreases by only a factor of two between these temperatures. There is clearly a strong synergism between the thermal energy content and the spark ignition energy requirement even at temperatures that are well below that required for thermal autoignition. It is likely that a similar synergistic interaction is present for chemical ignition sources as well. Such synergisms make it very difficult to estimate the ignition probability, $Pr(i)$, when various types of ignition sources may be simultaneously present in a given system [*30–32*]. The effect of ambient pressure variations on the ignitability of dusts is largely unexplored.

Particle Size

Another important factor in determining the explosion hazard of a dust is a variable that is often "hidden." Dusts differ markedly from gases in that they have an additional degree of freedom in their composition variable that does not exist for gases; namely, their particle diameter. A knowledge of the particle diameter is essential for an adequate definition of the fuel composition on the essential microscopic scale. Typical data for the effect of particle size on the lean limits are shown in Fig. 12 for three dusts: polyethylene, a high volatile bituminous (hvb) coal, and a low volatile bituminous (lvb) coal. The lean limits are insensitive to particle diameter below some

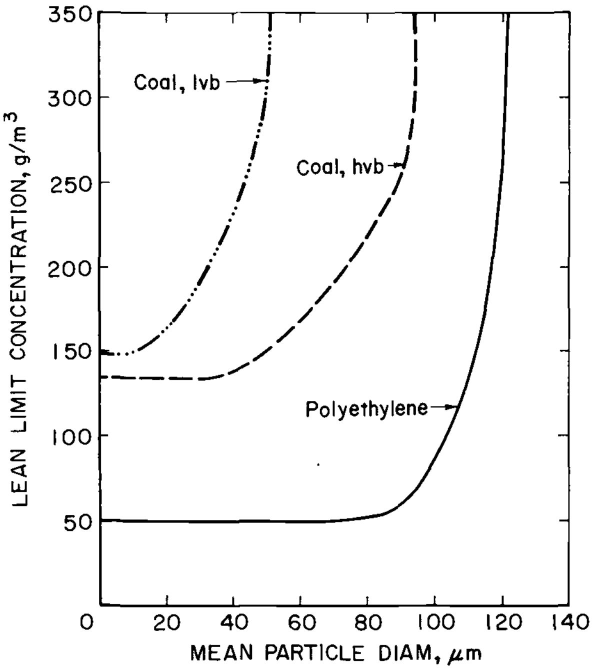


FIG. 12—*Effect of particle diameter on the lean flammability limits for two coals and polyethylene in air.*

characteristic diameter. For particle diameters above these characteristic values, the lean limit concentrations increase rapidly with increasing diameter until a critical size is reached above which the dust is nonignitable for any concentration (at ambient temperature and pressure) [*26*]. Both the characteristic diameter and the coarse size limit of flammability (critical diameter) were also observed to increase monotonically with increasing oxygen content of the dust–air mixture [*26*] as shown in Fig. 13. The data shown in both Figs. 12 and 13 are for chemical match ignitors with effective energies in the range of several hundred joules. The data, therefore, may be still somewhat ignitability limited. Using higher ignition energies, the shapes of the curves would be similar, but the absolute lean limit concentrations would probably be lower.

The data reported in Figs. 12 and 13 are for idealized tests in which dusts with narrow size distributions were used. In full-scale experiments designed to simulate actual, accidental explosions, very broad distributions are usually used. The particle size variations observed in these full-scale tests have trends that are similar to those reported here for monodispersed dusts; however, the strong size dependences seen here for monodispersed dusts are inevitably blurred or smoothed out for broad size distributions. The data with broad distributions may be more practical, but the results from narrow distributions are more fundamental.

The existence of the characteristic diameter is simply a reflection of the size at which the particle diameter becomes so large that the devolatilization rate process becomes limiting even at the low burning velocities near the limit concentrations. Below the characteristic diameters, the devolatilization rate is not limiting, the limit concentrations are insensitive to particle size, and the combustion process is "homogeneous" with a behavior that is similar to that of a premixed gas. Above the characteristic diameter, the combustion process becomes devolatilization rate limited and only the surface regions of the particles, or their sharpest corners, can contribute volatiles to the flame front. A larger dust loading is then required to generate a lean limit concentration of volatiles. Eventually, at the critical diameter, the dust is so coarse that it becomes essentially

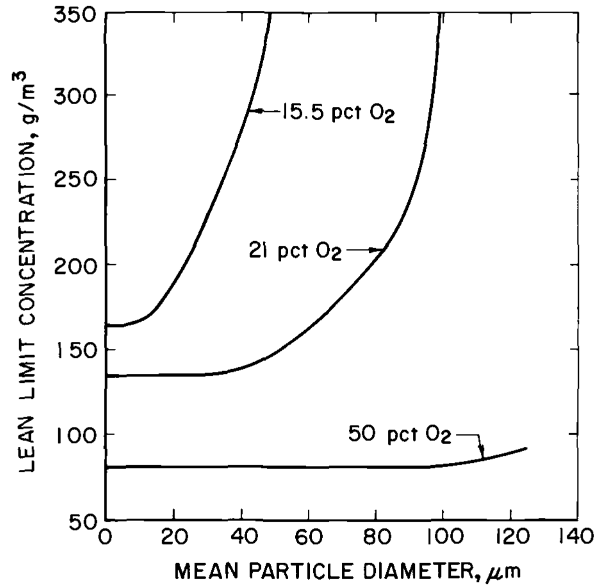


FIG. 13—*Effect of particle diameter on the lean flammability limit for a coal dust at three oxygen concentrations.*

nonexplosible because the devolatilization rate is too slow to generate even a lean limit concentration of volatiles in the time available for flame front passage [*26*].

The minimum AITs also vary with particle diameter in the same manner as the lean limits: there is a characteristic diameter below which the AITs are insensitive to particle diameter and above which the AITs increase with increasing diameter [*26,33*]. The heating of the dust mixtures to elevated initial temperatures eases the devolatilization rate limitations, and accordingly, the characteristic and critical diameters for AITs are larger than their respective values for the lean limits of the same dusts.

Hybrid Mixtures: Fuel Gases Added to Dusts

Still another important factor in determining the explosion hazard of a dust is the possibility of the copresence of a gaseous fuel. This is especially a problem in coal mines where the presence of methane magnifies the hazard associated with coal dust. The addition of a fuel gas to a dust–air mixture will naturally increase the explosion hazard if the gaseous fuel is more easily ignited than the dust. The spark ignition energies for the gaseous fuels in air are generally so much lower than those for dusts that the addition of a small amount of fuel gas may have a much more profound effect on the ignitability of the mixture than would be predicted by a simple linear relationship [*36*]. There are also complex synergistic effects between the various types of ignition sources: thermal, electrical, and chemical [*32*]. If the gaseous fuels are much more easily ignited by any one of those types of sources than a dust, then the resultant mixture will display nonlinearities in ignition behavior; that is, it will be highly sensitized by the presence of the fuel gas.

The thermal ignitability characteristics of hybrid mixtures of gases and dusts are essentially unexplored. The minimum AITs for hydrogen and methane in air are comparable in magnitude to those of the more volatile carbonaceous dusts [*33*]. Accordingly, one expects that a linear relationship would be valid for the AITs of the hybrid mixtures. On the other hand, for the heavier hydrocarbons, the AITs for the vapors are substantially lower than for the dusts and they may therefore have a more profound effect in sensitizing the hybrid mixture than would be predicted by a linear dependence on fuel concentration.

The most extensive measurements for hybrid mixtures involve the lean limit data for methane addition to coal dust, which have been measured in both laboratory systems and large scale mine experiments [*37*]. The laboratory-scale data are shown in Fig. 14*a*. Also shown are the data for hydrogen addition to cornstarch (Fig. 14*b*) [*27*] and the previously unpublished Bureau data for mixtures of coal dust and gilsonite dust (Fig. 14*c*). From Fig. 14*a* it can be seen that the lean limit concentrations for the hybrid mixtures of coal dust and methane in air are linearly weighted averages of the lean limits for the pure coal dust and pure methane. The weighting factor for each fuel is simply its fractional content in the mixture, and the resultant curve is a straight line, as predicted by Le Chatelier's law, originally discovered for homogeneous gas mixtures [*38*]. If the individual lean limit for a pure dust or gas is L_i, and the dusts or gases or both are mixed in any proportion, then the mixture concentrations, C_i, that are predicted to be explosive are given according to Le Chatelier's law by the condition $\Sigma C_i/L_i \geq 1$, where the summation is taken over all fuel gases and dusts in the mixture. The linear relationship for the lean limits seen in Fig. 14*a* shows clearly that Le Chatelier's law is valid for the heterogeneous system of coal dust and methane mixtures in air. The same linear relationship was measured for mixtures of methane with a low volatile coal and for mixtures of methane with an oil shale dust [*39,40*]. For mixtures of gilsonite dust and a low volatile coal dust (Fig. 14*c*), the linear relationship is also valid.

By contrast, the data of Gaug and co-workers [*27*] in Fig. 14*b*, for hydrogen addition to cornstarch dust, show significant departures from a linear relationship. Le Chatelier's law is derivable from the well-established concept of a constant limit flame temperature for a given class of fuels. The limit flame temperatures for methane and coal dust are of comparable magnitude (1400 to 1500 K) because their combustion reactions involve similar chemical kinetic reaction mechanisms for their hydrocarbon oxidation processes [*20*]. Accordingly, there are no significant changes in flame temperatures or reaction rates in going from the pure methane gas case to the pure coal dust case, and the linear relationship (Le Chatelier's law) is maintained. By contrast, the limit flame temperature for pure hydrogen is unusually low, only 700 to 800 K [*41*], much lower than the limit flame temperature for the cornstarch dust. There are, therefore, rather drastic changes in flame temperature and reaction rate in going from pure hydrogen gas to pure cornstarch dust. Although the hydrogen fuel can maintain its combustion rate at the lower temperatures, the devolatilization rate of the cornstarch dust or the reaction rates of its volatiles or both are too slow at those temperatures for the linear relationship to be followed. The required temperature of the limit mixture must therefore be higher than the linearly weighted average. More fuel dust is required to render the system flammable than is predicted on the basis of Le Chatelier's law.

Inerting and Extinguishment

The final factor to be considered in this enumeration of the fundamental variables that affect the explosion hazards of dusts is inerting. If either the fuel dust is diluted sufficiently with an inert dust or the oxygen in the air is diluted sufficiently with an inert gas, the mixture is rendered incapable of propagating an explosion ($Pr(f) = 0$). The simplest inertant to consider is the inert diluent that is already present in air—nitrogen gas. Adding excess nitrogen to almost all fuel–air systems will reduce the explosion temperature, and when that temperature is reduced to below the limit flame temperature, the system is rendered nonexplosible. The effect of such excess nitrogen addition on the flammability limits of methane–air and coal dust–air mixtures in an 8-L chamber [*26,42,43*] is shown in Fig. 15. For the methane case the flammable composition domain is the triangular region within the dashed contour. That contour profile has the shape of a "nose" whose tip clearly defines the amount of nitrogen that must be added to inert a stoichiometric ratio of fuel

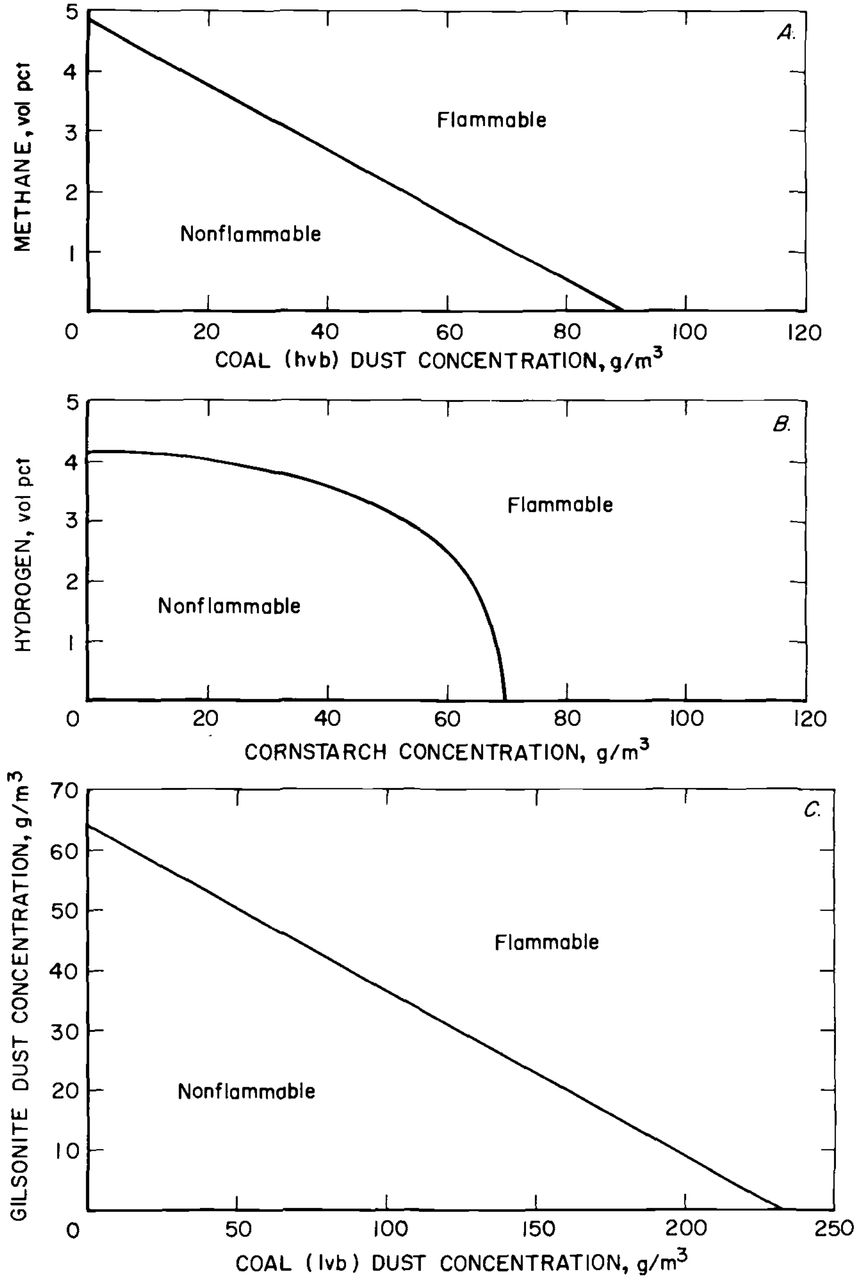


FIG. 14—*Lean flammability limits for hybrid mixtures of gases and dusts* (a,b) *and of two dusts* (c).

to oxidant. The inerting level for these test conditions occurs at about 36% added nitrogen [*42,43*]. All gaseous hydrocarbon fuels display a similar triangular shape for their flammability domain when inerted with excess nitrogen [*21,22*]. By contrast, for coal dust, there is no clearly definable "nose"; instead there is a "blunt brow" that extends upward to very high dust concentrations.

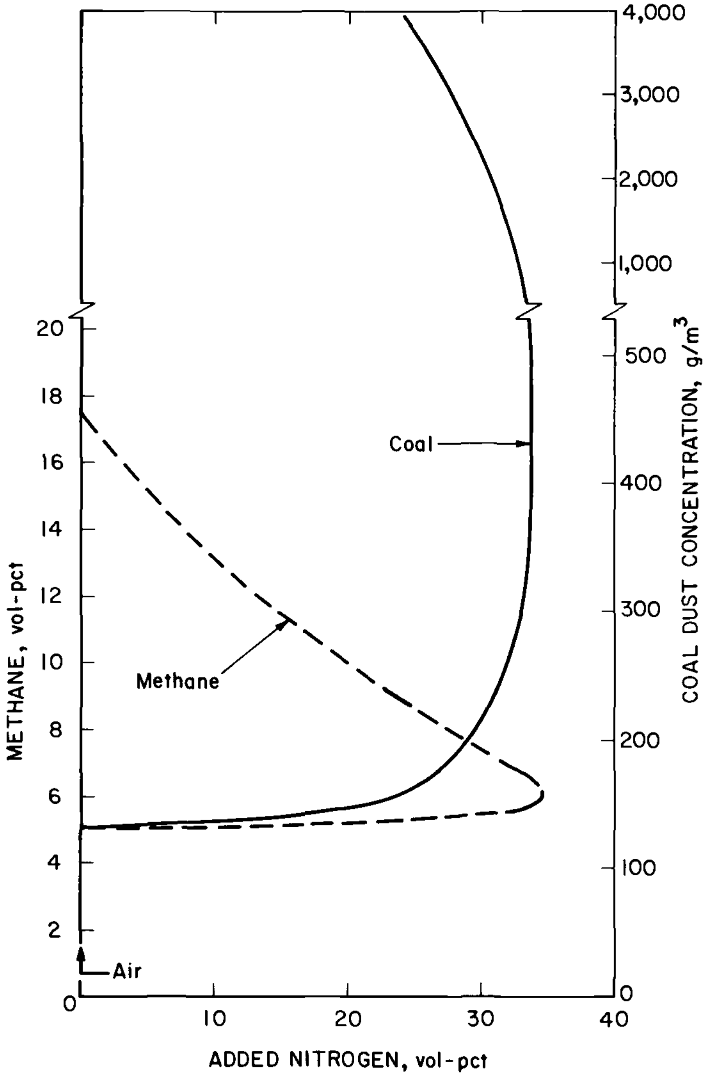


FIG. 15—*Flammability diagram for methane gas and coal dust with added nitrogen.*

The difference in behavior between homogeneous gases and heterogeneous dusts has already been discussed in detail, and is again related to devolatilization rate limitations. Despite those differences, however, Fig. 15 shows that methane and coal dust, being hydrocarbonlike fuels, require comparable nitrogen addition for inerting; namely, 34 to 36% for these test conditions [*26,42,43*]. These inerting levels correspond to minimum oxygen concentrations of 12% for the gas and 14% for the dust. Below these oxygen concentrations, flame propagation cannot be sustained in the ternary mixture of fuel–oxygen–nitrogen. Minimum oxygen concentrations of 11 to 14% characterize most saturated (or nearly saturated) hydrocarbon fuels and carbonaceous dusts [*22,25,32*]. Adding a reasonable safety margin to those measured inerting levels leads to a recommended [*32*] safe-inerting level of 8% by volume oxygen for organic dusts at ambient temperature and pressure when they are inerted with nitrogen.

In addition to nitrogen, other inerting gases can be used, such as carbon dioxide and water vapor, and they are generally more effective than nitrogen (on a volumetric basis) against gaseous hydrocarbon fuels [*21,22,36*] and carbonaceous dusts [*15,35*]. However, for the more reactive metal dusts, neither carbon dioxide nor water vapor is recommended because they are strong oxidants with respect to some metals. (The most notorious case is zirconium metal, which is still used as the primary heat-transfer interface in water cooled nuclear reactors even though its reaction with water vapor is very exothermic.) For inerting of stoichiometric methane–air, the addition of 27% by volume of water vapor is sufficient to inert the gaseous hydrocarbon [*22*]. Of course one

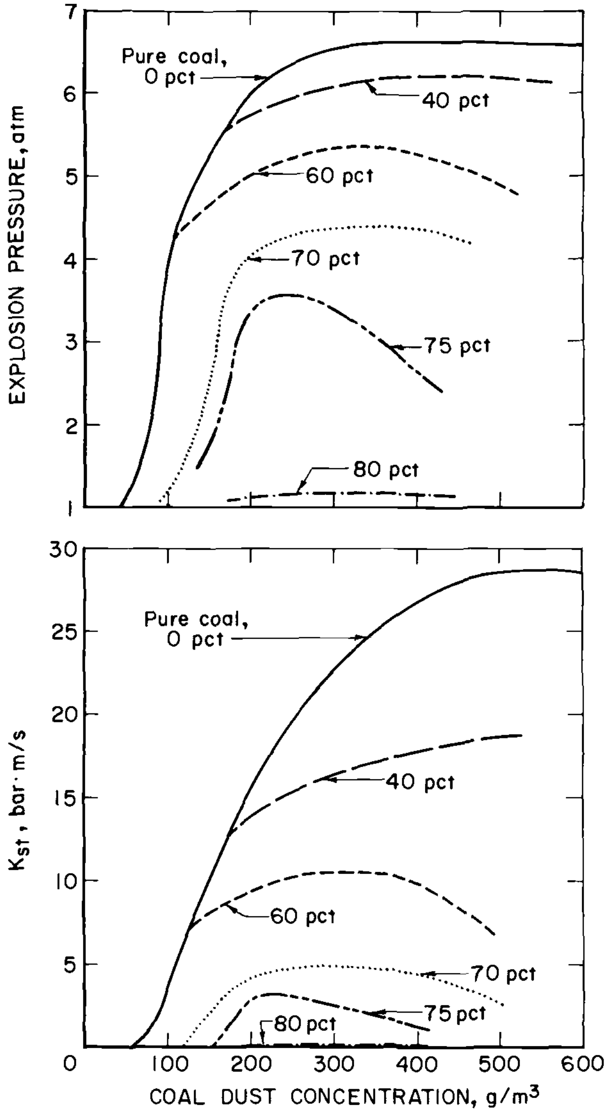


FIG. 16—*Explosibility data for mixtures of coal dust and limestone rock dust containing the listed amounts of rock dust.*

cannot maintain a 27% water vapor content in a system at room temperature because the saturation vapor pressure of water is at most 3 to 4% by volume at ambient temperatures. If steam were added at room temperature to inert such a system it would be ineffective because the water vapor would condense on the walls. However, if the system were operated above ambient temperatures, as, for example, a coal pulverizer which normally would operate at about 75°C, then saturation of the system with moisture would give a water vapor content that exceeds the inerting level even for methane–air. Wiemann [*35*] reports a value of about 12.5% maximum oxygen or about 40% water vapor for the inerting of brown coal dust at 150°C. Carini and Hules [*15*] report a lower value of 18% water vapor (corresponding to 17% oxygen) to inert a bituminous coal dust at 120°C. These values for the water vapor inerting of coal dusts were measured in laboratory chambers. Other engineers [*44*] have reported the practical steam inerting of subbituminous coal dust at an operating power plant that had a history of explosions. They found that a maximum oxygen level of 15 to 16% (corresponding to 23 to 28% water vapor) was sufficient to prevent coal mill explosions.

In addition to diluting the oxidant (air) with inert gases, the dust fuel can also be diluted with condensed phase solids or powders until it is rendered inert. The inertant whose use is required by law [*29*] in coal mines of the United States and other nations is rock dust, which is usually a limestone, whose structure is predominantly calcium carbonate. The effect of limestone rock dust addition on the explosion properties of coal dust [*37*] is shown in Fig. 16. The addition of rock dust raises the lean limit concentration and reduces the maximum explosion presssure and K_{St} value. When enough rock dust is added, the system is inerted and explosions are no longer possible. That inerting level occurs at a rock dust concentration of 75 to 80% by weight in the mixture of coal dust and rock dust [*37*]. However, rock dust is almost completely ineffective against methane gas explosions [*20,42,43*]. As a result, the presence of relatively small concentrations of methane in a mine is profoundly deleterious to the inerting effectiveness of rock dust. The data [*37*] show that the addition of only a few percent methane can increase markedly the ratio of rock dust to coal dust that is required to inert the hybrid mixture (Fig. 17).

Rock dust, prescribed for inerting in the mining industry, is both beneficial and practical because its cost is low, it is readily available, and it is insoluble in water. Nevertheless, the carbonate powders as a whole are less effective against coal dust and methane than are other inhibitors [*26,39,42,43*]. One of the most effective powdered inhibitors against coal dust is ammonium phosphate ($NH_4H_2PO_4$), whose superior effectiveness has been demonstrated in laboratory systems and in full-scale mine experiments [*25,39,42,43*]. The same phosphate is also most effective against methane [*20,42,43*].

Ammonium phosphate powder is also very effective when used in triggered barriers to suppress large scale dust explosions [*10,32,36*]. For suppression barriers, factors such as the time of extinguishant release, the spatial distribution and concentration of the extinguishant cloud, and the dynamics of dispersion play equally important roles [*10*]. The size of the inhibitor powder can also affect its efficiency in preventing or extinguishing explosions [*20,42*].

Conclusions

This introduction to the subject of dust explosions has considered many of the significant phenomena affecting accidental dust explosions in industrial facilities. This survey has emphasized the significant thermodynamic and fluid dynamic variables and phenomena associated with dust explosions and the major factors involved in developing a quantitative risk assessment for explosion hazards. The fundamental thermodynamic variables that determine those risks have been isolated and discussed. The subjects presented herein are not all-inclusive; some factors have been omitted and some specific subjects that may be exceedingly significant in a particular industry may not have been emphasized sufficiently. Many important factors are not yet isolated or explored and

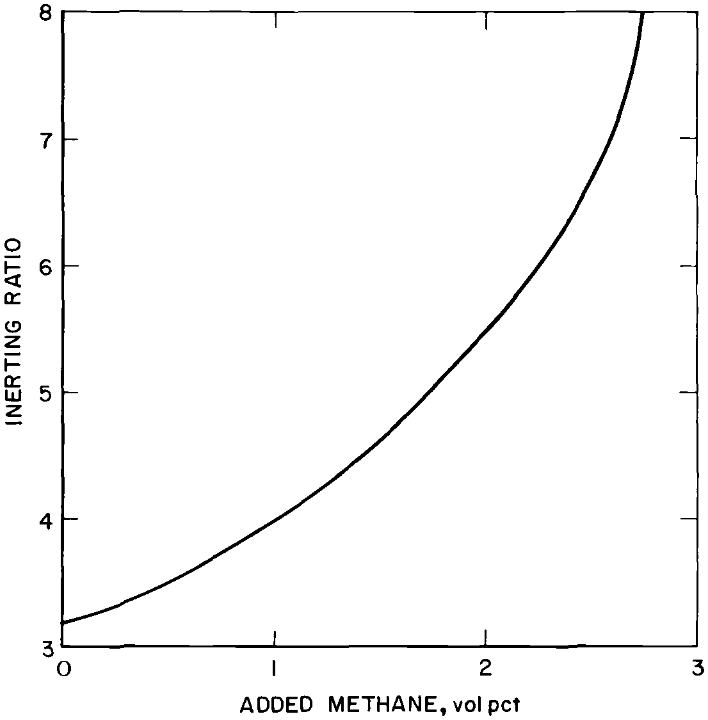


FIG. 17—*Increase in the inerting ratio (rock dust to coal dust) for added amounts of methane.*

will be the subjects of future research. Some subjects are still controversial, and differences of opinion and judgment remain. It is hoped that this book will provide the means for the constructive resolution of those controversies in ways that are consistent with the facts and their physical realities. Although the paths for future research remain multiple and unbounded, there is confidence that the most constructive of those directions will evolve naturally in the form of a reasoned consensus among the various researchers.

References

[1] Lewis, B. and von Elbe, G., *Combustion, Flames and Explosions of Gases*, Academic Press, New York, 1961, pp. 367–381.

[2] Cashdollar, K. L. and Hertzberg, M., "Infrared Temperatures of Coal Dust Explosions," *Combustion and Flame*, Vol. 51, 1983, pp. 23–35.

[3] Berthelot, M. and Vieille, P., "On the Propagation Velocity of Explosion Phenomena in Gases," *Comptes Rendus de l'Academie des Sciences*, Paris, Vol. 93, 1881, pp. 18–22 (in French).

[4] Mallard, E. and Le Chatelier, H., "On the Flame Propagation Velocity of Explosive Gas Mixtures," *Comptes Rendus de l'Academie des Sciences*, Paris, Vol. 93, 1881, pp. 145–148 (in French).

[5] Taylor, G. I., "The Dynamics of the Combustion Products Behind Plane and Spherical Detonation Fronts in Explosives," *Proceedings of the Royal Society, A*, Vol. 200, 1950, pp. 235–247.

[6] Zeldovich, I. B. and Kompaneets, A. S., *Theory of Detonations*, Academic Press, New York, 1960.

[7] Verein Deutscher Ingenieure (Association of German Engineers), "Pressure Relief of Dust Explosions," VDI 3673, *Handbuch Reinhaltung der Luft*, Vol. 6, 1983.

[8] Van Wingerden, C. J. M. and Zeeuwen, J. P., "On the Role of Acoustically Driven Flame Instabilities in Vented Gas Explosions and Their Elimination," *Combustion and Flame*, Vol. 51, 1983, pp. 109–111.

[*9*] Solberg, D. M., Pappas, J. A., and Skramstad, E., "Observations of Flame Instabilities in Large Scale Vented Gas Explosions," in *Eighteenth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, PA, 1981, pp. 1607–1614.

[*10*] Moore, P. E., "Suppression of Maize Dust Explosions," in this volume, pp. 281–293.

[*11*] Pineau, J. P. and Ronchail, G., "Propagation of Coal Dust Explosions in Pipes," in this volume, pp. 74–89.

[*12*] Eckhoff, R. K., "A Differentiated Approach to Sizing of Dust Explosion Vents: Influence of Ignition Source Location with Particular Reference to Large, Slender Silos," in this volume, pp. 265–280.

[*13*] Richmond, J. K. and Liebman, I., "A Physical Description of Coal Mine Explosions," in *Fifteenth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, PA, 1975, pp. 115–126.

[*14*] Srinath, S. R., Kauffman, C. W., Nicholls, J. A., and Sichel, M., "Secondary Dust Explosions," in this volume, pp. 90–106.

[*15*] Carini, R. C. and Hules, K. R., "Coal Pulverizer Explosions," in this volume, pp. 202–216.

[*16*] Moen, I. O., "The Influence of Turbulence on Flame Propagation in Obstacle Environments," in *Fuel-Air Explosions,* University of Waterloo Press, Ontario, Canada, 1982, pp. 101–135.

[*17*] Burgess, M. J. and Wheeler, R. V., "Lower Limit of Inflammation of Mixtures of Paraffin Hydrocarbons With Air," *Journal of the Chemical Society,* Vol. 99, 1911, pp. 2013–2030.

[*18*] Simmons, R. F. and Wolfhard, H. G., "Some Limiting Oxygen Concentrations for Diffusion Flames in Air Diluted with Nitrogen," *Combustion and Flame,* Vol. 1, 1957, pp. 155–161.

[*19*] Zabetakis, M. G., Lambiris, S., and Scott, G. S., "Flame Temperatures of Limit Mixtures," in *Seventh Symposium (International) on Combustion,* Butterworths Scientific Publications, London, 1959, pp. 484–487.

[*20*] Hertzberg, M., Zlochower, I. A., and Cashdollar, K. L., "Volatility Model for Coal Dust Flame Propagation and Extinguishment," in *Twenty-first Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, PA, 1987.

[*21*] Coward, H. F. and Jones, G. W., "Limits of Flammability of Gases and Vapors," Bulletin 503, U.S. Bureau of Mines, Pittsburgh, PA, 1952.

[*22*] Zabetakis, M. G., "Flammability Characteristics of Combustible Gases and Vapors," Bulletin 627, U.S. Bureau of Mines, Pittsburgh, PA, 1965.

[*23*] Kuchta, J. M., "Investigation of Fire and Explosion Accidents in the Chemical, Mining, and Fuel-Related Industries—A Manual," Bulletin 680, U.S. Bureau of Mines, Pittsburgh, PA, 1986.

[*24*] Hertzberg, M., Cashdollar, K. L., and Zlochower, I. A., "Flammability Limit Measurements for Dusts and Gases: Ignition Energy Requirements and Pressure Dependences," in *Twenty-first Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, PA, 1987.

[*25*] Hertzberg, M., Cashdollar, K. L., and Lazzara, C. P., "The Limits of Flammability of Pulverized Coals and Other Dusts," in *Eighteenth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, PA, 1981, pp. 717–729.

[*26*] Hertzberg, M., Cashdollar, K. L., Ng, D. L., and Conti, R. S., "Domains of Flammability and Thermal Ignitability for Pulverized Coals and Other Dusts: Particle Size Dependences and Microscopic Residue Analyses," in *Nineteenth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, PA, 1982, pp. 1169–1180.

[*27*] Gaug, M., Knystautas, R., Lee, J. H. S., Benedick, W. B., Nelson, L., and Shepherd, J., "The Lean Flammability Limits of Hybrid Mixtures," in *Progress in Astronautics and Aeronautics,* Vol. 105, Dynamics of Reactive Systems, Part II, Modeling and Heterogeneous Combustion, AIAA, 1986, pp. 155–168.

[*28*] Ng, D. L., Cashdollar, K. L., Lazzara, C. P., and Hertzberg, M., "Electron Microscopy Studies of Explosion and Fire Residues," IC 8936, U.S. Bureau of Mines, Pittsburgh, PA, 1983.

[*29*] U.S. Congress, "Federal Mine Health and Safety Act of 1977," Public Law 95-164, Nov. 9, 1977, Code of Federal Regulations 30, Chapter 1, Part 75.

[*30*] Hertzberg, M., Conti, R. S., and Cashdollar, K. L., "Electrical Ignition Energies and Thermal Autoignition Temperatures for Evaluating Explosion Hazards of Dusts," RI 8988, U.S. Bureau of Mines, Pittsburgh, PA, 1985.

[*31*] Hertzberg, M., Conti, R. S., and Cashdollar, K. L., "Spark Ignition Energies for Dust–Air Mixtures: Temperature and Concentration Dependences," in *Twentieth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, PA, 1985, pp. 1681–1690.

[*32*] Bartknecht, W., "Preventive and Design Measures for Protection Against the Danger of Dust Explosions," in this volume, pp. 158–190.

[*33*] Conti, R. S. and Hertzberg, M., "Thermal Autoignition Temperatures from the 1.2-L Furnace and Their Use in Evaluating the Explosion Potential of Dusts," in this volume, pp. 45–59.

[*34*] Korol'chenko, A. Y., Perov, A. V., and Shebeko, Y. N., "Effects of Temperature on the Lower Concentration Limit of Flame Propagation in Air Suspensions," *Combustion, Explosion, and Shock Waves,* Vol. 18, 1982, pp. 112–113.

[*35*] Wiemann, W., "Influence of Temperature and Pressure on the Explosion Characteristics of Dust/Air and Dust/Air/Inert Gas Mixtures," in this volume, pp. 33–44.

[*36*] Bartknecht, W., *Explosions: Course, Prevention, Protection,* Springer-Verlag, New York, 1981, pp. 53–54.

[*37*] Cashdollar, K. L., Sapko, M. J., Weiss, E. S., and Hertzberg, M., "Laboratory and Mine Dust Explosion Research at the Bureau of Mines," in this volume, pp. 107–123.

[*38*] Le Chatelier, H. and Boudouard, O., "On the Flammability Limits of Gaseous Mixtures," *Bulletin de la Societe Chimique (Paris),* Vol. 74, 1898, pp. 483–488 (in French).

[*39*] Hertzberg, M., Richmond, J. K., and Cashdollar, K. L., "Flammability Limits and the Extinguishment of Explosions in Gases, Dusts, and Their Mixtures: Theory, Experiment and the Problem of Scale," in *Colloque International: Berthelot-Vieille-Mallard-Le Chatelier,* French Section of the Combustion Institute, 1981, pp. 202–210.

[*40*] Richmond, J. K., Sapko, M. J., and Miller, L. F., "Fire and Explosion Properties of Oil Shale," RI 8726, U.S. Bureau of Mines, Pittsburgh, PA, 1982.

[*41*] Hertzberg, M., "The Theory of Flammability Limits. Natural Convection," RI 8127, U.S. Bureau of Mines, Pittsburgh, PA, 1976.

[*42*] Hertzberg, M., Cashdollar, K. L., Zlochower, I., and Ng, D. L., "Inhibition and Extinction of Explosions in Heterogeneous Mixtures," in *Twentieth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, PA, 1985, pp. 1691–1700.

[*43*] Hertzberg, M., Cashdollar, K. L., Lazzara, C. P., and Smith, A. C., "Inhibition and Extinction of Coal Dust and Methane Explosions," RI 8708, U.S. Bureau of Mines, Pittsburgh, PA, 1982.

[*44*] DeGabriele, R. M., Causilla, H., and Henschel, J. P., "Dynamic Steam Inerting System for a Ball Tube Mill Pulverizing Subbituminous Coal," *Fire Technology,* Vol. 16, 1980, pp. 212–226.

Werner Wiemann[1]

Influence of Temperature and Pressure on the Explosion Characteristics of Dust/Air and Dust/Air/Inert Gas Mixtures

---

REFERENCE: Wiemann, W., "**Influence of Temperature and Pressure on the Explosion Characteristics of Dust/Air and Dust/Air/Inert Gas Mixtures,**" *Industrial Dust Explosions, ASTM STP 958,* Kenneth L. Cashdollar and Martin Hertzberg, Eds., American Society for Testing and Materials, Philadelphia, 1987, pp. 33–44.

ABSTRACT: The explosion characteristics of dusts change with the initial temperature. The maximum explosion pressure, the lower explosion limit, and the oxygen limit concentration decrease as the initial temperature rises. The normalized pressure rise rate (K_{St} value) does not show as clearly the influence of initial temperature. The explosion characteristics of dusts also change with the initial pressure. As the initial pressure is increased, there is a proportional increase of the maximum explosion pressure, the K_{St} value, and the lower explosion limit. The initial pressure rise also leads to a small decrease of the oxygen limit concentration.

KEY WORDS: dusts, explosion characteristics, maximum explosion pressure, rate of pressure rise, K_{St} value, lower explosion limit, oxygen limit concentration, influence of pressure, influence of temperature

For the correct application of protective measures against dust explosions, the explosion behavior of the dust in question must be known. Explosion behavior is described in terms of explosion characteristics, which are assigned to protective measures [*1*]. The maximum explosion pressure, for example, must be known when an apparatus is to be protected by explosion proof construction. Explosion pressure venting requires knowledge of the normalized pressure rise rate (K_{St} value) and the maximum explosion pressure of the specific dust. Oxygen limit concentrations within an installation must be considered if the oxygen concentration is diluted with inert gas, for example, nitrogen, to prevent an explosion.

Each dust has its specific explosion characteristics that are determined in explosion tests. Generally, such tests are carried out at ambient temperature and atmospheric pressure [*2*]. In industrial plants, however, different conditions prevail as a result of drying processes with distinctly higher temperatures, and pneumatic conveying installations with higher pressures. This means that in special applications the influence of temperature and pressure on the explosion characteristics had to be determined. To meet this need, appropriate explosion tests with coal dusts [*3*] and other industrial dusts were carried out.

Test Arrangements and Procedure

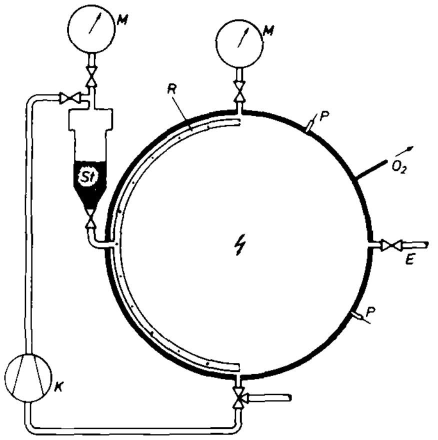
In Europe, the test method developed by Bartknecht is used to investigate explosion behavior of dusts [*4*]. A standardized test method—in accordance with Verein Deutscher Ingenieure (VDI)

[1] Diplom-Physiker, Westfälische Berggewerkschaftskasse, Bergbau-Versuchsstrecke, Postfach 140120, 4600 Dortmund-14, Federal Republic of Germany.

Regulation 3673—was used to measure pressure and rate of pressure rise of dust explosions in a 1-m^3 vessel [5] (Fig. 1). To ensure comparability and transferability of the results, the respective tests were carried out in compliance with the above test method. For this purpose, a cylindrical, double-wall, heatable 1-m^3 vessel almost equal in diameter and length was used. Oil was heated up in a separate heater and circulated between the two walls of the 1-m^3 vessel to heat it to a constant temperature up to 200°C. The temperature differences between the center of the vessel and the walls did not exceed 5°C.

The explosion tests in air are conducted as follows. The dust sample is blown into the 1-m^3 vessel from a 5-L reservoir, air pressurized to 20 bar (2000 kPa). The quantity of air injected into the test chamber is about 100 L in each test. The air is not preheated; it is at ambient temperature. Inside the explosion chamber the dust is dispersed via a semicircular perforated pipe. Ignition is provided by two pyrotechnical sources with an energy of 5000 J each, ignited in the center of the vessel 0.6 s (ignition delay time) after the dispersion of dust.

The dust concentration was varied in steps over a wide range, until maximum values of explosion pressure and rate of pressure rise were attained. The size of error in measuring maximum explosion pressure is $\leq 5\%$ and K_{St} value is $\leq 15\%$. Because of the so-called "cubic-law," the rate of pressure rise value is numerically identical with the K_{St} value in the 1-m^3 volume. To determine the lower explosion limit, the dust concentration was varied until no explosions were recorded. Reactions that generate an overpressure of more than 0.3 bar (30 kPa) are regarded as ignition events. In these tests, the ignition delay time of 0.6 s, being the optimum value for measuring the maximum explosion pressure and K_{St} value, was halved to 0.3 s. Because dust concentrations are smaller than 100 g/m^3 at lower explosion limits, these small quantities are dispersed in a shorter time in the explosion chamber, which leads to a reduction of the optimum ignition delay time at the lower explosion limit [2]. The explosion pressure was measured and recorded as a function of time, using two piezoelectric pressure transducers in conjunction with a light-spot line recorder.



M : gauge
St : dust
R : perforated pipe
P : pressure transducer
O_2 : oxygen sensor
K : compressor
E : inlet and outlet for air and inert gas

FIG. 1—*Schematic representation of test arrangement for investigating explosion behavior of dusts.*

Explosion tests with inert gas/air mixtures were carried out in the same test apparatus. Using the partial pressure method, an inert gas/air mixture with the requisite oxygen content was prepared in the 1-m^3 vessel, and the oxygen concentration was measured. The oxygen concentration was measured with an accuracy of $\leq 0.2\%$ by volume. The inert gas/air mixture is partially taken from the pressurized vessel and used as a propelling agent for the dust dispersion. By this measure, the same inert gas/air mixture is present in the 1-m^3 explosion vessel and in the dust reservoir so that no changes in oxygen concentration are caused by dispersion of the dust.

Together with the variations in dust concentration, the oxygen content was continuously reduced until explosions were no longer recorded; this is generally determined from the explosion pressure value. The oxygen concentration at which no reactions were just recorded is called the limit oxygen concentration.

Influence of Temperature on the Maximum Explosion Pressure, K_{St} Value, and Lower Explosion Limit

The influence of temperature on the explosion behavior of dust/air mixtures was investigated at atmospheric pressure. The explosion behavior of bituminous coal is presented in Fig. 2.

When the explosion limit is exceeded, the explosion pressure increases markedly with increasing dust concentration. Above the maximum explosion value, it decreases slowly. Similar behavior is observed for the rate of pressure rise. The explosion behavior at different temperatures shows a decrease of explosion pressure at elevated temperatures. This means that the corresponding pressure and concentration curves become rather flat and almost parallel. Figure 3 shows the corresponding explosion characteristics of bituminous coal as a function of the initial temperature. As the temperature rises, the maximum explosion overpressure falls from 7.7 bar (770 kPa) at 50°C to 6.3 bar (630 kPa) at 125°C and finally to 5.4 bar (540 kPa) at 200°C. This shows a linear change of the explosion pressure, proportional to the inverse value of the absolute initial temperature. The K_{St} values, however, show no distinct temperature influence in the investigated temperature range, remaining almost constant with 91 bar · m/s (9100 kPa · m/s) at 50°C, 105 bar · m/s (10 500 kPa · m/s) at 125°C, and 91 bar · m/s (9100 kPa · m/s) at 200°C. A similar temperature influence was found for eight other dusts (Table 1), with no corresponding temperature dependence of the respective K_{St} value.

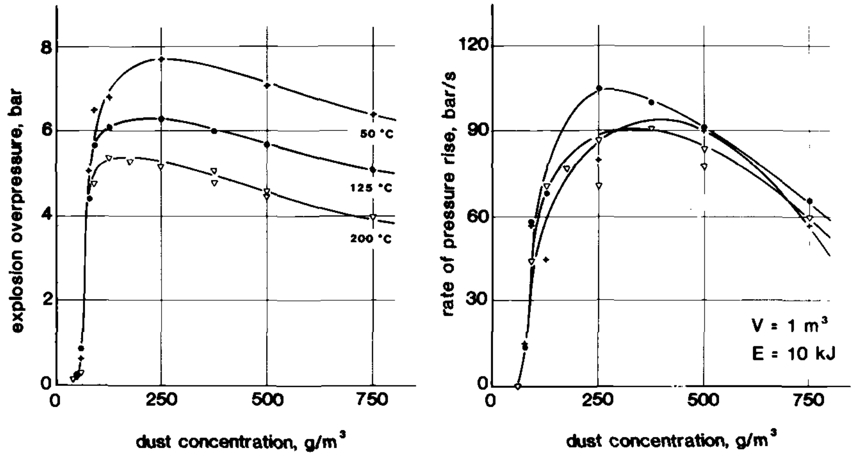


FIG. 2—*Explosion behavior of bituminous coal dust/air mixtures at different initial temperatures.*

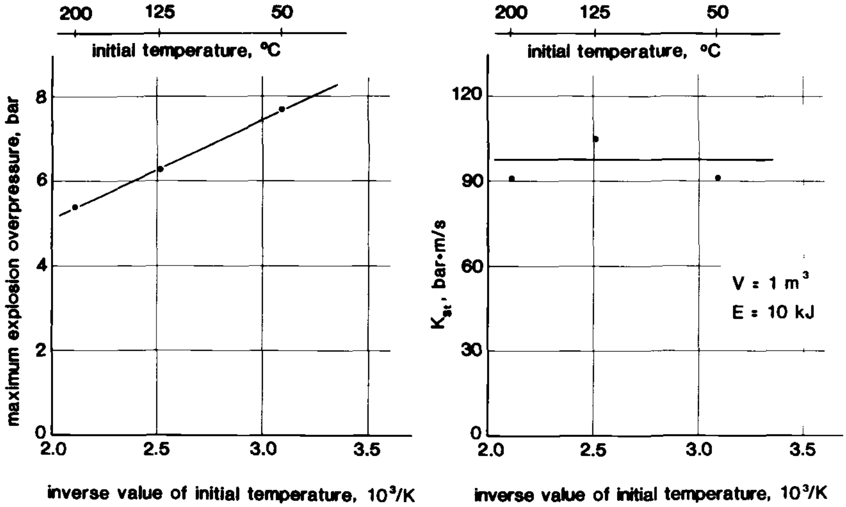


FIG. 3—*Explosion characteristics of bituminous coal at different initial temperatures.*

A distinct reduction of the K_{St} value by more than 15% is generally encountered at temperatures of more than 150°C. The temperature dependence of the maximum pressure in the investigated range is almost the same for all dusts, as shown in Fig. 4.

For a uniform evaluation, the maximum explosion pressure (absolute) P_i measured at the initial temperature T_i has been related to the maximum explosion pressure P_0 measured at the lowest initial temperature T_0. The maximum explosion pressure determined in this way is, in the first approximation, inversely proportional to the initial temperature.

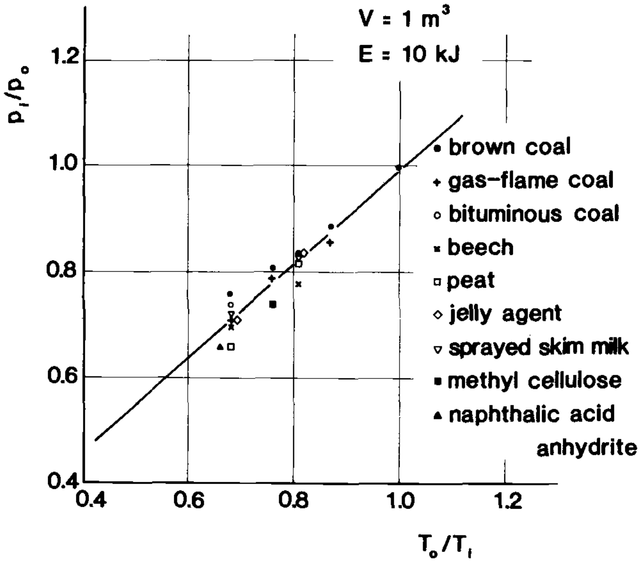


FIG. 4—*Temperature influence on the normalized explosion pressures of different dusts.*

TABLE 1—*Explosion characteristics of different dusts and oxygen limit concentrations in the case of different initial temperatures* (V = *1 m*^{3}, E = *10 000 J*). M = *mass media diameter.*

Type of Dust	Initial Temperature, °C	Lower Explosion Limit, g/m^3	Maximum Explosion Overpressure, bar[a]	K_{St} Value, bar · m/s[a]	Oxygen Limit Concentration, % by Volume
Brown[b] coal	50	50	8.0	121	12.4
M = 52 μm	100	50	7.0	130	11.9
	150	30	6.3	109	10.9
	200	30	5.8	111	10.4
Gas-flame[b] coal	50	50	8.1	107	13.8
M = 19μm	100	40	6.8	103	. . .
	125	. . .	. . .	. . .	12.9
	150	30	6.2	112	. . .
	200	30	5.5	117	11.9
Bituminous[b]	50	60	7.7	91	14.0
coal	125	50	6.3	105	13.4
M = 19 μm	200	40	5.4	91	11.0
Beech	50	70	8.4	166	13.5
M = 59 μm	125	60	6.8	168	12.0
	200	40	5.6	145	10.7
Peat	50	90	8.1	165	13.5
M = 26 μm	125	50	6.5	128	12.5
	200	30	5.0	127	10.9
Jelly agent	50	60	6.7	114	12.5
M = 43 μm	125	40	5.5	120	11.5
	200	40	4.5	88	10.5
Sprayed skim	50	70	7.9	110	15.5
milk	125	50	6.4	125	15.5
M = 65 μm	200	40	5.4	74	14.5
Methylcellulose	10	60	9.5	108	14.0
M = 49 μm	100	50	6.8	84	13.0
Naphthalic acid	5	60	9.0	≥95	12.5
anhydride	150	30	5.6	132	10.9
M = 16 μm					

[a] 1 bar = 100 kPa and 1 bar · m/s = 100 kPa · m/s.

[b] Proximate analysis is given in Table 1*a*.

TABLE 1*a*—*Proximate analysis of the coal dusts according to DIN 51718, 51719, and 51920.*

Type of Coal Dust	Total Moisture, by Weight	Ask Content (Dry), by Weight	Volatile Matter Content (Dry Ash Free), by Weight	Fixed Carbon (Dry Ash Free), by Weight
Brown Coal	6.7	5.2	53.8	46.2
Gas-flame coal	2.4	7.5	38.8	61.2
Bituminous coal	0.8	3.0	26.9	73.1

The following equation was applied:

$$\frac{P_i}{P_0} \sim \frac{T_0}{T_i}$$

A linear curve fitting gives the following equation, with which the maximum explosion pressure (absolute) P_i for any temperature T_i can be determined, when P_0 and T_0 are known:

$$P_i = 0.09 \cdot P_0 + 0.91 \frac{P_0 \cdot T_0}{T_i}$$

At an initial temperature of 200°C, this equation gives a maximum explosion overpressure of 5.4 bar (540 kPa) (measured value: 5.8 bar [580 kPa]) for brown coal, and 4.7 bar (470 kPa) (measured value: 4.5 bar [450 kPa]) for peat.

The lower explosion limit is also influenced by the initial temperature. For all dusts it decreases as the initial temperature rises. The decrease generally lies between 20 and 30 g/m^3 as the temperature rises from 50 to 200°C; exception is peat dust with a decrease of 60 g/m^3.

Oxygen Limit Concentration as a Function of Temperature

The influence of inert gas on the explosion behavior of brown coal, for example, is shown in Fig. 5. With decreasing oxygen concentration and increasing inert gas concentration, the explosion

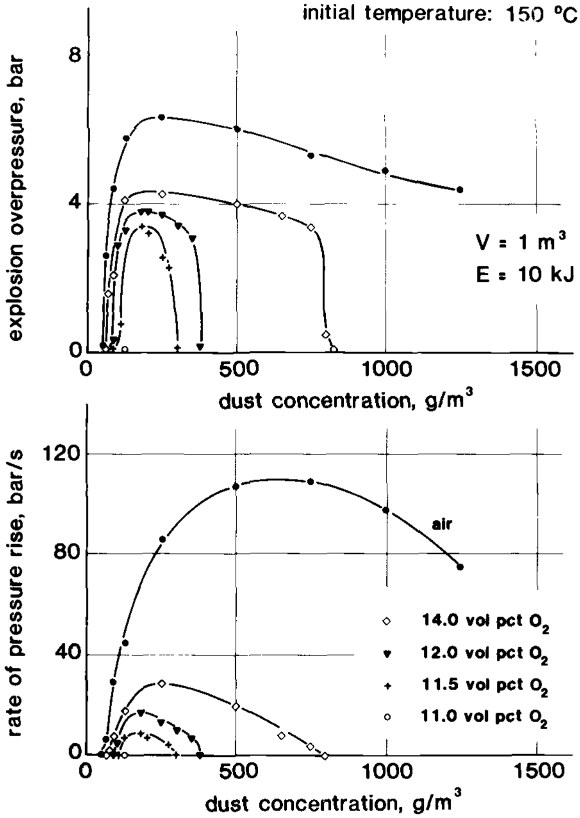


FIG. 5—*Explosion behavior of brown coal dust/air/nitrogen mixtures.*

pressure and rate of pressure rise decrease. The explosion range becomes narrower. The upper explosion limit moves to lower dust concentrations, whereas the lower explosion limit just slightly shifts to higher concentrations. Finally, at a specific oxygen concentration, upper and lower explosion limits coincide, and no explosion is possible.

To determine the limiting oxygen concentration, it is generally sufficient to take into account the change in the maximum explosion pressure and the K_{St} value together with the oxygen concentration (Fig. 6). In many cases there is a linear reduction of the K_{St} value as the oxygen concentration decreases. This decrease is far more distinct than that of the corresponding maximum explosion pressures. In the limit region between nonexplosion and explosion, the explosion pressure changes abruptly. Figure 6 gives a good example of the effectiveness of different gases.

Water vapor with an oxygen limit concentration of 12.3% by volume lies between nitrogen with 10.9% by volume and carbon dioxide with 13.0% by volume. The quantity of water vapor required for effective neutralization is about 330 g/m^3. This means that in technical drying processes, no effective neutralization with water vapor can be achieved. In addition, the action of water vapor can be affected by condensation.

The oxygen limit concentration depends not only on the effectiveness of the inert gas, but also on the type of dust. For example, the oxygen limit concentrations for skim milk are 3 to 4% by

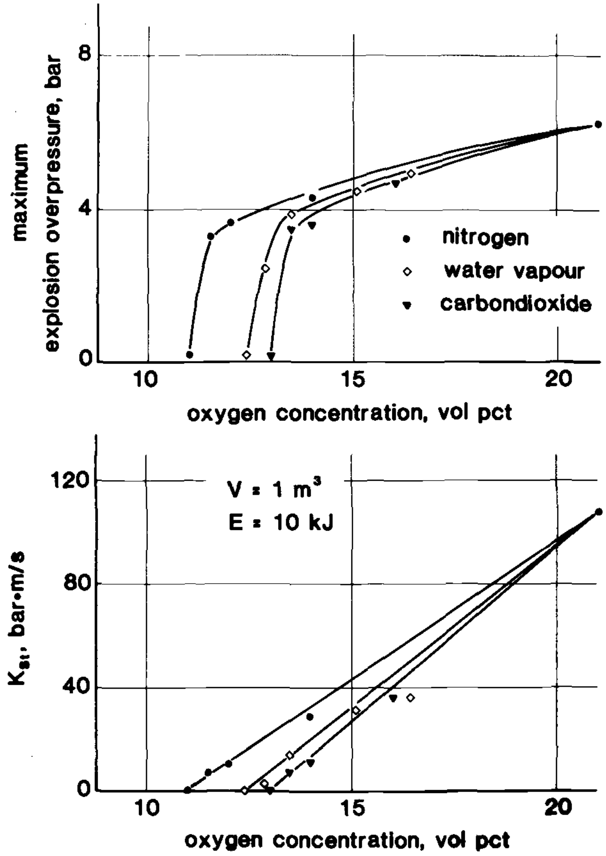


FIG. 6—*Influence of oxygen concentration on the explosion characteristics of brown coal dust/air/inert gas mixtures (initial temperature: 150°C).*

volume higher than those for brown coal. Figure 7 shows that for all dusts the oxygen limit concentration decreases with elevated initial temperature. When neutralization is effected with nitrogen, the decrease, depending on the type of dust, is between 0.7 and 1.9% by volume when the temperature is increased by 100°C. A similar temperature dependence is found for carbon dioxide [*6*], and is given by the following equation:

$$S_{\theta_0} = \alpha\,(\theta_0 - \theta_0) + S_{\theta_0}$$

where

S_θ, S_{θ_0} = oxygen limit concentration for the temperatures θ and θ_0,

θ, θ_0 = temperatures in °C, and

α = temperature coefficient, which describes for a specific inert gas the function of oxygen limit concentration and temperature.

From the present test results, a mean temperature coefficient of $\alpha = -14 \cdot 10^{-3}$% by volume/°C is derived. This should allow a sufficiently exact assessment of the oxygen limit concentration S_θ, when the oxygen limit concentration S_{θ_0} is known. A safety factor of about 2% by volume is subtracted from the calculated or experimental value before the value is applied as a maximum value to an operational safety system. Because of this, one can say that the assessment is sufficiently safe. The recorded temperature dependence corresponds to that measured for terephthalic acid dust, although the value was obtained with a different measuring method, the so-called vertical tube method [*7*].

Influence of Initial Pressure on Maximum Explosion Pressure, K_{St} Value, and Lower Explosion Limit

The influence of the initial pressure on the explosion behavior of brown coal dust/air mixtures was investigated at a constant initial temperature of 40°C and is shown in Fig. 8. At elevated

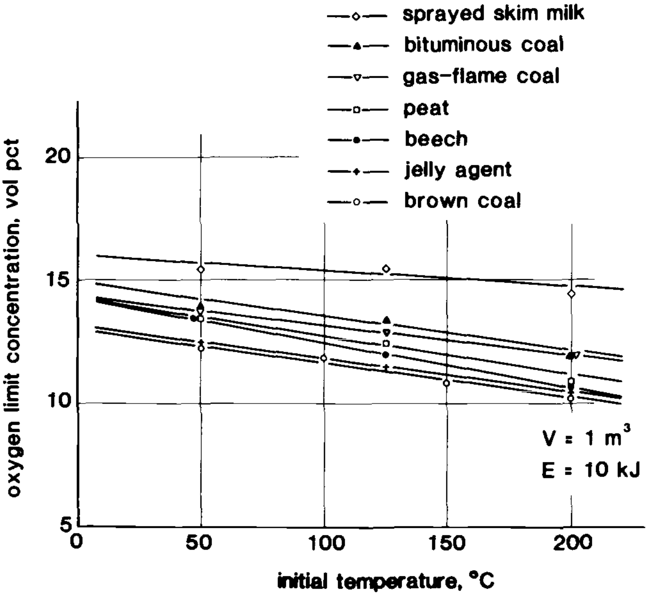


FIG. 7—*Influence of temperature on the oxygen limit concentration of different dusts with nitrogen neutralization.*

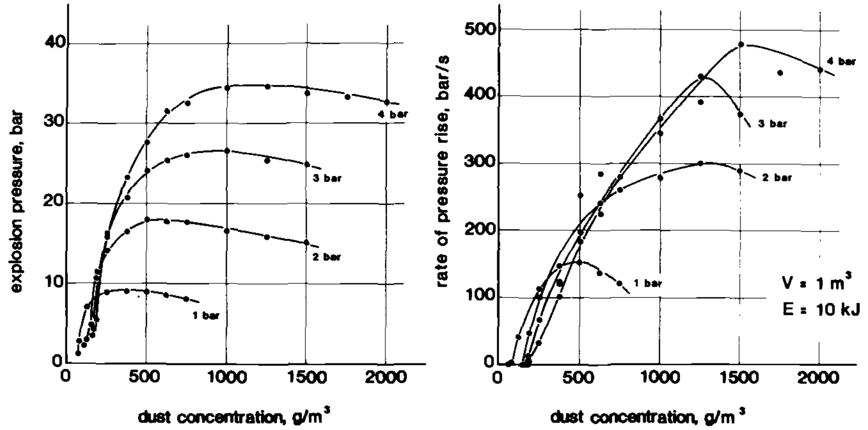


FIG. 8—*Explosion behavior of brown coal dust/air mixtures at different initial pressures (absolute).*

initial pressure, an increase in explosion pressure and rate of pressure rise is recorded, the maximum values of which shift to a higher dust concentration, which is proportional to the initial pressure. Therefore, for example, doubling the initial pressure doubles the optimum dust concentration.

A similar linear relation is found between dust concentration at the lower explosion limit and initial pressure, as shown in Fig. 9. These data for the lower explosion limit versus initial pressure are similar to the values obtained from the 20-L explosibility test chamber [*8*]. The respective explosion characteristics are given in Table 2.

Maximum explosion pressures as well as K_{St} values increase at elevated initial pressures (Fig. 10). This means that they change in direct proportion to the initial pressure. The influence of

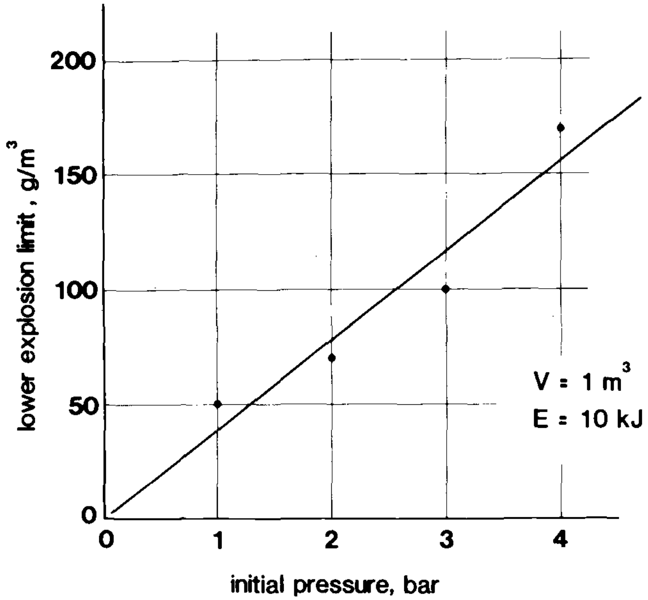


FIG. 9—*Lower explosion limit for brown coal dust as a function of initial pressure (absolute).*

TABLE 2—*Influence of initial pressure on the explosion characteristics of brown coal dust and oxygen limit concentration in the case of nitrogen neutralization* (V = *1 m*^{3}*;* E = *10 000 J*).

Initial Pressure, bar	Lower Explosion Limit, g/m^3	Maximum Explosion Pressure, bar[a]	K_{St} Value, bar · m/s[a]	Oxygen Limit Concentration, % by Volume
1	50	9.0	152	12.5
2	70	17.9	300	12.0
3	100	26.5	429	12.0
4	170	34.6	479	11.5

[a] 1 bar = 100 kPa and 1 bar · m/s = 100 kPa · m/s.

pressure on the maximum explosion pressure and K_{St} value is given by the following equations:

$$P_{\max} = \frac{P_{\max_0}}{P_0} \cdot P_a$$

$$K_{St} = \frac{K_{St_0}}{P_0} \cdot P_a$$

where:

$P_{\max}$ = maximum explosion pressure (absolute) at P_a,
P_a = initial pressure (absolute),
$P_{\max_0}$ = maximum explosion pressure at P_0,
P_0 = initial pressure (mostly atmospheric pressure),
K_{St} = K_{St} value at P_a, and
K_{St_0} = K_{St} value at P_0.

Whereas the maximum explosion pressure increases linearly in the investigated region, the K_{St} value increases linearly only up to a pressure of 3 bar (300 kPa). The reason why, at an initial pressure of 4 bar (400 kPa), the K_{St} value remains below the expected values lies in the chosen

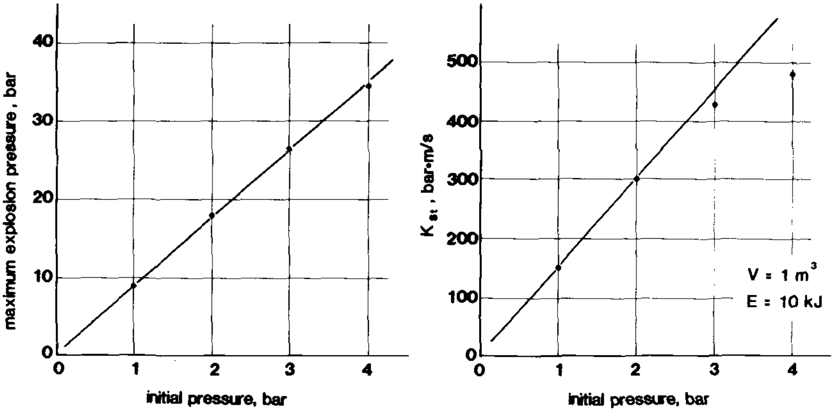


FIG. 10—*Explosion characteristics of brown coal dust at different initial pressures (absolute).*

investigation method. As already mentioned, to attain the maximum values of explosion pressure and pressure rise at elevated initial pressures (see Fig. 8), more dust had to be dispersed in the explosion vessel. The method of dispersion was the same as in all cases. Possibly, large dust concentrations generate different turbulence conditions from small dust concentrations. Since turbulence influences the K_{St} value far more than the maximum explosion pressure, this effect has no influence in the investigated pressure region. The pressure influence on dust explosion characteristics was also observed for two organic dusts [*9*]. The proportionality between initial pressure and explosion characteristics previously found for initial pressures (absolute) of ≤ 2 bar (200 kPa) could now be verified up to 4 bar (400 kPa) [*4*]. Consequently, the pressure influence on the explosion characteristics of dust is comparable to its influence on the characteristics of gases [*4*].

Pressure Influence on the Oxygen Limit Concentration

To determine the influence of initial pressure on the oxygen limit concentration, the same type of tests were carried out with brown coal dust/air/nitrogen mixtures. The measured oxygen limit concentrations are listed in Table 2 and shown in Fig. 11. Increasing the initial pressure (absolute) from 1 to 4 bar (100 to 400 kPa) decreases the oxygen limit concentration slightly by 1% by volume. A similar pressure influence has been reported for certain gases [*10*]. In the case of two organic dusts, the change in the oxygen limit concentration was less [*9*]. In the pressure region with investigated dusts, the influence of elevated initial pressure on the oxygen limit concentration is not as clear as for the explosion pressure and K_{St} value.

Conclusion

The explosion behavior of dust/air and dust/air/inert gas mixtures as a function of initial temperature and initial pressure was investigated in a heatable, pressure tight 1-m^3 vessel. As the initial temperature rises from 50 to 200°C, the lower explosion limit generally decreases by 30 g/m^3. The maximum explosion pressure decreases inversely to the absolute initial temperature. The K_{St} value remains largely unchanged. For a 100°C temperature rise, the oxygen limit concentration

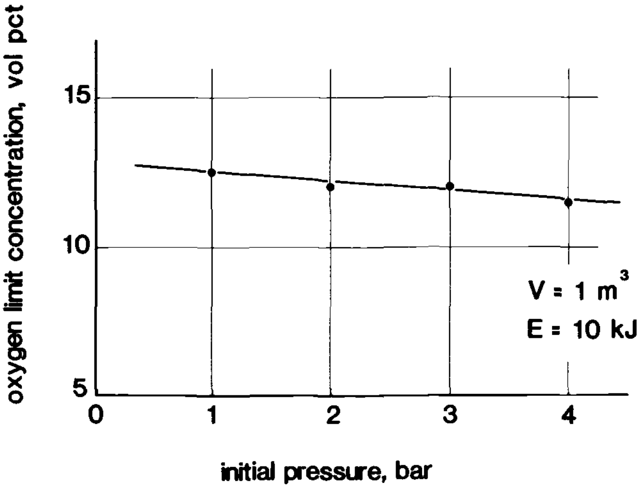


FIG. 11—*Brown coal limiting oxygen concentration as a function of initial pressure (absolute).*

decreases by approximately 1.4% by volume. A rise in initial pressure, from 1 to 4 bar (100 to 400 kPa), raises the lower explosion limit. Both the maximum explosion pressure and K_{St} value increase linearly with an elevated initial pressure. The oxygen limit concentration scarcely changes.

Acknowledgments

The author wishes to thank the Minister of Economy of the state of Northrhine-Westphalia (FRG) for his financial support.

References

[*1*] Verein Deutscher Ingenieure (Association of German Engineers), "Staubbrände und Staubexplosionen, Gefahren-Beurteilung-Schutzmaßnahmen (Dust Fires and Dust Explosions, Hazards-Assessment-Protective Measures)," VDI 2263, VDI-Handbuch Reinhaltung der Luft, Band 6.

[*2*] Forschungsbericht Staubexplosionen, *Brenn- und Explosionskenngrößen von Stäuben,* Hauptverband der gewerblichen Berufsgenossenschaften, Bonn.

[*3*] Scholl, E. W. and Wiemann, W., "The Influence of Temperature on the Explosion Characteristics and the Neutralization of Coal/Dust/Air Mixtures," in *Safety in Mines Research,* (Proceedings of the 21st International Conference of Safety in Mines Research Institutes, Sydney, Australia, 21–25, Oct. 1985), A. R. Green, Ed., A. A. Balkema, Rotterdam and Boston, 1985, pp. 631–635.

[*4*] Bartknecht, W., *Explosions, Course, Prevention, Protection,* Springer, New York, 1981.

[*5*] Verein Deutscher Ingenieure (Association of German Engineers), "Druckentlastung von Staubexplosionen (Pressure Release of Dust Explosions)," VDI 3673, VDI-Handbuch Reinhaltung der Luft, Band 6.

[*6*] Wiemann, W., "Einfluß der Temperatur auf die Sauerstoff-Grenzkonzentration bei der Inertisierung," presented at the 9th International Symposium on the Prevention of Occupational Accidents and Diseases in the Chemical Industry, Lucerne, Switzerland, 5–7 June 1984.

[*7*] Craven, A. D. and Foster, M. G., "Dust Explosion Prevention-Determination of Critical Oxygen Concentration by Vertical Tube Method," *Combustion and Flame,* Vol. 11, No. 5, 1967, pp. 408–414.

[*8*] Cashdollar, K. L. and Hertzberg, M., "20-L Explosibility Test Chamber for Dusts and Gases," *Review of Scientific Instruments,* Vol. 56, No. 4, April 1985, pp. 596–602.

[*9*] Walter, C.-D. and Schacke, H., "Evaluation of Dust Explosion Characteristics at Reduced and Elevated Initial Pressures," presented at the 5th International Symposium on Loss Prevention and Safety Promotion in the Process Industries, Cannes, France, 15–19 Sept. 1986.

[*10*] Zabetakis, M. G., *U.S. Bureau of Mines Bulletin,* Vol. 627, 1965, pp. 30–42.

Ronald S. Conti[1] and Martin Hertzberg[1]

Thermal Autoignition Temperatures from the 1.2-L Furnace and Their Use in Evaluating the Explosion Potential of Dusts

REFERENCE: Conti, R. S. and Hertzberg, M., "**Thermal Autoignition Temperatures from the 1.2-L Furnace and Their Use in Evaluating the Explosion Potential of Dusts,**" *Industrial Dust Explosions, ASTM STP 958,* Kenneth L. Cashdollar and Martin Hertzberg, Eds., American Society for Testing and Materials, Philadelphia, 1987, pp. 45–59.

ABSTRACT: The Bureau of Mines 1.2-L furnace for measuring the thermal autoignition temperatures (AITs) of dusts in air is described. The minimum AITs measured for a large number of dusts are presented, and the data are compared with those in the literature. The data reveal that the measured minimum AITs for the carbonaceous dusts correlate with their volatility yield and the temperature required for pyrolysis and devolatilization. Reaction kinetic factors play a role in determining the onset temperature for the pyrolysis–devolatilization process and in the exothermic oxidation reactions that lead to the autoignition of those volatiles.

The use of the minimum AIT data in estimating the explosion potential of a dust under a given set of operating conditions is also considered. The "ignition sensitivity" parameter and its use in an "explosibility index" are no longer recommended by the Bureau. Alternative means are discussed for evaluating the frequency or probability of explosions in terms of the measured minimum AIT and its relationship to operating conditions in a given facility and to other flammability properties of the dust.

KEY WORDS: dust explosions, autoignition, ignition temperature

Three conditions must be satisfied before a dust explosion can occur:

1. The dust contained within a volume must be *d*ispersed or mixed with the air.
2. The concentration of dispersed dust must be above the lean limit of *f*lammability (the minimum explosive concentration).
3. An *i*gnition source must be present of sufficient power density and total energy to initiate the combustion wave, whose propagation generates the explosion.

The probability of having an explosion is therefore the product of the separate probabilities for each of those conditions being met; thus

$$Pr(expl) = Pr(d)Pr(f)Pr(i)$$

This paper deals with the last of those probabilities: that of ignition, $Pr(i)$.

Ignition sources are characterized according to their type of energy source—electrical, chemical, or purely thermal. This paper deals with a purely thermal source. An ignition source can also have a variety of geometric sizes and shapes, as well as a variety of time-dependent profiles for its power density and energy delivery rate. The thermal source used in these studies is geometrically uniform in spatial extension and steady state in time. It is both spatially and temporally invariant,

---

[1] Electronics engineer and supervisory research chemist, respectively, U.S. Department of the Interior, Bureau of Mines, Pittsburgh Research Center, Cochrans Mill Rd., P.O. Box 18070, Pittsburgh, PA 15236.

that is, isothermal. The ignition behavior of such a thermal source can be reliably characterized by its temperature. One considers 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. One then asks 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 "autoignition temperature" (AIT) of the dust, using the same nomenclature as in the ASTM Test for Autoignition Temperature of Liquid Chemicals (E 659).

An example of the kind of AIT data obtained in the Bureau studies is illustrated in Fig. 1 for the case of lycopodium dust in air. The apparatus and method used are described in the next section. The data are for uniformly dispersed dusts, so that *Pr*(*d*) = 1. The autoignition and nonignition data points shown in the figure were 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*)*Pr*(*i*) = (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 data points for thermal autoignition (explosion) and nonignition (no explosion) are plotted in temperature versus concentration space (at ambient pressure). The upper curve (labeled *i*,*t* for ignition, thermal) is drawn to represent the thermal autoignition boundary as delineated by those data points. Also shown is a lower dashed curve, labeled (*f*), which is the lean flammability limit boundary in the same concentration–temperature space [*1*]. All states of the system below and to the left of the (*f*)-contour are nonflammable or nonexplosive because *Pr*(*f*) = 0. For states above and to the right of the (*f*)-contour, *Pr*(*f*) = 1, and the explosion probability is there equal to the ignition probability.

At still higher temperatures and concentrations one encounters the (*i*,*t*) contour, which is the innermost "core" or "heart" of all ignitability surfaces in the system's state space. Above the (*i*,*t*) contour explosion is certain because both *Pr*(*f*) and *Pr*(*i*) are unity. No external ignition source

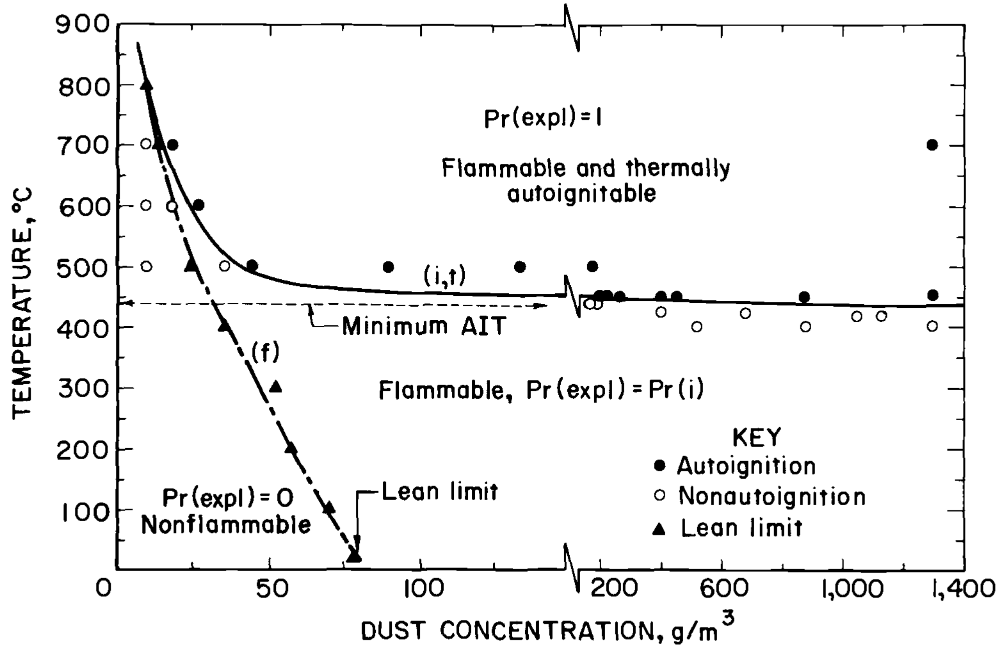


FIG. 1—*Domains of flammability and thermal autoignition for lycopodium dispersed in air.*

is necessary within that core because the system ignites spontaneously as soon as those dust concentrations are dispersed at those initial temperatures. The combinations of dust concentrations and temperatures at or above the *(i,t)* 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 *(f)*-contour and the *(i,t)*-contour for any given dust are also shown in Fig. 1. 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 somtimes also called the "minimum cloud ignition temperature." Those two coordinates in temperature–concentration space accurately characterize those two contours. The two contours are generally well behaved with monotonic slopes as indicated.

Elevated temperatures increase both the flammability and thermal autoignitability of the system; hence, with increasing temperature the lean limit concentration decreases as does the concentration at which spontaneous autoignition occurs. At very high temperatures, the two contours generally converge.

The minimum autoignition temperatures to be reported here are those that lead to an explosion of the dust–air mixture. They are sometimes also referred to as the "cloud ignition temperatures." In either terminology, the word "ignition" refers to the generation of a self-sustained deflagration wave or explosion. It should be clearly distinguished from the "layer ignition temperature," which refers to the surface temperature at which a pile of dust in contact with a heated surface will undergo a self-sustaining heating within the pile of dust or at the boundary between the pile and the surrounding air. The exothermic heating within the layer or pile of dust will generate a smouldering mass, or a fire (diffusion flame). The layer ignition temperature is generally much lower than the cloud ignition temperature, and the final result of layer ignition is a much slower, mixing limited, diffusion flame in which the heating occurs on a very long time scale. Layer ignition will not, by itself, lead to an explosion or any significant pressure rise within the system or its surroundings, but rather to the very slow combustion of the dust in the boundary region between the dust pile and the surrounding air until the dust is oxidized or consumed The data reported here are exclusively "cloud ignition temperatures" that lead to deflagrations or explosions and should not be confused with the entirely different and less devastating ignition process that leads to a smouldering fire.

This paper will also consider the proper use of the minimum AIT data in evaluating the explosion hazards of dusts during their actual use in plants or facilities. It has been about 25 years since the Bureau first promulgated an "explosibility index" for evaluating the explosion hazards of dusts [*2*,*3*]. Over the decades since the initial formulation of that explosibility index, serious deficiencies in that concept have been revealed. Some of those deficiencies will be discussed in detail here, and an alternative means will be proposed for using the minimum AIT data for evaluating explosion hazards.

Experimental Procedure

1.2-L Furnace and Instrumentation

The detailed structure of the Bureau's 1.2-L furnace is shown in the perspective drawing in Fig. 2. The furnace is essentially cylindrical in shape and is of ceramic composition (magnesium aluminum silicate). It was designed to provide for accurate control of the internal temperature. The dust dispersion system injects and disperses a uniform dust cloud into the furnace. Temperature uniformity data and the dust dispersion effectiveness have been published elsewhere [*4*]. Detailed measurements of the autoignition temperatures for several selected dusts have already been published [*1*,*4*,*5*]. Based on the data already obtained, it has been recommended that this new 1.2-L system, or its equivalent in a larger volume, should replace the formerly used Godbert-

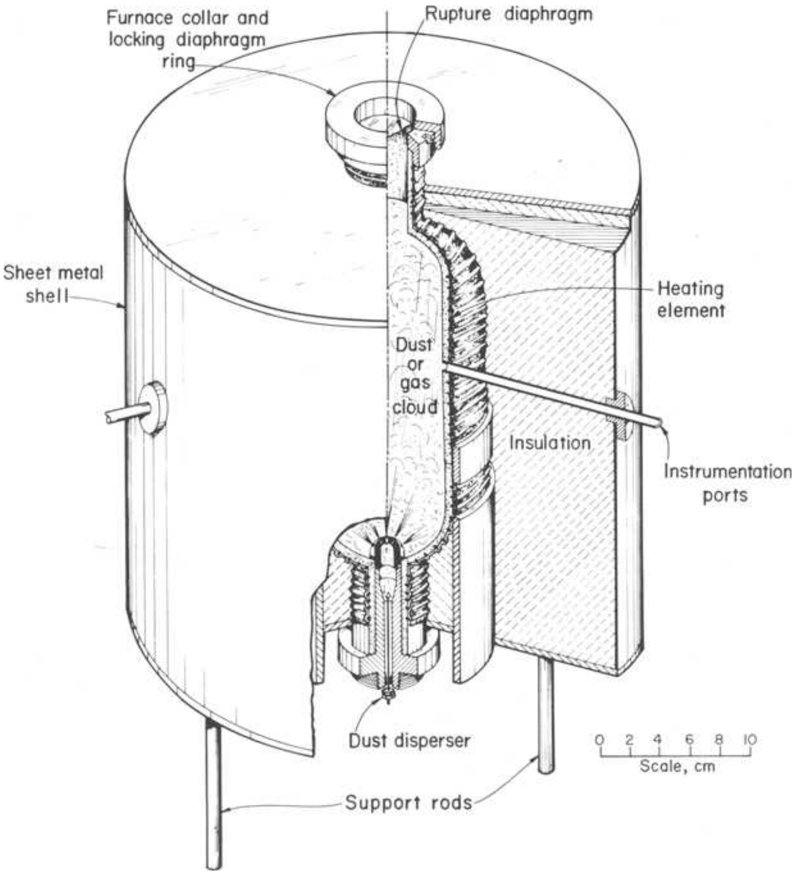


FIG. 2—*Perspective schematic of 1.2-L furnace.*

Greenwald (G-G) furnace [*6*]. The data to be presented here further support that recommendation.

There are four access holes in the side wall of the furnace, two of which are shown in Fig. 2. One is used for the thermocouple near the furnace wall, which controls the initial temperature of the furnace. Another is used for a thermocouple in the center of the furnace, which monitors the temperature of the dust–air mixture being studied. The wall thermocouple is a 318-μm Chromel-Alumel®[2] junction in direct contact with the wall. The thermocouple in the center of the furnace is a much finer, 25-μm platinum-rhodium thermocouple, whose time constant is fast enough to follow the thermal evolution of an explosion during ignition. The two remaining access ports in the side wall of the furnace are used for spark electrodes [*1,4*] or for gas sampling tubes [*7*]. The dust to be tested is placed in the disperser, which is placed into the bottom part of the furnace only moments before the sequence of ignition test events is started. A fiberglass rupture diaphragm covers the top part of the furnace in order to isolate the 1.2-L volume. An air dispersion pulse which lasts for 30 ms disperses the dust as it releases about 0.066 L of room temperature air from a pressurized reservoir into the furnace. The time constant for heating the dispersed dust–air mixture to the initial temperature of the furnace is usually much shorter than the time constant for ignition,

---

[2] Reference to specific products does not imply endorsement by the Bureau of Mines.

especially as one approaches the (*i,t*)-contour. Autoignition is accompanied by a rupture of the fiberglass diaphragm at an overpressure of 0.1 to 0.3 bar (10 kPa to 30 kPa). The criterion for ignition is the rupture of the diaphragm with the simultaneous emission of flame from the top of the furnace. Such ignition is always associated with a temperature rise within the reacting volume of at least 1000°C above the initial oven temperature.

Data and Discussion

The data points for thermal autoignition and nonignition for four dusts are shown in Fig. 3. The respective (*i,t*) curves for each dust are drawn to represent the autoignition boundaries.

The anthracite coal dust, which has the lowest volatility (8% by the ASTM Test for Volatile Matter in the Analysis Sample of Coal and Coke [D 3175]), has the highest value for its minimum AIT—760°C (1400°F). The Pittsburgh seam bituminous coal (36% volatility) has a minimum AIT of 560°C. Polyethylene dust, which is totally volatilizable, has the lowest minimum AIT of the carbonaceous dusts shown in Fig. 3—400°C. Sulfur dust has a minimum AIT of 280°C. Sulfur has the lowest AIT value for any of the dusts studied, but sulfur is not a carbonaceous dust. The

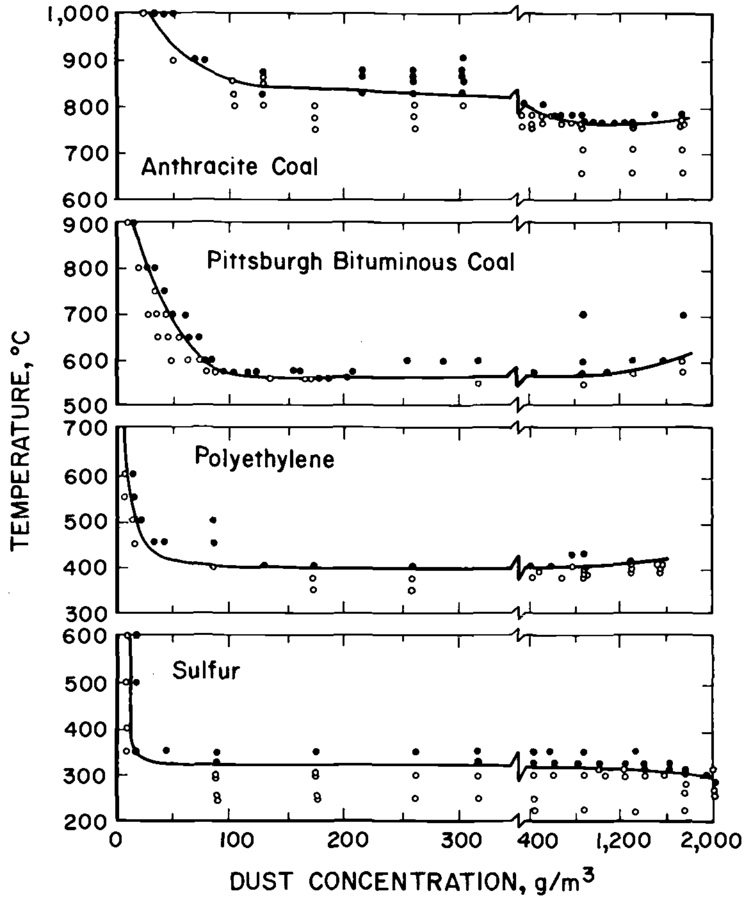


FIG. 3—*Thermal autoignitability data and autoignition boundaries for four dusts.*

general behavior of all the autoignition curves is quite similar: autoignition temperatures are quite high at lean concentrations but they decrease as the more reactive concentrations are approached. Eventually the AITs level off to their minimum values at concentrations that are nominally very rich. Such behavior is consistent with previous observations of the absence of a "normal" rich limit of flammability for the dusts [*5*,*8*], which is explained in terms of the particle devolatilization rate process becoming rate limiting at high dust loadings. The curves do sometimes contain slight hints of rich limiting behavior as they begin to curve back upward, but such recurvature is observed only at extraordinarily high dust loadings above 1000 g/m^3.

The same 1.2-L system was also used for control experiments with methane gas as the fuel. The purpose of those control experiments was to compare the Bureau's results with the large amount of data previously published for methane–air mixtures. The most recent set of independent measurements for methane was reported by British Gas Corp. [*9*,*10*] for stainless steel vessels of 0.8- to 1.0-L volumes. Their data are summarized in the shaded area of Fig. 4. Their range of values for the autoignition temperature of methane reflects variations in vessel volume, vessel shape, stirring conditions, and whether or not the steel surface was treated or untreated with a boric acid coating. The Bureau of Mines data are presented as contours for fixed ignition delay times (τ). The autoignition boundary, the (*i*,*t*) contour, corresponds to the contour with the longest ignition delay time that was observed (30 s). The possibility always exists that still larger test volumes would give longer ignition delays, corresponding to even lower minimum AITs. The comparison shows reasonably good agreement in the absolute values of the minimum AIT which are in the range of 600 to 605°C. There is also good agreement in the methane concentration at which the minimum AIT occurs (6 to 8% by volume).

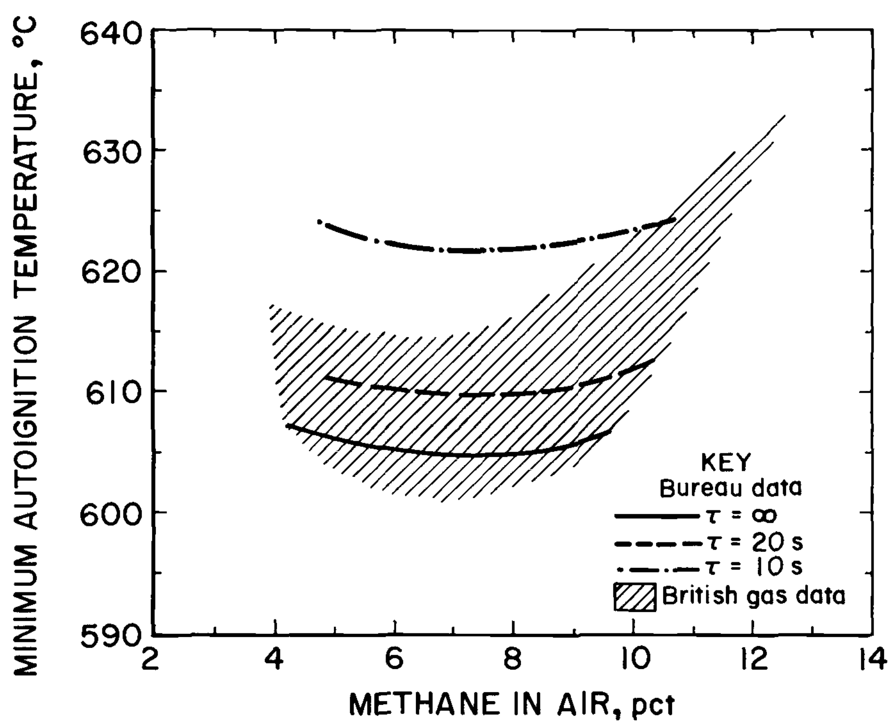


FIG. 4—*Comparison of 1.2-L furnace data with British Gas data* [9,10] *for methane.*

For some reason a value of 537°C is often listed in the handbooks for methane, but as the data show here, the measured values for these volumes are from 600 to 605°C. But as just indicated, the sensitivity of that AIT value to the chamber volume is yet to be determined.

A complete summary of the minimum AIT measurements for all the dusts studied is shown in Table 1. The data shown are for finely pulverized dusts with relatively broad size distributions.

TABLE 1—*Physical characteristics and minimum autoignition temperatures for dusts studied in the 1.2-L ignitability furnace.*

Dust Type	Volatility, %	Particle Diameter, μm		AIT, °C
		$\bar{D}_s$	$\bar{D}_w$	
Carbonaceous dusts				
Graphite:				
A	3	4	14	925
B	5	. . .[a]	. . .	815
Petroleum coke:				
A	6	11	54	720
B	7	25	53	675
Anthracite coals:				
Bethlehem	4	12	38	675
Reading	5	6	9	780
Pennsylvania	8	21	42	760
Bituminous coals:				
Pocahontas	16	16	59	635
Sewell	29	22	44	560
Pittsburgh	36	28	48	540
Subbituminous coals:				
Wyoming	38	31	49	535
Western:				
As received (10% H_2O)	35	25	71	475
Dried (fully)	39	25	71	450
Lignite coals:				
North Dakota:				
As received (26% H_2O)	33	43	115	600
Dried (fully)	43	43	115	555
Beulah, ND:				
As received (27% H_2O)	30	15	29	440
Dried (8% H_2O)	41	15	29	425
Pitch	53	81	124	575
Gilsonite	85	20	~50	480
Mineral dusts				
Oil shale, Green river	22–25	18–28	51–78	475
	9–19	22–29	49–88	500
Sulfide ore, Brunswick	NA[b]	27	44	550
Agricultural dusts				
Lycopodium	85	27	28	435
Cornstarch	87	18	21	400
Wood, treated	70	30	64	450
Miscellaneous chemicals or plastics				
Anthraquinone	99	28	67	740
Benzoic acid	100	. . .	. . .	575
Bisphenol A	99	110	130	570
Paraformaldehyde	100	. . .	. . .	475
Sulfur	. . .	~50	~90	290
Polyethylene	100	26	35	400
Decane (liquid)	100	NA	NA	275

[a] . . . = no data available.

[b] NA = not applicable.

The average sizes tabulated are the surface-area-weighted mean diameter, $\bar{D}_s$, and the mass or volume mean diameters, $\bar{D}_w$. The volatility of the dusts, as measured by the ASTM Test D 3175, is also indicated for the cases where it is relevant.

The initial moisture contents of the lower rank subbituminous and lignite coals are quite high. Because moisture content is an important variable in their explosibility properties, those coals were tested in both "as received" and "dried" states. The drying procedure consisted of placing the dust sample in a calcium sulfate ($CaSO_4$) desiccator until the weight loss leveled off in time. As can be seen from Table 1, the lowest autoignition temperatures for the coals are for the lower rank, finer particle coals in their dried states. Those coals also display the greatest intrinsic tendency for self-heating, and it is therefore not surprising that the subbituminous coals have been the most troublesome for coal pulverizers in utility power plants.

The particle size also is an important variable, and its influence on the minimum AIT must be known to apply the data shown in Table 1 in a meaningful way to an industrial setting. Careful studies of the particle size dependences for the minimum AITs for several dusts were reported earlier [5], and those data are reproduced in Fig. 5. The data are for narrow size distributions that were described earlier [5]. For Pittsburgh seam coal, the minimum AIT becomes independent of particle size for diameters below 50 μm. Accordingly, the value listed for the Pittsburgh seam coal dust in Table 1 is truly representative of the lowest autoignition temperature for that dust. Polyethylene is a similar case because its minimum AIT also becomes independent of particle size for diameters below 80 μm. By contrast, for the higher rank, lower volatility Pocahontas coal, there is a significant particle size dependence down to diameters of 2 μm. Hence, the minimum AIT for the 16-μm Pocahontas coal listed in Table 1 is not representative of the values obtained for the finer Pocahontas coal dusts. The AIT value for the 16-μm Pocahontas coal dust is some 75°C higher than the value obtained for the 2.5-μm dust.

The existence of characteristic diameters below which the minimum AITs become size-invariant exactly parallels the existence of similar characteristic diameters for the lean limits of flammability

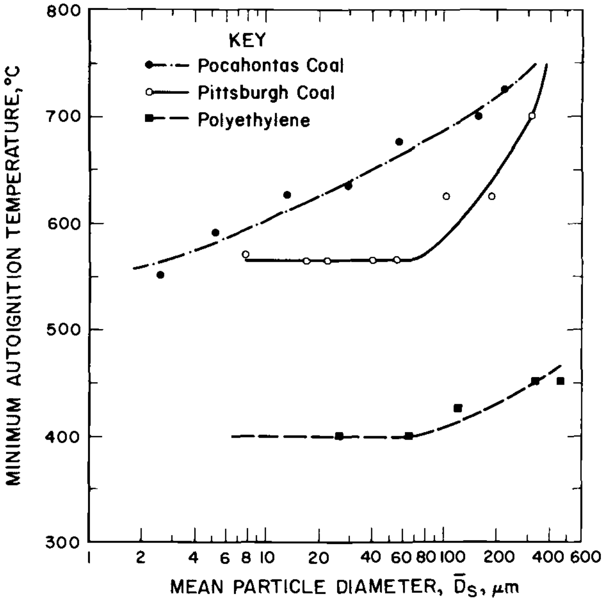


FIG. 5—*Minimum autoignition temperatures as a function of particle size for three dusts.*

[5]. The higher volatility dusts tend to have larger characteristic diameters, whereas the lower volatility dusts have smaller characteristic diameters. Such behavior is a manifestation of the devolatilization rate control process. For a given volatile yield, the finer particles devolatilize more rapidly than the coarser ones. Dusts with a higher volatility yield also tend to devolatilize more rapidly than those with a lower volatility yield. Thus, for a high volatility dust the characteristic size at which the devolatilization process becomes rate controlling occurs at surface-area-weighted mean diameters, $\bar{D}_s$, that are larger than 20 to 30 μm. For the low volatility dusts the characteristic size at which the devolatilization process becomes rate controlling occurs at diameters that are much smaller than 20 to 30 μm. Accordingly, for the higher rank, lower volatility dusts, the AITs measured even for the finely pulverized dusts with $\bar{D}_s$-values in the 20- to 30-μm range may not be representative of the values obtained for the still finer sizes.

A careful examination of data such as those shown in Fig. 5 for particle size dependences, and their comparison with the data for the dusts listed in Table 1, reveals that the particle size variable may still be a "hidden variable" for some of the dusts studied. By "hidden," it is meant that for some dusts the values listed are representative of the values expected for finer sizes, but for others the tabulated values may be unrepresentative. It is only for those dusts that have a high volatility yield and a high intrinsic devolatilization rate that the minimum AIT values listed for dusts in the 20- to 30-μm range are representative of the values obtained for finer dusts. For the lower volatility dusts such as anthracite, graphite, and Pocahontas coal or for dusts with a low intrinsic rate constant for devolatilization, the AIT values listed in Table 1 can be considerably higher than the values obtained for their finest sizes.

A general view of the data in Table 1 leads to the broad generalization that the major factor controlling the minimum AIT for the coals and other carbonaceous dusts is their volatility yield on pyrolysis. Carbonaceous dusts with a high volatility have low minimum AITs, whereas those carbonaceous dusts with a low volatility yield have high minimum AITs. There are some notable exceptions to that generalization, namely oil shale dust and methane gas, which will be discussed later. But for the major fraction of the carbonaceous dusts—from the pure carbons, to the coals of various rank, to the plastics dusts—the generalization seems to hold. The lower is the volatility yield, the higher is the minimum AIT. But that generalization may also contain a hidden variable in the sense that the volatility yield may simply reflect the onset temperature for significant pyrolysis or devolatilization. Those carbonaceous dusts with a high volatility yield also have a low onset temperature for pyrolysis and devolatilization, whereas those dusts with a low volatility yield also have a high onset temperature for pyrolysis or devolatilization. For carbonaceous dusts those pyrolysis and devolatilization temperatures may, in fact, be the more fundamental variable. The volatility yields for the carbonaceous dusts may simply reflect those variations in pyrolysis temperature. Carbonaceous dusts with high H:C ratios will pyrolyze and devolatilize at low temperatures. At those lower temperatures the liquid "metaplasts" and hydrocarbon fragments generated during pyrolysis can readily volatilize without significant char formation. Carbonaceous dusts with low H:C ratios, however, require higher temperatures for pyrolysis. At those higher temperatures the volatilization of the liquid metaplasts and hydrocarbon fragments must now compete with parallel and competing condensation reactions that lead to char formation. The lower the H:C ratio, the higher the temperature required to initiate the pyrolysis process, and the more aromatic the structure of the metaplasts and hydrocarbon fragments formed during pyrolysis. Both those factors combine to enhance the rate of the secondary condensation reactions that generate the char residues and thus reduce the yield of volatiles for carbonaceous dusts with low H:C ratios.

The first exception to the correlation between volatile yield and AIT, namely the oil shale dusts, tends actually to support the above argument. The oil shale dusts have AITs that are much lower than one would expect on the basis of their volatility. The Green River oil shales studied here have volatilities in the 8 to 20% range, and yet their AITs are considerably lower than those of the coals in the same volatility range. Clearly, the kerogen matrix in the shale pyrolyzes more rapidly and at a lower temperature than the coal matrix. The kerogen matrix thus has a higher intrinsic devolatilization rate than the coal matrix. In addition, for the oil shale dusts, essentially the same minimum AIT is observed regardless of the oil yield or volatile content. The minimum AIT was essentially invariant at 475 to 500°C as the oil content varied between 20 and 55 gal/ton (83 and 235 mL/kg). The effect of increasing the oil content (volatility) was merely to decrease the dust concentration at which the minimum AIT was reached. Thus the general correlation between the volatility yield and the intrinsic rate of devolatilization that is observed for the structural matrix that characterizes the coals does not extend to the kerogen matrix in the oil shale. The reason is simply that in the coal matrix the variation in the yield of combustible volatiles with varying coal rank is associated with essential differences in the structure of the coal matrix as reflected in the changing H:C ratio. For the oil shale dusts, the variations in volatility yield are associated only with variations in the fraction of the dust's mass that consists of kerogen. The essential structure of the kerogen matrix remains unchanged as one progresses to the richer shales. Their pyrolysis-devolatilization temperature is therefore invariant, and that is reflected in an invariant AIT for the various ranks of oil shale dust [*11*].

The other dramatic exception to the correlation between volatility yield and AIT is methane. Because methane is initially a gas, there is no devolatilization rate limitation, yet it has a much higher AIT than polyethylene, which must first devolatilize before it can autoignite. The free radical initiation reactions for methane involve the stronger and less reactive C–H bond, whereas for polyethylene, free radical initiation involves the weaker C–C bond and is generally more rapid. The slower initiation kinetics for free radical generation from methane are reflected in a methane AIT that is some 200°C higher than the value for polyethylene.

The data for other saturated hydrocarbons clearly support the above argument regarding methane's anomalous behavior. The lowest value for the minimum AIT for any hydrocarbonaceous substance studied was 275°C for liquid decane. It was dispersed into the furnace as a liquid spray using essentially the same procedure as that used for the dusts. The value reported in the literature [*12*] for decane is 210°C using the ASTM E 659 test in which the ignition criterion is a visual flame observed during a 10-min exposure time.

A comparison of the criteria used here and those used in the ASTM test shows clearly that the 1.2-L system criterion used in these studies is considerably more stringent ("harder") than the criterion used in the ASTM test. The "ignition event" in the 1.2-L system must lead to an actual "explosion." The criterion used in the current ASTM test is less stringent. The comparison is also complicated by the presence of oscillatory "cool flames" that characterize all such rich mixtures of heavy hydrocarbons in air [*4*].

A final anomaly in the data presented in Table 1 is the rather high AIT value of 740°C for anthraquinone dust. Kinetic factors are probably responsible for such a high AIT value for such a completely volatilizable dust.

A detailed comparison of the data reported in Table 1 with the literature tabulations [*2*] of data obtained with the Godbert-Greenwald furnace is complicated by several factors. For the low volatility dusts, such as anthracite or carbon, there is considerable uncertainty in identity or source of the dust and its particle size distribution. These uncertainties were carefully reviewed, and a selection was made for a more careful comparison. For several of the more important dusts the minimum AITs reported here are compared in Table 2 to those reported by other investigators. For methane, the agreement between the 1.2-L Bureau data and the British gas data is excellent, as indicated earlier. When there is no uncertainty about the identity of the dust or ambiguity in the particle size effects, the comparison of the recent 1.2-L Bureau data with the older Bureau data for "minimum cloud ignition temperature" as measured in the 0.3-L Godbert-Greenwald furnace shows a systematic difference. Despite the more stringent criterion used for the new data, they give systematically *lower* autoignition temperatures. That systematic difference is attributed to the larger volume of the newer 1.2-L system, to the fact that the volume is now *confined* so that the

TABLE 2—*Comparison of the minimum autoignition temperatures measured in the Bureau 1.2-L furnace with the data reported by other investigators.*

Dust/Gas	1.2-L Furnace minimum AIT, °C	Other Investigators	
		Reference[a]	Ignition Temperature, °C
Methane	605	B-G	601
Pocahontas coal	625	G-G	640
Pittsburgh coal	540	G-G	610
		BAM	580
Gilsonite	490	G-G	580
Lycopodium	435	G-G	480
		BAM	425
Benzoic acid	575	R-S	540
Sulfur	290	R-S	230

[a] B-G = British Gas data, Refs *9* and *10;* BAM = Recent German data in modified BAM Furnace, Ref *13;* G-G = Bureau of Mines data from the Godbert-Greenwald furnace, Ref *2;* R-S = Recent Soviet data in a 3.1-L cylindrical chamber, Ref *14*.

exposure time is now longer, to the fact that the new, larger volume is more isothermal, and to the fact that the dust dispersion is more uniform and more carefully controlled. The older G-G furnace was smaller and was open at the bottom so that its dispersion volume was uncontrolled and the actual dust concentration within the hot furnace during autoignition was uncertain. Those systematic differences shown in Table 2 between the 1.2-L autoignition temperatures and the 0.3-L Godbert-Greenwald cloud ignition temperatures would probably be even *larger* if the "soft" criterion used in the latter case were made as stringent as the criterion used here. Also shown in Table 2 are the data obtained in a modified BAM furnace [*13*], which gives fair agreement with the 1.2-L data for Pittsburgh coal and lycopodium dust.

Also shown in Table 2 is a comparison of the data obtained here using the 1.2-L furnace and the data reported by Soviet researchers for benzoic acid and sulfur using a 3.1-L volume [*14*]. Their data are 30 to 60°C lower. Although their volume was larger than 1.2-L, their surface-to-volume ratio was comparable to that of the 1.2-L furnace. Their ignition criterion was visual flame propagation, which is probably a softer criterion than that used with the 1.2-L furnace, which could account for their somewhat lower AIT values.

There is some independent evidence obtained from the data for very coarse polyethylene dust that the 1.2-L furnace may not be large enough to yield data that are insensitive to surface-to-volume ratio [*4*]. Hence it remains to be seen whether still larger test volumes would further reduce the measured minimum AITs. Considerable caution should therefore be exercised in attempting to extrapolate the absolute values of the minimum AITs reported here to the much larger operating volumes in plants and factories. The absolute values for the minimum AITs in such large heated systems (pulverizers, dryers, reactors, and so forth) may be even lower than those reported here.

Use of Minimum AIT Data

The minimum cloud ignition temperature as measured in the older 0.3-L Godbert-Greenwald furnace was used as part of an explosibility index. That index, proposed some 25 years ago, was the product of two parameters: the ignition sensitivity and the explosion severity [*3*]. The ignition sensitivity parameter was defined in terms of the product of three numbers: the minimum cloud (auto) ignition temperature (T_{min}, in °C); the minimum spark ignition energy (ϵ_{min}, in joules); and the minimum explosive concentration (C_L, in g/m^3). The lower the product of those three quantities, the more hazardous the dust. The ignition sensitivity parameter was made independent of the particular units used to express those quantities by using the values for Pittsburgh seam bituminous coal dust as a "standard." The product of those three quantities for Pittsburgh seam pulverized coal dust divided by the product of those same quantities for any other dust defined the ignition sensitivity for that dust.

A major problem with that ignition sensitivity parameter is its use of the minimum explosive concentration, C_L, which is not really a measure of ignitability. The use of C_L in an ignition sensitivity parameter serves to confuse the ignition probability, *Pr*(*i*), with the probability of having a flammable volume, *Pr*(*f*). The mixing of C_L with $T_{\min}$ and $\epsilon_{\min}$ is like mixing apples with oranges. The problem of determining *Pr*(*f*) in terms of the fraction of time a system spends at concentrations within the flammable domain is a function of C_L, but that question should be kept separate from the question of the ignitability of the dust.

It is possible to satisfy the above objection by simply removing C_L from the ignition sensitivity parameter. One would then be left with the product of $T_{\min}$ and $\epsilon_{\min}$, 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 $\epsilon_{\min}$ 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 [*1,15–18*]. A detailed consideration of the problem of reliably determining $\epsilon_{\min}$ for a dust is beyond the scope of this paper, but a recent analysis has appeared elsewhere [*1,18*]. There are so many contradictory requirements involved in the experimental conditions needed, and such extraordinary complications, that a reliable determination of $\epsilon_{\min}$ for a dust is dubious, even under the best of circumstances. Furthermore, there are very few well documented cases of electrically initiated dust explosions. Yet, if one looks at the tabulations of the old ignitability index, one finds that the index is determined mainly by the $\epsilon_{\min}$ value. The $\epsilon_{\min}$ value varies by orders of magnitude among the various dusts, whereas $T_{\min}$ varies by factors of only two or three [2]. While there are some important circumstances in which the electrical ignitability properties of a dust can be significant in determining its explosion hazard, the current test methods for measuring $\epsilon_{\min}$ are not reproducible or reliable enough to justify its use as the dominant factor in evaluating the overall ignition probability, *Pr*(*i*).

The probability of electric ignition, *Pr*(*i*, spark), requires a separate consideration and is beyond the scope of this paper. With the removal of C_L from the ignitability parameters, and a separate consideration for $\epsilon_{\min}$, one is left finally with $T_{\min}$, the minimum autoignition temperature which controls the purely thermal component of the ignition probability. Let us focus then on the purely thermal autoignition probability *Pr*(*i*, thermal) since that is the central subject of this paper.

The ratio ($T_{\min}$)Pgh coal:($T_{\min}$) 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 Celsius degrees for $T_{\min}$ leads to absurdities. While such absurdities can be eliminated by expressing $T_{\min}$ in °K rather than °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 K (27°C) 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 to 150°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 simply 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 difference between those two dusts. One is dealing with orders of magnitude of differences in the *Pr*(*i*, thermal) values for those cases, yet the linear dependence is giving only factors of two.

Clearly the linear relationship is not just arbitrary: It grossly underestimates the importance of the temperature variable. A more sensitive function of temperature is needed, and a more logical choice is an exponential one. However, even with a more sensitive temperature function, an important point would still be missing if one retains the $T_{\min}$ for Pittsburgh coal as the "standard" by which other autoignition temperatures are to be 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 *Pr*(*i*, 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 *Pr*(*i*, thermal) is the fraction of time the dust-bearing system operates at temperatures that approach or exceed the autoignition temperature. If that 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 *Pr*(*i*, 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, $T_{\min}$. In the real world, 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. But the point to be made here is that even with those uncertainties, the critical parameter is not the ratio, $(T_{\min})$ Pgh coal:$(T_{\min})$; instead, it is the temperature difference, $T_{\min} - T_o$.

With the previously demonstrated need for a more sensitive, exponential function to relate *Pr*(*i*) to $T_{\min}$, and with the choice of $(T_{\min} - T_o)$ as the important temperature variable, one is led quite naturally to a very familiar functional form for *Pr*(*i*, thermal). As indicated above, in the real world, a precise knowledge of the fraction of time the dust-bearing system spends at each temperature is lacking. There are inevitable statistical and operational fluctuations in the system temperatures that are associated with startup and shutdown transients, with emergency trips of the system, with variations in the properties of the material feed, and with 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 quite analogous to the well known problem of statistical mechanics: that of determining the fraction of particles in a gas, at a temperature *T*, whose energy exceeds some critical level ϵ_i. That fraction is given by the Boltzmann distribution function, $\exp(-\epsilon_i/kT)$, 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:

$$Pr(i, \text{thermal}) = \exp[-C\,(T_{\min} - \overline{T_o(t)})/\overline{T_o(t)}]$$

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, $\overline{T_o(t)}$, 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*, thermal) becomes unity and explosion is certain if the dust is dispersed at a flammable concentration. Normally, of course, $\overline{T_o(t)} < T_{\min}$, and the explosion probability is small. With the proper choice of the constant C, $Pr(i$, 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 $\overline{T_o(t)}$ and the constant C. For safe operation, the constant C should be as large as possible and $\overline{T_o(t)}$ 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 $Pr(i$, 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 [*1,18*]. 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 $Pr(i$, 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, $T_{min} - \overline{T_o(t)}$, 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 $\overline{T_o(t)}$ were small in magnitude, the constant C would be large and the purely thermal autoignition probability could be quite low even at $\overline{T_o(t)} = 200$°C. However, if the spark ignition probability, $Pr(i$, 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 $Pr(i$, spark). Clearly 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 explosive 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

Data presented here for the thermal autoignition temperatures for a large number of dusts compare favorably with those of other researchers. The major uncertainties that persist involve at least two hidden variables—particle size and furnace volume. Some particle size data were presented here, but the effect of furnace volume has yet to be reliably quantified. The data show that for carbonaceous dusts the minimum autoignition temperatures are determined by the chemical structure of the dust. Its chemical structure determines the onset temperature for its pyrolysis and devolatilization, which determines its volatile yield of combustible gases, which in turn determines its autoignition temperature.

The use of data in estimating explosion hazards has also been addressed in terms of the broader context of the factors that determine the probability of the occurrence of a dust explosion. The measured minimum autoignition temperatures together with the measured lean limit concentrations appear to be sufficient to characterize the intrinsic thermal ignitability of a dust and its intrinsic flammability; however, an exclusive focus on the intrinsic properties of a dust by itself does not adequately define the problem of evaluating its explosion hazard. The only component of that hazard that has been addressed here is thermal autoignition, but a quantitative means has been proposed for estimating the probability or frequency of thermal ignition in terms of the measured minimum autoignition temperature, and its relationship to the average operating temperature of a given facility and to the extremes in that operating temperature.

References

[1] Hertzberg, M., Conti, R. S., and Cashdollar, K. L., "Electrical Ignition Energies and Thermal Autoignition Temperatures for Evaluating Explosion Hazards of Dusts," Report of Investigation 8988, U.S. Bureau of Mines, Pittsburgh, PA, 1985.

[2] National Fire Protection Association (NFPA), *Fire Protection Handbook*, 14th Ed., NFPA, Boston, 1976, pp. 3-106–3-108.

[3] Jacobson, M., Nagy, J., Cooper, A. R., and Ball, F. J., "Explosibility of Agricultural Dusts," Report of Investigation 5753, U.S. Bureau of Mines, Pittsburgh, PA, 1961.

[4] Conti, R. S., Cashdollar, K. L., Hertzberg, M., and Liebman, I. "Thermal and Electrical Ignitability of Dust Clouds," Report of Investigation 8798, U.S. Bureau of Mines, Pittsburgh, PA, 1983.

[5] Hertzberg, M., Cashdollar, K. L., Ng, D., and Conti, R. S., "Domains of Flammability and Thermal Ignitability for Pulverized Coals and Other Dusts: Particle Size Dependences and Microscopic Residue Analyses," in *Nineteenth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, 1983, pp. 1169–1180.

[6] Godbert, A. L. and Greenwald, H. P. "Laboratory Studies of the Inflammability of Coal Dusts," Bulletin 389, U.S. Bureau of Mines, Pittsburgh, PA, 1935.

[7] Conti, R. S., Hertzberg, M., Duda, F. T., and Cashdollar, K. L., "Rapid-Sampling System for Dusts and Gases," *Review of Scientific Instruments*, Vol. 54, 1983, pp. 104–108.

[8] Hertzberg, M., Cashdollar, K. L., Zlochower, I., and Ng, D. L., "Inhibition and Extinction of Explosions in Heterogeneous Mixtures," in *Twentieth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, 1985, pp. 1691–1700.

[9] Reid, I. A. B., Robinson, C., and Smith, D. B., "Spontaneous Ignition of Methane: Measurement and Chemical Model," in *Twentieth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, 1985, pp. 1833–1843.

[10] Robinson, C. and Smith, D. B., "The Auto-Ignition Temperature of Methane," *Journal of Hazardous Materials*, Vol. 8, 1984, pp. 199–203.

[11] Cashdollar, K. L., Hertzberg, M., and Conti, R. S., "Explosion Hazards of Oil Shale Dusts: Limits, Pressures, and Ignitability," in *Seventeenth Oil Shale Symposium Proceedings*, Colorado School of Mines Press, Golden, CO, 1984, pp. 243–254.

[12] Zabetakis, M., "Flammability Characteristics of Combustible Gases and Vapors," Bulletin 627, U.S. Bureau of Mines, Pittsburgh, PA, 1965, pp. 44, 114.

[13] Hattwig, M., "Combustion, Unstable, and Strongly Oxidizing Gases, Combustible Dusts," in *Symposium (International) on Explosion Hazard Classification of Vapors, Gases, and Dusts*, National Material Advisory Board and National Research Council, Washington, DC, 1986, Chap. 9B.

[14] Korol'Chenko, A. Ya, Perov, A. V., and Shebeko, Yu, N. "Effect of Temperature on the Lower Concentration Limit of Flame Propagation in Air Suspensions," *Combustion, Explosions and Shockwaves*. Vol. 18, 1982, pp. 112–113.

[15] Lewis, B. and von Elbe, G., *Combustion, Flames, and Explosions of Gases*, Academic Press, New York, 1961, pp. 334–335.

[16] Eckhoff, R. K., "Towards Absolute Minimum Ignition Energies for Dust Clouds," *Combustion and Flame*, Vol. 24, 1975, pp. 53–64.

[17] Eckhoff, R. K. and Enstad, G., "Why Are 'Long' Electric Sparks More Effective Dust Explosion Initiators Than 'Short' Ones?," *Combustion and Flame*, Vol. 27, 1976, p. 129.

[18] Hertzberg, M., Conti, R. S., and Cashdollar, K. L., "Spark Ignition Energies for Dust–Air Mixtures: Temperature and Concentration Dependences," in *Twentieth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, 1985, pp. 1681–1690.

Alan R. Abrahamsen[1]

The U.K. Approach to Dust Explosibility Assessment and Its Relevance to Explosion Prevention and Protection

REFERENCE: Abrahamsen, A. R., "**The U.K. Approach to Dust Explosibility Assessment and Its Relevance to Explosion Prevention and Protection,**" *Industrial Dust Explosions, ASTM STP 958,* Kenneth L. Cashdollar and Martin Hertzberg, Eds., American Society for Testing and Materials, Philadelphia, 1987, pp. 60–73.

ABSTRACT: Dust explosibility assessment in the United Kingdom is in a transitory period as traditional test methods based on the Hartmann apparatus become superceded by methods in line with European codes of practice.

The minimum explosible concentration is measured in the open Hartmann tube using a test method with severe drawbacks. Recent years have seen the use of a 15-L apparatus and the 20-L sphere as means of generating a dust cloud more representative of the industrial scale. The sensitivity to ignition of a dust cloud in relation to electrostatic hazards is represented by its minimum ignition energy. The corresponding test method is the subject of controversy in terms of the spark generating mechanism and various methods may be adopted to simulate a typical "industrial" spark.

Minimum ignition temperatures of dust clouds are measured in the Godbert-Greenwald furnace. However, this apparatus has the disadvantage of not having an independent ignition source to enable minimum explosible concentration or ignition energy measurements to be made at elevated temperatures. A 1.2-L furnace based on a U.S. Bureau of Mines design partly overcomes this problem.

The determination of explosion pressures and rates of pressure rise is essential for the optimum design of explosion protection systems. Methods for measuring these parameters have undergone radical change in recent years, and although the Hartmann bomb apparatus is still accepted in U.K. industry, its use nowadays is not recommended, the 1-m^3 or 20-L sphere vessels being preferred.

The lack of a dedicated British Standard on dust explosibility testing is one of the reasons for the apparently confused attitude towards the subject which exists in many parts of industry. The use of a vessel, such as the 20-L sphere, to measure all dust explosibility parameters (except minimum ignition temperature) is strongly advocated to give data which can be reliably applied to full-scale situations, something which the small Hartmann tube cannot be expected to give.

KEY WORDS: dust explosions, explosion prevention, explosion protection, minimum explosible concentration, ignition temperature, ignition energy, explosion pressure

Although dust explosions and fires in the United Kingdom occur on a regular basis, only a very few can be thought of as major incidents with consequent media coverage. Statistics on dust explosions are difficult to obtain; however, in the period 1962 to 1980 there were 485 explosions and 715 fires reported in the United Kindgom which involved flammable dusts. These resulted in 26 fatalities and 639 injuries. More recent data are currently unavailable, but the most serious dust explosion incidents during the past few years have involved aluminum powder at Holyhead in 1983, rapeseed dust at Hull in 1984, and flour at Ashford (Kent) in 1984.

[1] Higher scientific officer, Protection Systems Section, Department of the Environment, Building Research Establishment, Fire Research Station, Borehamwood, Hertfordshire, WD6 2BL U.K.

This is a good record when one considers the large amounts of materials occurring in powdered form either as product or waste. This paper considers the state of the art on dust explosibility assessment in relation to the apparently low probability of a major dust explosion occurring.

Legal Requirements

The powder handling industry in the United Kingdom together with all those that produce combustible dust by whatever means have certain legal responsibilities. These are detailed in the 1961 Factories Act and the 1974 Health and Safety at Work Act. The Specific clauses are detailed below.

Factories Act 1961 Section 31

> Where, in connection with any grinding, sieving, or other process giving rise to dust, there may escape dust of such a character and to such an extent as to be liable to explode on ignition, all practicable steps shall be taken to prevent such an explosion by enclosure of the plant used in the process, and by removal or prevention of accumulation of any dust that may escape in spite of the enclosure, and by exclusion or effective enclosure of possible sources of ignition.
>
> Where there is present in any plant used in any such process as aforesaid dust of such a character and to such an extent as to be liable to explode on ignition, then, unless the plant is so constructed as to withstand the pressure likely to be produced by any such explosion, all practicable steps shall be taken to restrict the spread and effects of such an explosion by the provision, in connection with the plant, of chokes, baffles and vents or other equally effective appliances.
>
> No plant, tank or vessel which contains or has contained any explosive or inflammable substance shall be subjected:
>
> a) to any welding, brazing or soldering operation;
>
> b) to any cutting operation which involves the application of heat; or
>
> c) to any operation involving the application of heat for the purpose of taking apart or removing the plant, tank or vessel or any part of it;
>
> until all practicable steps have been taken to remove the substance and any fumes arising from it, or to render them non-explosive or non-flammable; and if any plant, tank or vessel has been subjected to any such operation, no explosive or inflammable substance shall be allowed to enter the plant, tank or vessel until the metal has cooled sufficiently to prevent any risk of igniting the substance.

The Health and Safety at Work (HSW) Act 1974 Chapter 37 Part 1 Section 2

> It shall be the duty of every employer to ensure, as far as is reasonably practicable, the health, safety and welfare at work of all his employees.
>
> Without prejudice to the generality of an employer's duty under the preceding subsection, the matters to which that duty extends include in particular:
>
> (a) the provision and maintenance of plant and systems of work that are, so far as is reasonably practicable, safe and without risks to health;
>
> (b) arrangements for ensuring, so far as is reasonably practicable, safety and absence of risks to health in connection with the use, handling, storage and transport of articles and substances;
>
> (c) the provision of such information, instruction, training and supervision as is necessary to ensure, so far as is reasonably practicable, the health and safety at work of his employees;
>
> (d) so far as is reasonably practicable as regards any place of work under the employer's control, the maintenance of it in a condition that is safe and without risks to health and the provision and maintenance of means of access and egress from it that are safe and without such risks;
>
> (e) the provision and maintenance of a working environment for his employees that is, so far as is reasonably practicable, safe, without risks to health, and adequate as regards facilities and arrangements for their welfare at work.

The HSW Act was drawn up to cover all aspects of industrial hazards, and consequently, the section detailed above forms only a minute part of the overall legislation. However, it is the most relevant with respect to the dust explosion hazard.

The Notification of Accidents and Dangerous Occurrences Regulations 1980 specify requirements for the notification of an incident to the appropriate enforcing authority. These regulations are due to be replaced in 1986 by the Reporting of Injuries, Diseases and Dangerous Occurrences Regulations. Responsibility for enforcing these legal requirements lies with the Health and Safety Executive (HSE) via Her Majesty's Factory Inspectorate (HMFI).

Guidelines for Explosion Prevention and Protection

A significant factor in the United Kingdom is that there are no universally accepted standards for either dust explosibility tests or the specification of explosion prevention and protection equipment. Consequently, it is up to the companies handling combustible powders to operate according to their own written codes of practice, while complying with the statutory requirements, and this can lead to a great deal of confusion. In the absence of a general U.K. standard, companies may use either the American NFPA 68 [*1*] code of practice or the German VDI 3673 [*2*]. The Institution of Chemical Engineers (I Chem E) have also published guidelines [*3,4*] on dust explosion prevention and protection which for the first time in the United Kingdom have provided plant designers with guidance on design and operation of plant handling combustible powders.

Guidance on the control of electrostatic hazards is provided for by two British Standards BS 5958 Parts 1 and 2 [*5*].

For many years there has been a demand, by equipment manufacturers and users, for standards to cover the construction, installation, and use of electrical equipment in dust atmospheres.

Part 1 of a new British Standard, BS 6467 [*6*], is a specification covering apparatus construction. It provides for two classes of electrical apparatus, dust tight and dust proof. The problems that are overcome in the design specified by BS 6467: Part 1 are that electrical or mechanical malfunctioning could lead to overheating within the apparatus, which could then lead to ignition externally. This process differs from that with flammable gases in that with them there is possibility of an explosion within the apparatus causing flame to be emitted which causes an external explosion. With dusts there is also the possibility of accumulation on the exterior of the casing of the apparatus which heats to ignition with the subsequent risk of fire and explosion. The problem with dusts is particularly severe, when compared to gases, because they can be in contact with the hot surface for long periods permitting ignition from a relatively low temperature, whereas gases would normally have only short-term contact because of the effects of convection.

Since 1960, the Fire Research Station (FRS) has been the major supplier of dust explosibility data to U.K. industry using test methods that agree with Her Majesty's Factory Inspectorate (HMFI). The current test methods are discussed below and it will be noted that newer methods, particularly those based on the work of Bartknecht et al. [*7*] are currently coming into increasing favor. FRS completes on average some 200 investigations per annum each of which involves advice concerning interpretation of the data in respect to explosion prevention and protection techniques.

Dust Explosibility Tests

Current test methods, although small scale, have been shown capable of giving data that can be applied to the full industrial scale. Test methods are described in detail elsewhere [*8,9*], but the methods viewed in the light of new and alternative methods are discussed below.

Explosibility Classification

In cases where the explosibility of a dust has not been determined or is in doubt, it is necessary to know whether or not the dust will ignite and propagate flame before consideration can be given to specifying explosion protection measures. The classification test provides a qualitative assessment of whether or not a suspended dust is capable of initiating and sustaining an explosion in the presence of small sources of ignition. The classification is made purely on a visual observation of flame propagation in an open vertical tube based on the U.S. Bureau of Mines Hartmann apparatus [*10*] (Fig. 1). An explosible dust, termed "Group A," is one which causes flames to move away from the ignition source, and a nonexplosible dust, termed "Group B," is one which does not propagate flame away from the ignition source.

This classification test, although providing only qualitative information that cannot generally be used to specify explosion protection requirements, is nevertheless very important since it establishes whether or not an explosion hazard exists with a given dust.

The main drawbacks of the test method are its applicability to only ambient conditions (no more than 100°C) and the use of weak ignition sources. However, as a simple screening exercise, the test is quite adequate, being both cheap and simple to operate, and is generally acceptable throughout the U.K. industry.

Alternative classification systems based on VDI 3673 (the St system) tend to be used in conjunction with the design of explosion relief venting (discussed later), rather than as an indication of explosibility alone. This is largely due to the much higher costs involved in determining the St classification using a 1-m^3 or 20-L sphere apparatus. The modified Hartmann tube with flip off lid is not widely used in the United Kingdom, and is not at present offered as a test by FRS.

Future demands will have to take into account classification tests at elevated temperature in the presence of independent ignition sources. A 1.2-L furnace developed at the U.S. Bureau of Mines [*11*] is the most suitable apparatus currently available for this. Also the question of weak versus strong ignition sources must be examined since it is possible that a Group B classified material may prove explosible if a large ignition source is present. In other words, it may give an St1 classification in the 20-L sphere apparatus necessitating the provision of expensive explosion

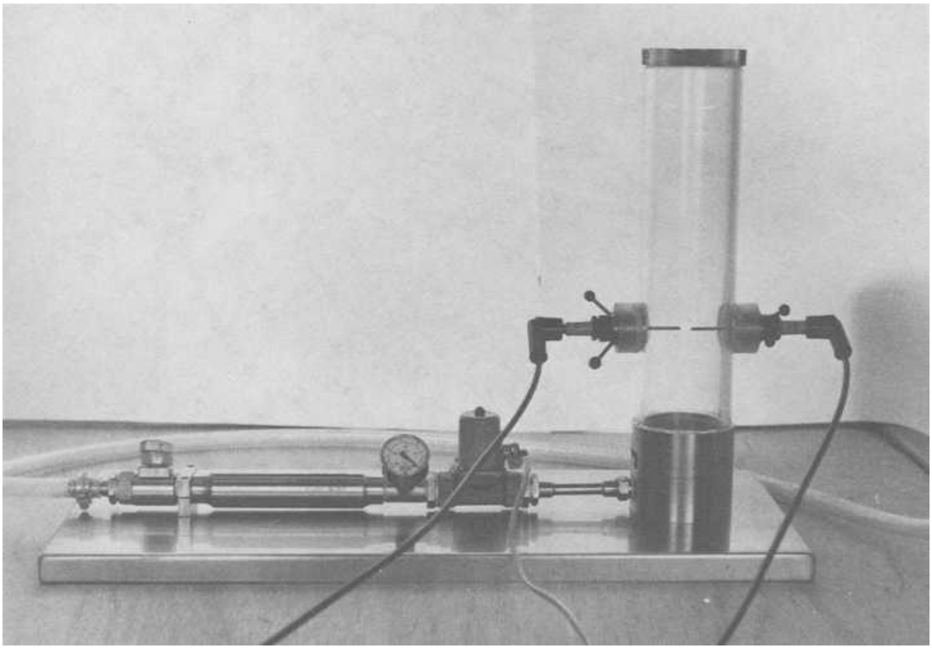


FIG. 1—*Vertical tube apparatus.*

protection, whereas the current practice would indicate that none is needed. This may mean a demand for simple quantitative classification tests in relation to specific powder handling processes.

Minimum Explosible Concentration

The minimum explosible concentration (MEC) of a dust is the smallest amount of dust suspended into a given volume that is capable of igniting and sustaining flame propagation. The value gives an indication of the hazardous concentration in a plant. This parameter is measured in the vertical tube apparatus with an electric spark as the source of ignition; no flame propagation on ten consecutive occasions is the test criterion.

Although the test was originally designed to give an identical MEC for Pittsburgh coal dust obtained in large scale tests, its use with all types of dust has several drawbacks:

1. It is very difficult to obtain a uniform concentration in the vessel particularly with denser materials.
2. The ignition source is present when the dust is dispersed; consequently, the dust cloud will ignite before it has filled the vessel leading to an overestimation of the MEC.
3. Only one type of ignition source is used; the glowing wire coil can sometimes ignite a dust cloud when a spark cannot, thereby causing confusion.

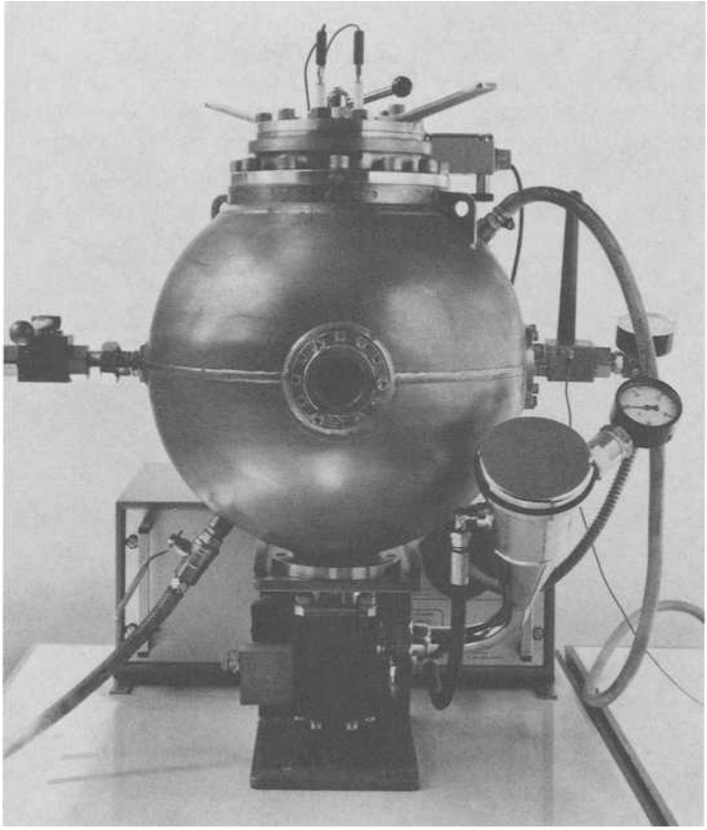


FIG. 2—*Twenty-litre sphere apparatus.*

On the basis of these inadequacies, it is not surprising that other test methods are now being considered to provide a more realistic indication of MEC. These are based on the 20-L sphere (Fig. 2) developed by Siwek [*12*] and manufactured by Adolf Kuehner AG, Basel, Switzerland, and the 15-L "Nordtest" apparatus (Fig. 3) originally developed by Eckhoff et al. [*13*]. The former uses a 10 000-J chemical ignition source which might be considered too powerful, but is in accordance with the standard test procedure. Ignition of the powder cloud is indicated by an increase in pressure above that normally generated by igniters alone (above 1 bar [100 kPa]). Providing this procedure is followed (discussed later), the same degree of turbulence in the dust-air system can be reproduced on each test, something which the Hartmann tube cannot readily achieve. The "Nordtest" method [*14*] involves selecting the dispersion conditions to suit the powder being handled, that is, in order that the dust cloud can fill the vessel as uniformly as possible before the spark ignition source is activated. The criterion for ignition is flame propagation of at least 100 mm. The concentration that gives a 50% probability of ignition is deemed to be the minimum explosible concentration. Table 1 gives comparisons beween the three methods for several powders. The 10% probability of ignition in the 15-L vessel is also included as a direct comparison with the Hartmann tube method.

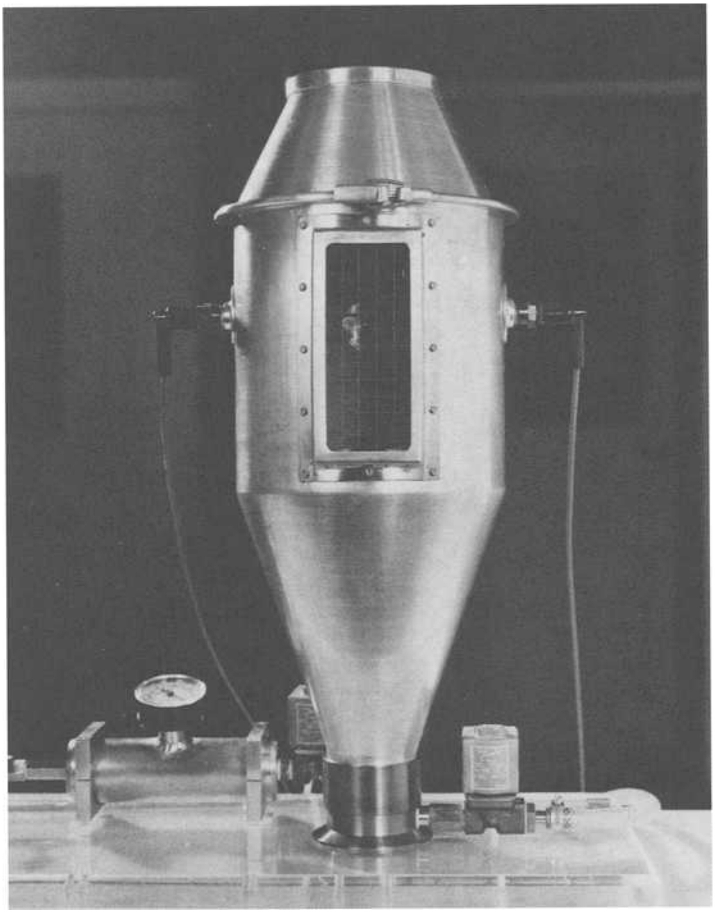


FIG. 3—*Fifteen-litre "Nordtest" apparatus.*

TABLE 1—*Comparison of minimum explosible concentration data for a selection of dusts.*

Dusts	Hartmann Tube, kg/m^3	15-L Vessel, 10% Probability, kg/m^3	15-L Vessel, 50% Probability, kg/m^3	20-L Sphere, kg/m^3
Polyethylene	0.020	0.015	0.039	0.010
Maize starch	0.040	0.050	0.070	0.008
Lycopodium	0.020	0.035	0.054	0.008
Iron	0.650	0.558	0.690	0.450
Woodflour	0.060	0.038	0.065	0.025
Sodium stearate	0.150	0.250	0.480	0.020

Various interesting points arise from these results. The MEC values in the Hartmann tube and the 15-L vessel with 10% ignition probability show close agreement, whereas the 15-L vessel with 50% ignition probability gives values two to three times higher than the Hartmann tube method. In the 20-L sphere, MEC values are generally up to nine times lower than in the other apparatus. The question, of course, is which method gives values appropriate to the industrial situation. To answer this the use of MEC data in relation to explosion prevention must be examined.

One of the criteria for a dust explosion to occur is that the concentration of dust must be within its explosible range, so that an effective form of explosion prevention is to maintain dust levels below the minimum explosible concentration. In practice, there are relatively few processes where this can be done reliably, so that it could be argued that MEC data are of limited use, other than as a comparison between the hazards of different materials. In process plants, levels of turbulence vary greatly and MEC data may depend on turbulence to some extent, and unless this can be controlled in the test apparatus, the results may be unhelpful. Both 15- and 20-L test methods can vary turbulence levels, yet the MEC values differ greatly. Again, this comes down to the different ignition sources used.

Although the results in Table 1 are only part of a more substantial program of work[2] currently being carried out, it can be seen that the future probably lies with either the 15-L vessel or the 20-L sphere, but several points should be considered:

1. How relevant are MEC data to different types of plant?
2. Is it realistic to assume "worst possible case" data obtained in the 20-L sphere with a 10-kJ ignition source?
3. Should there be a test method for MEC at elevated temperature?

Minimum Ignition Temperature

The minimum ignition temperature (MIT) of a dust cloud is the lowest temperature at which it will spontaneously ignite and propagate flame. The current test method uses the Godbert-Greenwald furnace [*10*] (Fig. 4) which is comprised of a 216- long by 36-mm inside diameter vitrosil tube wound with 20 SWG Kanthal "A" wire in such a way as to give an even axial temperature distribution. A small quantity (for example, 0.2 g) of dust is dispersed down through the furnace and any flame propagation is observed. The furnace temperature is reduced until no ignition occurs on ten consecutive tests. It is normal when applying test results to industrial scale to adopt a significant safety margin and operate at temperatures not greater than about 70% of the measured value. This supposedly accounts for the limitations of the test method which are as follows:

1. The furnace tube is very small making the formation of an adequate dust cloud difficult.

---

[2] S. A. Ochia, private communication, Fire Research Station, Borehamwood, U.K., 1986.

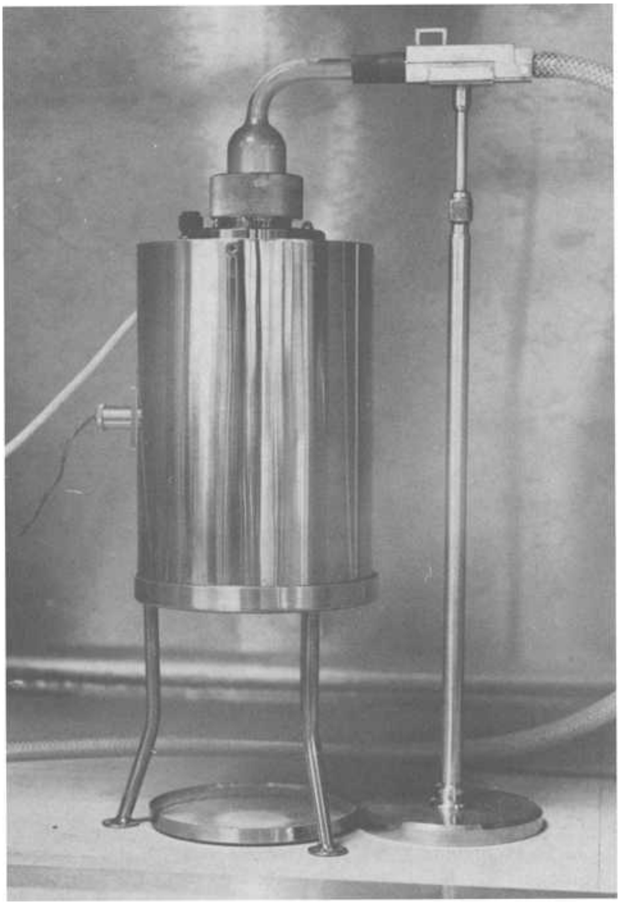


FIG. 4—*Godbert-Greenwald furnace.*

2. Dust is dispersed with cold air, and the residence time of dust in the furnace tube is low, especially for dense powders.
3. The dust when dispersed from the storage chamber has to negotiate a right angle bend into the furnace tube; this results in easy blockage particularly for dusts which have low melting points.

The application of data is also well documented in the form of a specific guide to the use of dryers from the I Chem E [*15*] (currently being updated). However, MIT data is only relevant to hot environments and heated surfaces and little consideration is given to effects on minimum explosible concentrations, minimum ignition energies (MIE), and explosion pressure data at elevated temperatures. FRS are currently evaluating a 1.2-L furnace apparatus (Fig. 5) similar to that developed at the U.S. Bureau of Mines [*11*] which can be fitted with electrodes to enable both elevated temperature classification tests and MIE tests to be carried out. In addition, upward dispersion of dust into the furnace would give longer dust residence times more in line with industrial situations, but would increase the likelihood of ignition of smoldering gases which, it may be argued, should be taken into consideration in any case.

One problem with powder handling systems operating at elevated temperatures is the possibility of solvents being driven off in the drying process allowing the likelihood of hybrid vapor-dust

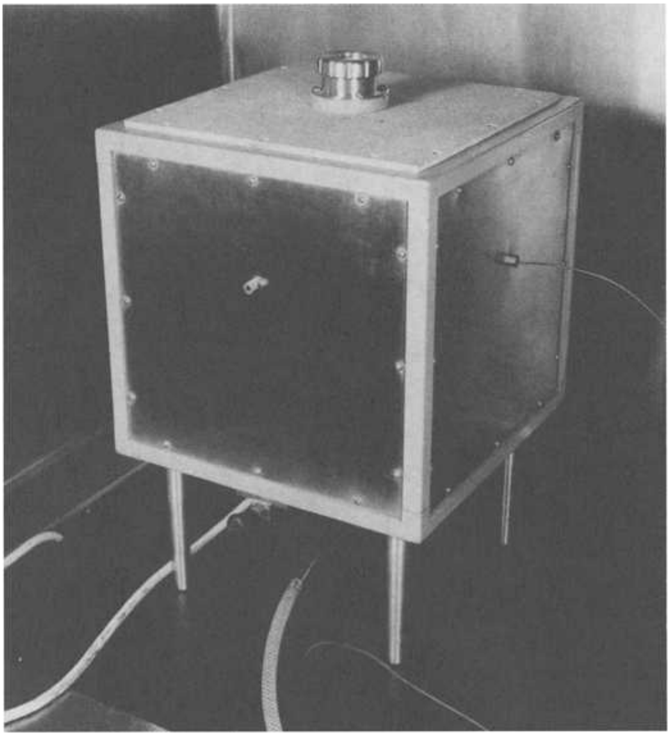


FIG. 5—*1.2-litre furnace.*

mixtures. It is a well-known fact that the minimum explosible concentration of a hybrid mixture is below the MECs of its components, but little work appears to have been done on effects of other parameters. Although coal dust/methane have been reasonably well documented, relatively little information is available on other systems, so there is room for the development of test methods relevant to industrial operations involving hybrid mixtures.

Minimum Ignition Energy

Minimum ignition energy is the lowest energy of spark that will ignite and propagate flame. The traditional method still used by FRS, and that from which most published data is obtained, is based on the Hartmann tube and uses a bank of capacitors which are charged to a low voltage (up to 300 V) and then discharged through a 10-kV step-up transformer to provide a spark across the electrodes. The equation $E = \frac{1}{2}CV^2$, where E is the spark energy, C is the capacitance, and V the voltage to which the capacitors are charged, is used to evaluate the minimum ignition energy. It is accepted that significant losses occur in the circuit used and the theoretical spark energy value is likely to be substantially higher than the actual energy of the spark. However, if all that is required is an indication of the relative sensitivities to ignition of dust clouds, then this test method may be considered adequate. However, the existence of BS 5958 Parts 1 and 2 [5] means essentially that such data cannot be applied to these codes of practice, but that data obtained by the British Standard method must be used. In essence, this involves generating a series of sparks in a Hartmann tube apparatus by charging a capacitor from a high voltage DC supply until a spark occurs; a series resistor is included in the circuit to lengthen the spark duration. Spark energies of 500, 25, 10, and 1 mJ are recommended to equate directly with the code of practice.

Despite this standard test method, its use in the United Kingdom appears not to be widespread and various schools of thought exist on the best spark generating circuit to use. Because of the complex nature of spark ignition [*16*], the number of variables is so large that a range of values for MIE may be determined for a specific dust cloud depending on the circuit used and the particle characteristics of the dust cloud tested. The current points of discussion in terms of test methods can be summarized as follows:

1. The use of a series inductance as opposed to a series resistance in the spark generating circuit will minimize the amount of stored energy lost in the circuit enabling a greater degree of accuracy to be obtained from $E = \frac{1}{2}CV^2$.

2. The duration of spark is an important factor since "long" sparks generally give lower MIE values. However, the majority of spark discharges in practice are capacitive from conductor to conductor and from conductor to nonconductor and include corona, brush, and spark discharges. These are very fast events (<50 ns), and simulating these sparks on a laboratory scale by direct capacitor discharges tends to result in relatively higher MIE values than obtained by other methods of spark generation. Parker [*17*] has discussed in detail various aspects of this problem which are however beyond the scope of this paper.

3. The nature of the electrode material and electrode spacing also affect the measured MIE value.

In view of these points and the differences of opinion between workers in various countries, it is unlikely that a universally accepted test method will be established in the near future. From the plant designer's point of view, absolute values are little use since powder cloud characteristics vary so much and he has no control over a spark discharge in practice. In other words, it matters little that the MIE is 2 or 3 mJ. What he is concerned about is whether the MIE is 2 or 20 mJ since this will determine the level of precautions needed to guard against accidental ignition. As such, the British Standard test method, or something similar, is quite adequate for most practical purposes. However, MIE should also be looked at in terms of specific items of plant and not just in terms of a number. The test vessel, of course, should also be considered since this will affect the nature of the dust cloud. As has been discussed earlier, the Hartmann tube gives little scope for reproducibly varying the degree of turbulence so it seems likely that the 20-L sphere will eventually be used for MIE determinations.

Maximum Permissible Oxygen Concentration to Prevent Ignition

Until the late 1970s this test was carried out in a modified form of the Godbert-Greenwald furnace at 850°C. However, FRS work [*18*] indicated that this test method gave unrealistically low values because the high temperature used was not typical of industrial conditions. A new apparatus was developed in 1978, using the Hartmann tube, but with facilities for purging with oxygen-inert gas (nitrogen usually) and dispersing the dust with the same mixture. The method gives values that can be reliably used in full-scale situations. The overall demand for this type of test is low reflecting the high capital and running costs of protection by inerting or partial inerting. Reappraisal of the test method is therefore unlikely since the current method appears to work well. However, it is thought that the use of the 20-L sphere as a standard test vessel should be encouraged, although how the 10-kJ ignition source compares to the weak ignition sources currently used in terms of limiting oxygen concentrations remains to be seen.

Maximum Explosion Pressures and Rates of Pressure Rise

It is the determination of these parameters which has shown the greatest change in the United Kingdom over the past five years with a gradual move away from the Hartmann bomb apparatus to the 1-m^3/20-L sphere apparatus.

Hartmann Bomb—The Hartmann bomb consists of a stainless steel combustion tube fitted with an ignition source and a piezoelectric pressure transducer for pressure measurement. Dust is dispersed into the tube, and ignited normally by either an electric spark or a hot filament. The explosion is confined within the tube and the pressure-time trace is recorded. The maximum rate of pressure rise determined in this test can be used to specify the size of explosion relief vents for a given vessel. An empirical relationship has been traditionally used in the United Kingdom and is referred to as the vent ratio method.

The values given in Table 2 have been specifically "designed" for vessels that can only withstand pressures up to 0.14 bar (14 kPa) (that is, relatively weak plant). In addition, since the vent ratio is a dimensional parameter for vessels having volumes above 30 m^3, the ratio is often reduced progressively from $1/6$ to $1/25$ m^{-1}. For larger vessels above 300 m^3, consideration may have to be given to incorporating a relief vent equal to half of the whole cross-sectional area of the vessel.

20-L Sphere—An alternative method of determining explosion pressure parameters is now generally preferred following extensive research and development in Switzerland [*7,12,19*]. From large-scale venting experiments a series of nomographs has been derived and incorporated in VDI 3673 which relates the vent area to vessel volume for a dust whose explosibility is known. A laboratory scale apparatus, the 20-L sphere, was developed, and, provided that precise experimental conditions are followed with this apparatus, the data obtained can be applied to the nomographs.

This approach makes use of the cube root law:

$$(dp/dt)_{\max} \cdot V^{1/3} = K_{st} \tag{1}$$

where

$(dp/dt)_{\max}$ = the maximum rate of pressure rise,
V = the volume of the vessel, and
K_{St} = a constant for the dust (units, bar/m · s).

A dust may be ascribed a dust hazard class of St number depending on its K_{St} value as shown in Table 3. K_{St} values or St numbers can then be applied to an appropriate nomograph to determine the vent size for a specific vessel handling a given dust. The nomograph can be applied to vessels having volumes up to 1000 m^3 with length-to-diameter ratios 5 to 1; the vessels must be strong enough to withstand pressures of at least 0.2 bar (20 kPa) (that is, existing nomographs cannot be used for relatively weak plant).

In the United Kingdom, the sizing of explosion relief vents has often been the subject of considerable discussion. A comparative study was made of some commonly used methods for sizing explosion relief vents by Field [*20*] in which the two above methods were considered with a more theoretical approach suggested by Rust [*21*].

TABLE 2—*Vent ratio method.*[a]

Maximum Rate of Pressure Rise, bar/s (Hartmann Bomb)	Vent Ratio (Area of Vent Per Volume of Plant), m^{-1}
<345	1/6
345–690	1/4.5
>690	1/3

[a] 1 bar = 100 kPa.

TABLE 3—*Dust hazard class of St number of a dust determined from its* K_{St} *value.*[a]

Dust Hazard Class St Number	K_{St} Value, bar m/s
1	<200
2	>200–300
3	>300

[a] 1 bar = 100 kPa.

The study resulted in the following recommendations in respect to the application to the relief venting of industrial plant.

1. For plant that is relatively strong, that is, capable of withstanding pressures greater than 0.2 bar (20 kPa), the nomograph approach should be used if appropriate data are available (that is, K_{St} or St values for the dust being handled). If these data are not available, and cannot be determined, the vent ratio and Rust approaches can be applied, and the smaller vent area prescribed by the two approaches should be adopted (since both are likely to be larger than necessary).
2. For plant that is relatively weak, that is, capable of withstanding only about 0.14 bar (14 kPa), the nomograph approach cannot be used. The vent ratio and Rust approach can again be used and the smaller vent area adopted. The work carried out for this paper indicates that the Rust method can be used satisfactorily for dust giving rates of pressure rise in the Hartmann bomb up to about 345 bar/s (34.5 MPa/s) (larger vents are likely to be prescribed by the vent ratio method). For dusts giving rates of pressure rise in the range 345 to 690 bar/s (34.5 to 69 MPa/s), a useful approach would be to use the smaller vent prescribed by the Rust or vent ratio methods. For dust giving rates in the Hartmann bomb greater than 690 bar/s (69 MPa/s), vents determined by the Rust method are likely to be excessively large particularly for large volumes. The vent ratio method is preferred.
3. Generally, if the vent area prescribed by the Rust or vent ratio method can be accommodated without difficulty or unreasonable burden, this should be done; since, although it may be larger than necessary, it will more than adequately cope with the explosion pressure, that is, it will err on the side of safety.

It is anticipated that all plant manufacturers will construct sufficiently strong plant to enable the nomograph method of vent sizing to be used, thereby making the Hartmann bomb obsolete, even less popular, or relevant, thus avoiding confusion over published pressure data. Indiscriminate use of Hartmann bomb data to obtain K_{St} values directly is not unknown. It has been suggested [*22*] that Hartmann bomb and 20-L sphere data can be related empirically, but this is not generally recommended. The main drawback of the 20-L sphere is its unreliability in handling relatively coarse materials. The recommended median particle size is 63 μm principally to get the "worst case." Although there is no upper particle size limit recommended, experience at FRS has shown that significant quantities of particles larger than 63 μm tend to reduce the efficiency of dispersion and cause blockage of the dispersion nozzle.

The use of worst case or highly turbulent conditions for the nomographs also needs to be reviewed in terms of various types of plant in which turbulence of the dust cloud is different. It is unreasonable to put the same vent area on a silo, say, with low turbulence and a grinding installation where the dust is in a highy turbulent state.

Large Scale Tests and the Future

Tests in the United Kingdom involving full-scale plant items are rarely reported because of the large cost of carrying out such work. The development of new realistic test methods largely depends on full-scale tests so that the conditions, in terms of dust cloud turbulence in particular, can be reliably scaled down to laboratory scale. This of course has been done satisfactorily in developing VDI 3673, and recent U.K. work [*23*] has proven the reliability of this vent sizing method for dust collectors. Consideration needs to be given to various types of ignition sources in industrial equipment so that laboratory test methods give even more realistic results. In particular, a test to indicate the risk of ignition from frictional sparks is needed. An important project concerned with the effect of ducts fitted to explosion relief vents is currently in progress on both small and large scale, and the results of this should enable effective use of vent sizing methods in situations where ducts must be used. Guidelines on this subject are particularly vague at the moment.

Acknowledgments

This paper forms part of the work of the Fire Research Station, Building Research Establishment, Department of the Environment. It is contributed by permission of the Director, BRE. It is U.K. Crown copyright.

References

[*1*] *Guide for Explosion Venting,* NFPA 68, NFPA, Boston, 1978.

[*2*] "Pressure Relief of Dust Explosions," VDI Richtlinien 3673, VDI Verlag, Dusseldorf, 1979.

[*3*] Schofield, C., *Guide to Dust Explosion Prevention and Protection, Part 1—Venting,* I Chem E, Rugby, 1984.

[*4*] *Guide to Dust Explosion Prevention and Protection, Part 2—Suppression,* I Chem E, Rugby, 1986.

[*5*] "Code of Practice for the Control of Undesirable Static Electricity," BS 5958: Parts 1 and 2, BSI, London, 1980 and 1983.

[*6*] "Electrical Apparatus with Protection by Enclosure for Use in the Presence of Combustible Dusts," BS 6467: Part 1, BSI, London 1985.

[*7*] Bartknecht, W., *Explosions—Course, Prevention, Control,* Springer Verlag, Heidelberg, Berlin, New York, 1981.

[*8*] Field, P., *Dust Explosions. Handbook of Powder Technology,* Vol. 4, Elsevier, Amsterdam, 1982.

[*9*] Field, P., "Explosibility Assessment of Industrial Powders and Dusts," Building Research Establishment Report, HMSO, London, 1983.

[*10*] Dorsett, H. G., Jacobson, M., Nagy, J., and Williams, R. P., "Laboratory Equipment and Test Procedures for Evaluating Explosibility of Dusts," R. J. 5624, U.S. Bureau of Mines, Washington, DC, 1960.

[*11*] Hertzberg, M., Conti, R. S., and Cashdollar, K. L., "Electrical Ignition Energies and Thermal Autoignition Temperatures for Evaluating Explosion Hazards of Dusts," R.I. 8988, U.S. Bureau of Mines, Pittsburgh, 1985.

[*12*] Siwek, R., "20-liter Laborapparatur für die Bestimmung der Explosionskennzahlen brennbarer Staube," Ciba-Geigy Ltd., Basel/Winterhur Engineering College, Winterthur, 1977.

[*13*] Eckhoff, R. K., "A New Laboratory Scale Method for Determining the Minimum Explosible Concentration of Dust Clouds," CMI Report 78002-3, CMI, Bergen, 1978.

[*14*] "Dust Clouds: Minimum Explosible Concentration," Nordtest Method NT FIRE 011, Nordtest, Stockholm, 1980.

[*15*] *User Guide to Fire and Explosion Hazards in the Drying of Particulate Material,* I Chem E, Rugby, 1977.

[*16*] Van Laar, G. F. M. and Zeeuwen, J. P., "On the Minimum Ignition Energy of Dust-Air Mixtures," *Archiv für Combustion,* Vol. 5, No. 2, 1985, pp. 145–159.

[*17*] Parker, S. J., "Low Energy Spark Ignition III—Tests Using Four Dust Clouds," CMI Report 853351-4, CMI, Bergen, 1985.

[*18*] Tonkin, P. S. and Fardell, P. J., "The Determination of Maximum Permissible Oxygen Concentrations in a Small Vertical Tube Dust Explosion Apparatus," FR Note 928, Fire Research Station, Borehamwood, U.K., 1972.

[*19*] Siwek, R., "Experimental Methods for the Determination of Explosion Characteristics of Combustible Dusts," in *Loss Prevention and Safety Promotion in the Process Industries,* Vol. 3, ECFE, Basel, 1980.

[*20*] Field, P., "Dust Explosion Protection—A Comparative Study of Selected Methods for Sizing Explosion Relief Vents," *Journal of Hazardous Materials.* Vol. 8, 1984, pp. 223–238.

[21] Rust, E., "Explosion Venting of Low Pressure Equipment. A Theoretical Solution to Explosion Relief," *Chemical Engineering*. Nov. 1979.

[22] Abrahamsen, A. R. and Field, P., "Application of Dust Explosion Pressure Data to the Sizing of Explosion Relief Vents," in *Solidex 84 Conference*, Harrogate, 1984.

[23] Lunn, G. and Cairns, F., "Dust Explosions in an Industrial Dust Collector," *Staub Reinhaltung der Luft*, Vol. 26, No. 2, 1986, pp. 97–100.

Jean P. Pineau[1] *and Gino Ronchail*[1]

Propagation of Coal Dust Explosions in Pipes

REFERENCE: Pineau, J. P. and Ronchail, G., "**Propagation of Coal Dust Explosions in Pipes,**" *Industrial Dust Explosions, ASTM STP 958,* Kenneth L. Cashdollar and Martin Hertzberg, Eds., American Society for Testing and Materials, Philadelphia, 1987, pp. 74–89.

ABSTRACT: This paper discusses the possibilities of pulverized coal explosions in pneumatic conveying. To characterize the coal dust explosions, we measured, at different points on rectilinear pipes, possibly connected to a 1-m^3 vessel, explosion overpressures, P_{max}, and flame speeds.

Trials in an isolated, 250-mm-diameter, 20-m-long pipeline and ignition near a closed end showed the difficulty of the flame propagation that did not surpass 10 m with P_{max} values at the maximum equal to 0.6 bar (60 kPa) for a one-end-open duct and 0.95 bar (95 kPa) for a closed duct. On the other hand, with the pipeline connected to a 1-m^3 vessel, with ignition in the vessel, the P_{max} values inside the pipe can reach 10 bar (1000 kPa) and flame speeds 1500 to 2000 m/s. When exchanging the 250-mm-diameter pipe for a 440-mm one, such a character is not obtained and flame speeds are 600 m/s at the maximum with overpressures around 2.5 bar (250 kPa). If the open end, 250-mm-diameter pipe connected to a 1-m^3 vessel is only 10 m long, overpressures inside remain under that obtained in the vessel, that is, around 4 bar (400 kPa). With a 40-m-long pipe, the high speed flames seem unable to be sustained.

In the 1-m^3 vessel and 150-mm-diameter open end pipe system, the overpressures in the pipe have similar values to that obtained in the vessel (P_{max}: 5 bar [500 kPa]) and the flame propagates up to 20 m. When the pipe is 40 m long, P_{max} values remain the same, but the flame stops generally after 20 m.

With closed end, 150- and 250-mm pipe connected to a 1-m^3 vessel, flames cannot propagate the full length of the duct, but explosion overpressures may be 10 to 20 bar (1000 to 2000 kPa).

For low concentration it has been noticed, outside the duct, that the concentration is heterogeneous but shows periodical figures; when the flame appears the same periodicity is found again. This may be due to the geometry of the studied system.

All these trials demonstrate the difficulty of a pulverized coal explosion in a pipe with a diameter less than or equal to 250 mm and the influence of the dust cloud local concentration.

KEY WORDS: coal dust explosions, pneumatic conveying, pipes, explosion overpressures, flame speeds

In industrial installations which process and handle combustible materials in powder, vessels can be grinders, cyclones, dryers, blenders, bag filters, and storage hoppers of more or less elongated form, which may be protected against explosion effects by vents [*1*] or by explosion suppression systems [2].

Even when the equipment is well protected against explosions, the propagation of an explosion inside the connecting ducts is a hazard that must be envisaged.

The possibility of dust explosion propagation, after flame initiation, in isolated ducts of a diameter greater than or equal to 200 mm, has already been studied especially by Bartknecht [*3*]

---

[1] Head of explosive substances and explosion safety group and engineer in same group, respectively, CERCHAR (Centre d'Etudes et Recherches de Charbonnages de France), B.P. 2, 60550 Verneuil-en-Halatte, France.

and by Pineau and Ronchail [*4*] for wheat flour. Diverse authors have also examined the possibility of detonation initiated by shock wave [*5,6*].

When the explosion is flame initiated, we will examine here the characterization of the possibilities of pulverized coal explosions in 150-, 250-, and 440-mm-diameter ducts in two particular cases: rectilinear isolated duct and rectilinear duct connected to a 1-m^3 vessel where the explosion was initiated.

According to the test assembly configuration and to the duct diameter and length, we interpret the results obtained while taking into consideration maximum explosion overpressures, flame speeds, distance-time diagrams for pressure waves and the flame front, and the flame aspect when emerging from the duct.

This study was undertaken to determine explosion risks caused by pulverized coal during its manufacture (grinding installation, dust removing system) and its handling by pneumatic conveying.

Material, Measuring System, and Coal Characteristics

Material

The two test assemblies are represented in diagram form in Fig. 1. Tests were carried out with the operational methods previously used at CERCHAR [*2,4*].

In the case of test Assembly 2 where only the 250-mm-diameter duct was used, the dust was previously regularly deposited in suitable quantity in a corner iron fixed all along the dust interior, then raised up by compressed air thanks to a perforated tube placed at the corner iron base (see Fig. 1).

After a 0.3-s delay, t_v, after the dust raising, the dust cloud was ignited by a 20-g ball of guncotton placed near the closed end.

With the test Assembly 1, the dust was systematically dispersed in the 1-m^3 vessel with the usual pulverizing device. Initially placed in a storage tank, the dust is expelled by compressed air at 6 to 8 bars (600 to 800 kPa) through a Lechler full cone nozzle. The dust cloud ignition was brought about after a delay $t_v = 0.1$ s by 20 g of guncotton. In 440- and 250-mm ducts connected to the vessel it was possible to disperse the dust using the corner iron and perforated tube device described above. In the case of the 150-mm-diameter duct, the dust previously regularly distributed in a corner iron was then deposited on the duct floor by upturning the corner iron.

Measuring Systems

The pressure changes at different points of the system (positions indicated by C in Fig. 1) were recorded using piezoelectric transducers, which made it possible to measure maximum explosion overpressures (relative pressures) at these different positions. Simultaneously, photodiodes were used to detect the flame passage (positions indicated by F in Fig. 1); it was thus possible to calculate the average flame speed between two points, successively measured.

Subsequently, we will give only the highest maximum explosion overpressure (P_{max}) and flame speed (V_{max}) values.

Certain tests were filmed (at about 400 frames/s) and show the aspect of the dust cloud and the flame emerging from the duct end into open air.

Coal Characteristics

Two types of french coal were used:

- Montrambert coal used in France for explosion tests (volatile index: 21.71%, moisture content: 0.86%, ash: 6.4%)[2] and

---

[2] T. Matsuda, personal communication, 1982.

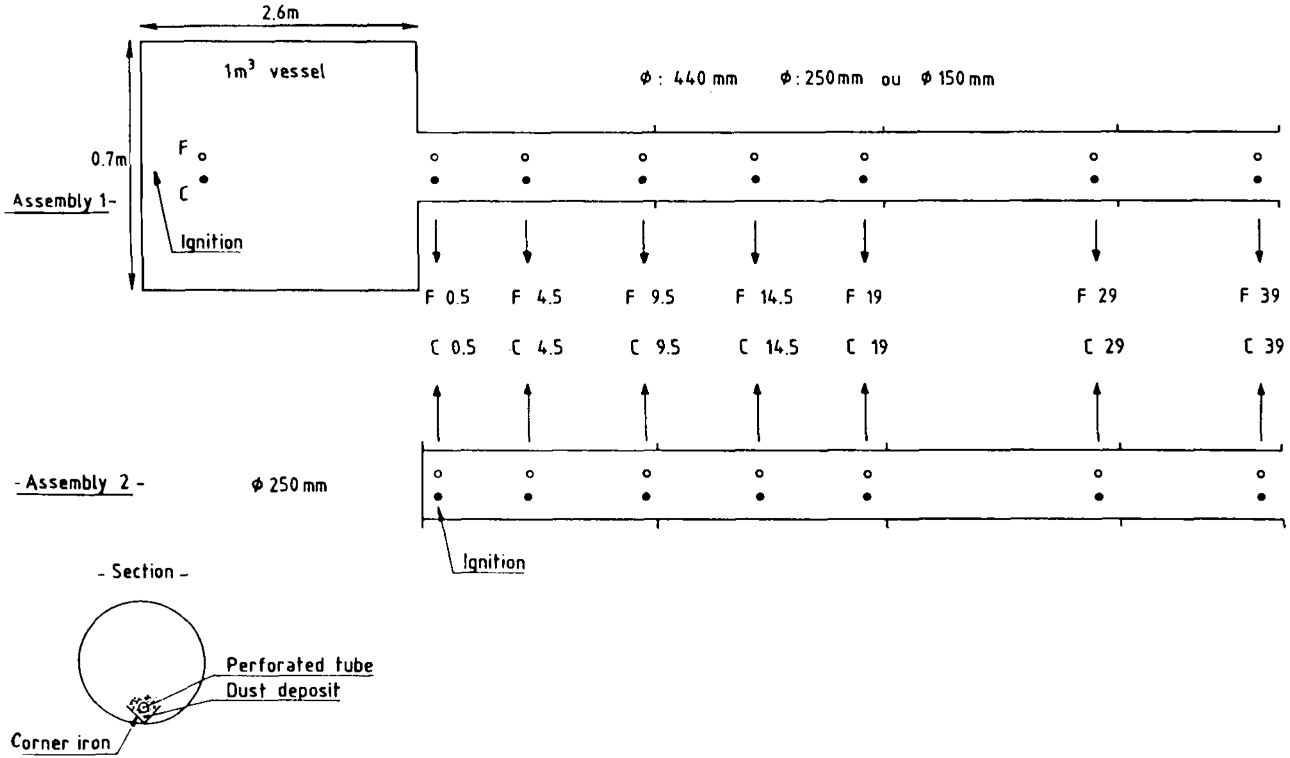


FIG. 1—*Testing facilities.*

- Freyming 820 150 coal (3 to 4% of product > 100 μm, median diameter 29 μm), (volatile index: 36.16%, moisture content: 2.8%, ash: 7.1%).[2]

The explosion severity, determined in a 1-m^3, elongated, closed vessel (same vessel shown on Fig. 1) according to the CERCHAR operating procedure, gives maximum explosion overpressure values, P_{max}, and maximum rate of pressure rise values, V_{MP}, shown graphically as a function of concentration in Fig. 2.

Dust Explosion Propagation in Isolated Ducts

As we had previously obtained *[4]* wheat flour explosion propagation in 250-mm diameter isolated ducts, we began the tests in this diameter duct, using Freyming coal dust which has higher explosion severity characteristics than the wheat flour ones. Dust is predispersed along entire length of pipe before activation of ignition source (20 g of guncotton).

With 20- or 40-m-long ducts, results compared with those obtained using wheat flour *[4]* show that Freyming coal does not propagate explosion readily since the maximum explosion overpressure does not exceed 0.6 bar (60 kPa) in an open ended configuration and 0.95 bar (95 kPa) in a closed end configuration. In all cases, the maximum flame length equals several tens of metres. It is possible to affirm that the coal is ignited by the initiation source since the source alone gives at most a 0.175-bar (17.5 kPa) maximum overpressure and a 0.35-s flame duration.

Explosion propagation appears to be easiest with 150- to 250-g/m^3 concentrations. More thorough tests are needed to confirm that flame propagation is possible.

Matsuda[3] has in fact been able to show that, in a 75-mm-diameter pneumatic conveyor, a coal dust explosion flame could be propagated over a length exceeding 50 m.

Dust Explosion Propagation in Ducts Connected to a 1-m^3 Vessel

Characteristics of Explosions in a 1-m^3 Vented Vessel

The P_{max} and V_{MP} values obtained in Freyming coal explosion tests carried out with a 250-mm-diameter vent hole are shown graphically versus dust cloud concentration on Fig. 3.

Characteristics of Explosions in the 1-m^3 Vessel Connected to a One-End-Open Duct Assembly

Tests in a 1-m^3 Vessel Connected to a 250-mm-Diameter Duct Assembly—Test results carried out with 10-, 20-, 30-, and 40-m duct lengths are shown in Table 1.

Judging from the tests carried out in a 10-m length duct, it appears always possible to obtain flame propagation throughout the duct; maximum flame speeds can reach 340 to 565 m/s in the part of the duct nearest the open end. The initial concentration in the duct appears to play a weak role. If it is accepted that the blast wave produced in the duct at the vessel connection point has a peak pressure of the order of 3 bar (300 kPa), it leads to a flow speed of the order of 300 to 400 m/s. Consequently, in this case, phenomena in the duct are practically entirely governed by what happens inside the vessel.

Using a 20-m-long duct, it is possible to obtain, for precise conditions of initial duct concentration, flame speeds in the region of 1600 m/s in the part of the duct nearest the open end. Pressures in the duct then reach 10 bar (1000 kPa). These values are clearly higher than those in the vessel (≈5 bar [500 kPa]), and in this case, propagation is greatly influenced by the initial dust concentration. It is for a concentration in the region of 150 g/m^3 that this fairly easily reproduced phenomenon may be obtained. The distance-time diagram for pressure wave and flame front for Tests 2414 is given in Fig. 4.

[2] T. Matsuda, personal communication, 1982.

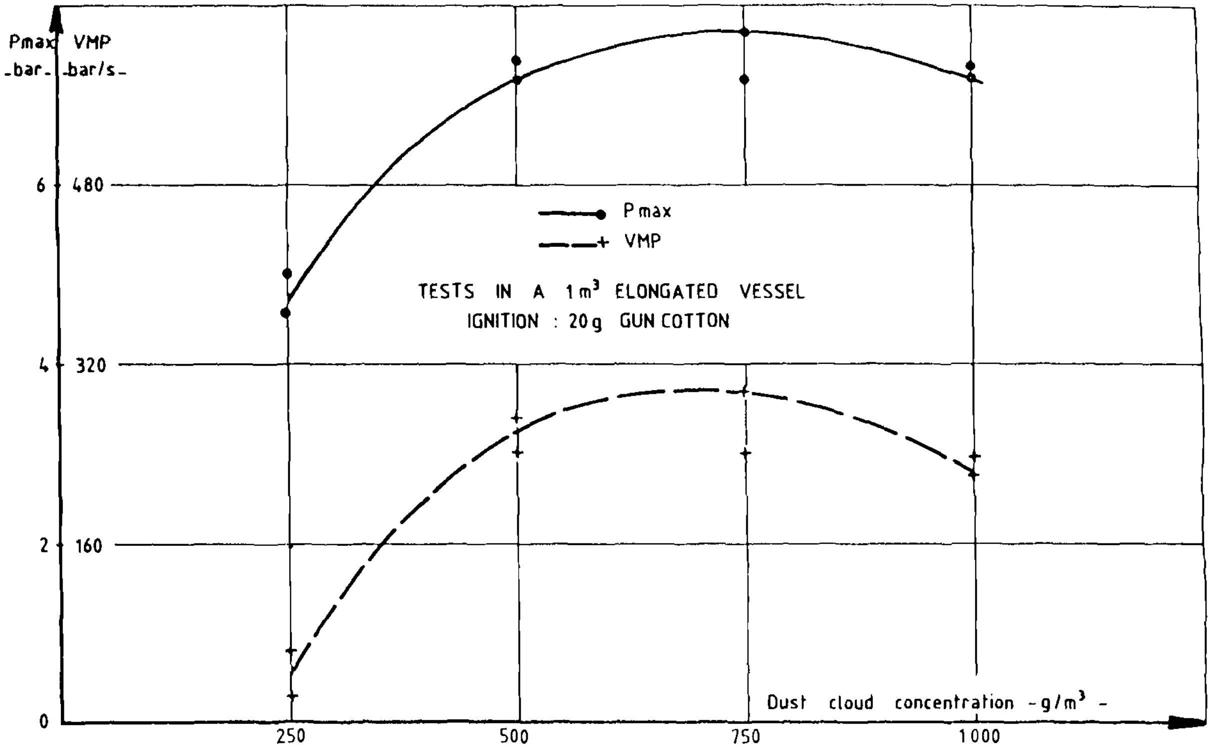


FIG. 2—*Maximum explosion overpressure (P$_{max}$) and maximum rate of pressure rise (V$_{MP}$) versus dust cloud concentration. Tests with Freyming pulverized coal.*

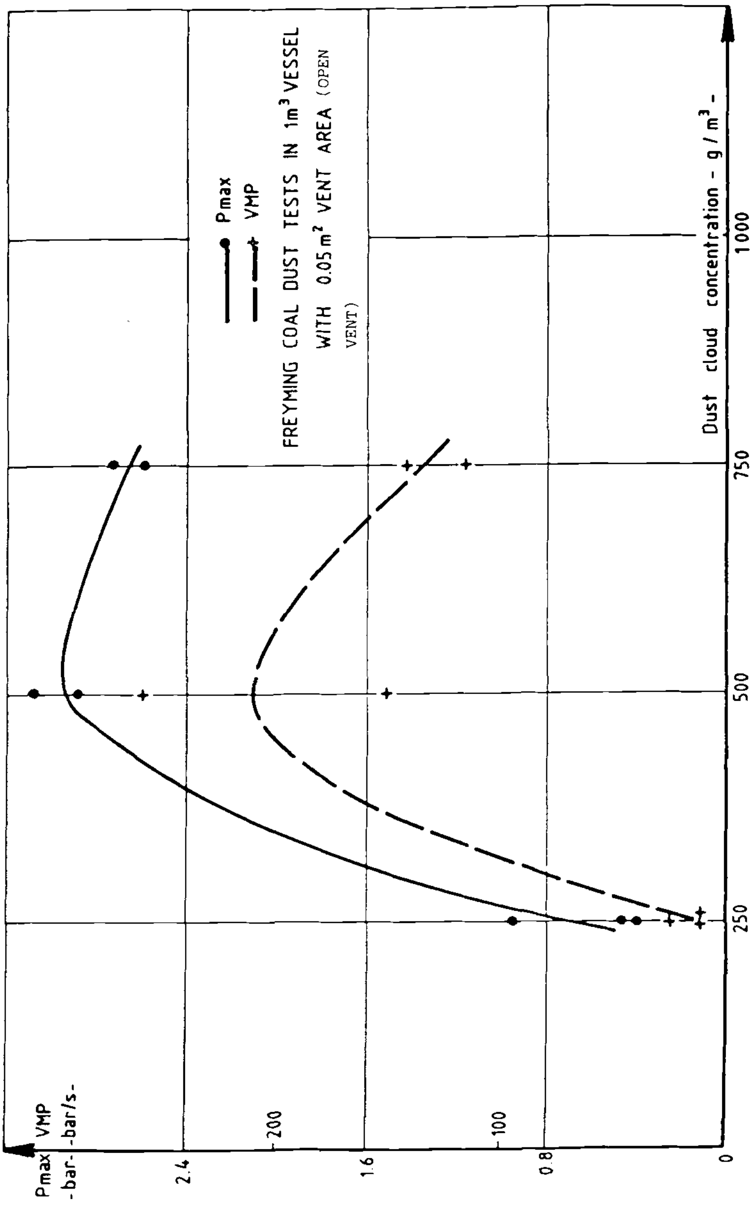


FIG. 3—*Maximum explosion overpressure* (P_{max}) *and maximum rate of pressure rise* (V_{MP}) *versus dust cloud concentration.*

TABLE 1—*Tests in the 1-m³ vessel and 250-mm ∅ duct assembly.*

Test	Duct Length, m	Dust concentration, g/m³		P_{max}, bar[a]		V_{MP} Vessel, bar/s	V_{max}, m/s	Flame Length in Duct, m
		Vessel	Duct	Vessel	Duct			
FREYMING								
2400	10	750	0	3.8	4.0	196	565	10
2399	10	500	500	3.85	3.6	160	460	10
2391	10	500	0	4.25	3.75	220	340	10
2401	10	250	500	2.5	3.00	45	510	10
2410	20	500	500	4.2	4.00	183	640	14
2411	20	500	500	4.6	4.2	260	300	14
2404	20	500	250	2.8	2.6	70	415	20
2412	20	250	500	2.9	2.7	47	750	14
2409	20	500	0	4.0	3.7	180	400	19
2424	20	500	135	4.7	9.5	206	1000	20
2414	20	500	150	5.3	10	210	1600	20
2425	20	500	150	4.7	9.6	180	835	20
2449	30	500	260	4.2	3.6	190	500	≃30
2448	30	500	0	4.0	3.6	211	500	≃30
2439	40	500	250	3.3	4.0	194	455	40
2428	40	500	100	4.5	6.8	247	820	≃30
2426	40	500	0	3.8	2.7	167	264	≃15
2438	40	500	0[b]	4.0	8.2	159	900	≃40
MONTRAMBERT								
2145	30 with bend	500	460	3.4	3.45	73.5	260	23
2146	30 with bend	500	350	3.2	4.75	60	415	30
2144	30 with bend	500	0	3.55	3.5	94	304	23

[a] 1 bar = 100 kPa.

[b] In fact, deposit on walls.

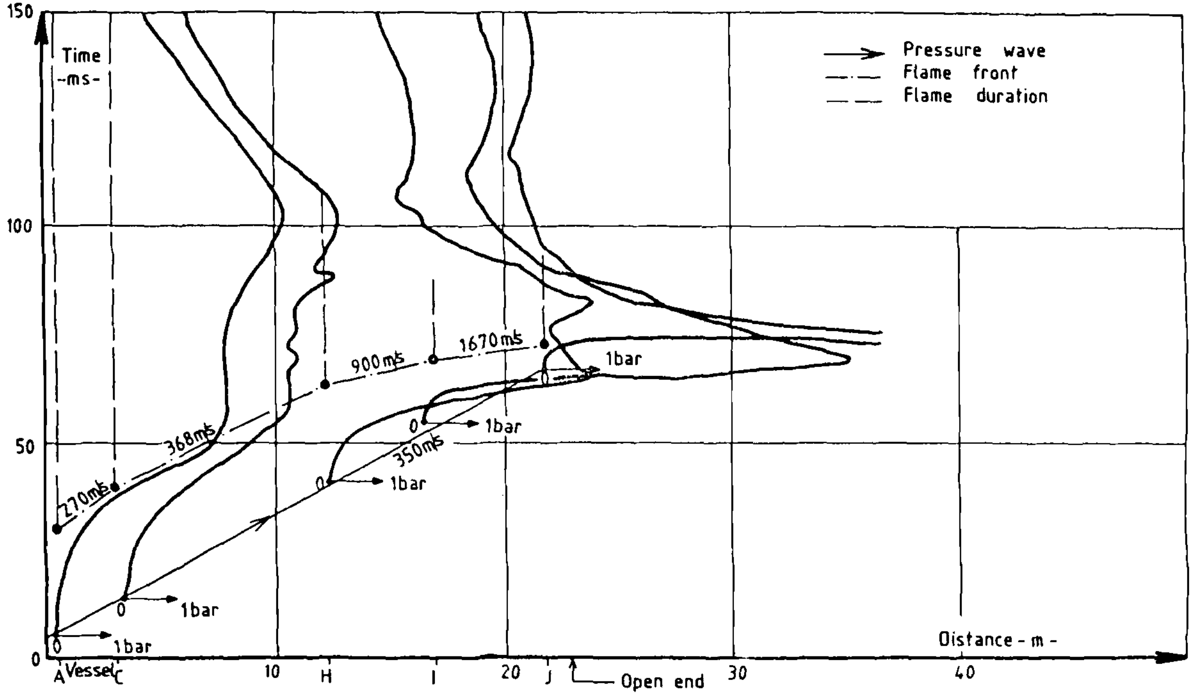


FIG. 4—*Distance-time diagram: Test 2414 with Freyming coal dust in a 1-m³ vessel connected to a ∅ 250-mm-diameter 20-m-long duct.*

To verify if this phenomenon is maintained, we also carried out tests with 30- and 40-m-long ducts. It is always observed that the highest flame speeds are obtained at around the 20th metre, then flame speeds decrease again, as is shown in the distance-time diagram for pressure wave and flame front for Test 2438 (Fig. 5). To explain this behavior, it may be supposed that the local concentration in the duct at the moment the flame passes is no longer sufficient. This detail is examined further later on.

The various tests using Montrambert coal and a 30-m-long duct show, as with Freyming coal, that concentration is of great importance, but we have not carried out sufficient tests to determine if analog phenomena are possible.

Tests in a 1-m³ Vessel Connected to a 150-mm-Diameter Duct Assembly—Test results using Freyming coal for 20- and 40-m lengths are set out in Table 2.

With this assembly, explosion overpressures in the vessel are slightly higher than in the previous case with the 250-mm 0 vent hole (approximately 5 bar (500 kPa) compared to 4 bar [400 kPa]). For a 20-m length, explosions may lead to P_{max} values in the duct which exceed those measured in the vessel, to flame speeds exceeding 500 m/s, and systematically to a flame propagation right to the end of the duct.

For a 40-m length, the flame is not propagated throughout the duct. We suppose that the propagation is even more influenced by the concentration than for the 250-mm diameter. However, as we do not easily dominate this concentration, we have not pursued these tests.

Tests in a 1-m³ Vessel Connected to a 440-mm-Diameter, 25-m-Long Duct Assembly—The Freyming coal test results using this assembly are set out in Table 3.

These results show that, for a duct in the region of 20 m long, flame speeds of the order of 500 m/s may again be obtained, but maximum explosion overpressures maintain fairly similar values both in the vessel and the duct (of the order of 2.5 bar [250 kPa]).

Tests in a 1-m³ Vessel Connected to a Closed End Duct Assembly—The results obtained are set out in Table 4.

In 250-mm-diameter ducts as well as in 150-mm-diameter ducts, comparison of Table 4 results with those of Tables 1 and 2 shows that maximum explosion overpressures measured in the vessel are slightly higher in the closed end assembly than in the assembly with the one-end-open duct. The duct maximum overpressures have values included between 10 and 20 bar (1000 and 2000 kPa). Maximum flame speeds are at the maximum equal to 350 to 475 m/s and the flame travels along only a part of the duct (from half to three quarters of its length). Examination of the distance-time diagram for pressure wave and flame front (Fig. 6) shows that there is probably an interaction between the reflected pressure wave at the end of the duct and the flame front, which then leads to a flame stoppage before the closed end.

All in all, it must be noted that it is possible to obtain pressures clearly higher (in the region of 20 bar [2000 kPa]) in the duct than in the vessel. These values depend on the overpressure, P_E, existing in the duct at the moment the flame front arrives (for example, P_E = 3 bar [300 kPa] at the Point E for the Test 2459, see Fig. 6).

Interpretation of Obtained Phenomena

In all the studied cases of a duct connected to a 1-m³ vessel, when the explosion is initiated in this vessel, it was shown that the explosion flame could be propagated in 150-, 250-, and 440-mm-diameter ducts, of about 20 m long, on condition that the duct end is open. It is for a 250-mm-diameter duct linked to the 1-m³ vessel that a propagation with the highest flame speeds (1000 to 1650 m/s) can be obtained in the duct, especially towards its last quarter (nearest the open end).

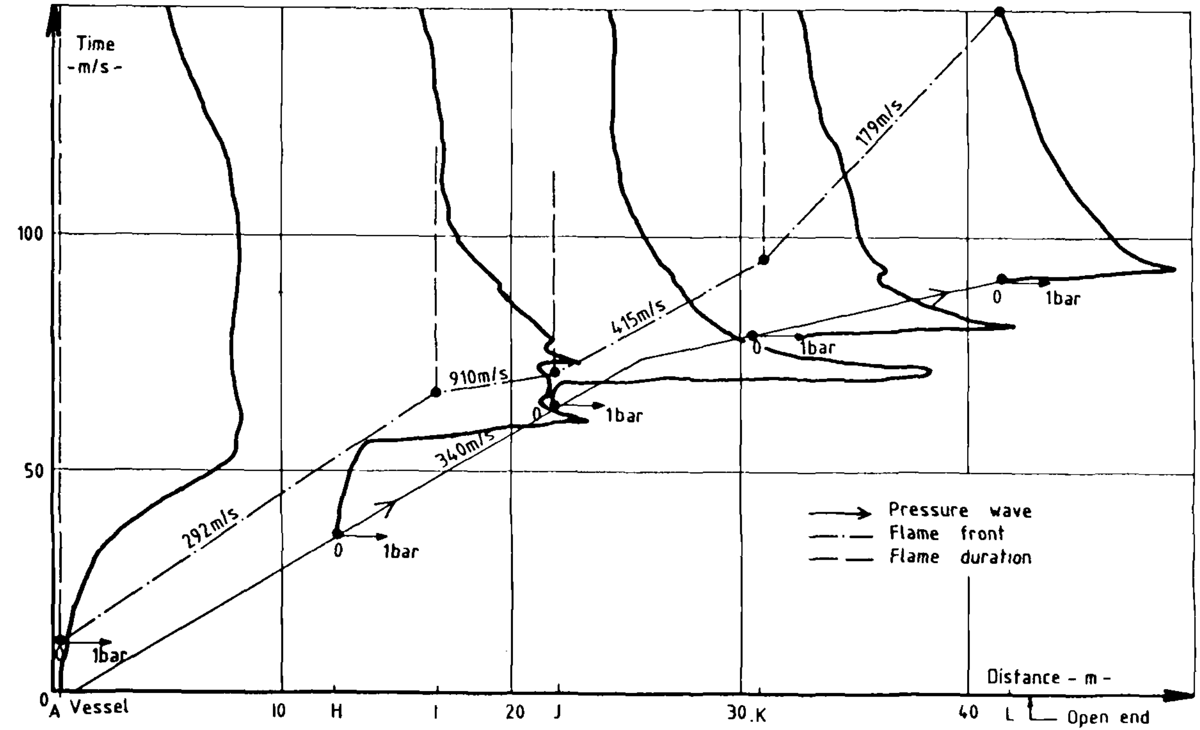


FIG. 5—*Distance-time diagram: Test 2438 with Freyming coal dust in a 1-m³ vessel connected to a Ø 250-mm-diameter 40-m-long duct.*

TABLE 2—*Tests in the 1-m³ vessel and 150-mm ∅ duct assembly.*

Test	Duct Length	Dust Concentration, g/m³		P_{max}, bar		V_{MP} Vessel, bar/s	V_{max}, m/s	Flame Length in Duct, m
		Vessel	Duct	Vessel	Duct			
2452	20	500	0	5.0	4.0	160	357	20
2453	20	500	0	5.1	4.0	205	330	20
2483	20	500	0	4.9	4.2	150	384	20
2458	20	500	280	5.3	7.4	186	835	20
2462	20	500	280	5.4	5.8	153	550	20
2484	20	500	150 g deposited	5.2	4.0	210	435	20
2457	20	500	150 g deposited	5.0	6.2	190	525	20
2478	40	500	0	5.1	5.8	185	500	30
2481	40	500	0	4.9	3.6	160	294	10
2482	40	500	150 g deposited	4.3	2.8	113	95	5

TABLE 3—*Tests in the 1-m^3 vessel and 440-mm Ø duct assembly.*

Test	Duct Length, m	Dust Concentration, g/m^3		P_{max}, bar		V_{MP} Vessel, bar/s	V_{max}, m/s	Flame Length in Duct, m
		Vessel	Duct	Vessel	Duct			
2291	25	500	350	1.9	1.8	80	142	15
2299	25	400	0	1.7	1.6	42	233	25
2293	25	400	250	2.4	2.55	84	405	25
2298	25	400	300	2.5	2.75	76	540	25

TABLE 4—*Tests in the 1-m³ vessel and closed end duct assembly.*

Test	Duct		Dust Concentration, g/m³		P_{max}, bar		V_{MP}, bar/s	V_{max}, m/s	Flame Length, m
	Diameter, mm	Length, m	Vessel	Duct	Vessel	Duct			
2393	250	10	750	0	7.0	11	216	342	≃5
2395					5.6	11.2	180	373	≃5
2459			500	0	5.7	10.2	224	385	≃15
2460	150	20	500	50 g deposited	5.7	8.4	235	350	≃15
2461	150	20	500	100 g deposited	6.5	21	216	. . .	. . .
2463	150	20	500	100 g deposited	5.9	17.2	121	476	≃15
2464	150	20	500	100 g deposited	6.3	18.2	186	430	≃17

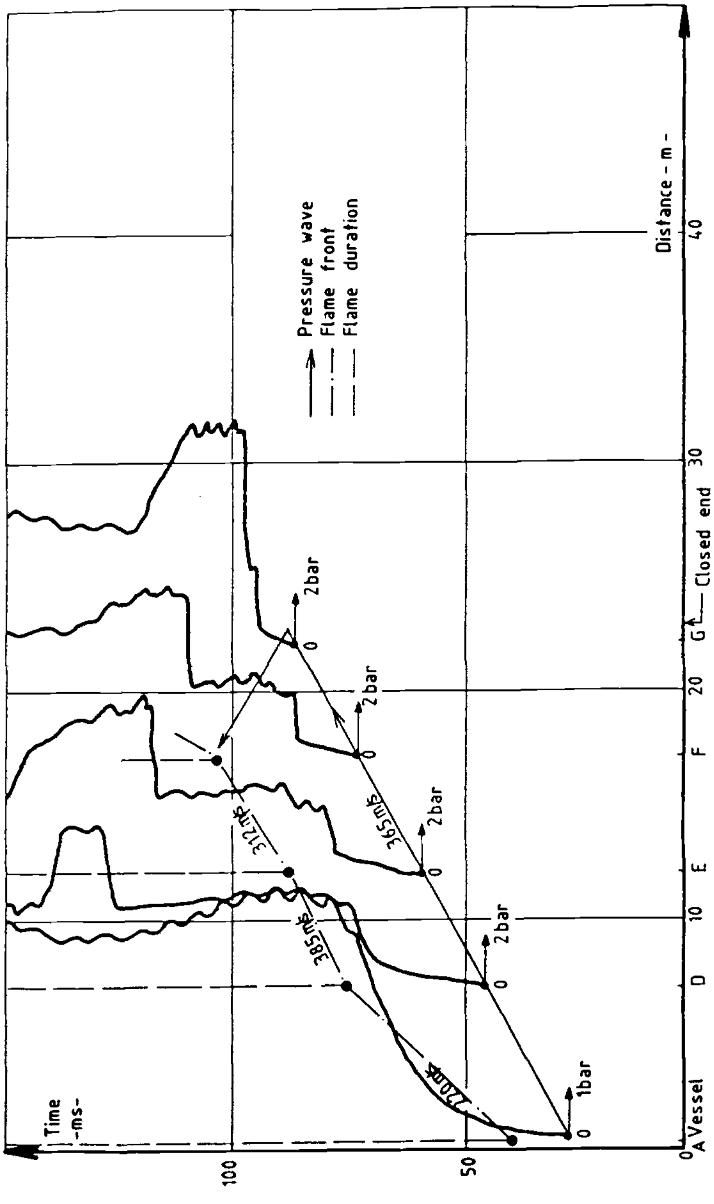


FIG. 6—*Distance-time diagram: Test 2459 with Freyming coal dust in a 1-m³ vessel connected to a Ø 150-mm-diameter 20-m-long duct.*

All the tests carried out till now in 250-mm-diameter ducts tend to show that with ducts of lengths exceeding 20 m, speeds of this order cannot be maintained in the duct further than the 20th metre.

Similar assumptions may be noted for tests carried out in the 1-m^3 vessel with 150-mm duct assembly, but the probability of obtaining flame speeds in the region of 800 m/s is lower than in a 250-mm-diameter duct.

If reference is made to the model established by Pickles [7], it must be supposed that the effect of the initial flow speed in the duct, and of the particle burning time, is to be considered seriously.

Still concerning the case of a duct connected to a 1-m^3 vessel, to explain the change to a rate where flame speeds can reach 1000 to 1650 m/s, it is of course necessary for a flame speed acceleration to occur. Pickles indicates that the important factor is the relation between the particle burning time and the time scale of the turbulent mixing. But to explain all these results it is necessary to study the mechanism of mixing.

To have an idea of this, we studied the aspect of the flame emerging into open air from a 250- or 150-mm-diameter, 20-m-long duct. We accepted that the dust cloud just at the duct exit was representative of the one inside the duct. Study of the films shows the appearance of symmetrical patterns (nodes) corresponding to zones of greater dust cloud concentration before the arrival of the flame. This fact is otherwise confirmed when the flame appears since it is then of greater intensity in these nodes than in the rest of the dust cloud. These more or less great, local concentrations can explain why explosion propagation may be more or less easy.

The study of the films taken during the 1-m^3 vessel and 440-mm-diameter duct assembly do not show such patterns; maximum flame speeds can reach 500 m/s, but pressure inside the vessel is then clearly lower (in the region of 1.9 bar [190 kPa]).

Conclusions

Pulverized coal dust, explosion propagation tests (volatiles content on dry $\simeq 36\%$) in 150-, 250-, and 440-mm-diameter ducts have led to very different results according to the test configuration.

For ducts under atmospheric pressure, with a diameter lower than or equal to 250 mm, and longer than 20 m, taken as isolated, with an open end emerging in open air (or in a volume considerably greater than that of the duct) or with the duct completely closed, flame propagation is hardly likely after several metres, even when an important ignition source (flame) is present. Maximum explosion overpressures then reach 1 bar (100 kPa) maximum.

On the other hand, the course of an explosion in a duct initially under atmospheric pressure is totally different if this is connected to a volume at least equal to that of the duct. Moreover, explosion effects will differ according to whether the duct has one end open or is closed.

- For 150- and 250-mm-diameter ducts of a 20-m maximum length connected to a 1-m^3 vessel and with one end open, the flame can always travel the whole duct length whether this initially contains dust or not, and can reach speeds in the region of 1600 m/s. Maximum explosion overpressures then hardly exceed 10 bar (1000 kPa). With more than 20-m-long ducts, the flame does not always travel the whole duct length.
- For these same 150- and 250-mm-diameter ducts, with one closed end and connected to a 1-m^3 vessel, the flame can reach 350 to 475 m/s and stops in the duct after having traveled more than half its length. In the duct alone, maximum explosion overpressures can have values included between 10 and 20 bar (1000 to 2000 kPa).
- Several tests carried out in a 1-m^3 vessel and 440-mm-diameter—of a 20-m maximum length—open end duct assembly, show that flame speeds in the region of 500 m/s can also be reached, but maximum explosion overpressures in that case do not exceed 2.5 bar (250 kPa) in the vessel and in the duct.

The rapid cinematography films of the flame emerging from 150- and 250-mm ducts connected to a 1-m^3 vessel showed that, in certain conditions, well demarcated zones of greater cloud dust concentration (symmetrical patterns) could be obtained. This phenomenon appears to be linked to given flow conditions in the duct and therefore to the explosion severity in the 1-m^3 vessel.

The interpretation of the dust explosion in a duct and of the flame propagation phenomenon necessitates leading research into a better understanding of the initial structure of the air/dust mixing and its evolution throughout the explosion propagation, and thus in particular, the measuring of local and instantaneous concentrations.

In addition, it would be indispensable for the vessel and duct assemblies, to study more widely the influence of the vessel volume where the explosion is initiated (ignition source's role), of the duct diameter and length, as well as the nature of the combustible dust concerned.

Acknowledgment

We would like to thank the Direction of the Gas, Electricity and Coal Industries (France)—DIGEC—du Ministère du Redéploiement Industriel et du Commerce Extérieur which financed this research and a large part of the equipment allowing it to be carried out.

References

[*1*] Pineau, J. P., Chaineaux, J., and Ronchail, G., "Influence on Gas and Dust Development of Lengthening and Presence of Obstacles in Closed or Vented Vessels," presented at 5th International Symposium on Loss Prevention and Safety Promotion in the Process Industries, Cannes, France, 15–19 Sept. 1986.

[*2*] Pineau, J. P. and Ronchail, G., "Suppression des explosions de gaz et de poussières combustibles par extincteurs déclenchés," presented at the 9th International Symposium on the Prevention of Occupational Accidents and Diseases in the Chemical Industry, Lucerne, Switzerland, 5–7 July 1984.

[*3*] Bartknecht, W. "Explosionstechnische Kenndaten brennbarer Staübe in Rohren mit engen Querschnitten," presented at the International Symposium on Dust Explosion Risks in Mines and Industry, Karlovy-Vary, Czechoslovakia, 11–13 Oct. 1972.

[*4*] Pineau, J. P. and Ronchail, G., "Propagation of Dust Explosions in Ducts: Characteristics of the Explosions Studied at CERCHAR," presented at the OYEZ Symposium: the Control and Prevention of Dust Explosions, Basel, Switzerland, 16–17 Nov. 1982.

[*5*] Kauffman, C. W., Wolanski, P., Ural, E., and Nicholls, J. A., "Detonation Waves in Confined Dust Clouds," presented at the 19th International Symposim on Combustion, Pittsburgh, 1982.

[*6*] Tulis, A. J. and Selman, J. R., "Detonation Tube Studies of Aluminum Particles Dispersed in Air," presented at the 19th International Symposium on Combustion, Pittsburgh, 1982.

[*7*] Pickles, J. H., "A Model of Coal Dust Duct Explosions," *Combustion and Flame*, Vol. 44, 1982, pp. 153–168.

Srinivasa R. Srinath,[1] C. William Kauffman,[1] J. A. Nicholls,[1] and Martin Sichel[1]

Secondary Dust Explosions

REFERENCE: Srinath, S. R., Kauffman, C. W., Nicholls, J. A., and Sichel, M., "**Secondary Dust Explosions,**" *Industrial Dust Explosions, ASTM STP 958,* Kenneth L. Cashdollar and Martin Hertzberg, Eds., American Society for Testing and Materials, Philadelphia, 1987, pp. 90–106.

ABSTRACT: Industrial dust explosions typically occur in a sequence—a primary explosion in a predispersed dust cloud followed by one or more secondary explosions. The convective flow induced by the primary explosion disperses the surrounding layered dust, resulting in a dust cloud into which the flame continues to propagate. Continual repetition of this process results in a secondary explosion—a rapidly accelerating flame accompanied by substantial overpressures, that causes most of the damage. Such secondary explosions have been studied in the laboratory in a flame acceleration tube (FAT), a 36.6-m-long tube with an internal diameter of 0.3 m. Tests have been conducted with flow-enhanced cornstarch, small size cornstarch, baghouse dust, floor sweepings, wheat dust, and navy bean dust. The development of the secondary explosions in these dusts is compared and discussed in terms of the observed pressures, fame velocities, gas velocities, gas temperatures, and dispersed dust concentrations. The presence of turbulence-generating grids in the flame path is found to result in flame acceleration, quite analogous to gaseous flames. This observation confirms the findings of numerical models. Experimental results from a study of dust entrainment using high-speed motion photography are presented.

KEY WORDS: dust explosions, grain elevator explosions, agricultural explosions, industrial explosions, secondary explosions, dust combustion, heterogeneous combustion, flame acceleration, turbulent reacting flows, two-phase flows

Dust explosions occur in coal mines, in agricultural handling and processing facilities, and in wood, sugar, metal, paper, chemical, and rubber industries. Once the importance of dust as a fuel in these explosions was established [*1*,*2*], dust explosions have been studied extensively. Much of the research was conducted with coal and grain dust in constant volume combustion chambers where the dust being tested was dispersed and ignited, and the resultant explosion was studied [*3*–*6*]. In most industrial dust explosions, however, the dust is normally present in layers that subsequently get dispersed to form a dust cloud. The explosion occurs in the form of a rapidly accelerating flame that propagates into this cloud. The dispersion of the layered dust by the induced convective flow and the resultant mixing to form a cloud of dust are critical to this type of flame propagation. The earliest research on this type of process was done in experimental coal mines and coal dust galleries [*7*–*9*].

A laboratory-scale apparatus was built at the University of Michigan for studying propagating flames sustained by layered dust, referred to here as secondary explosions. Although the apparatus is smaller than many industrial structures, it is, nevertheless, large enough to make the application of the results to the explosion problem in large-scale structures meaningful. At the same time, it is small enough to afford convenient control on some of the parameters that are critical to explosion development such as layer thickness and moisture content. Secondary dust explosions sustained

---

[1] Postdoctoral research fellow, associate research scientist, professor of aerospace engineering, and professor, respectively, University of Michigan, Department of Aerospace Engineering, Ann Arbor, MI 48109-2140.

by many agricultural dusts, for which data were not previously available, have been studied. In the first part of this paper results are presented for floor sweepings, bean dust, and some processed corn starches, and are compared to previously published results for baghouse dust and wheat dust [*10–12*]. In the second part, results from a study of the effect of turbulence-generating grids in the flame path are presented and discussed. The turbulence generated by obstacles in the flame path results in enhanced burning velocities, which in turn lead to rapid flame acceleration in premixed gases [*13–15*]. Here the burning velocity is the velocity with which the flame propagates relative to the unburned gases ahead of it. Results from numerical modeling studies have shown that the increase in the burning velocity as a result of turbulence plays a major role in dust flame propagation as well [*10,12,16*]. Finally, some qualitative results from high-speed motion photography of the dust entrainment process are presented.

Experimental Setup

Only a brief description of the experimental apparatus and the operational procedure is given here as the details have been published previously [*10–12*]. The apparatus, called the flame acceleration tube (FAT), is shown in Fig. 1. It consists of a 36.6-m-long main tube with an internal diameter of 0.3 m (a length to diameter ratio of about 120 to 1). The ignition source is provided by a 64-mm-diameter detonation tube filled with a stoichiometric mixture of hydrogen and oxygen to a maximum initial pressure of 1.01×10^5 N/m^2 (1 atm). This detonation tube is attached to the closed end of the main tube and is separated by a thin Mylar diaphragm. The open end of the main tube terminates in an exhaust section consisting of a smooth elbow and a vented straight section. Strain gage pressure transducers are used to measure static pressures as well as dynamic pressures from Pitot tubes at a number of locations along the tube. Photodiodes sensitive to infrared and visual light radiation and fine gauge thermocouples are also mounted at these locations. A dust concentration probe based on the principle of light attenuation [*12,17*] and a four-color optic pyrometer [*12,18*] are mounted at the tube's midsection. The voltage outputs from the various instruments are suitably amplified and fed to a 32-channel analog to digital converter module. The digital data are finally transferred to an IBM 9000 microcomputer for processing.

Operationally, the dust is deposited on a V-channel in the first 3.66 m of the tube, from which it can be dispersed using air jets. The mass loading of the dust in the V-channel, divided by the volume of that 3.66 m of the tube, is the primary dust concentration. In the rest of the tube, the dust is deposited in a layer using a motorized cart at a given mass loading per unit length. This mass loading per unit length, divided by the volume of the tube per unit length, is referred to as the nominal secondary dust concentration. Unless specifically mentioned as the dispersed dust concentration (as measured by the concentration probe), the term "dust concentration" refers to this nominal secondary dust concentration. The motorized cart is capable of depositing dust in three different layers—a 13-mm-wide layer referred to as the thick layer, a 90-mm-wide layer called the medium layer, and a thin layer where the dust is uniformly distributed around the circumference of the tube using a centrifugal blower. A slow flow of dry air is used to control the dust moisture content and the humidity of the oxidizer air in the tube. In this paper, dry conditions refer to a dust moisture content of about 0.2% by mass and a dew point of 250 K for the air in the tube; moist conditions correspond to about 9% dust moisture content and a dew point of 266 K for the air, and wet conditions refer to dust moisture content and air dew point of about 9% and 283 K, respectively. The V-channel primary dust is first dispersed using air jets. The H_2/O_2 mixture is detonated after a time delay of 0.25 s by energizing the glow plug, thereby rupturing the Mylar diaphragm and igniting the dispersed V-channel dust, thus initiating a primary explosion. The burned gases expand, causing compression waves to propagate down the tube. This induces a convective flow which, in turn, causes the layered dust to be dispersed, resulting in a cloud of dust into which the flame continues to propagate. Typically an accelerating flame accompanied by

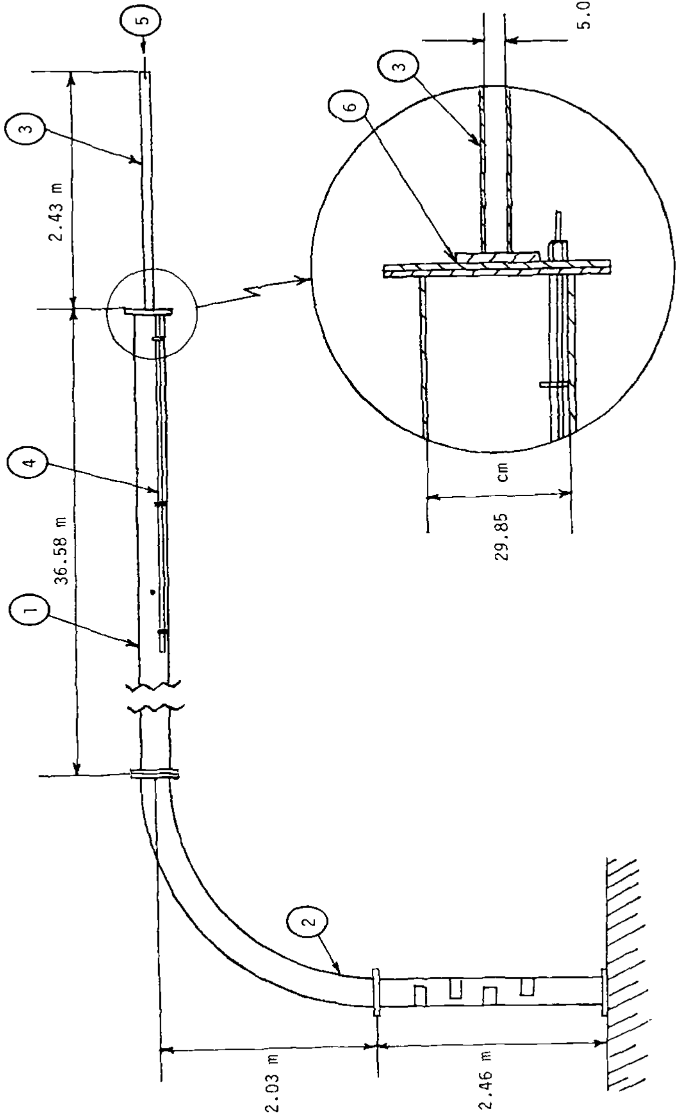


FIG. 1—*Flame acceleration tube:* (1) *main tube,* (2) *exhaust section,* (3) *initiator detonation tube,* (4) ***V**-channel,* (5) *glow plug, and* (6) *Mylar diaphragm.*

substantial overpressures, called the secondary explosion, is realized and its progress is monitored by the instrumentation mounted on the FAT.

It has been reported earlier that the primary explosion does not dominate the secondary explosion [*11,12*]. When the dust in the V-channel is dispersed and ignited to produce a primary explosion, the overpressures obtained when there is no dust in the remainder of the tube are significantly lower compared to the case where there is secondary dust present. Further, if there is no primary or secondary dust present and the H_2/O_2 mixture is detonated, very low overpressures are obtained and there is no radiation detected by the nearest photodiodes which are at 6 m.

Experimental Results and Discussion

Typical pressure–time histories at different locations in the FAT from a test conducted with dry baghouse dust in a thin layer are given in Fig. 2. The nominal secondary dust concentration was 366 g/m^3, the V-channel dust concentration was 500 g/m^3, and the initiator tube was at a pressure of 1.01×10^5 N/m^2 (1 atm). As shown in Fig. 2, the pressure, P, is normalized with the ambient pressure, P_O; the distance, x, with the diameter of the tube, D; and the time, t, with the time taken by an acoustic wave to traverse the length of the tube, t_O (where $t_O = L/a_O = 0.106$ s, L is the length of the FAT, and a_O is the ambient speed of sound). An x–t diagram for the flame front is also shown. Note that this is for the leading edge of the luminous zone of the flame front as detected by the light-sensitive photodiodes. The first disturbance to arrive at any location can be seen to be the shock wave resulting from the rupture of the initiator diaphragm. The compression of the air ahead of the flame can be seen as a gradual increase in the static pressure at any given location. This increase is more rapid at downstream locations as successive waves coalesce. The compression waves induce a convective flow toward the open end, which in turn disperses the layered dust, resulting in a dust cloud into which the flame propagates. At the given conditions, it can be seen that an accelerating flame was realized. Near the open end of the FAT, the measured flame velocity was about 670 m/s accompanied by an overpressure of about 5.30×10^5 N/m^2 (5.23 atm), enough to cause substantial damage to most industrial structures. Once the flame exits from the open end, an expansion wave propagating at about 700 m/s (the speed of sound in the burned gases) propagates toward the closed end, reducing the pressures inside the FAT. The system is brought to equilibrium by a sequence of reflected waves. Time histories obtained for the gas velocty, gas temperature, particle temperature, and dispersed dust concentration are reported elsewhere [*10–12*].

A number of different dusts have been tested in the FAT. The particle size distribution for the dusts reported in this paper are given in Table 1. Pure food powder (PFP) is a processed corn starch with a maximum particle diameter of 25 μm [*19*] obtained from A. E. Staley Manufacturing Co. Mira Gel is similar to PFP in processing, except for the addition of a special flowing agent [*20*]. The better flowing ability of Mira Gel was readily evident during handling, as compared to PFP which was fairly adhesive and tended to agglomerate even after drying in a vacuum chamber. The baghouse dust obtained consisted mostly of corn and soybean and had a very low ash content of about 2.4% [*21*]. In contrast, the floor sweepings dust obtained from a grain elevator had a higher ash content of about 9.5% [*21*] and was determined to consist primarily of wheat after physical inspection and comparison of the ash content to available literature [*22*]. The generic grain dusts, namely, baghouse dust, floor sweepings, wheat, and navy bean dust, were sieved into different size ranges and tested, while the processed corn starches, namely, PFP and Mira Gel, were tested as is. The dusts were stored in a freezer or in an inert atmosphere to prevent chemical deterioration.

Tests were conducted by depositing the different dusts in a thin layer under dry conditions at a nominal secondary dust concentration of 366 g/m^3. The test zone length (the length of the zone in which the dust was deposited) was the total length of the straight section of the tube. The same

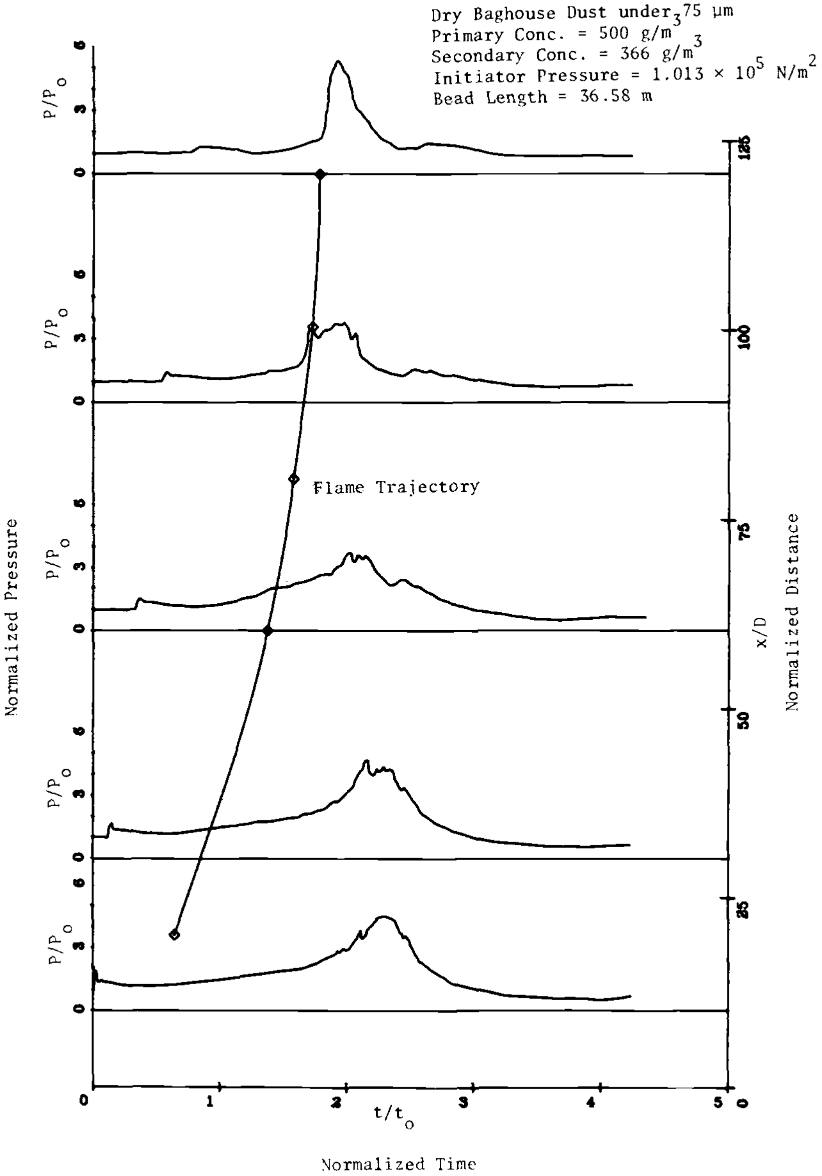


FIG. 2—*Typical experimental pressure histories at different tube locations.*

kind of dust that was used in the secondary section was used in the primary V-channel section as well as a concentration of 500 g/m^3. The initiator tube was pressurized to 1.01 × 10^5 N/m^2 (1 atm). The maximum pressure and the maximum flame velocity, which are indicative of the explosibility of a given dust, and the dispersed dust concentration at the instant of flame arrival, which is indicative of the flowing ability of the dust, are given in Table 2. It can be seen that the floor sweepings, even though tested with all particle sizes up to 425 μm, produced higher pressures and flame velocities than wheat dust with particle sizes less than 75 μm, probably due to the other

TABLE 1—*Percentage particle size distributions for different dusts.*

Size Range, μm	Dust Type					
	Mira Gel	PFP	Baghouse Dust	Floor Sweepings	Wheat Dust	Bean Dust
>425	...	...	15.6	35.2	15.5	17.6
<425	...	...	84.4	64.8	84.5	82.4
<300	...	...	80.5	49.6	77.9	78.5
<212	...	...	67.5	34.2	64.2	72.5
<150	99.0	...	NA	22.7	NA	62.9
<75	81.3	...	35.6	8.6	10.5	36.1
<53	44.0	...	21.5	NA	3.2	NA
<38	10.8	...	0.1	NA	0.1	NA
<25	NA[a]	99.5	NA	NA	NA	NA
<5	NA	15.0	NA	NA	NA	NA

[a] NA = Data not available because a given sieve was not used during sizing.

dusts present on the elevator floor. The floor sweepings produced lower pressures and flame velocities than baghouse dust in the same size range. This is due to a much lower ash content [*21*] and the type of dusts present in the specific samples of baghouse dust tested. It was found that the floor sweepings would support a secondary explosion with about the same pressures and flame velocities even when tested as is, that is, including the particles with diameters greater than 425 μm. However, if the dust in the V-channel alone was replaced with corn starch, thereby increasing the primary explosion strength, the maximum pressure and flame velocity increased to 2.79×10^5 N/m^2 (2.75 atm) and 343 m/s, respectively.

In initial tests using navy bean dust with all particle sizes up to 300 μm, a propagating flame could not be realized. If the V-channel dust was replaced with corn starch, however, a flame propagating at an almost constant velocity of about 123 m/s and resulting in an overpressure of

TABLE 2—*Comparison of maximum pressure, maximum flame velocity, and dispersed dust concentration for different dusts.*[a]

Dust Type	Size, μm	Test Zone Length, m	Maximum Pressure, 10^5 N/m^2	Maximum Flame Velocity, m/s	Dispersed Dust Concentration, g/m^3
Floor sweepings	<425	36.58	2.28	204	NA
Wheat dust	<75	36.58	1.31	157	155
Baghouse dust	<425	36.58	3.37	364	NA
Bean dust (corn starch in V-channel)	<75	36.58	1.91	147	NA
Mira Gel	As is	24.39	6.38	751	131
PFP	As is	24.39	5.17	753	76
Baghouse dust	<75	24.39	4.55	498	96

[a] Dry dust primary concentration = 500 g/m^3; secondary concentration = 366 g/m^3. Initiator pressure = 1.013×10^5 N/m^2, thin layer.

1.83 × 10^5 N/m^2 (1.81 atm) was realized. If tested with particles smaller than 75 μm in the same manner, the overpressure and flame velocity increased to 1.91 × 10^5 N/m^2 (1.89 atm) and 147 m/s, respectively. Therefore, bean dust is capable of supporting a secondary explosion under certain conditions, and it can act as a flame carrier.

While testing with the processed corn starches it was necessary to limit the length of the test zone, that is, the extent of dust deposition, to the first 24.4 m of the tube for safety reasons. The remaining 12.2 m of the tube was used as an attenuation device. Mira Gel produces the highest pressures, followed by PFP and baghouse dust in that order (see Table 2). The maximum flame velocity is about equal for Mira Gel and PFP, followed by baghouse dust. Considering the dispersed dust concentration at the time of flame arrival, it can be seen that the dispersed dust concentration for Mira Gel is almost double that of PFP. This is expected because Mira Gel is

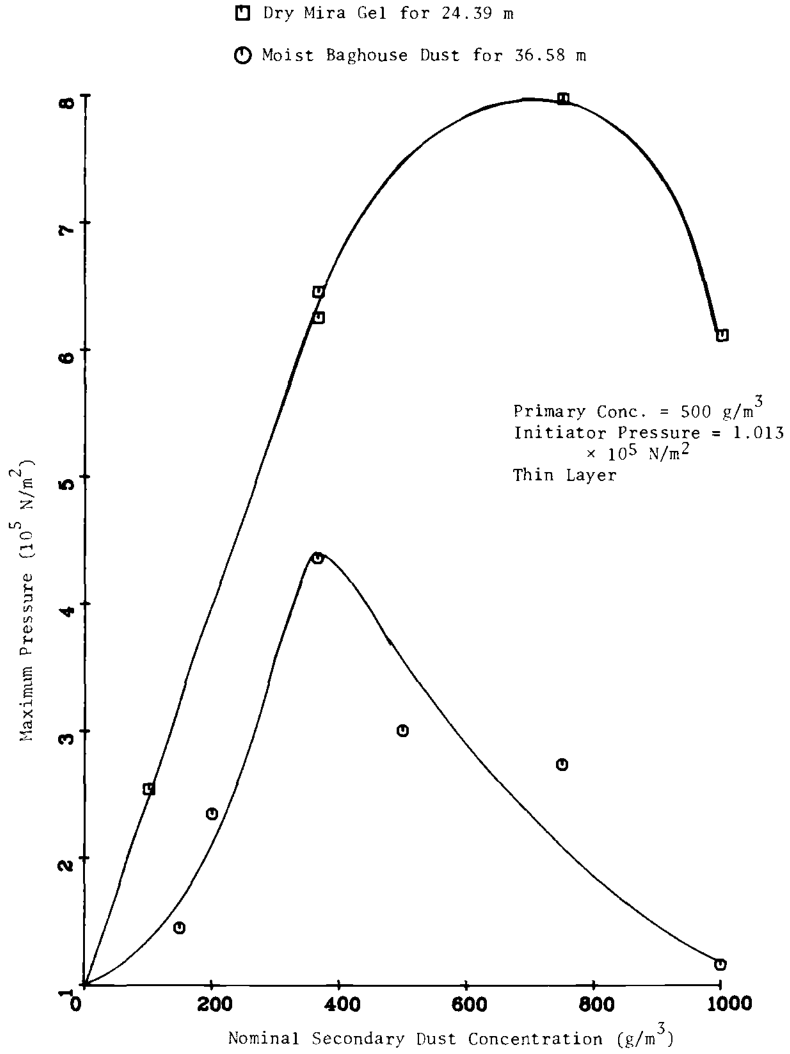


FIG. 3—*Variation of maximum pressure with nominal secondary dust concentration for Mira Gel and baghouse dust.*

specially coated for better flow characteristics. To understand the importance of the dispersion characteristics of Mira Gel in secondary explosions, one can consider Fig. 3 in which the maximum pressure observed in tests conducted with dry Mira Gel and moist baghouse dust of comparable size ranges in a thin layer is given as a function of nominal secondary dust concentration. These tests were conducted with a primary V-channel dust concentration of 500 g/m^3 and an initiator pressure of 1.01 × 10^5 N/m^2 (1 atm). Mira Gel, even though deposited for only 24.4 m, produces substantially higher pressures than baghouse dust deposited throughout the FAT at all concentrations. Further, the peak for the Mira Gel curve occurs at a secondary dust concentration of about 750 g/m^3, while the peak for baghouse dust is at about 366 g/m^3. A similar trend can also be noted for the maximum flame velocity data for the two dusts presented in Fig. 4. The peaks typically occur at fuel rich concentrations for all dusts due to partial dispersion of the layered dust and incomplete combustion of the dispersed dust. Despite better dispersion characteristics, the peak for Mira Gel occurs at a much higher concentration than baghouse dust. This could be attributed to a higher stoichiometric concentration for Mira Gel compared to baghouse dust as a result of the shielding action of the coating of flowing agents on Mira Gel particles. The above data suggest that the coating of flowing agents tends to reduce the reactivity of dispersed Mira Gel, but the better dispersion characteristics of the dust result in enough entrained particles to cause it to be more

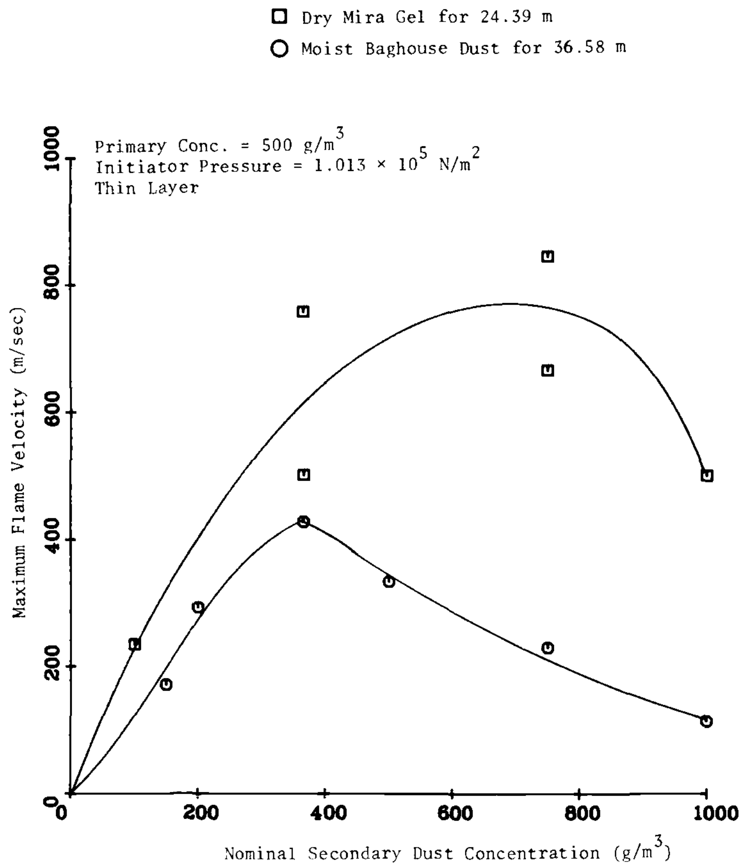


FIG. 4—*Variation of maximum flame velocity with nominal secondary dust concentration for Mira Gel and baghouse dust.*

reactive. It is interesting to note that PFP produces high pressures despite having the lowest dispersed concentration (see Table 2). This could be because PFP particles are much finer than the other two dusts. From the above data, it is evident that processed corn starches like Mira Gel and PFP are significantly more explosive than generic grain dusts and require special safety precautions.

Figure 5 shows the maximum pressure observed in a test given as a function of location in the FAT. Data are presented for Mira Gel and PFP under three conditions—thin layer under dry conditions, thin layer under wet conditions, and thick layer under dry conditions. All the tests were conducted at a secondary dust concentration of 366 g/m^3, a primary V-channel concentration of 500 g/m^3, and an initiator tube pressure of 1.01 × 10^5 N/m^2 (1 atm). Recalling that there is layered dust only in the first 24.4 m, it is interesting to observe the thin layer data after this location. With Mira Gel, the combustion process tends to intensify even though there is no additional layered dust. The good flow characteristics of Mira Gel enable it to be effectively entrained by the convective flow and dispersed in adequate concentrations in the last 12.2 m of the tube. PFP particles, on the other hand, tend to agglomerate easily even under dry conditions. Therefore, the process is more dependent on local dispersion of the dust and results in decreasing pressures toward the end of the tube. Comparing the data for dry Mira Gel in a thin layer to wet

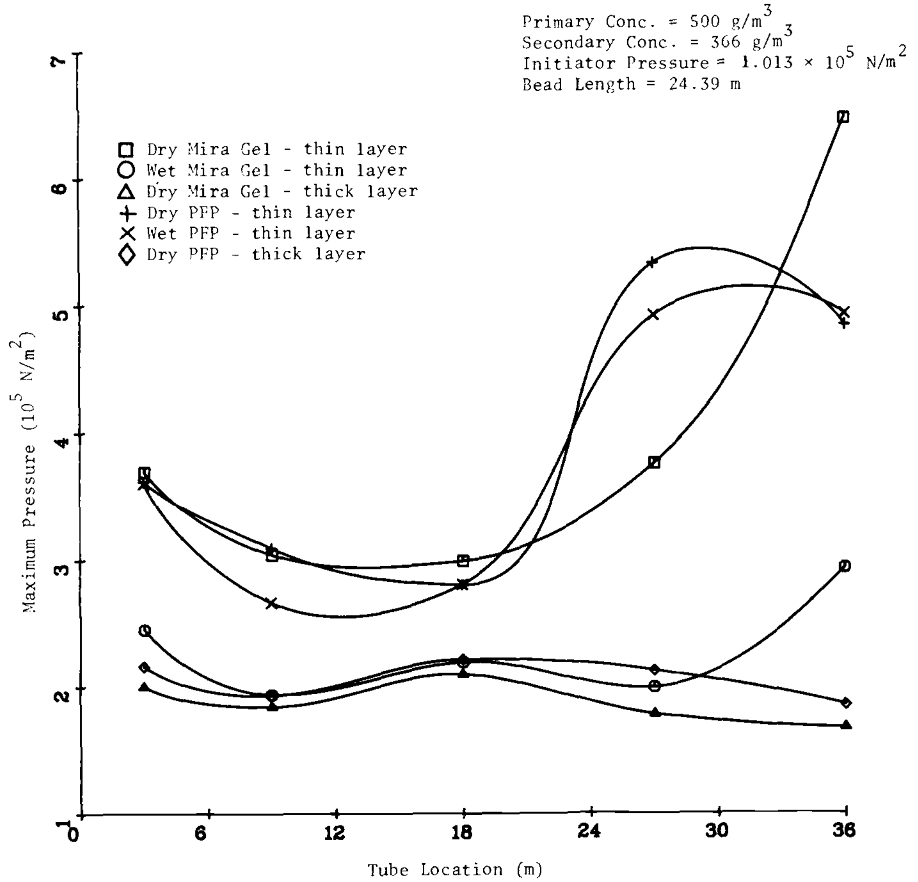


FIG. 5—*Variation of maximum pressure with tube location for Mira Gel and PFP under different conditions.*

Mira Gel in a thin layer, it is seen that the overpressures are significantly higher under dry conditions compared to wet conditions. The same effect was noted in tests conducted with a number of other dusts [*11,12*]. In tests conducted elsewhere with predispersed polyacrylic nitrate and organic peat dust in a modified Hartmann bomb apparatus [*23*], it was found that the peak pressures do not drop significantly until the dust moisture content is raised to about 35% by mass. In contrast, the pressures produced by secondary layered dust explosions are reduced substantially even though the moisture content is only 9%. This is due to the suppression of entrainment as wet particles agglomerate easily compared to dry dust. It is interesting to note that in the case of PFP the wet layer produces only slightly lower overpressures than the dry layer. As mentioned earlier, PFP particles tend to agglomerate even under dry conditions so the effect of moisture content is marginal. Comparing the thick layer data under dry conditions to the thin layer data under dry conditions, it can be seen that both Mira Gel and PFP produce much lower pressures when tested in a thick layer than in a thin layer. A similar trend was noted for the flame velocities generated under the different conditions discussed above.

To investigate the effect of turbulence-generating grids in the flame path, tests were conducted with moist baghouse dust under 75 μm distributed in three different layer thicknesses at nominal secondary dust concentrations of 300, 500, and 1000 g/m^3. For the thick and medium layers dust was deposited throughout the length of the tube, while the thin layer deposition was restricted to 24.4 m for safety reasons. The primary V-channel dust concentration was held constant at 1000 g/m^3 and the initiator tube was pressurized to 1.01×10^5 N/m^2 (1 atm). At each condition the tests were repeated after introducing two sets of grids—one at 12.2 m and the other at 24.4 m—and the results were compared to the tests without grids. The grids were made up of six 12.7-mm-diameter cylindrical rods (see Fig. 6) and provided a blockage ratio of 0.26.

The maximum pressure observed in each test is given as a function of the nominal secondary dust concentration in Fig. 7. It can be readily seen that the pressures increased with the introduction of the grids for all conditions. The same trend can be seen for the maximum flame velocity data presented in a similar manner in Fig. 8. The extent of the effect is quite surprising considering that only two sets of grids were used. To understand the reasons for the above phenomena, one

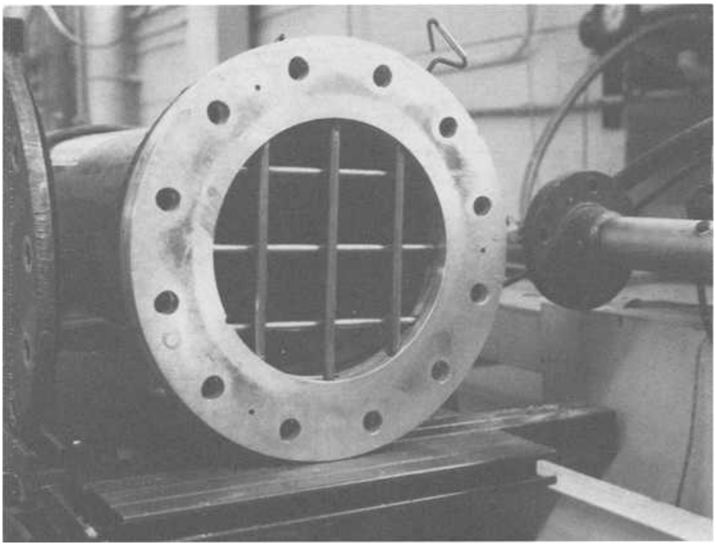


FIG. 6—*Photograph of turbulence-generating grids used in the FAT.*

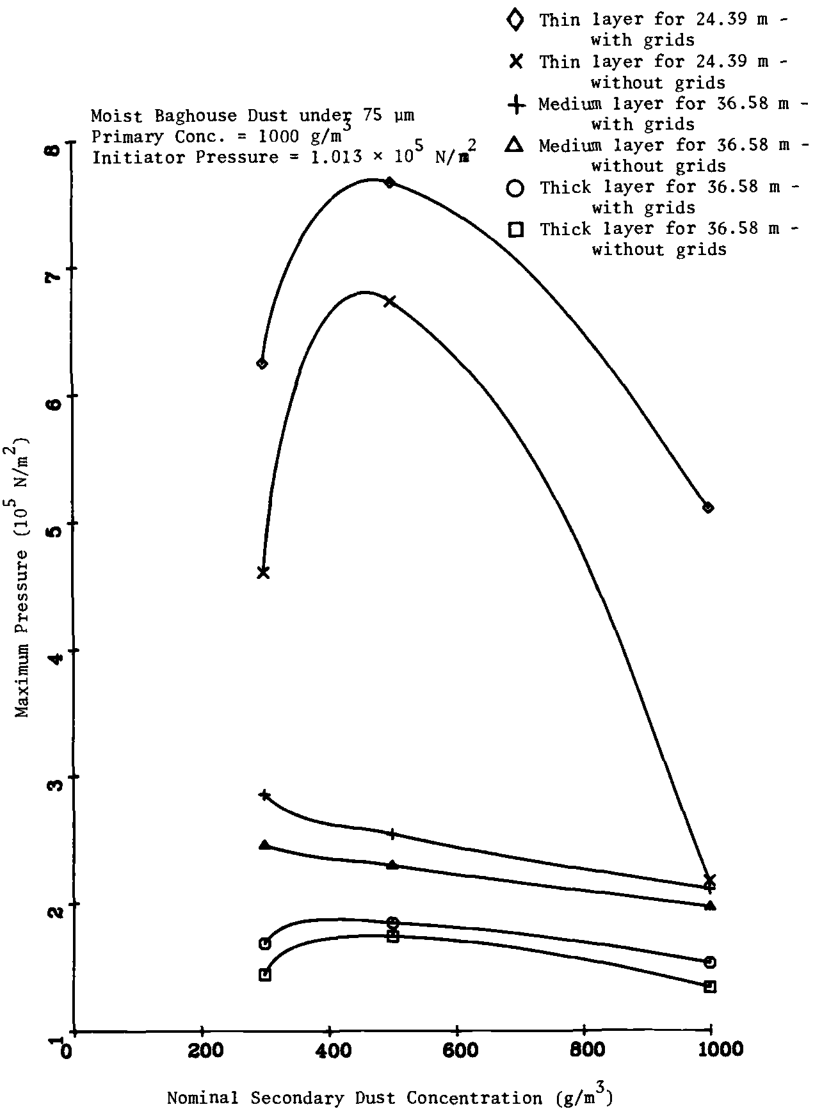


FIG. 7—*Effect of grids: comparison of maximum pressure.*

can consider the ratio of the dispersed dust concentration at the time of flame arrival observed in the test without grids to the same quantity from a test with grids (see Fig. 9). In most of the cases presented the ratio is greater than one, suggesting that the introduction of the grids actually suppressed the dust dispersion. The reason for this effect can be seen in Fig. 10 where the maximum gas velocity is given as a function of nominal secondary dust concentration. In most cases the gas velocities were somewhat reduced by the introduction of the grids, perhaps as a result of a "choking" effect. Considering the maximum gas temperatures presented in Fig. 11, it is difficult to find any particular trend in the results due to the introduction of the grids. From the above data it can be seen that despite slighly lower dispersed dust concentrations and gas velocities,

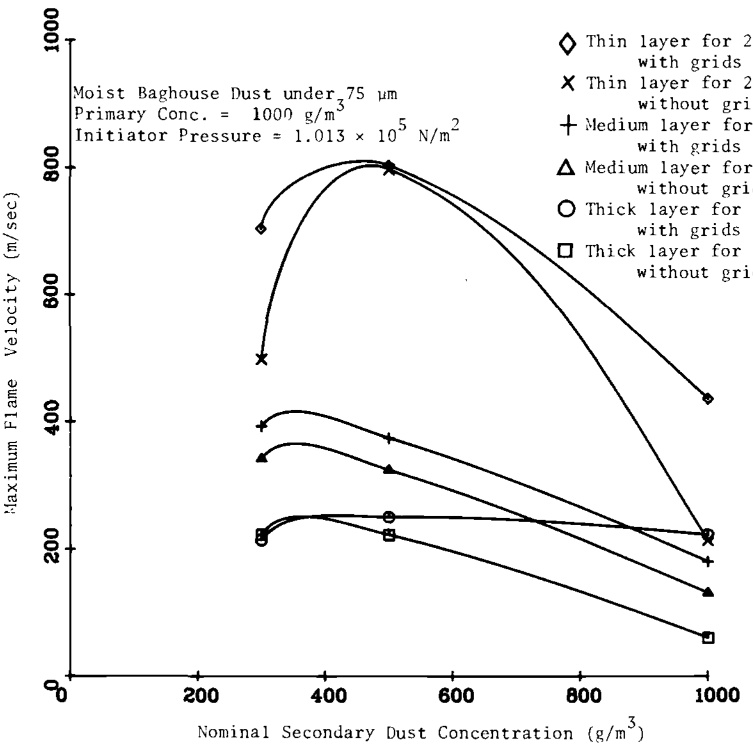


FIG. 8—*Effect of grids: comparison of maximum flame velocity.*

both pressures and flame velocities increase due to the introduction of grids. This result can be attributed to the increase in the turbulent burning velocity and seems to confirm the findings from numerical modeling which have shown that the increase in the burning velocity as a result of turbulence is important in secondary dust flame propagation [*10,12,16*]. This effect is analogous to the gaseous case where obstacles in the flame path were found to result in rapid flame acceleration [*13–15*]. It is also found that, in tests conducted with a thick layer at a concentration of 1000 g/m³, the flame would propagate throughout the length of the tube with the grids introduced, but would propagate for only 12 m with the grids removed. This explains the large differences in the data presented in Fig. 7 through 11 for the thick layer at a concentration of 1000 g/m³.

Photographic studies of the dust dispersion process were conducted as follows. Moist mixed dust in the size range 75 to 300 µm was deposited at a secondary dust concentration of 300 g/m³ for the first 27.5 m of the FAT. The primary V-channel dust concentration was 500 g/m³ for these tests, and the initiator tube pressure was 0.34 × 10^5 N/m² (⅓ atm). These conditions were chosen because the resultant combustion process was relatively slower and afforded greater time for recording the details. Three optic glass windows, 302 by 29 mm in size, were installed 26 m from the closed end, one at the top and two at the sides of the tube. Movie pictures were taken from the top and from the sides at 2000 frames per second. In all cases the dust was illuminated by two quartz lamps on either side of the camera, thereby using the backscattered light from the dust particles to record the images on the film.

Movies taken from tests conducted with a thick layer were compared to those taken from the corresponding thin layer tests to study the difference in the dispersion process between the thin and thick layers. A similar comparison was made in order to study the effect of introducing the

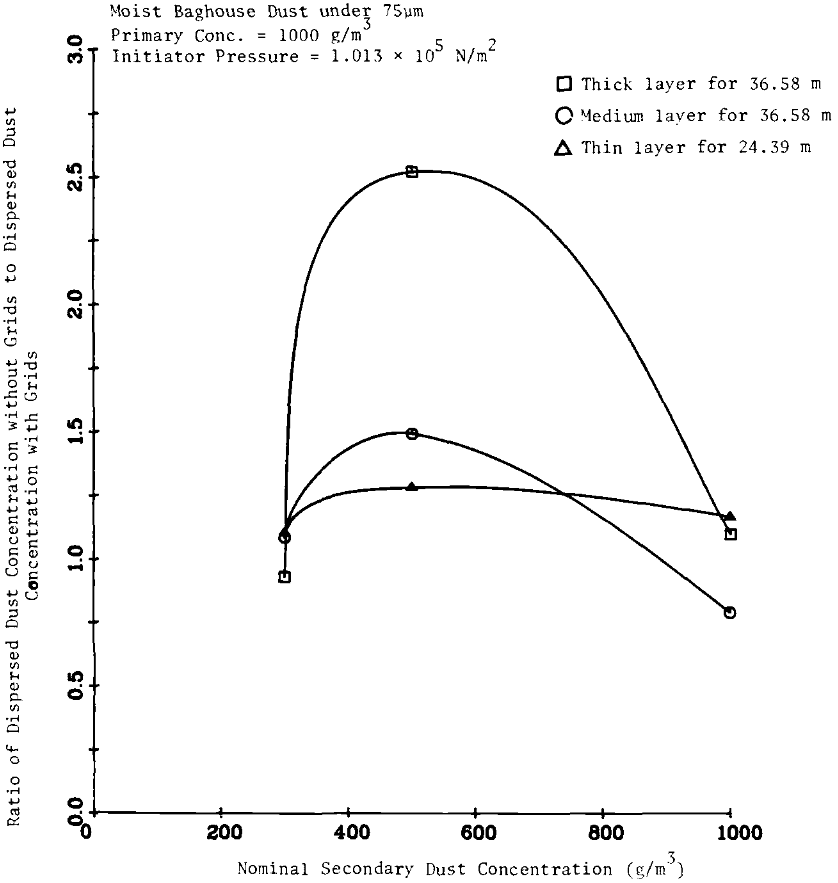


FIG. 9—*Effect of grids: comparison of dispersed dust concentration.*

grids on the dust entrainment process. While this method afforded some qualitative details, it was not possible to generate quantitative data from these movies.

Two sequences of photographs are presented in Fig. 12. The field of view shown corresponds to 52 by 38 mm. The left column corresponds to the thick layer and the right column to the thin layer. The top picture is a photograph of the layer before initiation of the process. The shock wave from the rupture of the initiator diaphragm breaks up the dust layer and partially disperses the dust, as can be seen from the second picture which shows the dust layer immediately after passage of the shock wave and before the convective flow due to the flame can be observed. It is almost immediately followed by the convective flow due to the flame which causes the window area to be completely filled with dispersed dust, whether viewed from the top or from the sides. The third picture shows the extent of dust dispersion before flame arrival while the fourth shows the flame itself. Once the flame exits the tube, an expansion wave travels from the open end to the closed end where it is reflected as an expansion wave propagating toward the open end. This causes a flow reversal that carries some dust toward the closed end. The subsequent system of waves and the induced flows carry no dust, necessitating the use of asbestos tufts to visualize the flow direction. This observation is consistent with the fact that at the end of a test some dust can be found near the closed end but the tube is clean of dust from about midway to the open end. The fifth and final photograph, taken at the end of the process, shows that there is no dust left in

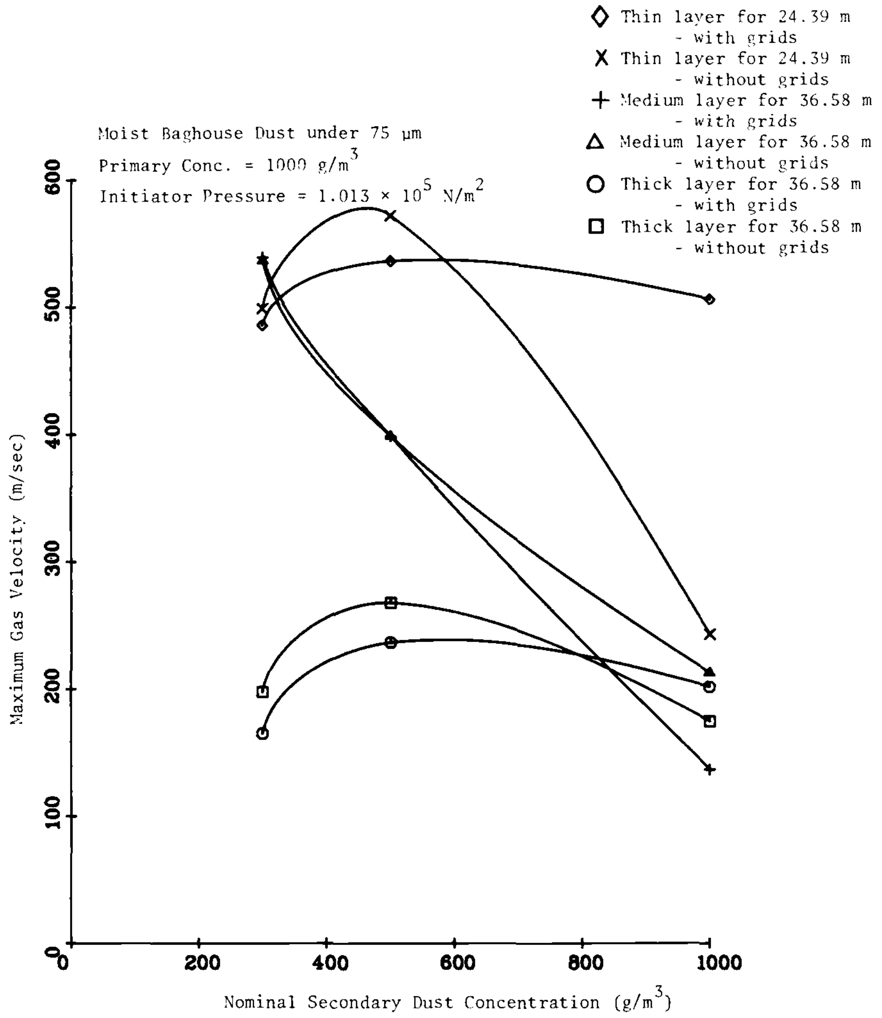


FIG. 10—*Effect of grids: comparison of maximum gas velocity.*

that section of the tube. From these movies, and from those made for studying the effect of grids on dust entrainment, no fundamental changes in the dust dispersion process could be noted.

Conclusions

Data have been presented comparing secondary dust explosions supported by baghouse dust and floor sweepings deposited in the form of a layer. The differences observed are due to the type of dust contained in the specific samples tested. Bean dust can sustain secondary dust explosions under certain conditions and thus act as a flame carrier. The processed corn starches tested are substantially more explosive than generic grain dusts—Mira Gel because of its better flowing abilities and PFP because of its finer size—and need special attention from a safety point of view. Turbulence-generating grids in the path of dusty flames increase pressures and flame velocities, while they decrease gas velocities and dispersed dust concentrations. This result is probably due

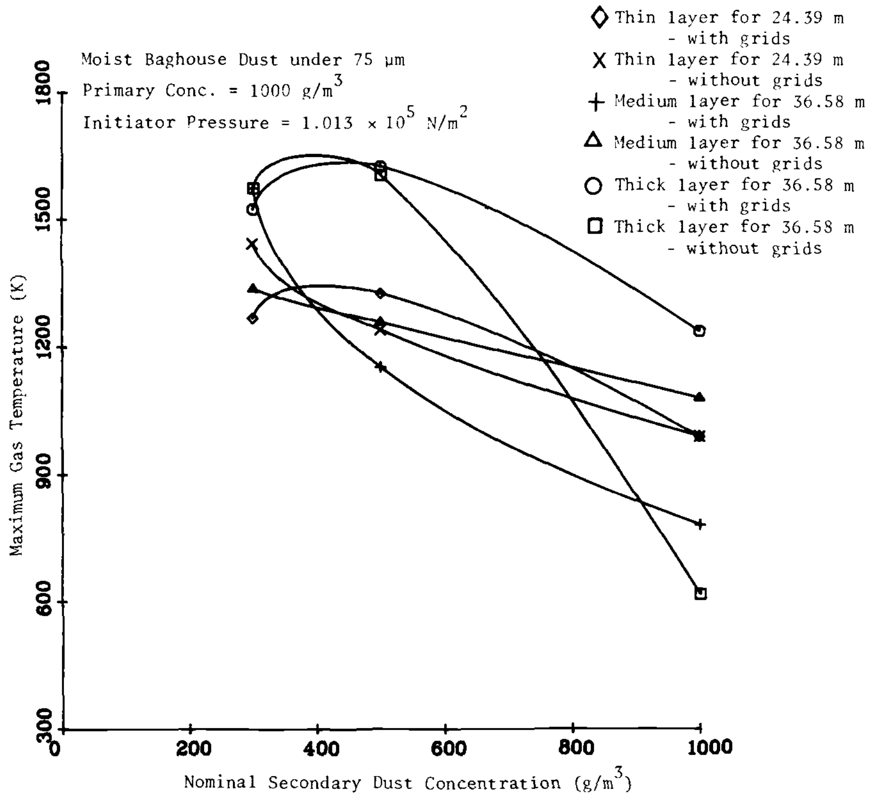


FIG. 11—*Effect of grids: comparison of maximum gas temperature.*

to the increase in turbulent burning velocity, which has been shown to play a major role in secondary dust explosions. The increase in pressures and flame velocities due to obstacles in the flame path is analogous to similar results in gaseous flames. No fundamental changes in the dust dispersion process can be observed using high-speed motion photography when grids are introduced in the flame path or when the dust layer thickness is substantially reduced at a given mass loading.

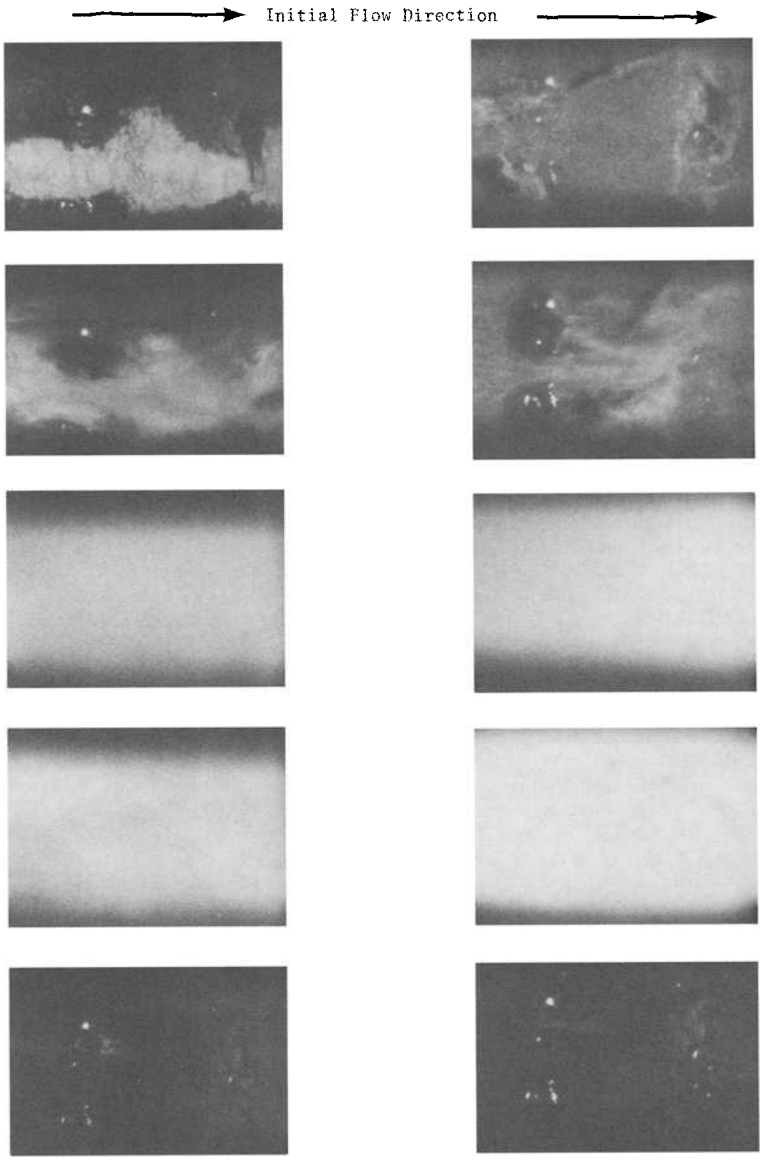
Acknowledgments

The authors would like to thank the Department of Health and Human Services, National Institute for Occupational Safety and Health, for funding the research program under Grant No. OH01122-06 and R. J. Ettema, E. J. Krieg, and J. J. Slawski for their assistance with the experimental studies.

References

[*1*] Faraday, M. and Lyell, C., "Report to the Home Secretary on the Explosion at the Haswell Colliery on 28 September 1844," *Philosophical Magazine*, Vol. 26, 1845, pp. 16–30.

[2] Price, D. J. and Brown, H. H., "Dust Explosions," National Fire Protection Association, Boston, MA, 1922.



(a) Thick layer

(b) Thin layer

FIG. 12—*Results from high-speed motion photography: comparison of dust entrainment for thin and thick layers.*

[3] Dorsett, H. G., Jr., Jacobson, M., Nagy, J., and William, R. P., "Laboratory Equipment and Test Procedures for Evaluating Explosibility of Dusts," Report of Investigation 5624, U. S. Bureau of Mines, Pittsburgh, PA, 1960.

[4] Ishihama, W. and Enomoto, H., "New Experimental Method for Studies of Dust Explosions," *Combustion and Flame*, Vol. 21, No. 2, 1973, pp. 177–186.

[5] Hartmann, J., Jacobson, M., and Williams, R. P., "Laboratory Explosion Study of American Coals," Report of Investigation 4725, U. S. Bureau of Mines, Pittsburgh, PA, 1950.

[6] Enomoto, H., ''Explosion Characteristics of Agricultural Dust Clouds,'' *International Symposium on Grain Dust Explosions,* National Academy of Sciences, Washington, DC, 1977, pp. 143–170.

[7] Cybulski, W., *Coal Dust Explosions and Their Suppression,* Foreign Scientific Publication Department of the National Center for Scientific, Technical and Economic Information, Warsaw, Poland, 1975.

[8] Rae, D., ''Initiation of Weak Coal-Dust Explosions in Long Galleries and the Importance of the Time Dependence of the Explosion Pressure,'' in *Fourteenth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, PA, 1973, pp. 1225–1234.

[9] Richmond, J. K. and Liebman, I., ''A Physical Description of Coal Mine Explosions,'' in *Fifteenth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, PA, 1975, pp. 115–126.

[10] Srinath, S. R., Kauffman, C. W., Nicholls, J. A., and Sichel, M., ''Flame Propagation Due to Layered Combustible Dusts,'' in *Tenth International Colloquium on Dynamics of Explosions and Reactive Systems,* Berkeley, CA, 4–9 Aug. 1985.

[11] Kauffman, C. W., Srinath, S. R., Tezok, F. I., Nicholls, J. A., and Sichel, M., ''Turbulent and Accelerating Dust Flames,'' in *Twentieth Symposium (International) on Combustion,* The Combustion Institute, Pittsburh, PA, 1985, pp. 1701–1708.

[12] Srinath, S. R., ''Flame Propagation Due to Layered Combustible Dust,'' Ph.D. thesis, University of Michigan, Ann Arbor, MI, 1985.

[13] Moen, I. O., Donato, M., Knystautus, R., and Lee, J. H. S., ''Flame Acceleration Due to Turbulence Produced by Obstacles,'' *Combustion and Flame,* Vol. 39, 1980, pp. 21–32.

[14] Hjertager, B. H., Fuhre, K., Parker, S. J., and Bakke, J. R., ''Flame Acceleration of Propane-Air in a Large Scale Obstructed Tube,'' in *Ninth International Colloquium on Dynamics of Explosions and Reactive Systems,* Poitiers, France, 3–8 July 1983.

[15] Chan, C., Moen, I. O., and Lee, J. H. S., ''Influence of Confinement on Flame Acceleration Due to Repeated Obstacles,'' *Combustion and Flame,* Vol. 49, Nos. 1-3, 1983, pp. 27–39.

[16] Clark, D. P. and Smoot, L. D., ''Model of Accelerating Coal Dust Flames,'' *Combustion and Flame,* Vol. 62, No. 3, 1985, pp. 225–269.

[17] Cashdollar, K. L., Liebman, I., and Conti, R. S., ''Three Bureau of Mines Optical Dust Probes,'' Report of Investigation 8542, U.S. Bureau of Mines, Pittsburgh, PA, 1981.

[18] Wolanski, P. and Waudby-Smith, P., ''Four Wavelength Pyrometer: Operation and Calibration,'' Departmental Communication, Department of Aerospace Engineering, University of Michigan, Ann Arbor, MI, 1980.

[19] Tamanini, F., ''Dust Explosion Propagation in Simulated Grain Conveyor Galleries,'' Technical Report OF1R2.RK, Factory Mutual Research Corporation, Norwood, MA, July 1983, pp. 31–35.

[20] ''Mira Gel 463 Starch,'' Technical Data Sheet, A. E. Staley Manufacturing Co., Decatur, IL, Aug. 1984.

[21] ''Report Comparing Baghouse and Floor Sweepings Grain Dust Samples,'' U. S. Department of Labor, OSHA Analytical Laboratory, Salt Lake City, UT, 21 Feb. 1986.

[22] Martin, C. R., ''Characterization of Grain Dust Samples,'' Paper 781-1 3020, presented at the American Society of Agricultural Engineers Summer Meeting, Logan, UT, 27–30 June 1980.

[23] ''Forschungsbericht Staubexplosionen: Brenn-und Explosions—Kenngrossen von Stauben,'' Schriftenriehe des Hauptverbandes der Gewerblichen Berufsgenossenschaften e.V., Bonn, 1980, pp. 18–20.

Kenneth L. Cashdollar,[1] *Michael J. Sapko,*[1] *Eric S. Weiss,*[1] *and Martin Hertzberg*[1]

Laboratory and Mine Dust Explosion Research at the Bureau of Mines

---

REFERENCE: Cashdollar, K. L., Sapko, M. J., Weiss, E. S., and Hertzberg, M., "**Laboratory and Mine Dust Explosion Research at the Bureau of Mines,**" *Industrial Dust Explosions, ASTM STP 958,* Kenneth L. Cashdollar and Martin Hertzberg, Eds., American Society for Testing and Materials, Philadelphia, 1987, pp. 107–123.

ABSTRACT: This paper describes the results of recent dust explosibility testing in a 20-L laboratory chamber and in the Bruceton and Lake Lynn Experimental Mines in Pennsylvania. Laboratory data on the lean flammability limits for coals and oil shales are compared to mine data for both predispersed tests and nominal loadings that are dispersed by a gas ignition zone. A linear relationship for the lean flammability limits for mixtures of bituminous coal dust and methane gas was measured in both laboratory and mine tests. This paper also compares data on the amount of limestone rock dust necessary to inert coal dusts and coal–methane mixtures. The good agreement between the 20-L chamber data and the mine data means that the laboratory chamber can be used for screening tests before full-scale mine tests.

KEY WORDS: dust explosions, underground explosions, coal dust, coal mines, inhibitors

There have been over 500 major dust or gas explosions or both in coal mines during the past 100 years in the United States [*1*]. The frequency and magnitude of these explosions have decreased as a result of regulations that require the addition of rock dust or stone dust to the coal dust and that require the dilution of methane by ventilation air. However, the explosion hazard has not been completely eliminated, and major coal mine explosions still occur [*2*]. There have also been dust explosions in gilsonite and sulfide ore mines [*1*].

The Bureau of Mines has been studying dust explosions in both laboratory and full-scale mine tests since 1910. Explosion characteristics measured include lean flammability limits or minimum explosible concentrations, maximum explosion pressures, amounts of various inhibitors necessary to inert coal dusts, and the effects of the addition of a few percent methane to the air.

Mining regulations have always been based on the results of full-scale mine tests. Laboratory tests in chambers and ducts were also conducted, but there was often wide disagreement between laboratory and mine tests [*3*]. In the past ten years, the Bureau has designed an 8-L chamber [*4–7*] and a 20-L chamber [*8–10*]; data from these chambers agree well with those from full-scale mine tests. These two chambers have replaced the 1.2-L Hartmann chamber [*11,12*], which was limited by both nonuniform dispersion and a weak ignition source. They have also replaced the vertical ducts [*3,13*] whose inhibitor data did not agree with mine results. The 20-L chamber is now used routinely for preliminary screening tests before full-scale mine tests are conducted.

---

[1] Research physicist, supervisory chemical engineer, mining engineer, and supervisory research chemist, respectively, United States Department of the Interior, Bureau of Mines, Pittsburgh Research Center, Cochrans Mill Rd., P.O. Box 18070, Pittsburgh, PA 15236.

Laboratory and Mine Test Facilities

The laboratory data presented in this paper were collected in the 20-L chamber [*8*] shown in Fig. 1. The test procedure includes the partial evacuation of the chamber and the dispersion of the dust by a blast of air from the bottom. The ignition source is energized after the pressure has returned to about 1 bar (100 kPa) absolute and the dust has been uniformly dispersed. At ignition, there is a moderate turbulence level, which is lower in intensity than the turbulence level in Siwek's 20-L chamber [*14–16*]. The latter was designed to measure rates of pressure rise at turbulence levels comparable to those of many industrial systems. The Bureau's chamber was designed primarily to measure flammability limits of combustible dusts with and without added inhibitor dusts. (Details of the operating procedures and dust dispersion uniformity measurements are in Ref *8*.) Instrumentation with the 20-L chamber includes a pressure transducer, optical dust probes [*17,18*] for measuring dispersion uniformity, and multichannel infrared pyrometers [*19,20*] for measuring explosion temperatures. The mine tests were conducted in the Bureau's two underground experimental mines. At the Bruceton Experimental Mine near Pittsburgh, there has been a continuous testing program since 1910 [*1,21–27*], The new test facility at the Lake Lynn Laboratory [*28*], 60 miles south of Pittsburgh, was designed to be more representative of modern mining geometries. In some of the mine tests, the dust was first dispersed in the air and then ignited. In other tests, the traditional test method was used—a nominal dust loading was placed on the floor, ribs (side walls), and/or roof and then dispersed and ignited by a gas–air explosion.

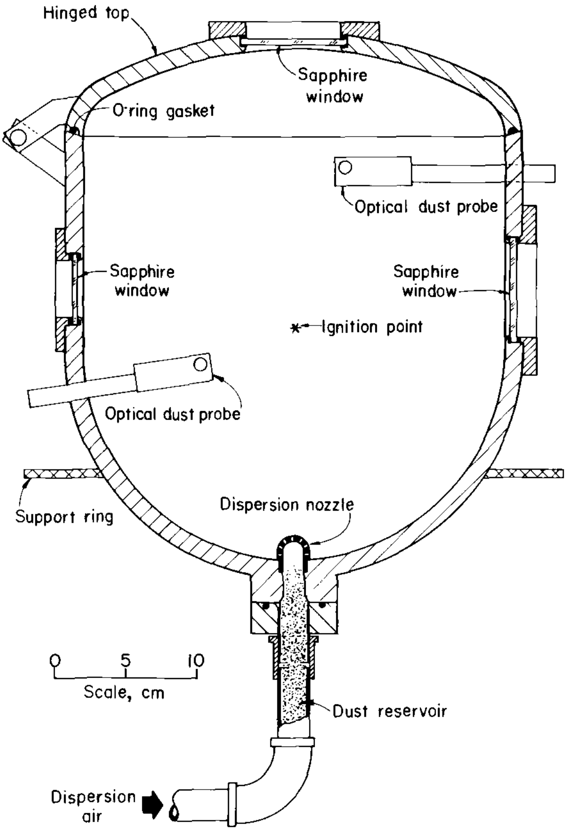


FIG. 1—*20-L laboratory explosibility test chamber.*

The section of the Bruceton Experimental Mine in which the predispersed tests were conducted is shown in Fig. 2. Two methods were used to disperse the dust. In Fig. 2*a*, there are seven V-troughs containing the dust. Pressurized air, exiting from holes in the bottom of the V-troughs, disperses the dust. The resulting dust cloud is confined by the plastic diaphragm. In Fig. 2*b*, the dust is dispersed from a single V-trough by a detonator cord. The mine entry in Fig. 2 is 1.8 m high by 2.7 m wide, and the dust in both dispersion methods is initially confined to 9.1 m by the plastic diaphragm. Therefore, the total initial volume of the test zone is 45 m^3. Various strong chemical ignitors are used to initiate the tests. In some tests, the ignitor powder is in a bag at the positions shown in Fig. 2; in other tests, the ignitor mixture is placed in the cannon near the face (closed end). If the dust cloud is flammable, the resulting explosion pressure rise will break the diaphragm, and the flame will propagate down the entry. Instrumentation shown in Fig. 2 includes optical flame sensors, pressure transducers, an infrared pyrometer [*19*], optical dust probes [*17,18*], and a high-speed movie camera.

In the larger scale tests in the Bruceton Experimental Mine, a nominal dust loading is placed on the floor and/or on shelves on the ribs and roof. Tests were done in both the single-entry configuration (Fig. 3*a*) and the double-entry configuration (Fig. 3*b*). In both cases, the ignition of a natural gas and air mixture at the face initiates the explosion tests. The gas explosion disperses the nominal dust loading and ignites it; the dust flame then propagates down the entry. A typical length for the dust test zone is shown in Fig. 3, but the lengths may vary from 23 to 150 m for pure coal dust tests and from 60 to 150 m for coal–rock mixture tests. As in the predispersed mine tests, instrumentation includes flame sensors, pyrometers, optical dust probes, pressure transducers, and high-speed movie cameras. The predispersed tests (Fig. 2) were made in the section of the mine where the gas zone is shown in Fig. 3. This paper includes data from mine tests during the past ten years in which the authors participated and also data from earlier tests by other Bureau researchers [*1,21–27*].

The new underground mine test facility at the Lake Lynn Laboratory [*28*], a former limestone mine, is shown in Fig. 4. Five new drifts (A–E) were developed so that they simulate the geometries of modern coal mines. The drifts are 2.1 m high by 6.0 m wide in cross section. D-

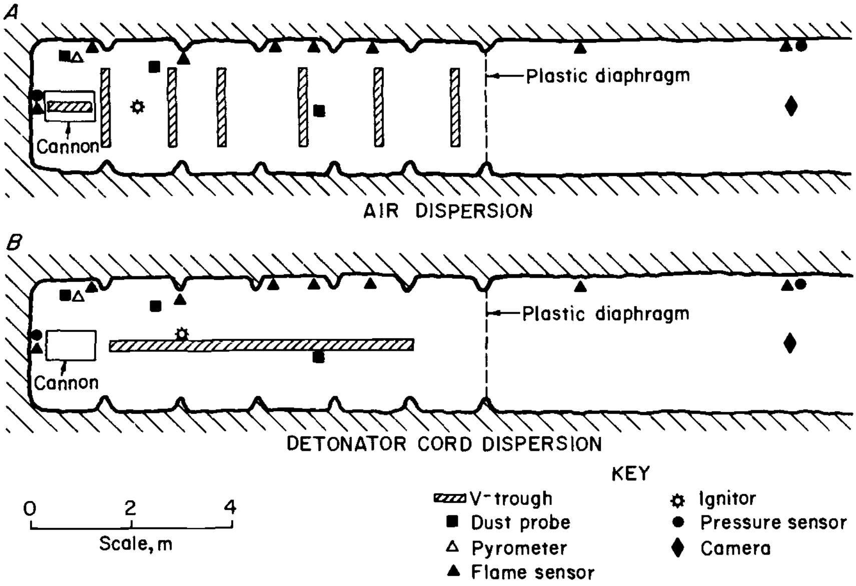


FIG. 2—*Plan views of the face area of the Bruceton Experimental Mine used for predispersed dust tests.*

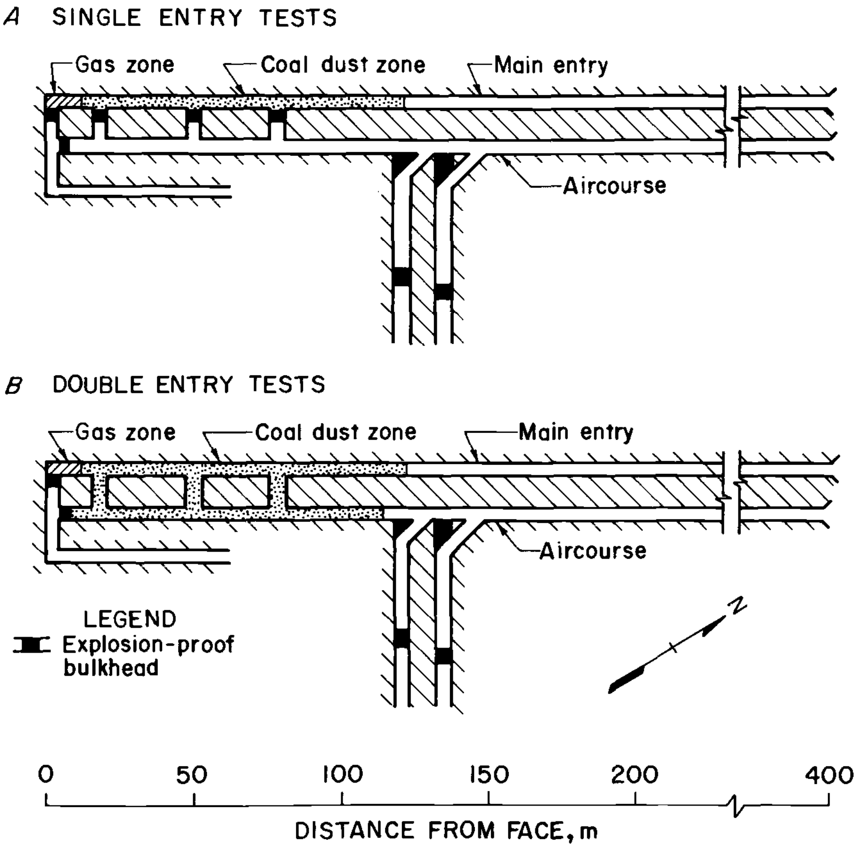


FIG. 3—*Plan views of the Bruceton Experimental Mine showing configurations for full-scale tests with nominal dust loadings.*

drift simulates a single entry similar to Fig. 2*a* for the Bruceton Mine. E-drift can be used to simulate a longwall section. A multiple entry configuration is simulated by drifts A, B, and C. The explosion-proof doors are used to divide the mine into the various configurations. The dust explosion tests conducted so far have all been in D-drift. The lengths of the dusted zones can be varied; the 64-m zone used for the tests reported in this paper is shown in Fig. 4.

The purpose of this paper is to compare results of tests that can be made in both the 20-L laboratory chamber and the experimental mines. These tests include the measurement of lean flammability limits of coal dust, the amounts of inhibitor dusts necessary to inert coal dusts, and the effect of small amounts of methane gas added to the coal dusts. There are many additional types of tests and phenomena that can be studied in either the mines or the laboratory chamber but not in both. Measurements of the effects of crosscuts and wall roughness on flame propagation can only be measured in the mines. Another mine test measures the effect of varying the distribution of dust by placing it on the floor, rib shelves, or roof shelves. The effect of thin layers of float coal dust on top of a floor loading of coal-rock dust can be measured in mine tests but not in the laboratory chamber. The testing of passive barriers to suppress coal dust explosions propagating in the Bruceton Experimental Mine is described in another paper in this Symposium volume [*29*]. Tests that can be conducted in the 20-L laboratory chamber but not in the mines include measurement

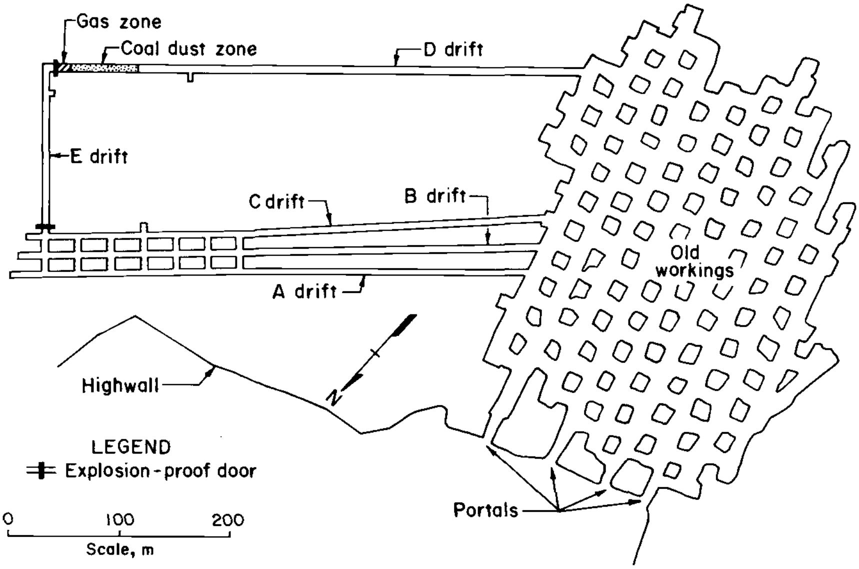


FIG. 4—*Plan view of the Lake Lynn Laboratory underground mine, showing the configuration for nominal dust loading tests in D-drift.*

of the effect of varying initial pressure on flammability limits and measurement of the minimum oxygen concentration for dust flammability.

Experimental Data

The majority of the experimental data in this paper were collected using Pittsburgh seam pulverized bituminous coal dust (PPC). Its "as received" analysis is 37% volatile matter (volatility), 1% moisture, 6% ash, and 56% fixed carbon, as measured by ASTM Standard for Proximate Analysis of Coal and Coke (D 3172). Its heating value is 7730 cal/g as measured by ASTM Standard for Gross Calorific Value of Solid Fuel by the Adiabatic Bomb Calorimeter (D 2015). The size analysis of the PPC was obtained by combining sonic sieving data and Coulter counter [*30*] data.[2] The surface mean diameter, $\bar{D}_s$, is 30 μm and the weight or volume mean diameter, $\bar{D}_w$, is 50 μm. Approximately 80% of the dust is minus 200 mesh (<75 μm).

Dispersibility and flammability data for PPC in the 20-L chamber are shown in Fig. 5. The coal dust concentration is calculated from the mass of dust dispersed in the 20-L volume. The optical dust probes [*17,18*] used to measure the transmission have a path length of 3.8 cm through the dust cloud. The optical probe data in Fig. 5 show good agreement in the measured transmissions at different heights, showing good dispersion uniformity. The data also generally follow the expected linear relationship (between the logarithm of the transmission and the concentration) on this semilogarithmic graph [*8,17,18*]. Also shown in Fig. 5 is the normalized pressure rise rate

$$K_{St} = (dP/dt)_{\max} V^{1/3}$$

where the maximum pressure rise rate, *dP/dt,* is multiplied by the cube root of the chamber volume, *V*. K_{St} is proportional to the flame speed and is the number used in sizing vents for

---

[2] Reference to specific trade names or manufacturers does not imply endorsement by the Bureau of Mines.

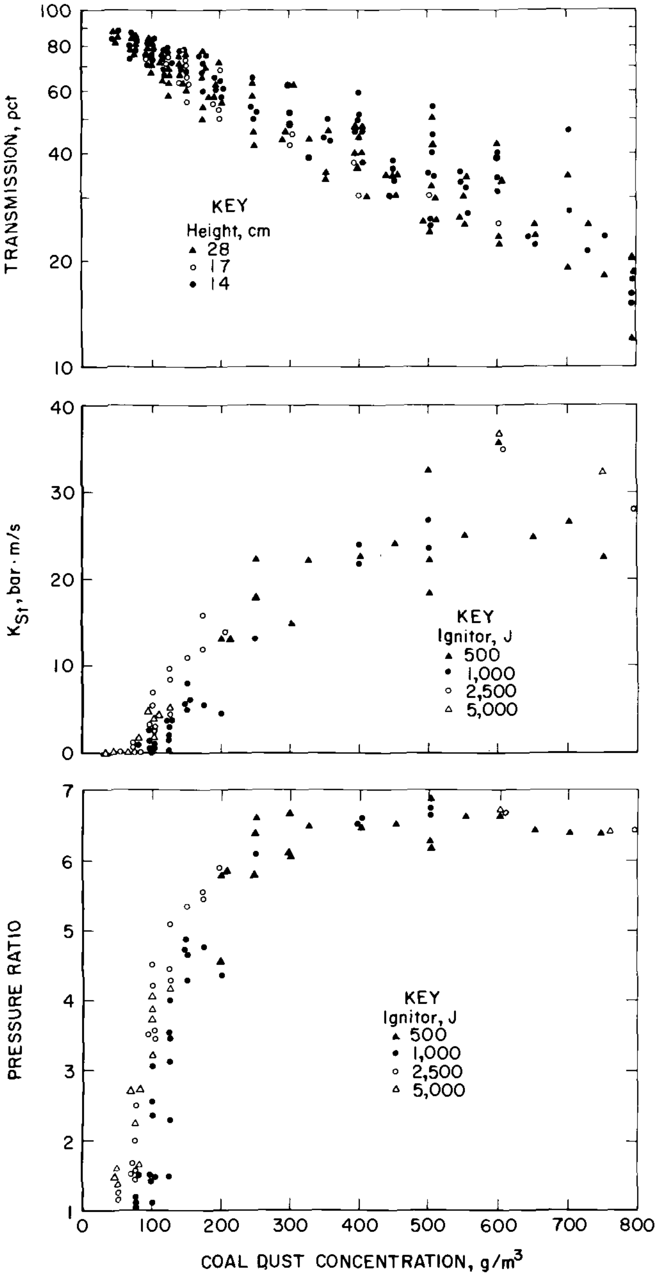


FIG. 5—*Dispersability and flammability data for Pittsburgh pulverized bituminous coal dust in the 20-L chamber at different ignitor energies.*

explosion relief. Note that K_{St} is dependent on the turbulence level in the chamber and that a more rapid dispersion of the dust and a shorter ignition delay would result in higher values for K_{St}. The pressure ratio, *PR*, is the maximum explosion pressure (absolute) divided by the pressure at ignition (about 1 bar [100 kPa] absolute), and it corresponds approximately to the absolute explosion pressure in atmospheres or bar. At the lowest dust concentrations tested, there is only a small pressure rise as a result of a small amount of burning around the ignitor and the K_{St} data are essentially zero. At higher concentrations, every test results in an explosion. Based on a double propagation criterion of $PR>2$ and $K_{St}>1.5$ bar m/s (150 kPa m/s), the lean flammability limit for this size of Pittsburgh coal is about 90 g/m^3 for the two strongest chemical ignitors (2500 and 5000 J). There is no evidence of a rich flammability limit in the data of Fig. 5. Additional tests have shown no rich limit out to a concentration of 4000 g/m^3. This agrees with the mine and laboratory data of other researchers [*1,31*].

Similar data on the flammability of PPC in predispersed tests (Fig. 2) in the Experimental Mine are shown in Fig. 6, which includes data from both detonator cord and air dispersion of the dust. Data from the three optical dust probes in the test zone showed that, as expected, the dispersion in the mine was not as uniform as the dispersion in the 20-L chamber. The coal dust concentration in Fig. 6 is the total mass of dust divided by the 45-m^3 test zone. In a few of the mine tests, two pairs of 5000-J chemical ignitors were used; but in most of the tests, a pair of ignitors composed of black powder and coal dust in a small bag and having an energy of approximately 950 kJ each were used. These bag ignitors produce a fireball that is about 1 m in size. Although these bag

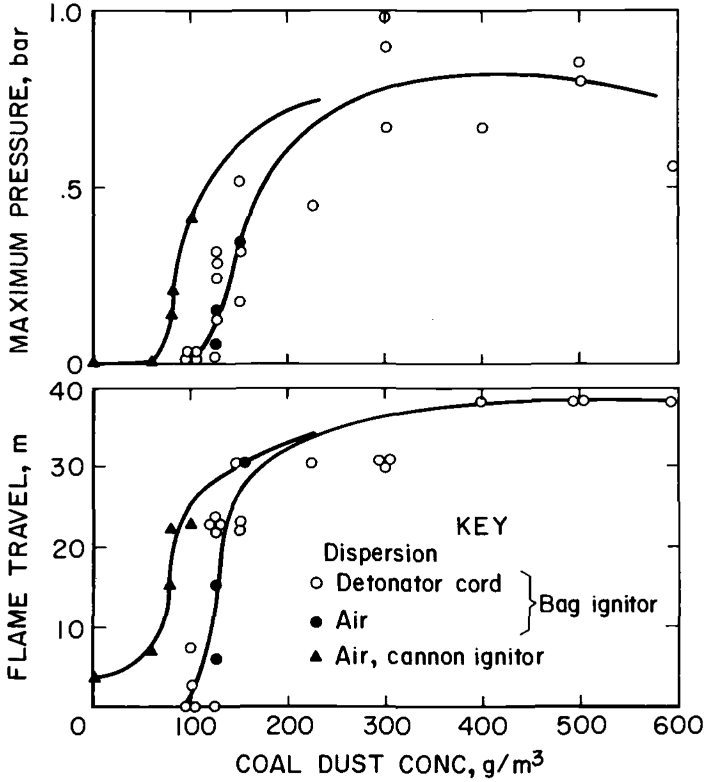


FIG. 6—*Flammability data for Pittsburgh pulverized coal tested in the predispersed mode in the Bruceton Mine.*

ignitors have a much greater energy than those used in the laboratory tests, the energy density relative to the total test zone volume is only 42 kJ/m^3 for the pair, compared with 250 kJ/m^3 for one 5000-J ignitor in the 20-L chamber.

Additional tests were made at the lower concentrations using an even stronger ignitor mixture shot out from the cannon (Fig. 2). The mixture contained ammonium nitrate and fuel oil (ANFO) with added aluminum powder. This cannon ignitor has a total energy of 2.8 MJ or an energy density of 63 kJ/m^3 relative to the test zone. The flame from this ignitor by itself travels about 3 m. In addition to the consideration of the energies of the ignitors, it is important that the size of the ignitor fireball be larger than the size scale at which the dust cloud concentration is uniform. This is one reason why stronger ignitors are required for limit measurements in the predispersed mine tests compared with those in the predispersed 20-L laboratory tests.

The maximum pressures (gauge) for explosions in these mine tests are much lower than those in the 20-L constant volume laboratory chamber because one end of the zone is free to vent after the plastic diaphragm breaks. The length of flame travel was measured by optical flame sensors at various positions in the mine entry. At the higher dust concentrations, the flame traveled four times the length of the initial dust zone. Based on a double propagation criterion of flame travel past the diaphragm (>9 m) and an overpressure greater than 0.1 bar (10 kPa), the lean flammable limit for PPC in the predispersed mine tests is about 120 g/m^3 using the bag ignitors. With the stronger cannon ignitor, the lean limit is about 70 to 80 g/m^3. These values agree well with the 90-g/m^3 value from the 20-L chamber considering the uncertainties in the measurements.

In other tests in the Bruceton Experimental Mine (Fig. 3) and in the Lake Lynn Mine (Fig. 4), the dust is placed on the mine floor and/or on roof or side shelves to simulate the conditions in working mines. The dispersion and ignition source is usually a zone of methane–air at the face, ignited by an electric match. (Ignition of pockets of methane is usually the cause of primary explosions, which often lead to secondary coal dust explosions in commercial underground mines.) The results of the tests are sensitive to both the location of the dust and the strength of the dispersion/ignition source. Dust on roof shelves is more hazardous because it is more easily dispersed than floor dust. Therefore, to obtain the most conservative data for the hazards of pure coal dust, all of the dust is usually placed on roof shelves. Only tests near the lean explosible limit can be made for pure coal because the destructive pressures generated at high concentrations could severely damage the mine. In previous tests in the Bruceton Mine, the minimum nominal loading for PPC dust explosions ranged from 50 to 60 g/m^3 [*1,23,26*]. Recent data from the Lake Lynn Mine give a minimum nominal loading of 40 to 50 g/m^3. These values are based on the nominal loading, assuming perfect dispersion throughout the cross section of the mine. In reality, the dispersion is not perfectly uniform, as shown by optical dust probe data [*17,26*]. This may explain why the nominal loading lean limits are somewhat lower than the predispersed values for PPC.

Other coal dusts have also been studied in both 20-L laboratory and full-scale mine tests. Pulverized Pocahontas coal, a low volatility (17%) bituminous, has a lean limit of 140 g/m^3 using the 2500-J ignitors and 100 g/m^3 with the 5000-J ignitors in the 20-L chamber. In previous mine tests [*24*], the lean limit for a nominal loading was about 100 g/m^3. A few predispersed tests with Pocahontas coal were also made in the Bruceton Mine, but a lean limit was not determined. No tests with this coal have yet been made at Lake Lynn. The agreement between the lean limits from the predispersed laboratory tests and nominal mine loadings is closer for this low volatility bituminous coal than it was for the Pittsburgh coal.

In addition to the coal dusts studied, tests were made with oil shales of various grades or assays. The 20-L laboratory data were reported previously in Ref *9*. The predispersed and nominal loading mine data from the Bruceton Mine were reported in Ref *32* to *36*. In both the laboratory and mine tests, the lowest assay of pulverized oil shale that would propagate an explosion was about 85 mL/kg (20 gal/ton). This oil assay corresponds to a volatility of about 9%. The oil assay was measured by ASTM Standard for Oil from Oil Shale (Resource Evaluation by the USBM Fischer Assay Procedure) (D 3904). Lean flammability limits were measured in the 20-L chamber and in both predispersed and nominal loading mine tests for oil shale of various assays from 85 to 200 mL/kg. In all of the tests, the measured lean limits for a specific assay of pulverized oil shale agreed to within a factor of two or better between laboratory and mine data. For example, the measured lean limits in the 20-L chamber for oil shale dust with an assay of 140 to 150 mL/kg (33 to 35 gal/ton) were about 400 g/m^3 with the 2500-J ignitor and about 250 g/m^3 with the 5000-J ignitor. For predispersed tests in the Bruceton Mine using the cannon ignitor, the lean limit was about 300 g/m^3 [*36*]. For nominal loading tests in the Bruceton Mine with a 91-m test zone, the minimum loading was 200 to 300 g/m^3 for this oil shale dust [*32,33,35*].

Hybrid mixtures of coal dust and methane are common hazards in the mining industry. Figure 7 shows the effect of added methane on the lean limit of Pittsburgh pulverized coal, as measured in the 20-L chamber. Data for both the 1000- and 2500-J ignitors are included. The data points are the measured lean limits for the coal dust with various added amounts of methane. The data for either ignitor follow an approximately linear relationship for the lean limits of the mixtures, as predicted by Le Chatelier's law, which was originally proposed for homogeneous mixtures of flammable gases [*37*]. The 2500-J ignitor appears to be overdriving the system somewhat for pure methane, but may not be overdriving the system for the harder-to-ignite pure coal. Therefore, the flammability boundary line is drawn with weighting factors for ignitor strength, as shown in Fig. 7. In reality, it would probably be more accurate to think of the measured flammability boundary as a band of finite width rather than as a sharp line because of the variations with ignitor energy.

Similar tests were run in the predispersed configuration (Fig. 2*b*) in the 45-m^3 test zone in the Bruceton Mine. In this case, PPC was dispersed into a natural gas (containing about 91% methane, 5% ethane, and 3% higher hydrocarbons) and air mixture. The expected lean flammability limit for the natural gas is 4.7% compared with 5.0% for pure methane, based on data from flammability tubes [*38*]. The data points in Fig. 8 show either propagation or nonpropagation for various mixtures of PPC and natural gas. The initiation sources used for these tests were the same black

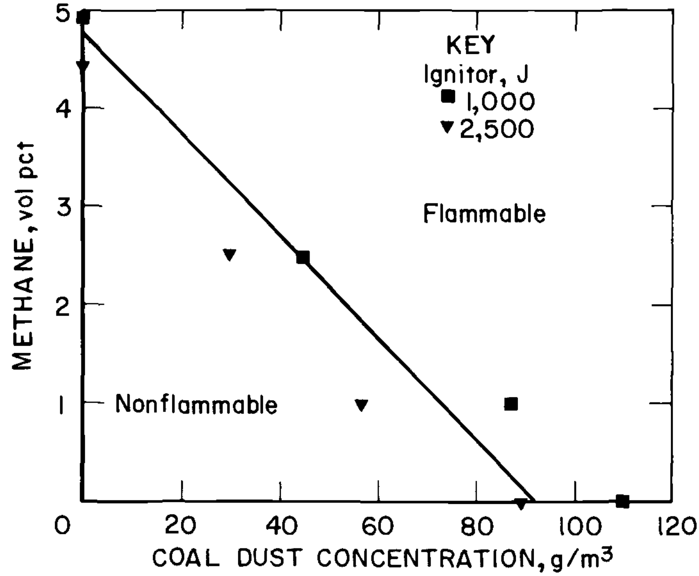


FIG. 7—*Lean flammability limits for mixtures of Pittsburgh pulverized coal and methane gas at two ignitor energies in the 20-L chamber.*

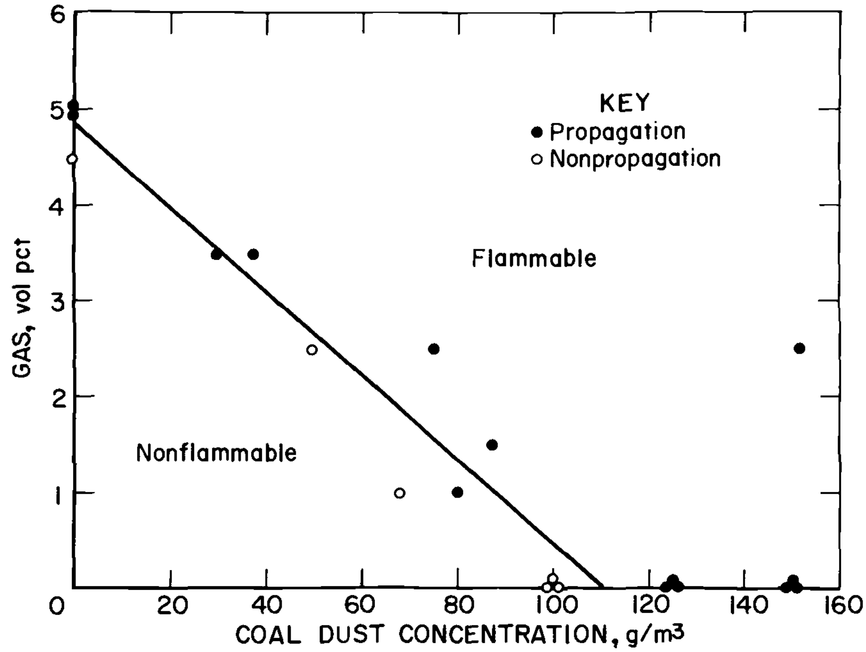


FIG. 8—*Explosion tests of mixtures of Pittsburgh pulverized coal and natural gas in the predispersed mode in the Bruceton Mine.*

powder and coal dust bag ignitors as were used for the pure dust tests shown in Fig. 6. As with the 20-L data, the mine data show a linear relationship for the lean limits of the gas–dust mixtures. The data do not fit the quadratic relationship proposed by Bartknecht [*15*] for some hybrid mixtures.

The amount of limestone (calcium carbonate [$CaCO_3$]) rock dust necessary to inert PPC was also measured in the 20-L chamber. The rock dust used was partly fluidized by the addition of 0.5% magnesium stearate. The mean diameters of the rock dust are $\bar{D}_s$ = 12 μm and $\bar{D}_w$ = 42 μm; the minus 200 mesh fraction is 77%. The data for rock dust addition to PPC are shown in Fig. 9. These tests were run with the 5000-J ignitors. The horizontal axis shows only the coal component of the total dust concentration. The key shows the percentages of rock dust in the coal–rock mixtures for the various curves. The addition of rock dust reduces the maximum explosion pressure and rate of pressure rise; it also increases the lean flammability limit of the coal in the mixture. At 80% rock dust, the mixture cannot be ignited even with these strong 5000-J ignitors.

The 20-L data for mixtures of PPC and fluidized rock dust at two ignitor energies are plotted in a different way in Fig. 10. For each mixture tested, the average maximum *PR* and K_{St} values (measured at high coal dust concentrations) are plotted versus the amount of inhibitor in the mixture. As the amount of rock dust is increased, *PR* and K_{St} decrease until the mixture is totally inert at a high rock dust percentage. A somewhat higher percentage of rock dust is required to inert the mixture when the 5000-J ignitors are used, compared with the 2500-J ignitors. It is uncertain which of these ignitors gives the better value because the 2500-J ignitor may have insufficient energy to measure the true inerting percent, and the 5000-J ignitor might be overdriving the system and giving a value that is too high. Therefore, the range of values obtained in the 20-L chamber is reported and will be compared with data from large-scale mine tests.

In the Bruceton Experimental Mine, only a few preliminary tests have been made with predispersed coal dust and rock dust mixtures using the experimental system of Fig. 2*a*. Difficulties

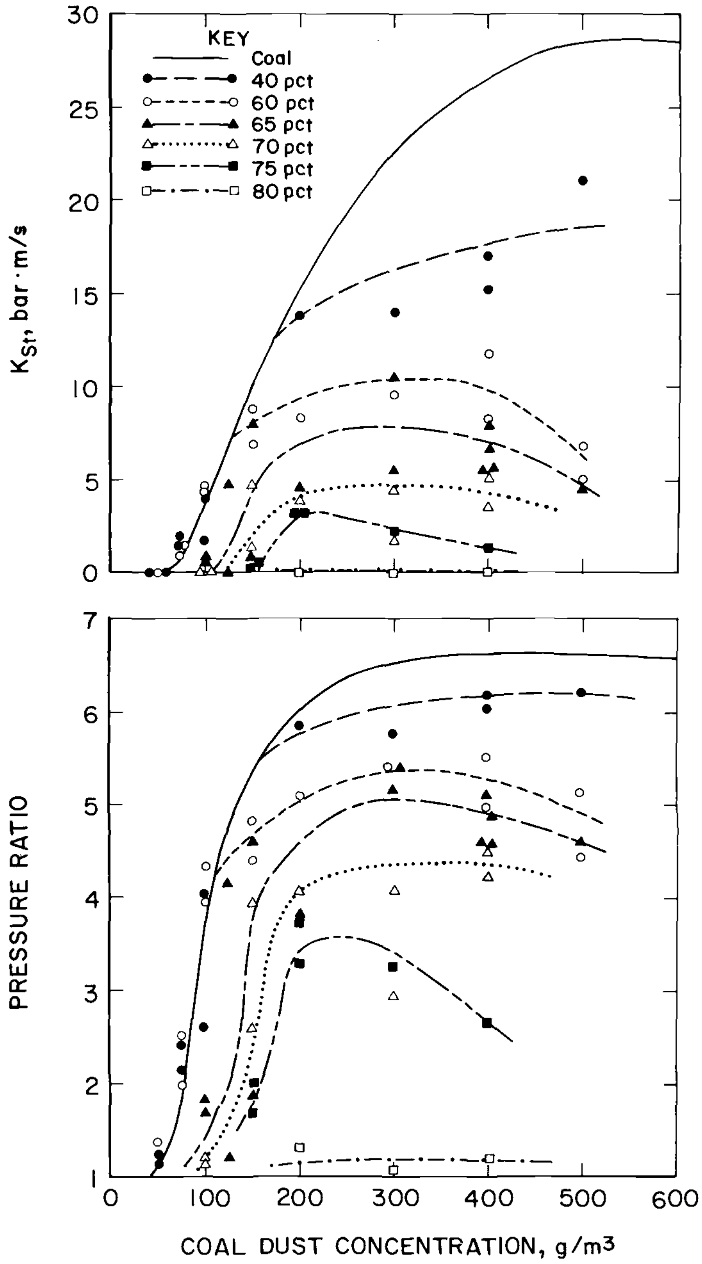


FIG. 9—*Flammability data from the 20-L chamber for mixtures of Pittsburgh pulverized coal and limestone rock dust containing the listed amounts of rock dust.*

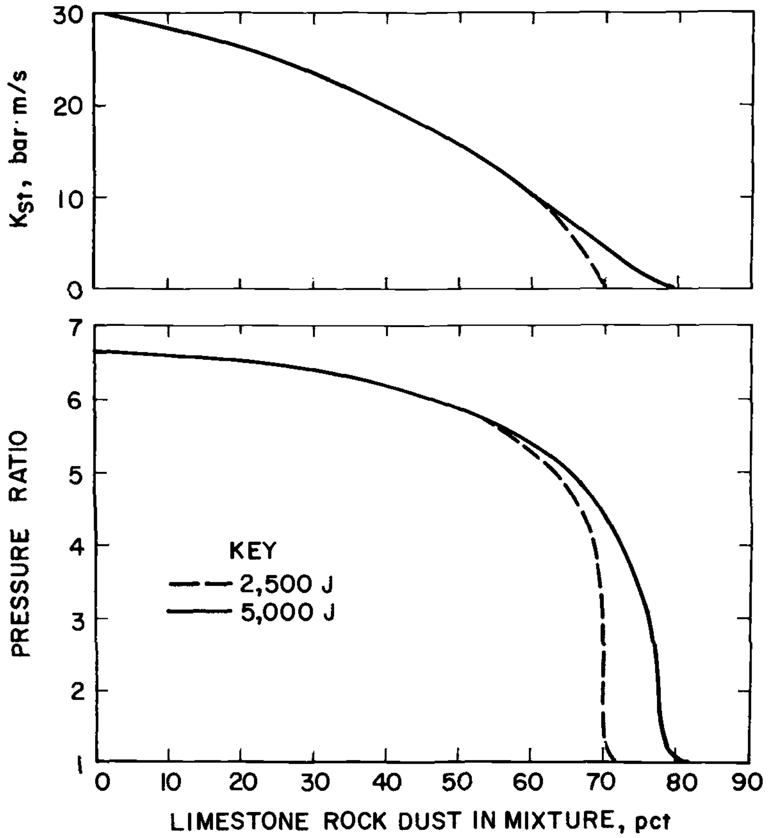


FIG. 10—*Maximum explosion pressure and pressure rise rate at two ignitor energies for mixtures of Pittsburgh pulverizd coal and limestone rock dust in the 20-L chamber.*

were encountered in predispersing such large amounts of dust uniformly throughout the mine cross section and in igniting such mixtures reproducibly. However, using the cannon ignitor, a PPC and 60% rock dust mixture did ignite and propagate. In a similar test with 70% rock dust, the mixture did not ignite.

Measurements of the amount of limestone rock dust necessary to inert Pittsburgh coal dust in nominal loading tests have been made over a period of decades in the Bruceton Mine. The results depend on the strength of the ignition source, the location of the nominal dust loading (floor, ribs, and/or roof), and the size of the coal dust. The propagation criterion for these tests is flame travel past the end of the dusted zone.

Richmond et al. [*24*] reported data on a series of single entry tests (Fig. 3*a*) on the amount of rock dust needed to inert PPC and other pulverized bituminous coals. The rock dust used had to meet the requirements of ASTM Specification for Limestone for Dusting of Coal Mines (C 737). The coal dust and rock dust were mixed and laid down in the mine at a nominal loading of 300 g/m^3 for the coal component of the mixture. One third of the dust mixture was broadcast on the floor, one third was placed on shelves attached to the ribs, and one third was placed on roof shelves. The test zone was 100 m long. The tests with PPC used the "standard weak initiation source" consisting of 16 m^3 of 7% natural gas and air at the face and a 3-m booster zone of pure PPC. The flame travel from this ignition source alone was about 15 m. This initiation source disperses the coal–rock dust mixture in the test zone and ignites it if it is explosible. Under these test conditions, about 70% limestone rock dust in the mixture was required to inert the PPC and rock dust mixture. Similar tests were made using the double-entry configuration of Fig. 3*b* [*26,27*]. The amount of limestone rock dust needed to inert PPC was again about 70% using the same ignition source.

Earlier tests were made in the Bruceton Mine using two stronger ignition sources [*1,21–23*]. These tests were made with both the single-entry and double-entry configurations, with a typical test zone being 150 m long. The rock dusts used included both shale and limestone. The coal and rock dust mixtures were placed on the floor, ribs, and roof of the mine. The first ignition source was 45 kg of pure PPC ignited by a blown out shot of black powder (1.8 kg) from a cannon; this source itself produced a flame 30 m long. The second type of ignition source was 40 to 80 m^3 of near stoichiometric natural gas in air. The smaller gas volume produced a flame by itself of about 30 m in the single entry, and the larger volume produced a flame of about 40 m in each entry of the double-entry configuration. The amount of rock dust necessary to inert a PPC and rock dust mixture under these test conditions was about 76%.

Recent tests in the Bruceton Mine were made with very heavy loadings of floor dust alone and using a strong ignition source. The nominal loading was 700 to 900 g/m^3 for the coal component of the mixture, but only a part of the dust mixture was lifted and dispersed. The test zone was 92 m long. The ignition source consisted of a 30-m^3 zone of 6.5% natural gas and air at the face, followed by a 24-m-long booster zone of 31 kg of pure PPC on the floor and on roof shelves. This ignition source by itself produced a flame 75 m long. Under these test conditions, the amount of limestone rock dust necessary to inert a PPC and rock dust mixture was between 76 and 80%.

In tests on Pittsburgh coal and rock dust mixtures made recently at the Lake Lynn Mine (Fig. 4), half of the dust mixture was broadcast on the floor and half was placed on roof shelves. The test zone was 64 m long. The usual nominal loading was 200 g/m^3 of coal dust. The ignition zone was a 150-m^3 zone of near stoichiometric natural gas in air at the face of D-drift. This ignitor by itself produced a flame about 60 m long. Under these test conditions, 78 to 80% limestone rock dust was necessary to inert PPC. In the Lake Lynn experiments, the dust is more difficult to disperse than in the Bruceton Mine as a result of the lower turbulence level from the gas–air flame in the smoother walled, larger entries. However, once the coal dust explosion has started, it appears to be more difficult to extinguish in these larger entries.

In previous laboratory tests in vertical ducts and in the 1.2-L Hartmann chamber, only 40 to 45% rock dust was observed to be sufficient to inert Pittsburgh pulverized coal dust [*3,12,13*]. Those data disagreed with the higher levels of rock dust required in mine tests. The data reported in this paper show that, in mine tests, a range of 70 to 80% limestone rock dust is needed to inert PPC–rock dust mixtures, with the exact value dependent on the test conditions. However, this is the same range of values obtained in the 20-L chamber using the 2500- and 5000-J ignitors. Therefore, there is now good agreement between laboratory and mine results.

In addition to the research on the amount of limestone rock dust necessary to inert PPC-rock mixtures, tests on the effectiveness of other inhibitor dusts have been run in the 8- and 20-L laboratory chambers and in the Bruceton Mine [*6,7,10,27*]. The inhibitors tested included fire extinguishant powders named ABC (ammonium phosphate [$NH_4H_2PO_4$]), BCD (sodium chloride [$NaCl$]), Super K (potassium chloride [KCl]), and Purple K (potassium bicarbonate [$KHCO_3$]) in addition to the limestone (calcium carbonate [$CaCO_3$]) previously discussed. In summary, the order of effectiveness of the various inhibitors was the same in both the laboratory and mine tests, and the approximate amounts required to inert PPC were similar in both test systems.

In addition to the experiments with Pittsburgh seam bituminous coal, tests have been conducted in both the 20-L laboratory chamber and the Bruceton Experimental Mine on the amount of rock dust required to inert other pulverized bituminous coals with a wide range of volatilities. Anthracite coals were tested to determine if they could propagate explosions. The results of these tests are summarized in Fig. 11. All of the coals were pulverized, with 70 to 90% minus 200 mesh. The

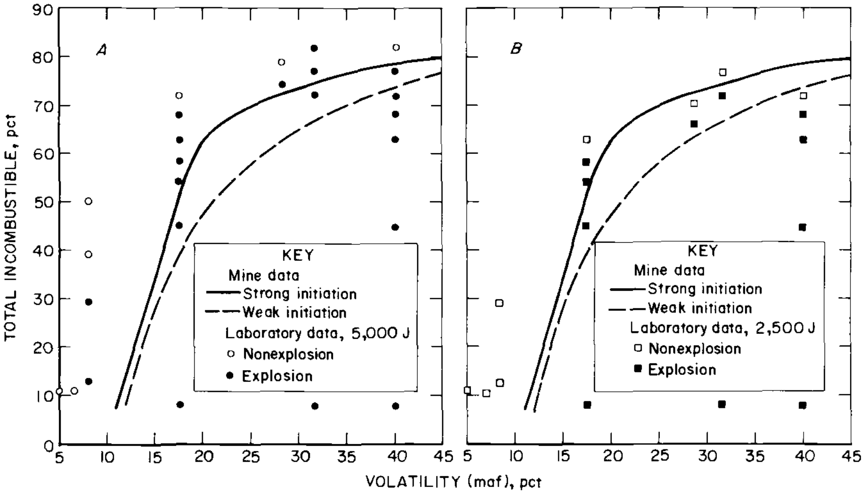


FIG. 11—*Comparison of Bruceton Experimental Mine data and 20-L laboratory data on the amount of rock dust necessary to inert pulverized coals of various volatilities.*

horizontal axes list the moisture–ash free volatility of the coals. The vertical axes show the total incombustible content of the coal–rock mixture. The total incombustible content includes the rock dust plus the ash and moisture fraction of the coal. The mine data are shown as curves—a solid curve for strong initiation and a dashed curve for weak initiation. Each curve represents a boundary between mixtures below that propagate explosions and mixtures above that do not propagate explosions under the specified test conditions. The same mine data curves are shown in both Fig. 11*a* and *b*. The mine data curve for the strong initiation source was reported in Refs *1* and *21*. Some additional confirming data for strong initiation were reported in Ref *24*.

The Bureau data curve for rock dust inerting of pulverized coals with the strong initiation source is also very close to the result obtained by Cybulski [*39*] for pulverized coals of similar size at the Experimental Mine Barbara in Poland. He used a 50-m^3 methane–air ignitor that by itself produced a flame of 30 to 40 m. Even more rock dust was required when Cybulski [*39*] used an ignitor that by itself produced a flame of 90 to 100 m. In this volume, Michelis and co-workers [*40*] report data on the amount of rock dust necessary to inert a coal of 25% volatility in tests at the Experimental Mine Tremonia in Germany. Their standard ignition source appears to be comparable to the Bureau's strong initiation source, but they required somewhat more total incombustible than that shown in the mine data of Fig. 11.

In the early Bureau tests, Rice and Greenwald [*21*] reported that, for coals with volatilities greater than 25%, the variation in the measured incombustible necessary to inert was generally about 3% but a few coals had as much as a 5% variation from the average curve for strong initiation shown in Fig. 11. For coals with volatilities less than 25%, this variability may be greater. The Bureau's strong ignitor by itself had a flame travel of 30 to 40 m, while the weak ignitor had a flame travel of about 15 m. The mine data curve for the weak initiation source is from Ref *24*. The 20-L laboratory data in Fig. 11 are shown as explosion or nonexplosion data points for the various mixtures tested. Each data point shown corresponds to a series of runs at various high coal dust concentrations for the particular coal and rock dust mixture. Laboratory data are shown for both the 2500- and 5000-J ignitors. The 5000-J ignitors appear to be overdriving the 20-L chamber in some cases, particularly for the lower volatility coals. Although there is not exact agreement between the laboratory and mine data, the minimum coal volatility required for explosions is similar in both tests, and the amount of rock dust necessary to inert the various coal–rock dust mixtures is comparable in both systems.

Experiments were also conducted to determine the amount of rock dust necessary to inert coal dust and small amounts of added methane gas. The previous Bruceton Mine tests [*21*] were conducted with the strong initiation source used for the data in Fig. 11. A nominal loading of coal dust and rock dust was placed on the floor, ribs, and roof of the mine entry. The test zone was 92 m long. Small amounts (1 or 2%) of natural gas were added to the ventilation air. Tests were conducted for various bituminous coals, and a formula was developed for the additional amount of rock dust, A, necessary for each percent of methane present. The formula is

$$A = (100 - I)/5,$$

where A is in percent and I is the total incombustible percent required in the absence of methane. For example, Pittsburgh pulverized coal required 78% total incombustible in the coal–rock mixture to prevent flame propagation in the absence of methane. With 1% gas in the ventilation air, 82% total incombustible was required; and with 2% gas present, 87% total incombustible was required in the mine tests. Recently, similar tests were made in the 20-L laboratory chamber with small amounts of added methane. The data agreed with the predictions of the formula on the extra amount of limestone rock dust needed to inert a PPC–rock dust mixture with 1 or 2.5% added methane. This again shows good agreement between laboratory and mine test results.

All of the data reported thus far in this paper were for pulverized (nominally 80% minus 200 mesh) dust. Additional data were also obtained for a coarse Pittsburgh bituminous coal dust, which has 100% minus 20 mesh (<850 μm) but only about 20% minus 200 mesh (<75 μm). The mean sizes are approximately 80 μm for $\bar{D}_s$ and 340 μm for $\bar{D}_w$. In the 20-L chamber, the lean flammability limits for this coarse coal are 270 g/m^3 using the 2500-J ignitor and 150 g/m^3 with the 5000-J ignitor. The fact that the measured limits vary greatly with ignition energy shows that this dust is very hard to ignite and that the true, energy-independent limit may be even lower than these values. In previous tests in the Bruceton Experimental Mine [*1,22*] the minimum nominal loading for flame propagation of this coarse coal was about 80 to 100 g/m^3, using the strong initiation sources described previously. In recent, preliminary tests at the Lake Lynn Mine, the minimum nominal loading for this coarse coal was lower, approximately 50 g/m^3.

Experiments were also conducted in the laboratory and mine to determine the amount of limestone rock dust necessary to inert the coarse Pittsburgh coal. In the 20-L chamber, almost 50% rock dust, or about 54% total incombustible, was required to inert the coal and rock dust mixture, using the 5000-J ignitors. Tests in the Bruceton Mine were conducted with both the weak and strong initiation sources described previously. With the weak initiation source, approximately 40 to 45% total incombustible was required to inert the mixture [*24*]. With the two strong initiation sources, 60 to 65% total incombustible was required [*1,21–23*]. From recent, preliminary tests at the Lake Lynn Mine, it is estimated that 65 to 70% total incombustible would be required to inert this coarse coal. As with the data for the pulverized coal dusts, there is reasonable agreement between the laboratory and mine data on the amount of rock dust necessary to inert a coarse coal and rock dust mixture.

Conclusion

The data presented in this paper show that there is reasonably good agreement between the results from the 20-L laboratory chamber and those from the full-scale tests in the Bruceton Experimental Mine and the Lake Lynn Mine. The comparisons were made for the lean flammable limits of various dusts, for the coal or oil shale volatility required to make the dust explosible, and for the amounts of limestone rock dust necessary to inert coal dust. Because there is good agreement between the laboratory and mine data, the 20-L chamber is routinely used for screening tests before full-scale mine tests. In one day, many tests can be made in the laboratory chamber, while the mine tests take one to two days per test. Therefore, much time and money can be saved by using the results of the 20-L tests to provide a starting point for the mine tests and thereby reduce the total number of mine tests required.

Both the Bruceton Experimental Mine and the new Lake Lynn Mine will continue to be used for full-scale explosion testing. The Lake Lynn facility allows testing in passageways that are more representative of modern mining geometries. However, there are also tests that can be conducted more easily in the Bruceton Mine, so it will also continue to be used for dust explosibility testing. A comparison of the results from the Bruceton and Lake Lynn Mines will give information on the scaling factors for different mine geometries.

References

[*1*] Nagy, J., "The Explosion Hazard in Mining," IR 1119, U.S. Mine Safety and Health Administration, Pittsburgh, PA, 1981.

[*2*] Richmond, J. K., Price, G. C., Sapko, M. J., and Kawenski, E. M., "Historical Summary of Coal Mine Explosions in the United States, 1959–81," IC 8909, U.S. Bureau of Mines, Pittsburgh, PA, 1983.

[*3*] Grumer, J., "Recent Research Concerning Extinguishment of Coal Dust Explosions," in *Fifteenth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, PA, 1975, pp. 103–114.

[*4*] Hertzberg, M., Cashdollar, K. L., and Opferman, J. J., "The Flammability of Coal Dust–Air Mixtures," RI 8360, U.S. Bureau of Mines, Pittsburgh, PA, 1979.

[*5*] Hertzberg, M., Cashdollar, K. L., and Lazzara, C. P., "The Limits of Flammability of Pulverized Coals and Other Dusts," in *Eighteenth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, PA, 1981, pp. 717–729.

[*6*] Hertzberg, M., Cashdollar, K. L., Lazzara, C. P., and Smith, A. C., "Inhibition and Extinction of Coal Dust and Methane Explosions," RI 8708, U.S. Bureau of Mines, Pittsburgh, PA, 1982.

[*7*] Cashdollar, K. L., Hertzberg, M., and Richmond, J. K., "Inhibition of Coal Dust Explosions: Comparison of the 8-Liter Laboratory Chamber and Experimental Mine," paper F-4 in proceedings of the 20th International Conference of Safety in Mines Research Institutes, Sheffield, England, Oct. 3–7, 1983.

[*8*] Cashdollar, K. L. and Hertzberg, M., "20-L Explosibility Test Chamber for Dusts and Gases," *Review of Scientific Instruments,* Vol. 56, 1985, pp. 596–602.

[*9*] Cashdollar, K. L., Hertzberg, M., and Conti, R. S., "Explosion Hazards of Oil Shale Dusts: Limits, Pressures, and Ignitability," in *Seventeenth Oil Shale Symposium Proceedings,* Colorado School of Mines Press, Golden, CO, 1984, pp. 243–254.

[*10*] Hertzberg, M., Cashdollar, K. L., Zlochower, I., and Ng, D. L., "Inhibition and Extinction of Explosions in Heterogeneous Mixtures," in *Twentieth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, PA, 1985, pp. 1691–1700.

[*11*] Dorsett, H. G., Jr., Jacobson, M., Nagy, J., and Williams, R. P., "Laboratory Equipment and Test Procedures for Evaluating Explosibility of Dusts," RI 5624, U. S. Bureau of Mines, Pittsburgh, PA, 1960.

[*12*] Nagy, J. and Verakis, H. C., *Development and Control of Dust Explosions,* Marcel Dekker, New York, 1983.

[*13*] Grumer, J., Miller, L. F., Bruszak, A. E., and Dalverny, L. E., "Minimum Extinguishant and Maximum Oxygen Concentrations for Extinguishing Coal Dust–Air Explosions," RI 7782, U.S. Bureau of Mines, Pittsburgh, PA, 1973.

[*14*] Siwek, R., "20-L Laborapparatur für die Bestimmung der Explosionskenngrössen brennbarer Stäube" (20-L Laboratory Apparatus for the Determination of the Explosion Characteristics of Flammable Dusts), Winterthur Engineering College, Winterthur, Switzerland, 1977, available from Ciba-Geigy AG, Basel, Switzerland (in German).

[*15*] Bartknecht, W., *Explosions: Course, Prevention, Protection,* Springer-Verlag, New York, 1981.

[*16*] Bartknecht, W., "Prevention and Design Measures for Protection Against the Danger of Dust Explosions," in this volume, pp. 158–190.

[*17*] Cashdollar, K. L., Liebman, I., and Conti, R. S., "Three Bureau of Mines Optical Dust Probes," RI 8542, U. S. Bureau of Mines, Pittsburgh, PA, 1981.

[*18*] Conti, R. S., Cashdollar, K. L., and Liebman, I., "Improved Optical Probe for Monitoring Dust Explosions," *Review of Scientific Instruments,* Vol. 53, 1982, pp. 311–313.

[*19*] Cashdollar, K. L. and Hertzberg, M., "Infrared Pyrometers for Measuring Dust Explosion Temperatures," *Optical Engineering*, Vol. 21, 1982, pp. 82–86.

[*20*] Cashdollar, K. L. and Hertzberg, M., "Infrared Temperatures of Coal Dust Explosions," *Combustion and Flame*, Vol. 51, 1983, pp. 23–35.

[*21*] Rice, G. S. and Greenwald, H. P., "Coal-Dust Explosibility Factors Indicated by Experimental Mine Investigations, 1911 to 1929," TP 464, U.S. Bureau of Mines, Pittsburgh, PA, 1929.

[*22*] Rice, G. S., Greenwald, H. P., and Howarth, H. C., "Explosion Tests of Pittsburgh Coal Dust in the Experimental Mine 1925 to 1932, Inclusive," Bulletin 369, U.S. Bureau of Mines, Pittsburgh, PA, 1933.

[*23*] Hartmann, I., "Studies on the Development and Control of Coal-Dust Explosions in Mines," IC 7785, U.S. Bureau of Mines, Pittsburgh, PA, 1957.

[*24*] Richmond, J. K., Liebman, I., and Miller, L. F., "Effect of Rock Dust on the Explosibility of Coal Dust," RI 8077, U.S. Bureau of Mines, Pittsburgh, PA, 1975.

[*25*] Richmond, J. K. and Liebman, I., "A Physical Description of Coal Mine Explosions," in *Fifteenth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, 1975, pp. 115–126.

[*26*] Richmond, J. K., Liebman, I., Bruszak, A. E., and Miller, L. F., "A Physical Description of Coal Mine Explosions. Part II," in *Seventeenth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, 1979, pp. 1257–1268.

[*27*] Liebman, I. and Richmond, J. K., "Ranking of Extinguishing Agents Against Coal Dust Explosions," paper B-6 in proceedings of 18th International Conference of Scientific Research in the Field of Safety at Work in the Mining Industry, Dubrovnik, Yugoslavia, Oct. 7–14, 1979, Vol. 1, pp. 239–247.

[*28*] Mattes, R. H., Bacho, A., and Wade, L. V., "Lake Lynn Laboratory: Construction, Physical Description, and Capability," IC 8911, U.S. Bureau of Mines, Pittsburgh, PA, 1983.

[*29*] Ng, D. L., Sapko, M. J., Furno, A. L., and Pro, R., "Coal Dust Explosion Suppression by Barriers," in this volume, pp. 138–151.

[*30*] Berg, R. H., "Electronic Size Analysis of Subsieve Particles by Flowing Through a Small Liquid Resistor," in *Symposium on Particle Measurement, ASTM STP 234*, American Society for Testing and Materials, Philadelphia, 1959, pp. 245–255.

[*31*] Deguingand, B. and Galant, S., "Upper Flammability Limits of Coal Dust–Air Mixtures," in *Eighteenth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, 1981, pp. 705–715

[*32*] Richmond, J. K. and Miller, L. F., "Explosion and Fire Properties of Oil Shale," in *10th Oil Shale Symposium Proceedings*, Colorado School of Mines Press, Golden, CO, 1977, pp. 45–59.

[*33*] Richmond, J. K., Sapko, M. J., Miller, L. F., Furno, A. L., and Dalverny, L. E., "Fire and Explosion Properties of Oil Shale, Part II," in *13th Oil Shale Symposium Proceedings*, Colorado School of Mines Press, Golden, CO, 1980, pp. 193–207.

[*34*] Richmond, J. K., Sapko, M. J., Miller, L. F., and Dalverny, L. E., "Explosion Hazards in Gassy and Non-Gassy Oil Shale Mines," in *14th Oil Shale Symposium Proceedings*, Colorado School of Mines Press, Golden, CO, 1981, pp. 61–74.

[*35*] Richmond, J. K., Sapko, M. J., and Miller, L. F., "Fire and Explosion Properties of Oil Shale," RI 8726, U.S. Bureau of Mines, Pittsburgh, PA, 1982.

[*36*] Richmond, J. K. and Beitel, F. P., "Dust Explosion Hazards Due to Blasting of Oil Shale," in *17th Oil Shale Symposium Proceedings*, Colorado School of Mines Press, Golden, CO, 1984, pp. 255–268.

[*37*] Coward, H. F. and Jones, G. W., "Limits of Flammability of Gases and Vapors," Bulletin 503, U.S Bureau of Mines, Pittsburgh, PA, 1952, p. 5.

[*38*] Zabetakis, M. G., "Flammability Characteristics of Combustible Gases and Vapors," Bulletin 627, U.S. Bureau of Mines, Pittsburgh, PA, 1965, p. 21.

[*39*] Cybulski, W., *Coal Dust Explosions and Their Suppression*, (translated from Polish), National Center for Scientific, Technical, and Economic Information, Warsaw, Poland, 1975, available as TT 73-54001 from National Technical Information Service, Springfield, VA, p. 107.

[*40*] Michelis, J., Margenburg, B., Müller, G., and Kleine, W., "Investigations into the Build-Up and Development Conditions of Coal Dust Explosions in a 700 m Underground Gallery," in this volume, pp.124–137.

Jürgen Michelis,[1] *Bernd Margenburg,*[1] *Gert Müller,*[1] *and Wolfgang Kleine*[1]

Investigations into the Buildup and Development Conditions of Coal Dust Explosions in a 700-m Underground Gallery

REFERENCE: Michelis, J., Margenburg, B., Müller, G., and Kleine, W., "**Investigations into the Buildup and Development Conditions of Coal Dust Explosions in a 700-m Underground Gallery,**" *Industrial Dust Explosions, ASTM STP 958,* Kenneth L. Cashdollar and Martin Hertzberg, Eds., American Society for Testing and Materials, Philadelphia, 1987, pp. 124–137.

ABSTRACT: To investigate the buildup and development of coal dust explosions, comprehensive tests were carried out in a 8-m^2, 700-m-long explosion gallery at the Experimental Mine Tremonia. The majority of these tests were done with "Dortmund standard coal dust" (coking coal) with a mean particle size between 18 and 22 μm. The following test conditions were varied: length of the fuel zone, strength of primary initiation and secondary initiation, coal dust concentration, mean particle size of coal dust, and inert content of coal dust. The test results are discussed.

KEY WORDS: coal dust explosions, initiation, fuel zone, coal dust concentration, particle size, explosion pressure, length of flame

Many miners still are killed or injured in explosions in underground coal mines. In the past 10 years (1976 through 1985) about 3500 miners are reported to have been involved in explosions (Table 1).

Almost all coal mining countries maintain research laboratories that are used to assess the explosibility of their respective domestic coals and to develop appropriate protection measures.

TABLE 1—*Total number—as far as recorded—of miners killed or injured in explosions in coal mines underground worldwide from 1976 to 1985.*

Year	Injured	Fatal	Total
1976	413	325	738
1977	106	342	448
1978	33	57	90
1979	129	119	248
1980	57	51	108
1981	126	204	330
1982	59	62	121
1983	236	291	527
1984	63	222	285
1985	273	223	496
Totals	1495	1896	3391

---

[1] Head of department of explosions and shotfirings and staff in same department, respectively, Versuchsgrubengesellschaft mbH (Tremonia Experimental Mine), Tremoniastraße 13, 4600 Dortmund 1, Federal Republic of Germany.

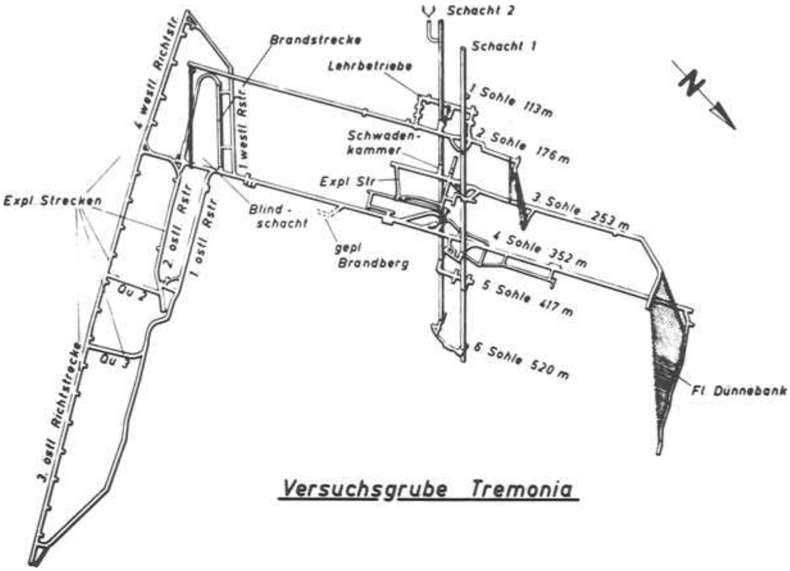


FIG. 1—*Chart of the underground facilities of the Tremonia Experimental Mine.*

The explosibility of a coal is determined for the West German mining industry according to the "Coal Dust Testing Regulations" of the mining authorities. In addition to determining the explosibility of a coal, it is essential for the development of appropriate explosion suppression measures to know the conditions under which explosions build up and propagate. In the Federal Republic of Germany, such investigations can be carried out at the Versuchsgrubengesellschaft (Experimental Mine Company) in Dortmund, in its Tremonia Experimental Mine. This mine consists of an underground explosionproof 2000-m gallery network on two levels with cross sections from 8 to 20 m², where large-scale explosion tests are conducted (Figs. 1 and 2). Here,

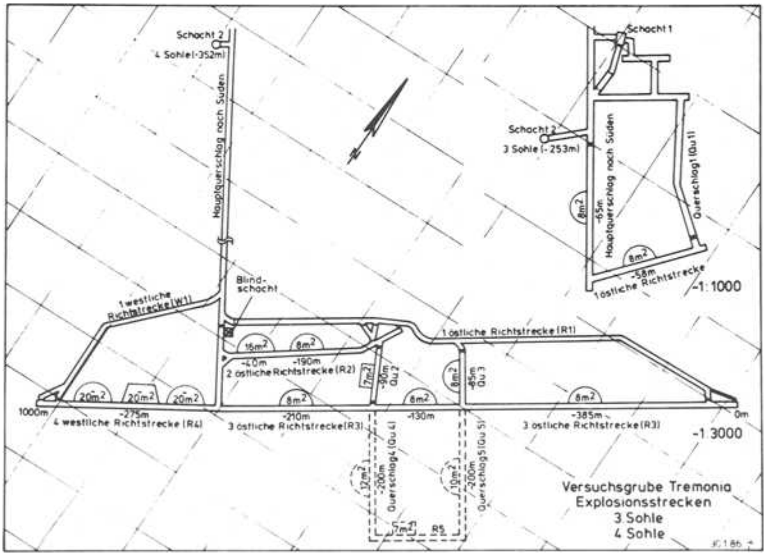


FIG. 2—*Explosion galleries of the Tremonia Experimental Mine.*

explosions of methane, coal dust, and hybrid mixtures with different concentrations are carried out. Explosion pressures range from a few millibars to about 20 bars (2000 kPa) and flame velocities from a few metres per second to more than 1000 m/s.

Buildup Conditions for a Propagating Coal Dust Explosion

Many different conditions for the buildup of an explosion are encountered in practice. To develop an explosion requires a sufficiently strong initiation, an ignitable fuel, and a sufficient oxygen concentration (explosion triangle). Because of the great number of possible initiation sources and different compositions of the fuel supply in the mining industry, the tests can be carried out in a great variety of ways. If, in addition, the tests are done in underground galleries, the study of buildup and propagation becomes a rather complicated task.

In the past years, a number of test series relevant to the above problem have been carried out in the Tremonia Experimental Mine 700-m-long explosion gallery which has a cross-sectional area of 8 m^2. The coal dust used in these experiments is the so-called "Dortmund standard coal dust," a coking coal dust with mass median particle diameter between 18 and 22 μm and a volatile content of about 25%. For the deposited dust-type of explosion test, the coal dust is dispersed pneumatically over the whole cross-sectional area of the gallery, but at the moment of ignition it has completely settled down and the deposited dust must then be dispersed and ignited (Fig. 3 left). For the ignition of a predispersed homogeneous coal dust/air mixture, the dust is blown into the free gallery cross section from pressurized bottles containing 5 kg of coal dust each under a pressure of 60 bar (6000 kPa) via specific nozzles and is then ignited (Fig. 3 right). The minimum "Dortmund standard coal dust" concentration for propagating explosions with deposited dust is $\simeq$100-g/m^3 gallery volume, and with a dispersed coal dust/air mixture it is between 35- and 50-g/m^3 gallery volume.

Coal dust explosions at the Tremonia Experimental Mine are normally ignited in two steps consisting of an explosive initiation with 2.5-kg black powder (primary initiation), followed by

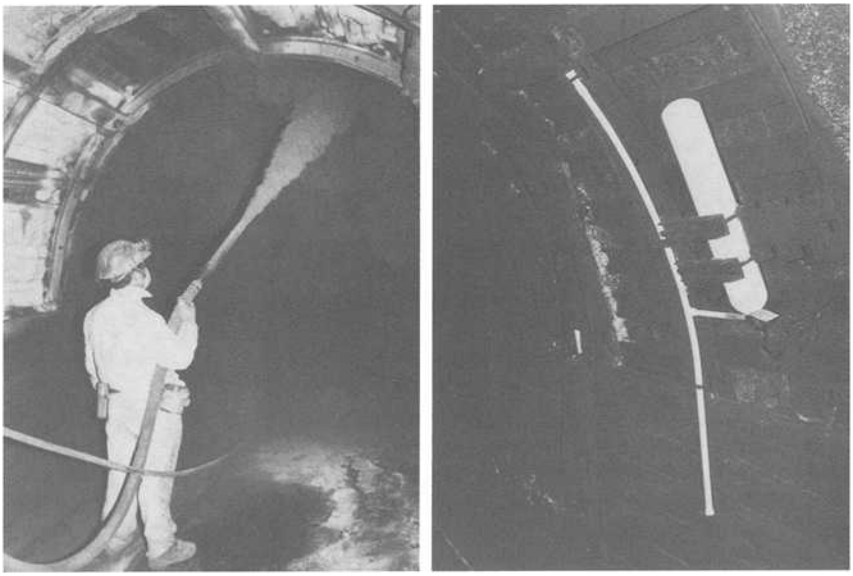


FIG. 3—*Pneumatic dispersion of coal dust* (left) *manual and* (right) *mechanical by bottles.*

10 kg of coal dust dispersed from pressurized bottles (secondary initiation). The explosive is ignited in a so-called W-Mortar (Fig. 4). If necessary, methane mixtures with different CH_4 concentrations can be used as initiation sources.

The course of a coal dust explosion is not only determined by the type of initiation but also by the length of the fuel zone and the composition and concentration of the fuel supply.

Instrumentation and Recording of the Explosion Tests

The 700-m explosion gallery is equipped with

- every 12.5 m: optical sensors (photo transmitters) to record the flame,
- every 25.0 m: pressure transducers to record the static pressure, and
- every 50.0 m: pressure transducers to record the dynamic (wind) pressure.

In addition, thermocouples measure temperature development during and after an explosion. Depending on the experimental tasks, special instruments are used to analyze the explosion fumes (CO, CO_2) (Fig. 5). Normally, the explosion tests are recorded by a video camera and one or two high speed cameras.

The measured data are transmitted to the surface by two separate systems. The one is a conventional analog system, in which every pair of cables leads separately to the surface where the measured values are recorded with light spot oscillography. The other system transmits the

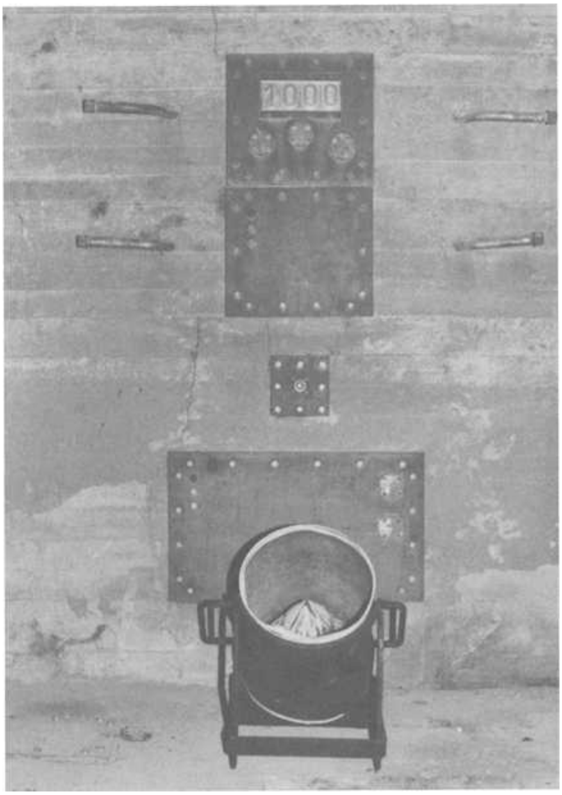


FIG. 4—*W-mortar for initiating coal dust explosions.*

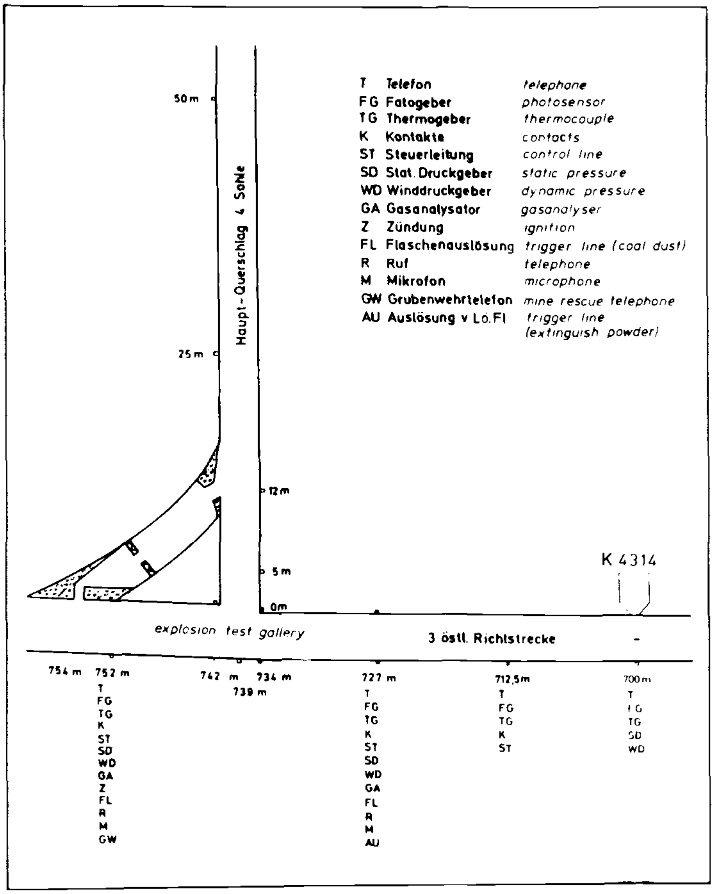


FIG. 5—*Extract of the measurement equipment in an explosion gallery.*

same values digitally to a data processing installation by means of the pulse-code-modulation (PCM) method (Fig. 6). The maximum data transmission rate of this installation is 1.28 Mbits/s. This means that 128 analog and 256 binary channels can be scanned.

Test Procedures and Results

In the test series the following parameters were varied to assess their influence on the course of the explosion:

- primary initiation: 0.675-, 1.25-, and 2.5-kg black powder and methane;
- secondary initiation: 5-, 10-, 15-, and 20-kg coal dust;
- length of fuel zone: 20, 40, 60, 80, 100, 200, and 300 m;
- coal dust concentration: 300- and 500-g/m^3 gallery volume;
- mean particle diameter of coal dust: 20, 220, and 330 μm; and
- quantity of inert matter in the coal dust: 0 to 80% by weight of rock dust.

From the different combinations of the test parameters the effects on the flame length and pressure development of the explosions could be determined.

FIG. 6—*Electronic data processing system.*

Influence of the Initiation Source

The Tremonia Experimental Mine standard procedure for initiating propagating coal dust explosions (2.5-kg black powder and 10-kg dispersed coal dust) generates a maximum dynamic pressure of 100 mbar (10 kPa). This dynamic pressure consistently raises the deposited coal dust. The relatively strong initiation guarantees the reproducibility of large-scale tests.

Of course, a propagating explosion can be initiated with smaller quantities of explosive, together with dispersed coal dust. Table 2 lists the dynamic pressure values obtained with less explosive and different quantities of dispersed coal dust for initiation.

It shows that the different combinations of initiation allow good monitoring of the violence of a coal dust explosion. The development of dynamic pressures for different combinations of initiation in the 700-m explosion gallery is shown in Fig. 7. Figure 8 gives the development of the static pressures with the same arrangement. With the chosen explosive initiation, a propagating coal dust explosion would not be possible without the added predispersed coal dust.

However, the combined explosive-coal dust initiation can be replaced by a gas initiation source. To attain the dynamic pressure of 100 mbar (10 kPa) with the standard Tremonia initiation, about 4.5-m^3 pure methane must be ignited in the 8-m^2 gallery (50-m^3 volume with 9% CH_4). Gas initiation is rarely used because its preparation takes more effort than an explosive coal dust initiation.

TABLE 2—*Dynamic pressure in mbar at 50 m and (100 m) from the face for different initiation sources.*

Quantity of Black Powder, kg	Raised Coal Dust, kg 10	15	20
0.625	0 (20)	100 (60)	0 (150)
1.25	. . . (40)	. . . (80)	180 (150)
2.5	80 (60)	230 (160)	170 (150)

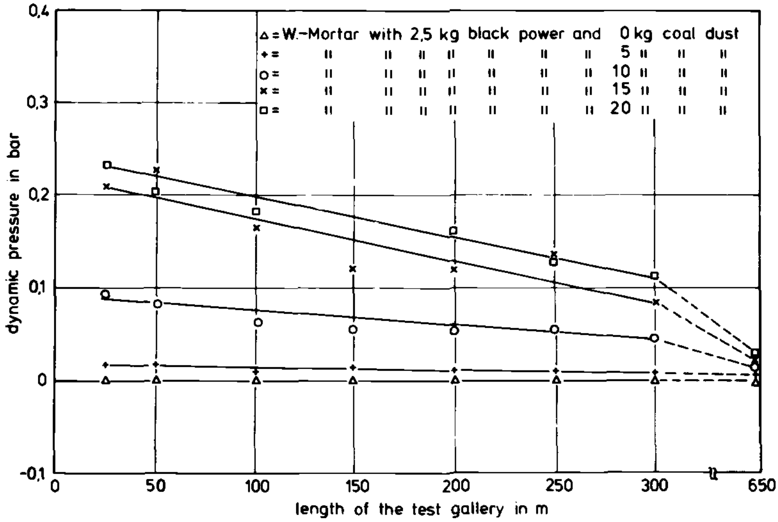


FIG. 7—*Dynamic pressures for different initiation sources.*

Fuel Zone

In coal mines, the length of roadways with deposited coal dust may attain several hundred or even several thousand metres. Therefore, it is important to investigate the development and course of coal dust explosions in different fuel zone lengths, especially the pressure development and flame length. The dynamic pressure development of explosions with fuel zones from 20 to 100 m long shows a distinct change and a shift of the maximum pressure values (Fig. 9). Increasing the length of the dusted zone by a factor of 5 from 20 to 100 m increases the dynamic pressure by factor 15. In the case of a 40-m fuel zone, the maximum pressure values are recorded at 50 m. If

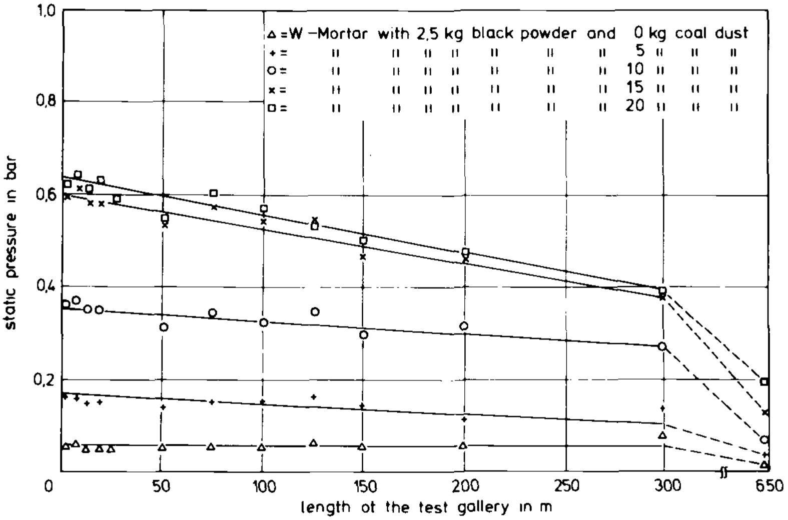


FIG. 8—*Static pressures for different initiation sources.*

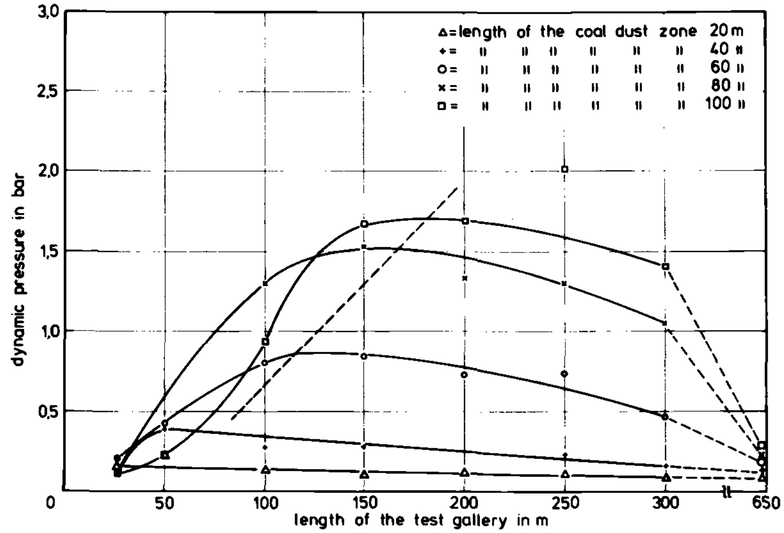


FIG. 9—*Dynamic pressure as a function of the length of the deposited coal dust zone (coal dust concentration* = *300 g/m*^{3}*).*

the fuel zone is 100 m long, these maximum values are recorded at 200 m from the face. For fuel zone lengths greater than 100 m, the maximum dynamic pressure values are 6 bar (600 kPa) for a 200-m zone and 7 bar (700 kPa) for a 300-m zone. Compared with the 100-m fuel zone, the dynamic pressure is increased by factor 4 in the case of a 300-m fuel zone with a threefold coal dust quantity (Fig. 10).

For maximum static pressure there is almost a linear relation between pressure and the length of the fuel zones (Fig. 11). With longer fuel zones, however, the static pressures show a different

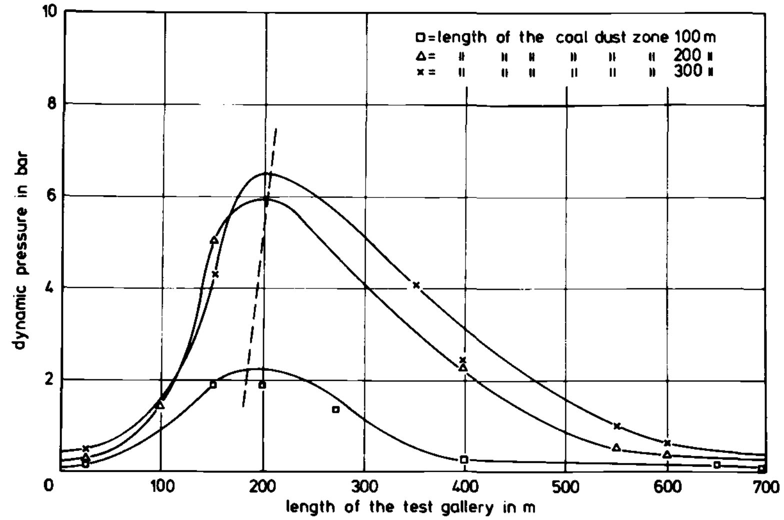


FIG. 10—*Dynamic pressure as a function of the length of the coal dust zone (100 to 300 m).*

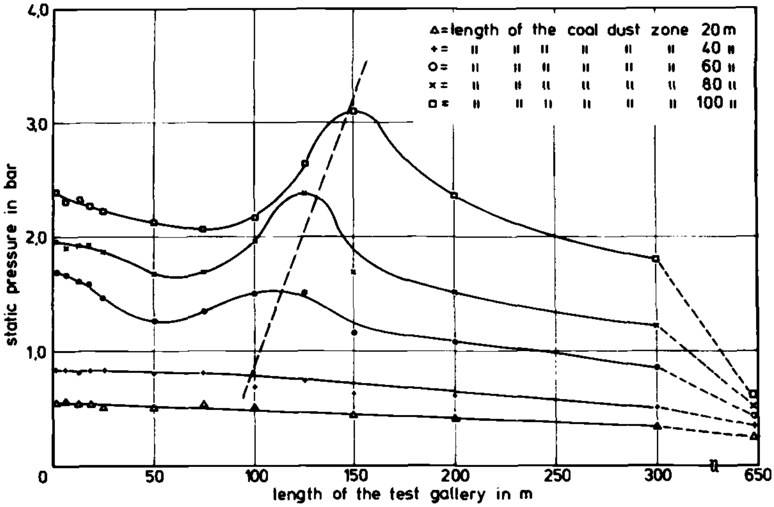


FIG. 11—*Static pressure as a function of the length of the coal dust zone (coal dust concentration = 300 g/m³).*

behavior (Fig. 12). Increasing the fuel zone length by a factor of 3 increases the static pressure by a factor of 6 for the 300-m fuel zone compared to the 100-m fuel zone. Regarding flame length as a function of the length of the fuel zone, a prolongation of flame length by a factor of 3 to 4 is obtained for fuel zones up to 100 m. For longer fuel zones, the factor is 1.5 to 2.0 (Fig. 13).

Coal Dust Concentration

The influence of the coal dust concentration on the course of the explosion was investigated at 300 and 500 g/m³ gallery volume. Compared with smaller coal dust concentrations, depending on

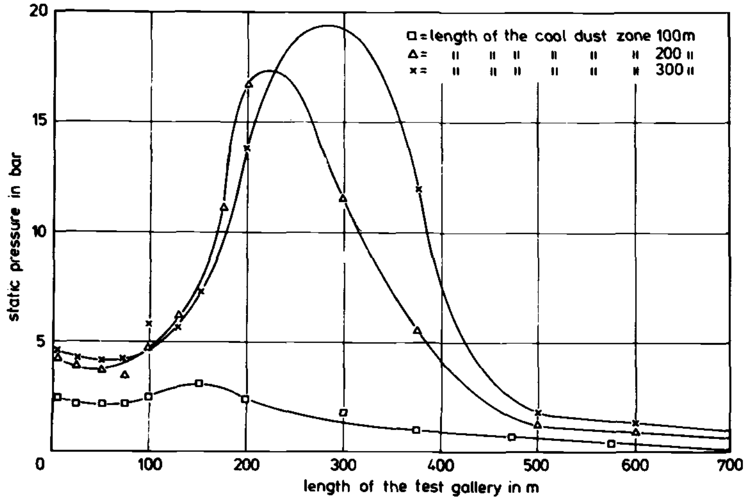


FIG. 12—*Static pressure as a function of the length of the coal dust zone (100 to 300 m).*

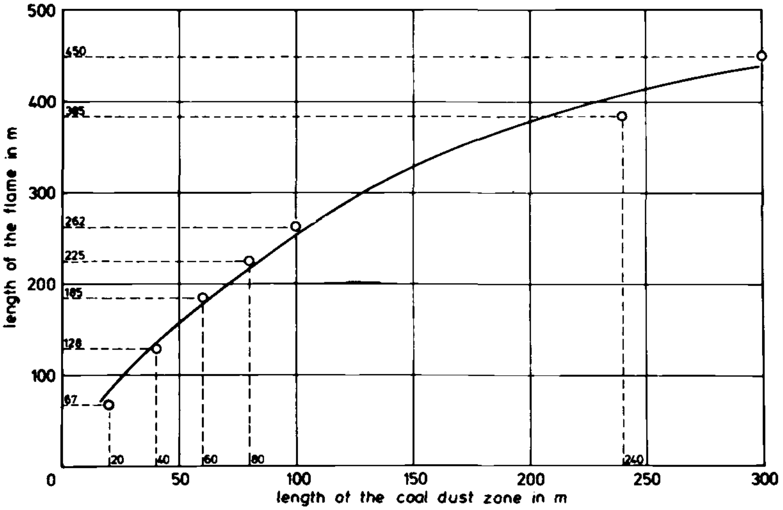


FIG. 13—*Length of the flame as a function of the coal dust zone (20 to 300 m).*

the fuel zone, the higher concentrations generated static pressures with more distinct maximum peak pressures values (Figs. 14 and 15). With elevated coal dust concentrations, this means that the explosions were more reactive. The maximum pressures were reached in a very narrow region and shifted from 95 to 125 m with increasing length of dusted zone. The maximum dynamic pressure values were not influenced by the increased coal dust concentrations, but merely led to an earlier rise in the dynamic pressure for the fuel zones exceeding 60 m (Figs. 16 and 17).

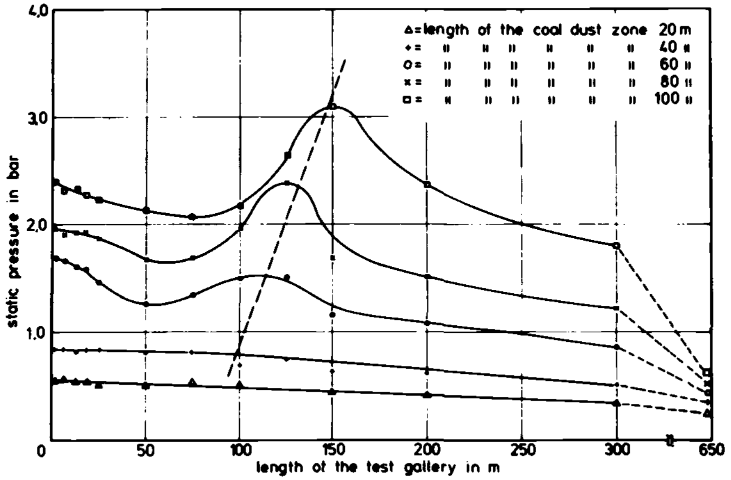


FIG. 14—*Static pressure as a function of the length of the coal dust zone (coal dust concentration = 300 g/m³).*

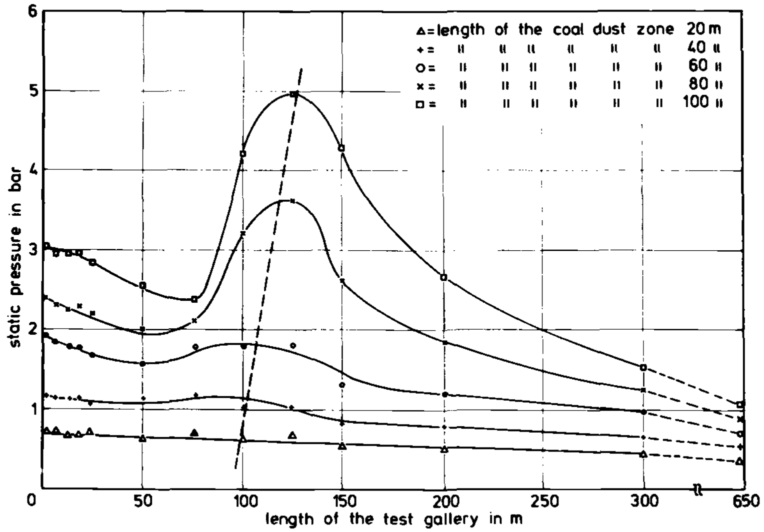


FIG. 15—*Static pressure as a function of the length of the coal dust zone (coal dust concentration = 500 g/m³).*

Particle Size of Coal Dust

The influence of particle size distribution on the course of an explosion has frequently been investigated. Within the scope of this study, particle sizes were investigated that are barely capable of supporting explosions. The Dortmund standard coal dust (median diameter of 20 μm) was compared with coarse dusts (coking coal) having median diameters of 220 and 330 μm. The sizes were determined by sieve analyses.

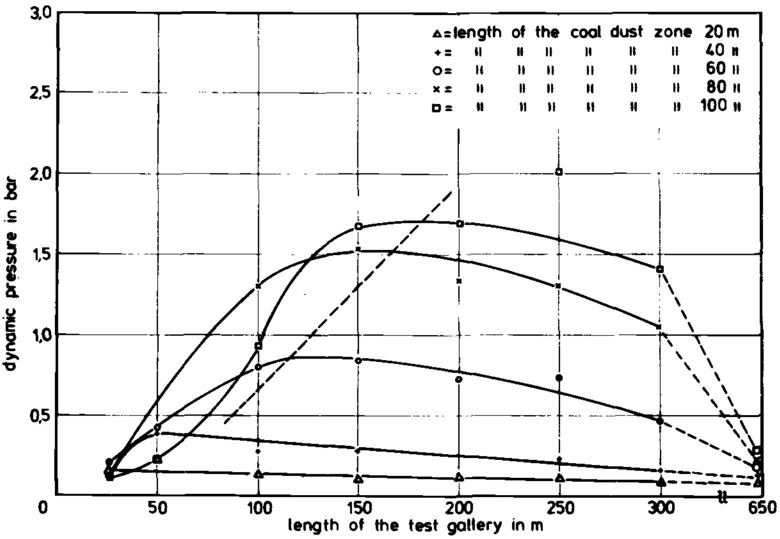


FIG. 16—*Dynamic pressure as a function of the length of the coal dust zone (coal dust concentration = 300 g/m³).*

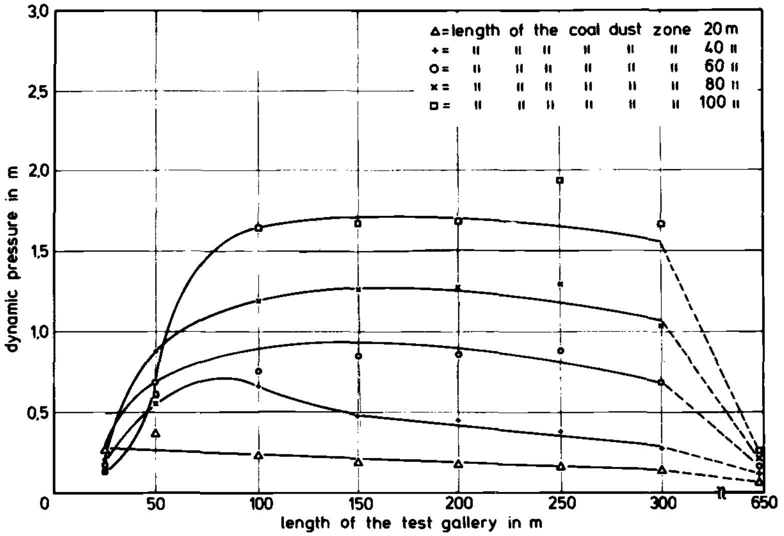


FIG. 17—*Dynamic pressure as a function of the length of the coal dust zone (coal dust concentration = 500 g/m*^{3}*).*

In fuel zones of 20- to 80-m length with coarse coal dust having a median value of 330 μm, no propagating explosions could be ignited. Explosion pressure and flame travel remained below the values obtained with standard initiation. Coarse coal dust with a median value of 200 μm, however, clearly reacted but the generated pressures were only slightly higher than the pressures generated with standard initiation. The flame travelled well beyond the fuel zones, generally to a length of twice the dusted zone.

Inert Fraction in the Coal Dust

According to the mining authority regulations for West German coal mines, the combustible content of the deposited dust must not exceed 20% by weight. This is examined by regular sampling. If the combustible content is higher than the required limit value, inert matter, for example, rock dust, must be added till that limit is reached.

With 80% by weight inert matter, no self-propagating explosion is possible. Figures 18 and 19 show the length of flame travel for different rock dust concentrations in 240- and 300-m fuel zones of the 20-μm Dortmund standard coal. The numbers in parentheses refer to the mass of coal dust (secondary) initiation. A reduction in the required 80 to 75% by weight causes a flame length that is 100 m longer than the fuel zone. The maximum static pressure increased to 0.7 bar (70 kPa). Concentrations of only 60 and 65% by weight of inert generate rather strong explosions with a flame that travels two times the fuel zone length. Maximum explosion pressures were between 4 and 5 bar (400 to 500 kPa).

Summary

The course of coal dust explosions underground is affected by many factors. In a 700-m long, 8-m^2 cross-sectional gallery at the Tremonia Experimental Mine, the influence of the following factors were investigated:

- initiation,

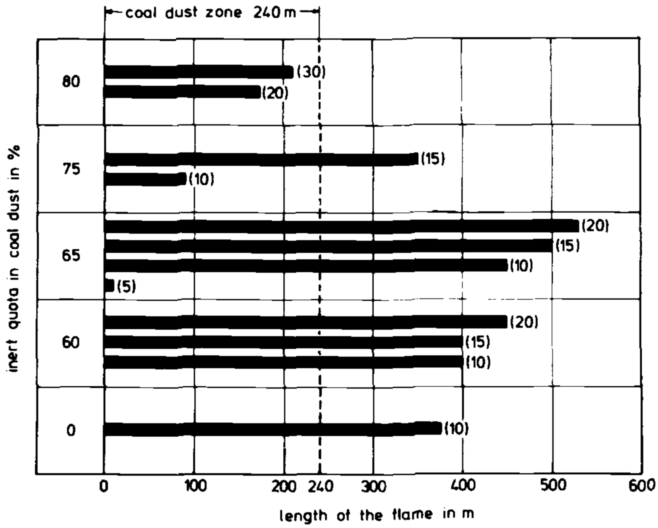


FIG. 18—*Length of the flame by different percentages of inert material in coal dust (coal dust zone = 240 m). The number in parenthesis refers to the amount of coal dust (kg) in the initiation zone (secondary initiation).*

- fuel zone,
- coal dust concentration,
- mean particle size of coal dust, and
- inert matter concentration in coal dust.

The following results were obtained. The Tremonia standard initiation of coal dust explosions consists of 2.5-kg black powder (primary initiation) and 10-kg dispersed coal dust (secondary initiation). This, by itself, generates a dynamic pressure of about 100 mbar (10 kPa) and consistently disperses the coal dust layer. A variation in the initiation combinations can be used to control coal

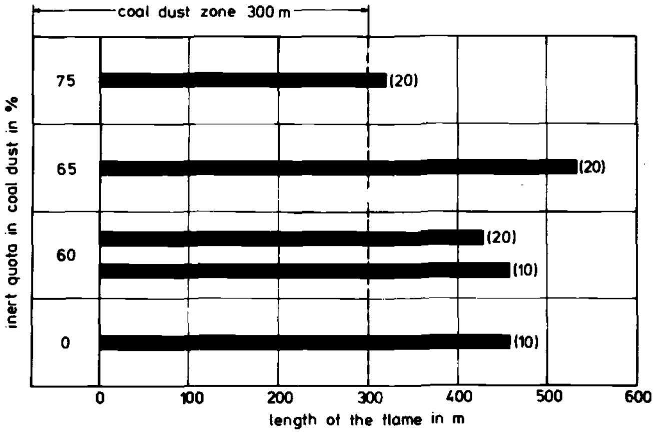


FIG. 19—*Length of the flame by different percentages of inert material in coal dust (coal dust zone = 300 m). The number in parenthesis refers to the amount of coal dust (kg) in the initiation zone (secondary initiation).*

dust explosions. Weakening the combined initiation does not lead to reproducible explosion behavior. A comparable methane initiation requires the quantity of 4.5-m^3 pure methane.

When the fuel zones were lengthened, the flame travel distance also increased. The ratio of flame travel to length of fuel zone is reduced from 4:1 for a 20-m fuel zone to 1.5:1 for a 300-m fuel zone. In the case of very long fuel zones, maximum static pressures of about 18 bar (1800 kPa) were generated.

A variation in coal dust loading had a marked influence, especially when the fuel zones were short. In the case of long fuel zones, the coal dust loading did not influence the flame length. Shifting of the maximum pressure values had to be regarded.

The tests with coarse coal dusts yielded different results from the fine coal dust tests. A coal dust with a median particle size of 220 μm generated explosion flames exceeding by far the fuel zones. With increased median value of 330 μm, flame lengths were constantly 50 m, regardless of the fuel zone length. The maximum explosion pressures in all cases were below the maximum values obtained with standard initiation alone.

Mixing coal dust with rock dust caused nonpropagating explosions when the inert matter content was 80% by weight. A reduction of the inert matter content to 75% by weight resulted in fully developed propagating explosions with maximum pressures of less than 1 bar (100 kPa).

Daniel Ng,[1] *Michael Sapko,*[1] *Aldo Furno,*[1] *and Richard Pro*[1]

Coal Dust and Gas Explosion Suppression by Barriers

REFERENCE: Ng, D., Sapko, M., Furno, A., and Pro, R., "**Coal Dust and Gas Explosion Suppression by Barriers,**" *Industrial Dust Explosions, ASTM STP 958,* Kenneth L. Cashdollar and Martin Hertzberg, Eds., American Society for Testing and Materials, Philadelphia, 1987, pp. 138–151.

ABSTRACT: Explosion suppression barriers are devices that contain fire extinguishants that are activated to disperse at some critical point during the propagation of an explosion to suppress it. Suppression of coal dust explosions using barriers (both triggered and passive) has been investigated by the U.S. Bureau of Mines. The work reported in the present study is an update of the continuing study of passive barriers of both rigid and flexible construction. Suppressants tested were water and ABC powder (ammonium phosphate). The coal dust mixtures contained 60 to 65% total incombustible matter and were distributed in the Bureau's single entry experimental mine for a total distance of 111 m (365 ft). Dust explosions were initiated by a 7% methane–air gas zone at the face. The passive barriers were located at distances of 60 to 108 m (200 to 356 ft) from the face. At these distances, the magnitude of the explosion pressure pulse was about 0.70 to 1.14 bar (70 to 114 kPa) at the time the flame front arrived at the barrier. With the exception of the powders, the pressure pulse was sufficiently energetic to fracture the troughs and disperse the suppressants.

The powder (approximately 180 kg per test) was almost totally ineffective when used with the rigid barrier because it did not disperse. One to four troughs of water effectively suppressed explosions. It was found that the mounting arrangement for the flexible troughs was most important for successful operation and release of the suppressant.

Triggered barrier systems for protection against incipient gas explosions were tested in a simulated longwall panel. Results show that ABC powder was much more effective in suppressing the developing explosion than equal amounts of water released from the same pressurized reservoir. Although water was effective in stopping fully developed dust explosions, it had little effect against an explosion during its incipient stage.

KEY WORDS: coal dust, dust explosion, underground explosion, coal mines, inhibitor, fire extinguishing agents, shock waves, fire suppressants, explosion barriers, mine explosions

Coal dust is produced throughout the working sections of mines from normal mine operations such as blasting, cutting, loading, and transporting coal. The finer fractions of float coal dust (<74 μm) are carried by the mine's ventilation system for long distances before settling on the roof, ribs (walls), and floor surfaces.

A coal dust explosion can be initiated by the ignition of methane gas pockets being released at the coal face (the solid surface of the unbroken portion of the coalbed at the advancing end of the working place). The methane–air mixture can be ignited by frictional ignition from the coal cutting bits, by electrical sparks, or by nonpermissible use of explosives. The methane explosion can disperse and ignite coal dust in its path. As coal dust burns, more dust is dispersed, and the

---

[1] Research physicist, supervisory chemical engineer, supervisory research physical scientist, and physical science technician, respectively, U.S. Department of the Interior, Bureau of Mines, Pittsburgh Research Center, Cochrans Mill Rd., P.O. Box 18070, Pittsburgh, PA 15236.

process continues to propagate to considerable distances, doing extensive damage to the mine, and with deadly consequences to the miners.

The main protective measure presently used in U.S. mines to prevent explosions is generalized rock dusting. Rock dust (for example, limestone, dolomite, or shale) is applied throughout the mine to inert the coal dust. The technique may not be totally effective in mine areas where fresh dust is being produced at a rapid rate. Therefore, other means of protection are required to supplement generalized rock dusting.

Additional protective measures have been aimed at preventing ignitions or rapidly suppressing flames after they have started. Barriers have been experimentally demonstrated, and some are used in mines in Europe for protection against coal dust explosions. The Bureau of Mines has been investigating the potential use of barriers for supplemental protection in U.S. mines [*1–2*].

Past research by the Bureau of Mines [*4,5*] has shown that rigid West German water barriers satisfactorily suppress moderate-strength dust explosions in single and conveyor belt entries. For slow moving dust explosions (below 30 m/s), those barriers initially were not so effective; however with slight modifications the barriers were shown to be effective even for mild dust explosions.

This report describes the use of water barriers to suppress coal dust explosions in the U.S. Bureau of Mine's Experimental Mine. Some rudimentary work on the use of trigger barriers in a simulated longwall mining situation will also be described.

Experimental Mine

Mine explosions are accidents or uncontrolled events. Simulated explosions conducted in the Bureau of Mine's Experimenal Mine under ontrolled conditions have a high degree of reproducibility. They are generated in the 396 m (1300 ft) long main single entry (in coal mining, an entry is a haulage road, gangway, or airway to the surface) of the Experimental Mine (Fig. 1), and are initiated by igniting a 7% methane gas–air mixture which is confined to the first 4.6 m from the mine face by a thin plastic diaphragm. This is followed by a 110-m test zone containing a nominal dust concentration of 200 mg/L. The coal dust was intimately mixed with rock dust (calcium carbonate) and distributed one third on the rib, one third on the floor, and one third on roof shelves. The Pittsburgh pulverized coal (PPC) dust consisted of 80 to 85% <74-μm diameter particles containing about 36% volatile matter. Premixing of coal and inert dust is performed so that the total incombustible content of the resulting dust mixture is 60 to 65%. This dust mixture

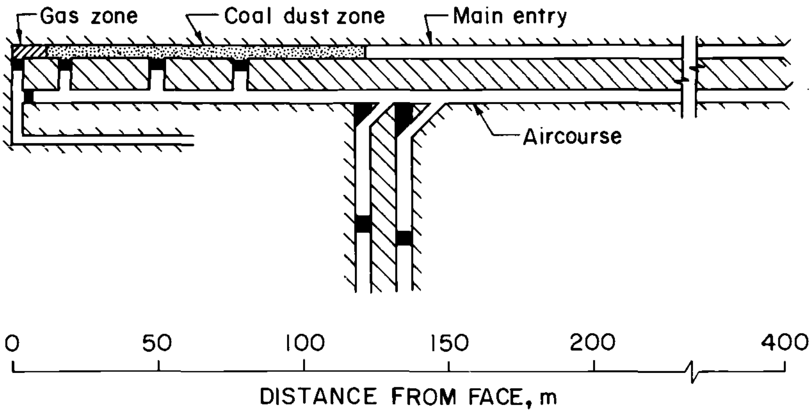


FIG. 1—*Schematic of the Experimental Mine test zone.*

is then spread throughout the test zones, which varied from about 60 m to over 106 m from the mine face to simulate various conditions in a working mine. The methane mixture is ignited remotely. The resulting gas explosion propagates into the dust-laden test zone, dispersing and igniting coal dust to produce a violent coal dust explosion.

Pressure transducers and flame sensors are placed at regular intervals along the full length of the entry. These instruments allow us to record, both on hardcopy and directly into automatic data processing hardware, the progression of the explosion as depicted by pressure, flame arrival time, and other pertinent information as a function of time and position. Graphic representations of some of these experimental explosions are shown later in this report. (More detailed descriptions of the instrumentation, test procedures, and so forth, appear in a previous publication of the Bureau of Mines [*6*].

Passive Barriers

Explosion suppression barriers are devices that contain fire-extinguishants that are activated to disperse at some critical point during the propagation of an explosion to suppress it. This report primarily focuses on suppressing coal dust explosions in a single entry using passive barriers. Passive barriers do not possess intrinsic mechanisms to release or disperse their extinguishant contents. They depend on the explosion itself to effect the dispersal.

Water is an effective extinguishing agent, and a passive water barrier consists of a volume of water in a container positioned at some location (usually near the roof) in a mine. Release of the water to suppress the explosion is achieved by harnessing the energy carried by the shock wave or aerodynamic disturbance that precedes the propagating coal dust explosion. The shock wave, traveling at sonic speed or greater, will arrive at the barrier location (anywhere from 75 to 100 m from the mine face) ahead of the flame front, which generally travels at a slower speed. The effectiveness of passive barriers depends on the time interval between the rupture of the barrier and the arrival of the flame at the barrier. For strong explosions this time interval may be too short, allowing little time for water dispersion, whereas for weak explosions the time interval may be too long, resulting in the loss of water to the rib, roof, and floor before flame arrival. Because of these dispersion limitations, explosions at the two extremes are more difficult to suppress.

In most cases, the shock waves (aerodynamic disturbances) are energetic enough to disperse the water in the barriers (either by tipping them over or by shattering them). The water barriers tested were mainly of two designs, rigid and flexible.

The German designed water barriers are basically troughs made of rigid polyvinyl chloride (PVC) plastic measuring approximately 30 by 50 by 75 cm (Fig. 2). Each barrier has a volume of about 80 L. These barriers are usually supported at their rim by a metallic frame. The barriers were tested singly, as a pair mounted side by side, or as multiple pairs separated by some distance along the mine entry. Previous Bureau researchers [*1,2*] have discovered that the ability of this type of barrier to release its contents improves if the width of the rims is reduced. This version of the rigid trough, referred to as the modified German trough, is used with or without a lid. The lid serves only to reduce the rate of evaporation and does not affect the performance of the barriers in suppressing coal dust explosions.

Fire-inhibiting agents such as di- and mono-ammonium phosphate (ABC) are known to be very effective as commercial fire-extinguishing agents. When they are premixed with coal dusts, they are also more effective than rock dusts in laboratory and full-scale mine dust explosion suppression [*7,8*]. Since ABC powder has been shown to be a more effective inert than water when mixed with coal dust, experiments were conducted with ABC substituted for water in these modified German troughs.

The choice of water as an extinguishant is natural due to its availability, ease of handling, and effectiveness against carbonaceous dust explosions.

FIG. 2—*Rigid water barriers (German design) hung from mine roof.*

FIG. 3—*Flexible water barriers (Japanese design).*

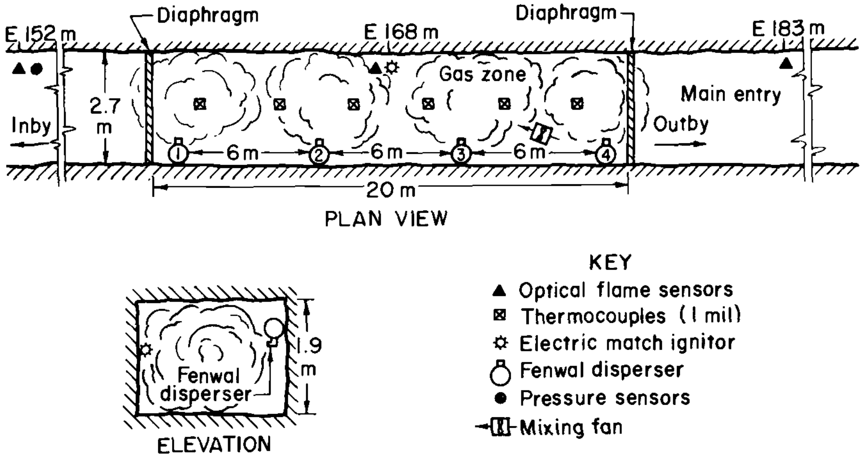


FIG. 4—*Simulated longwall in section of Experimental Mine.*

In some countries, including Japan, passive water barriers made of flexible plastic material in bag form are used. They are suspended from a support structure with hooks (Fig. 3). These flexible barriers have a semicircular cross section 25-cm radius, are either 60 or 120 cm long, and can hold 40 or 80 L, respectively.

Triggered Barriers

Methane gas ignitions can initiate dust explosions and are a hazard during underground coal mining. Most of these ignitions originate at the working face. The ignitions are caused by the impact between cutter bits and minerals. This frictional heating ignites methane, and a gas explosion ensues that can, in turn, initiate a coal dust explosion. The present defense against the methane ignition hazard is adequate ventilation of the face area. Such ventilation dilutes the methane to below its lean limit of flammability as it is released. However, ventilation is not always adequate—40 or more face ignitions are still reported every year in U.S. mines, and many more ignitions probably go unreported. To protect against these ignitions developing into a destructive explosion, the Bureau of Mines has been developing triggered barrier systems for use with mining machines. Triggered barriers typically consist of a flame sensor, disperser, and extinguishing agent. The flame sensor activates the disperser, which rapidly releases the agent stored under pressure. For the work discussed here, spherical Fenwal[2] dispersers were used to suppress ignitions on a longwall simulation. These spherical barriers are approximately 33 cm in diameter and operate satisfactorily when filled up to 70% with water or completely filled with powder. The water or dust is pressurized with nitrogen gas to 21 bar (2100 kPa). The material is released by the explosive rupturing of a prescored diaphragm and exits through a 90° elbow and a spiral nozzle.

The simulated longwall suppression tests were conducted in the main entry of the Bruceton Experimental Mine located near Pittsburgh, PA. A 20-m-long zone was partitioned off with plastic diaphragms at about 168 m from the face (Fig. 4). The left rib of the mine was used to simulate the longwall coal face, and the four triggered barriers (Fenwal dispersers) were located along the right rib approximately where the roof support system would be. The 120° spiral nozzles were

---

[2] Reference to specific tradenames is made for identification only and does not imply endorsement by the Bureau of Mines.

directed toward the simulated face. Several small thermocouples were positioned along the roof to detect the fireball and trigger the barriers. (Thermocouples are shown as xs enclosed in squares in Fig. 4 and numbered 1 through 6 from the inby direction. In mining, *inby* means toward the working face or interior of the mine, away from the shaft or entrance; a similar term, *outby,* is the opposite of inby.) The barriers were triggered from the output of these 1-mil-diameter thermocouples (Pt 10% Rh) located along the roof. If any one of the thermocouples 1, 2, or 3 inby sensed a temperature rise of 300°C (572°F), then barriers 1 and 2 were fired. Outby thermocouples 4, 5, and 6 triggered barriers 3 and 4. Methane gas was injected and mixed with a permissible fan, and methane content within the 20-m zone was determined before ignition. Ignition of the gas was in the center of the gas zone with an electric match. Only a limited number of tests were conducted in the Experimental Mine. The objective of these tests was to determine the effectiveness of water and ABC powder against developing gas explosions and the relative efficiency of dispersers and spiral nozzles in the longwall simulation.

Results and Discussions

Passive Barriers

More than 20 dust explosions were performed in the Experimental Mine using both rigid and flexible passive barriers. Each explosion was initiated by a 7% methane–air mixture as described above. The dust concentration and application were as described earlier. One or two rigid (German) or flexible (Japanese) barriers were mounted as described in previous reports and publications [*1,4,5*] at the test locations and filled with 40 to 160 L of water. The results of recent tests are summarized in Tables 1 and 2. In these tables are shown the explosion's flame speed as it approached the barrier, the distance between the flame and the barrier at the time of incipient rupture of barrier, and the time between rupture and arrival of the flame. Depending on the distance the barrier is away from the mine face, this time is between 240 and 460 ms.

The explosion is considered suppressed if the flame does not propagate more than 30 m beyond barriers.

Explosion suppression tests were conducted with the barrier located at distances ranging from 97 to 124 m from the face of the mine. Both modified and unmodified German rigid barriers were used. Two of these barriers, containing a total of 160 L of water consistently stopped the explosions at the barrier locations. The flame speeds approaching the barriers were generally around 180 to 250 m/s as measured and verified by the acoustic approximation using static pressure rise, at leading edge of flame arrival at the station:

$$P = dcv^2$$

where

d = gas density,
c = velocity of sound,
P = pressure at leading edge of flame, and
v = air (gas speed)

assuming flame speed equal to air speed at the flame front [*9*].

A pressure history measured at 122 m from the face for a typical strong explosion (Test 4097) of Pittsburgh coal dust and 65% rock dust mixtures in which the flame traveled to over 340 m (1100 ft) from the face is shown in the upper curve of Fig. 5. The maximum flame speed approaching this station was about 253 m/s, and the maximum static pressure was about 1.53 bar (153 kPa). The decrease in pressure at 3.1 s indicated the arrival of expansion waves from the open end, so that the static pressure started to drop below atmospheric.

Data for a typical suppression experiment with passive barriers are also shown in the lower

TABLE 1—*Rigid barrier results.*

Test No.	Total Incombustible, %	Barrier Site, m	Agent	Quantity, kg	Flame Travel, m	Suppression	Pressure at Barrier, bar[a]	Flame Speed, m/s	Elapsed Time to Flame Arrival, ms
4078	65	97	water	160	107	yes	1.10	268	270
4079	65	97	ABC	180	198	no	0.93	226	340
4080	65	97	ABC	180	198	no	0.83	201	330
4081	65	97	water	160	122	yes	0.93	225	300
4082	65	108	water	160	192	no	0.76	184	440
4083	65	108	water	320	168	marginal	0.69	167	460
4084	65	124	water	320	168	marginal	0.86	210	440
4085	65	122	water	320	137	yes	0.84	205	460
4086	64	121	water	160	137	yes	1.17	285	340
4087	65	121	water	160	137	yes	0.86	210	370

[a] Pressure readings are gauge values.

TABLE 2—*Flexible barrier results.*

Test No.	Total Incombustible, %	Barrier Site, m	Agent	Quantity, kg	Flame Travel, m	Suppression	Pressure at Barrier, bar[a]	Flame Speed, m/s	Elapsed Time to Flame Arrival, ms
4088	65	121	water	160	137	yes	0.97	235	350
4086	65	121	water	160	137	yes	0.83	200	410
4090	65	121	water	80	137	yes	1.14	276	360
4091	60	121	water	80	137	yes	0.93	226	250
4092	65	61	water	80	76	yes			260
4093	60	61	water	80	76	yes	0.64	156	243
4094	65	97	water	80	122	yes			463
4095	65	97	water	80	122	yes			335
4096	60	97	water	80	107	yes	1.45	359	278

[a] Pressure readings are gauge values.

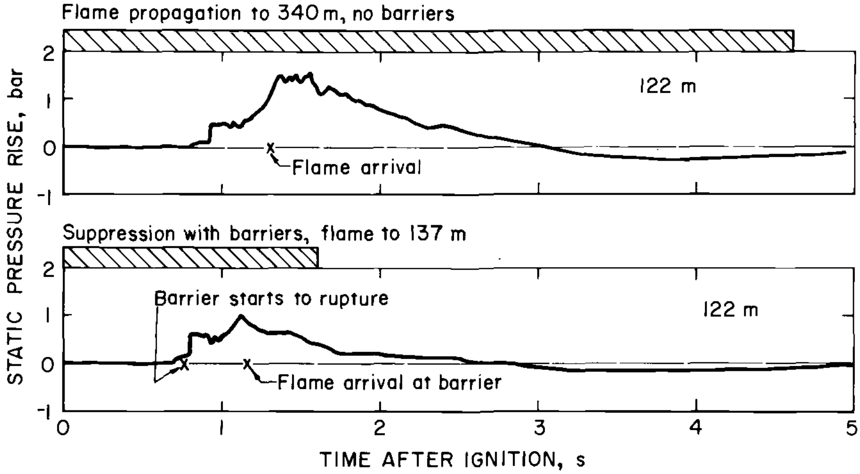


FIG. 5—*Wave diagram of an unsuppressed and suppressed explosion.*

curve of Fig. 5 showing flame arrival time, static pressure rise, and the time for the barrier to begin to rupture. Barrier breakage occurred when the flame front was about 76 m away, which allowed about 0.4 s for water dispersion in advance of the flame. Flame extinguishment occurred slightly beyond the 122-m station. After the tests, water was found on the floor of the mine, and sometimes on the roof extending 15 to 30 m outby.

The flexible Japanese design water bags were also used to suppress dust explosions of similar magnitudes. Previously, it was found that the flexible bags were not efficiently dispersing the water when suspended by J-shaped hooks. It was observed that the geometry of the hooks was interfering with the release of the bags. The ends of these hooks were shortened, and the bags were mounted as shown in Fig. 3. After these modifications, the bags operated more effectively.

Two large bags, containing the same amount of water (160 L) as two German barriers, were able to suppress similar explosions at 112 m (368 ft) from the face. The quantity of water was then reduced to 80 L in two small bags, and this suppressed similar dust explosions at the same location. Locating only one large flexible bag (containing 80 L) at 318 ft (97 m) from the mine face also suppressed similar explosions.

Eighty liters of water in two small flexible bags sixty metres from the face was sufficient to suppress similar explosions. These results indicated that the Japanese water bags were capable of suppressing moderate strength explosions from 60 to almost 120 m away from the source of ignition.

With the demonstrated success of using German troughs filled with water to suppress dust explosions, it was decided to try chemical extinguishants. ABC powder was proven to be effective in suppressing coal dust explosions when premixed with the coal at concentrations of 25 to 30% [*7,8*]. Two explosion tests were conducted using 180 kg of ABC powder instead of water in two rigid troughs; both modified and unmodified barriers were used.

The powder was almost totally ineffective in suppressing coal dust explosions of the same magnitudes. It had been reported previously [*4,5*] that water in the rigid barriers was well dispersed, as confirmed by high-speed movies [*1,5*] and visual examination of the barrier site after the experiment. In the case of powder filled barriers, observation of the barrier site after the explosion indicated that the powder was not dispersed. Instead, it was found on the floor a short distance from the barrier site in a single pile. The plastic barrier filled with water would have been shattered to small pieces by the shock wave; however, when filled with powder, it retained its structural shape. The failure to suppress explosions was attributed to the ineffective dispersion of the powder.

High-speed movies were taken of the reaction of barriers to the explosion pressure pulses. The Experimental Mine was prepared as it would be for a normal explosion test—the barriers were filled with water or powder chemical fire inhibitors. However, the usual coal–rock dust mixture was not used; the gas explosion at the face produced the necessary pressure at the barrier to rupture it. The powder chemical used in these experiments was Purple K, a commercial product consisting mainly of potassium bicarbonate also used in commercial fire extinguishers. Purple K was shown to have dispersal properties similar to those of the ABC powders used in barrier tests reported earlier.

Selected frames of the high-speed movies (Fig. 6) showed that the water in both the rigid and flexible barriers was easily and well dispersed by the shock wave produced by the gas explosion. Pictures in the left column of Fig. 6 show the action of the flexible barrier containing water; pictures in the right column show powder in the same barrier. Pictures in the middle column show water in the rigid barrier. From the instant that noticeable reactions of the barrier were observed, practically all the water is out of the barrier in less than 20 ms, and all the action is practically over within 100 ms. This was not the case with powders. It required about 400 ms for the same degree of barrier reaction to occur, and even at that instant the powder remained in very confined regions in its dispersal path. The reaction time constants of the two barrier systems differ by a factor of approximately four. A simple analysis of the action from the explosion pressure pulse on the barrier was carried out.

Assuming a one-dimensional traveling wave [*10*], considering the exchange of momentum between the gas flow ahead of the explosion and the barriers, and using values such as maximum pressure measured at the barrier location and the dimensions and mass, M, of the barrier, it was possible to estimate m, the mass of the gas involved; I, the magnitude of momentum that was exchanged; and E_i and E_f, the kinetic energies of the system before and after the interaction. The values obtained are

$m = 7.8\ \text{kg}$
$M = 80\ \text{kg}$
$I = 9.1 \times 10^2\ \text{kg-m/s}$
$E_i = I^2/m = 5.4 \times 10^4\ \text{joules}$
$E_f = I^2/(M + m) = 1.3 \times 10^4\ \text{joules}$

The impulse I is exchanged with the barrier during the passage of the pressure pulse across it. This momentum exchange produces a force on the barrier. The average magnitude of the force is equal to the impulse divided by the time interval during which the exchange takes place. For the case of a water-filled barrier, the exchange takes place in about 100 ms as observed by high-speed photography, which is also about the temporal length of the pressure pulse. Thus the momentum exchange produces a force and hence an acceleration given by

$$F = Ma = I/t$$

or

$$a = I/Mt$$

where $M = 80$ kg is the mass of the barrier and $t = 0.1$ s is the exchange time. For the case of water barrier, this gives

$$a = 1.1 \times 10^4\ \text{cm-s}^{-2} = 11.6\ g$$

where $g = 981\ \text{cm-s}^{-2}$ is the gravitational acceleration constant. A g force of 12 is a considerable force—enough to shatter many materials including water, which is easily deformable into droplets.

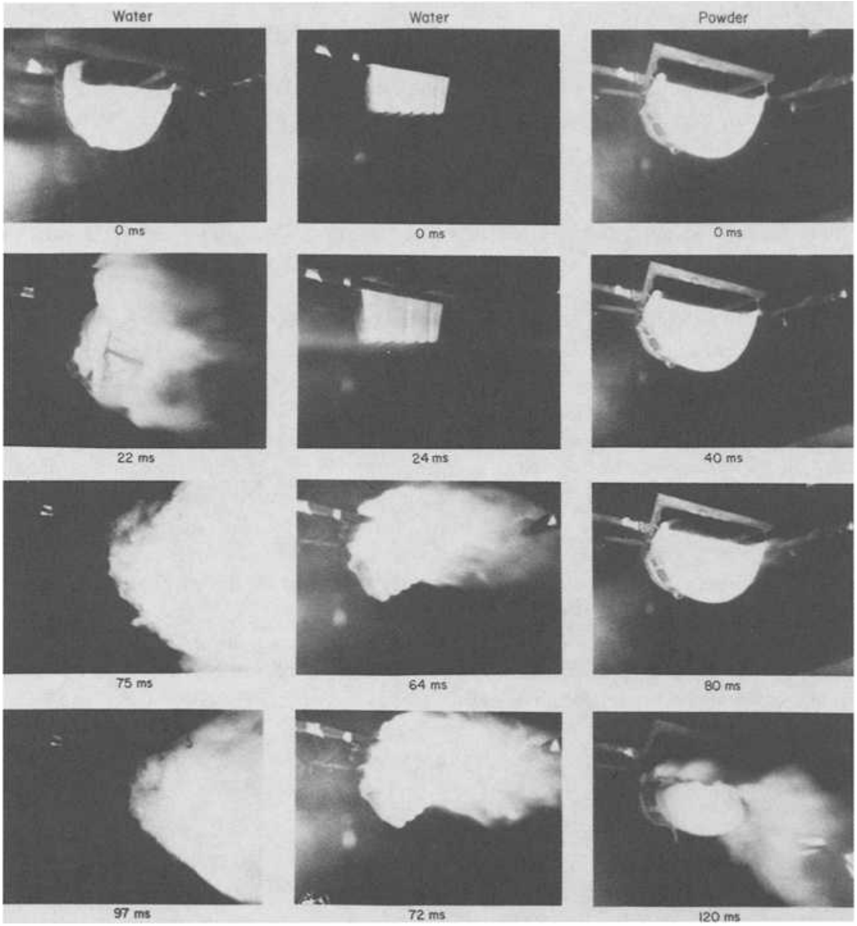


FIG. 6—*Movie sequence of powder and water barriers.*

The powder-filled barrier has about the same mass as the water (density of powder is about 0.97 to 1.16 g/cm^3). However, the powder has a damping effect which acts as a sponge to absorb energy and reduces the effectiveness of momentum transfer. High-speed movies show that it takes about four times longer for the barrier to have the same degree of action. The estimated resulting g force is only about 3. This smaller force is not capable of dispersing the powder in the barrier.

Triggered Barriers

Table 3 summarizes the conditions and results of the longwall ignition suppression trials in the Experimental Mine. It was established in Test 3922 that without the barriers, the methane explosion would propagate greater than 30 m inby and outby with respect to the point of ignition and result in a maximum pressure rise of 1.38 bar (138 kPa) at the mine face. In the tests interpreted as "suppressed," the flame did not propagate more than 15 m beyond the ignition source and a maximum face pressure rise was less than 0.57 bar (57 kPa). In the tests that resulted in "no suppression" the flame traveled at least 30 m both inby and outby the ignition source, the flame

TABLE 3—*Longwall ignition suppression by trigger barriers.*

Test	Suppressant,[a] kg	Gas, %	Maximum Pressure,[b] bar at Face	Maximum Pressure,[b] bar at 152 m	Extent of flame,[c] m Inby	Extent of flame,[c] m Outby	Remarks
3921	None	7.00	1.31	0.62	>31	>30	
3922	ABC, 45.4	8.00	0.59	0.29	16	30	partial suppression
3925	ABC, 45.4	7.00	0.61	0.33	16	15	suppression
3928	ABC, 45.4	8.00	0.50	0.27	16	30	partial suppression
3936	ABC, 45.4	7.00	0.13	0.07	0	15	suppression
3937	ABC, 45.4	7.50	0.50	0.36	0	15	suppression
3932	water, 40	7.00	1.39	0.69	>31	>30	no suppression
3933	water, 40	7.00	1.28	0.74	>31	>30	no suppression
3934	water, 40	7.00	1.28	0.81	>31	>30	no suppression
3935	water, 40	7.00	1.74	0.86	>31	>30	no suppression

[a] Spiral nozzle was used in all tests. Nitrogen reservoir pressure was 300 psi.

[b] Pressures are gauge values.

[c] Distances are measured with respect to the point of ignition.

continued to accelerate in passing the barrier, and the pressure rise was equal to or even greater than the gas explosion by itself. Tests in which the flame decelerated in passing the barrier zone, indicating a positive suppressant action, were called a "partial suppression." In the first group of tests of Table 3, using ABC powder, successful suppressions of 7 and 7.5% gas air were obtained and only partial suppression with 8% gas. In most suppressions, the flame went to or beyond the gas zone, and in most cases, flame extended more outby than inby the ignitor. In the second group of tests, the barriers were unable to suppress 7% gas explosions using the maximum water charge of 40 kg. These tests showed flame speeds and pressures exceeding those obtained without the barriers and were indicative of increased turbulence induced in the flammable gas by the rapid expulsion of water.

These same dispensers with water were adequate for quenching fully developed gas and dust explosions, presumably because the turbulent wind forces generated ahead of the flame serve to rupture the coarse water sprays into fine drops [*11*]. However, it is felt that the water is ineffective in quenching incipient gas explosions because a large fraction of water is lost to the surrounding surfaces and the wind forces necessary to rupture the water spray are absent. With powder, the fine particles stay in suspension longer and inert more of the flammable volume for similar discharge times.

Conclusion

Both rigid and flexible passive barriers were successful in suppressing moderately intense coal dust (65% incombustible) explosions when used with water as extinguishing agent. The ineffectiveness of chemical powder is not intrinsic to the powders but is due to the inability of the explosion pulse to disperse effectively the passive barrier contents. The inability to disperse the powder is due to the compressible nature of powder, which absorbs energy, thus reducing the pressure pulse's ability to disperse the extinguishant. Through effective powder dispersion, such as from a pressurized triggered reservoir, ABC powder is a viable explosion-suppressing agent.

Results of the longwall ignition suppression study indicate that ABC extinguishant is more effective than water in triggered barriers for suppressing incipient gas explosions. The tests also show that the explosion intensity was increased by the triggered barrier when discharging high-velocity water. This high-velocity discharge increases the turbulence of the unburned gas, causing an increase in the turbulent burning velocity.

Acknowledgment

We would like to acknowledge Dr. John Edwards and Dr. Charles Hwang for providing valuable discussions, and Ken Mura and Kevin Luster for assistance in the performing the experiments.

References

[*1*] Liebman, I. and Richmond, J. K., "Suppression of Coal Dust Explosion by Water Barrier in a Conveyor Belt Entry," Bureau of Mines Report of Investigations 8538, 1981.

[*2*] Cheng, L., Pro, R., Malcolm, D. R., and Furno, A. L., " In Mine Installation of Passive Water Barriers," Bureau of Mines Report of Investigations 8915, 1984.

[*3*] Cheng, L. and Liebman, I., "Design of a Passive Explosion Barrier for Low-Roof Coal Mines," Bureau of Mines Internal Report 4398, July 1983.

[*4*] Liebman, I. and Richmond, J. K., "Suppression of Coal-Dust Explosions by Passive Water Barriers in a Single-Entry Mine," Bureau of Mines Report of Investigations 7815, 1974.

[*5*] Liebman, I., Corry, J., and Richmond, J. K., "Water Barriers for Suppressing Coal Dust Explosions," Bureau of Mines Report of Investigations 8170, 1976.

[*6*] Richmond, J. K., Liebman, I., and Miller, L. F., "Effect of Rock Dusting on Explosibility of Coal Dust," Bureau of Mines Report of Investigations 8077, 1975.

[7] Hertzberg, M., Cashdollar K. L., Zlochower, I., and Ng, D., *20th Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, PA, 1984, pp. 1691–1700.

[8] Liebman, I. and Richmond, J. K., "Ranking of Extinguishing Agents against Coal Dust Explosions," paper B-6 in *Proceeding of 18th International Conference of Scientific Research in the Field of Safety at Work in the Mining Industry,* Dubrovnik, Yugoslavia, Vol. 1, 7–14 Oct. 1979, pp. 239–247.

[9] Richmond, J. L. and Liebman, I., "A Physical Description of Coal Mine Explosion," in *Fifteenth (International) Symposium on Combustion,* The Combustion Institute, Pittsburgh, PA, 1974, pp. 115–126.

[10] Landau, L. D. and Lifshitz, E. M., *Fluid Mechanics,* Pergamon Press, London, 1959.

[11] Liebman, I., Corry, J., Pro, R., and Richmond, J. K., "Extinguishing Agents for Mine Face Gas Explosions," Bureau of Mines Report of Investigations 8294, 1978.

Zhou Dian-Bang[1] *and Lu Jian-Zhang*[1]

Research on the Suppression of Coal Dust Explosions by Water Barriers

---

REFERENCE: Zhou, D-B. and Lu, J-Z., "**Research on the Suppression of Coal Dust Explosions by Water Barriers,**" *Industrial Dust Explosions, ASTM STP 958,* Kenneth L. Cashdollar and Martin Hertzberg, Eds., American Society for Testing and Materials, Philadelphia, 1987, pp. 152–157.

ABSTRACT: Chongqing Coal Research Institute has been conducting experimental research on water barriers to determine their feasibility for installation in underground coal mines in China. The performance tests of 40- and 80-L tubs indicate that when the dynamic wind pressure is equal to or more than 0.16 kg/cm^2 they rupture and water disperses to form a spray cloud, which lasts for 75 to 150 ms. The cloud is 7 m long and spreads about 4 m wide. For extinguishing coal dust explosions, water barrier tests were conducted in our experimental gallery (896-m total length and 7.2-m^2 cross section). The test results have shown that barriers can effectively suppress coal dust explosions propagating at speeds of 80 to over 700 m/s. It was found that a delay time of from 2 to 1100 ms between barrier operation and flame arrival does not reduce their effectiveness. However, when the flame propagates slowly and the explosion pressure does not develop sufficiently, the barrier can be ineffective. Further research is necessary to improve the tub materials, their design, and their configuration.

KEY WORDS: coal dust explosions, extinguishment, water barriers

Coal dust explosions are a serious hazard in underground coal mines. The practical effectiveness of water barriers in protecting against the propagation of such explosions is a question of considerable interest to the coal mining industry. In Chinese coal mines, most roadways are very damp and a water supply system is provided for dust control. It is therefore very convenient to use water as the explosion suppression agent. For this reason, research is being conducted and tests performed on water barriers. Their effectiveness for suppressing coal dust explosions is being examined, as well as their practical applicability in coal mine roadways. Some recent research and tests are described in this paper. They were conducted in a surface steel duct and in the underground experimental gallery.

Performance Test of Water Tubs

Test Conditions

The steel test duct (Fig. 1) was 29 m long and 2 m in diameter with one end closed. The gas ignition zone was 5.7 m long from the closed end (18 m^3 in volume) and contained 7.5 to 8.2% methane. Along the side walls of the duct were installed four infrared flame sensors and four pressure transducers. A high-speed camera (300 frames per second) was set at a distance of 7 m beyond the open end of the gallery to observe the action of water tubs and the formation of the

---

[1] Head of explosion division and deputy research director, respectively, Chongqing Coal Research Institute, Central Coal Mining Research Institute, The Ministry of Coal Industry, Chongqing, Shangqiao, Sichuan Province, The People's Republic of China.

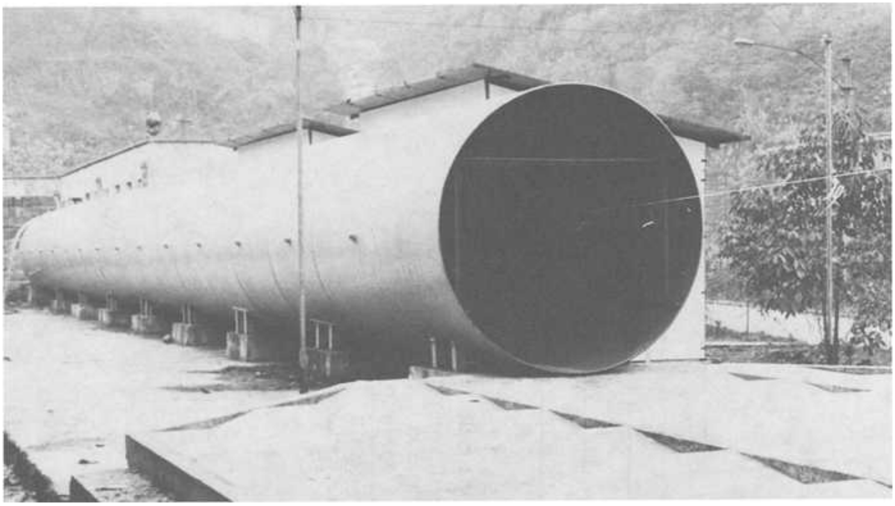


FIG. 1—*Steel experimental duct on the surface.*

water spray. The water barriers were installed within the duct at a distance of 0.3 m from the open end. The installation height for the water tub mounted in a metal frame is as shown in the cross section in Fig. 2.

Test Purpose and Results

After having established the relationship between the gas concentration, flame speed, and static pressure measured at the side wall of duct, the performance tests for water tubs were conducted. Satisfactory results were obtained for both 40- and 80-L polyvinylchloride (PVC) corrugated thin-wall water tubs (Fig. 3).

When the flame speed of explosion V was equal to or exceeds 29 m/s (the average speed in the section from 19 to 27 m) and the explosion pressure (static overpressure) P_s was equal to 1.77 to 2.06 kN/m^2, the cover of tub was blown off and about 2 L of water were sucked out of the tub and dispersed downstream.

When the explosion pressure (static overpressure) P_s was equal to or more than 15.69 kN/m^2 and flame speed V was equal to or more than 97 m/s, the water tubs were broken into small pieces and the water was fully dispersed. The features were as follows:

The actuation time for water tub was 75 to 150 ms.

The optimum spray lasted for 240 to 320 ms.

The spray column was more than 7 m long and 3.2 by 4 m in cross section. Figure 4 is a typical photographic sequence illustrating the actuation and dispersion of the water spray.

Tests of Water Barrier for Suppressing Coal Dust Explosions

Test Conditions

The total length of the underground experimental gallery was 896 m (Fig. 5). The main gallery was 398 m in length, and the inclined portion was 259 m long. The gallery was constructed of steel reinforced concrete in a semicircular arch configuration as shown. The cross-sectional area was 7.2 m^2. Along the sides of the main gallery from the starting point (the explosion proof door),

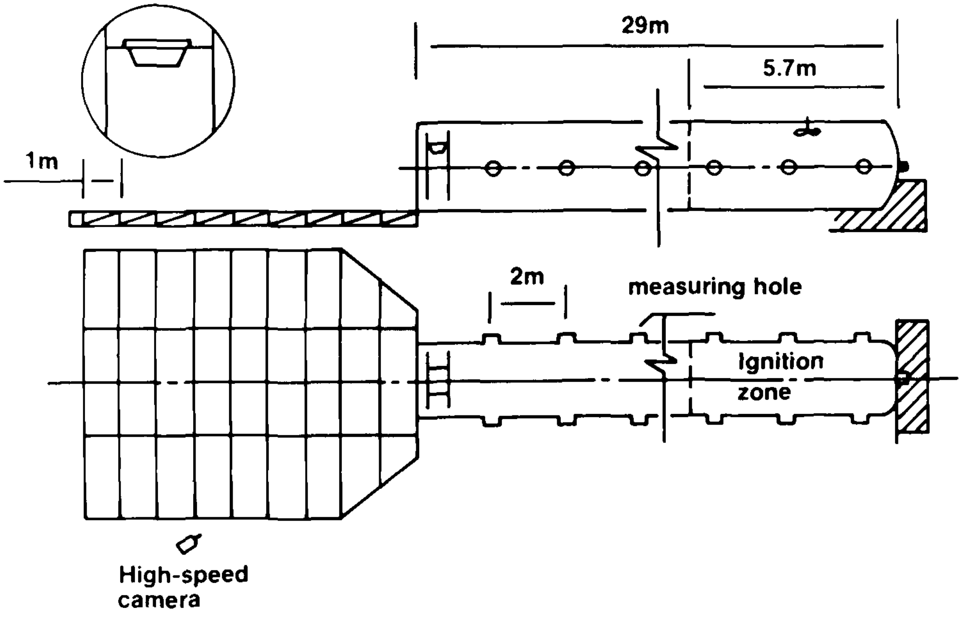


FIG. 2—*Arrangement of water tub for performance test in surface test duct.*

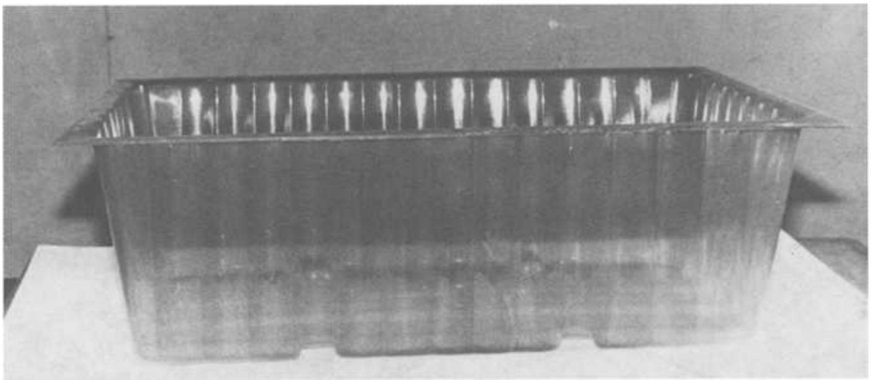


FIG. 3—*Corrugated thin-wall water barrier tub.*

instrument stations were provided at intervals of 20 m. They were used to measure the flame speed, the explosion pressure, and the extent of flame travel. From the variation of these measured parameters in the presence and absence of the barriers one could determine their effectiveness.

The ignition source was a 50-m^3 methane-air mixture located at the starting point of main volume of gallery, which contained 8.2 to 8.5% methane, and was ignited by an electrical match. The coal dust used for the tests was bituminous coal containing 43% volatiles consisting of fine particles, with 85% less than 200 mesh.

Coal dust was spread along the main gallery from the end of the ignition source volume (at 7 m). In the region between 7 to 40 m, two thirds of coal dust was spread on the roof shelves and one third on the floor dust plates. The arrangement of roof shelves and floor plates is shown in Fig. 6. Beyond 40 m, the coal dust was spread only on the floor plates. The amount of coal dust used was 130 to 150 g/m^3 of the gallery volume. Sometimes 30 to 40% rock dust was mixed with it to reduce the intensity of the coal dust explosion.

For the *concentrated* water barriers, the distance between rows was 1.2 to 1.65 m, and the quantity of water in the barrier system was 44 to 88 L/m^2 of gallery cross section.

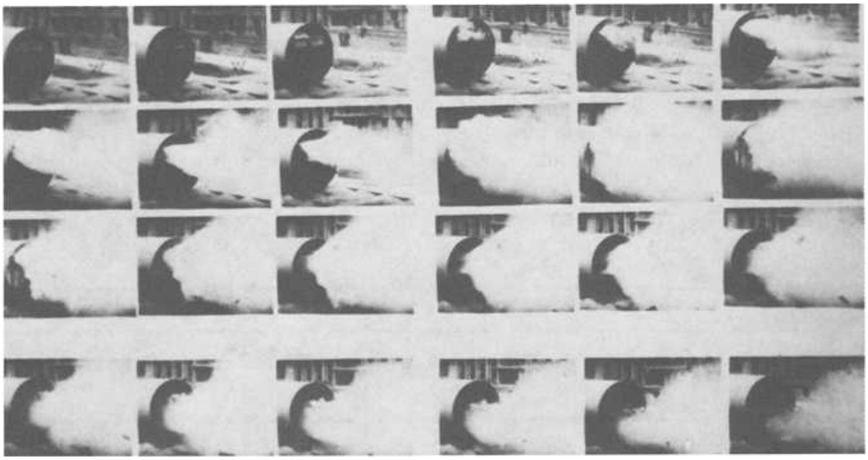


FIG. 4—*Typical water spray photograph.*

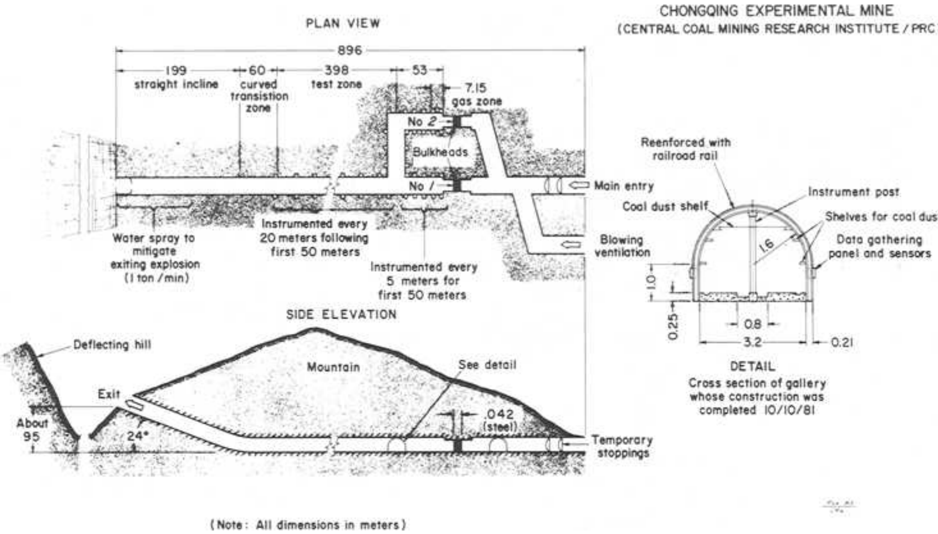


FIG. 5—*Underground experimental gallery.*

For the *distributed* water barriers, four sets were separately installed at 30, 60, 90, and 120 m, each consisting of three 40-L water tubs which were mounted in two metal frames in a delta arrangement (that is, two tubs were mounted in the first frame and one in the second frame). The quantity of water in the distributed barrier system was 0.56 L/m^3 of gallery volume.

Test Results

1. Tests were conducted with a concentrated water barrier which was located at 60 m from the ignition source and with 44 L/m^2 of water to suppress a weak coal dust explosion. The results indicated that when the flame speed was more than 80 m/s and the static pressure was equal to or more than 34.2 kN/m^2, the tubs in the barrier zone would all rupture and water would disperse as a fine spray, and thus stop the explosion propagation. The average length of penetration of the extinguished flame into the barrier zone was 6 m. When the static pressure was lower, 24.5 to 30.4 kN/m^2, the dynamic wind would not be strong enough to rupture the tubs effectively.

2. Tests were conducted with a concentrated water barrier that was positioned at 200 m from the explosion source and with water quantities of 55.5 to 88.8 L/m^2. Those tests showed that such barriers can suppress the propagation of a strong explosion with a flame speed of about 700 m/s (static pressure 670 kN/m^2). When the explosion developed more slowly and the speed of the

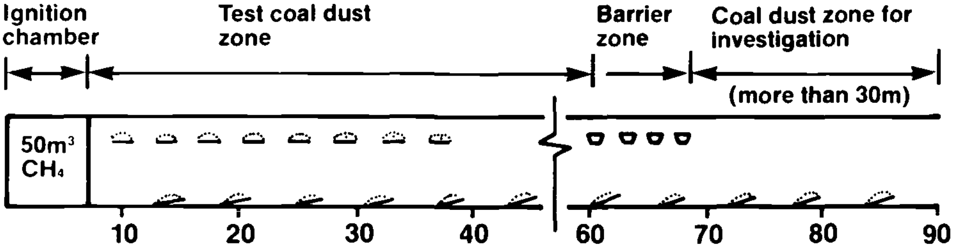


FIG. 6—*Schematic of test layout in underground gallery.*

flame near the barrier zone was 110 m/s, the delay time for flame arrival after barrier operation was 1070 ms, but that delay did not influence the effectiveness of water barrier in controlling the explosion. For that case, with the concentrated water barrier containing 88.8 L/m^2 of water, the dispersed and atomized water could wet more than 80 m of the periphery of gallery. For the case of the strong explosion, the water dispersed and the spray filled the entire gallery section to a distance of 12 m behind the first row of the water barrier.

3. Tests were also conducted with distributed water barriers which indicate that such an arrangement of water barriers is also feasible for the suppression of coal dust explosions. So long as the explosion penetrated into the zone of the distributed water barrier, it could be stopped in its early developing stages. For the two types of distributed water barriers with water quantities of 0.56 and 0.75 L/m^3 (of gallery volume), the effectiveness for the suppression of coal dust explosions was almost the same. Under identical conditions, the change from three two-row-arranged tubs into a one-row arrangement significantly reduced the effectiveness of the barrier in controlling the explosion. Depending on the nature of water dispersion, the distance between each set of distributed water barriers should be less than 30 m.

4. It is also feasible to install side water barriers near the ribs of the entry under certain conditions. The blockage ratio, which is the gallery width covered by the barriers relative to the maximum width of the gallery, has a great impact on the effectiveness of such a barrier in explosion suppression.

Conclusion

The purpose of these tests was, first, to determine the effectiveness of water barriers in suppressing explosions, and secondly to find the most effective means for their installation in Chinese coal mines. The research and tests indicate that the water barriers can stop explosions with flame speeds of 80 to 700 m/s. However, the water barrier which consisted of the tubs made of modified PVC cannot control weak explosions. To ensure the effectiveness of barriers in suppressing coal dust explosion, it is necessary to conduct further research on the materials of water barrier tubs and to improve their design and configuration.

Wolfgang Bartknecht[1]

Preventive and Design Measures for Protection Against Dust Explosions

REFERENCE: Bartknecht, W., "**Preventive and Design Measures for Protection Against Dust Explosions,**" *Industrial Dust Explosions, ASTM STP 958,* Kenneth L. Cashdollar and Martin Hertzberg, Eds., American Society for Testing and Materials, Philadelphia, 1987, pp. 158–190.

ABSTRACT: There is an inherent danger of a dust explosion when combustible dusts are handled in industry. This is proven by the many explosions which have resulted in substantial losses and often in fatalities. To counteract danger it is important to know the safety characteristics of the dust deposits or dust cloud. Based on the test methods used, it can then be decided which of the available protective measures should be applied. A distinction has to be made between preventive and design measures for the explosion protection.

Preventive measures avert a dust explosion by:

- preventing the formation of an explosible dust/air mixture,
- inerting or removing oxygen, and
- eliminating effective ignition sources.

Design measures will not prevent a dust explosion, but they will limit consequences to an acceptable level.

They include:

- explosion-resistant design for the maximum explosion pressure,
- explosion-resistant design for the reduced maximum explosion pressure in conjunction with explosion pressure venting or explosion suppression, and
- means to divert the explosion from entering peripheral equipment.

A general overview is given of all protective measures and the necessary decision making criteria.

KEY WORDS: dust explosions, protective measures, prevention, inerting, pressure venting, suppression

Dust explosions have been known since the introduction of the windmill some 200 years ago as a means of grinding corn [*1*]. Figure 1 shows the results of a grain dust explosion in the New Wesermill in Hameln (Germany) in 1887.

At the turn of the century it was already known that clouds of organic and metallic dusts are explosible. At that time, testing of combustible dusts was started using small equipment of a few litres capacity. On the one hand, the recorded pressures in the small equipment did not explain the damage caused by dust explosions; on the other hand, the theoretical calculations of the maximum possible pressure, based on thermochemical analyses, indicated much higher values. Therefore, the call for larger test equipment was imminent. But it was not until 1966 that a new test procedure for dusts was developed. This was limited initially to a 1-m^3 vessel, but this vessel does reproduce the turbulent dust/air mixtures encountered in practical applications (Fig. 2). Before testing, the dust is transferred into a bottle of specified volume equipped with a quick-acting valve.

---

[1] Ciba-Geigy Limited, Central Safety Service, Explosion Technology, Basel, Switzerland, c/o Reinhard E. Bruderer, specialist, Ciba-Geigy, P.O. Box 71, Toms River, NJ 08754.

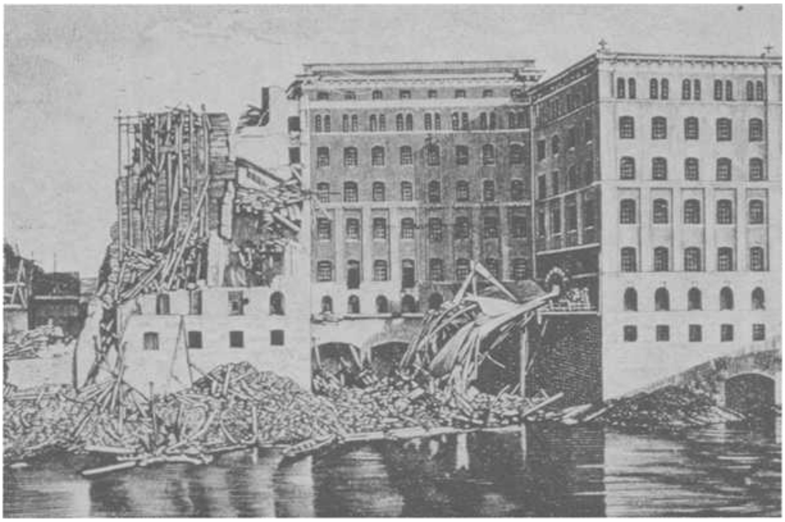


FIG. 1—*New Wesermill in Hameln (Germany) after a grain dust explosion in 1887.*

Then air pressure is applied to the bottle and maintained at a constant level. When the valve is actuated, the dust is dispersed through a special nozzle into the explosion chamber.

An ignition source is activated after a certain time has elapsed from the start of the dust injection. Because the dust bottle has just been emptied at that time, an approximate concentration can be established. Figure 3 shows the actual construction of the 1-m^3 vessel.

In the course of time, a 20-L laboratory vessel was designed, suitable for the same test method (Fig. 4).

This method was also used on vessels up to 250 m^3 (Fig. 5). The obtained characteristics, which describe the explosion and ignition behavior of dusts, are comparable for the different size vessels.

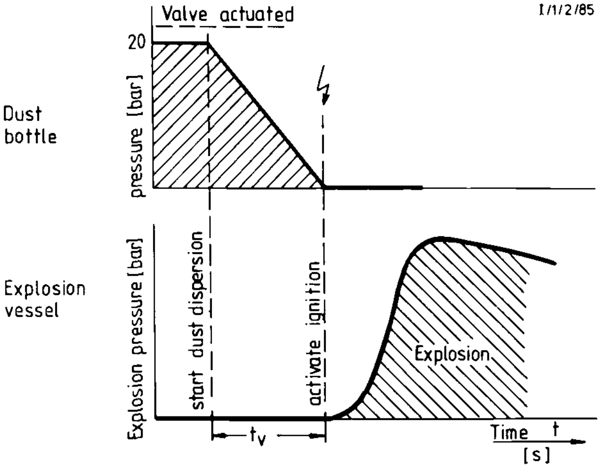


FIG. 2—*Dust testing procedure developed in 1966 for a 1-m^3 vessel (schematic).*

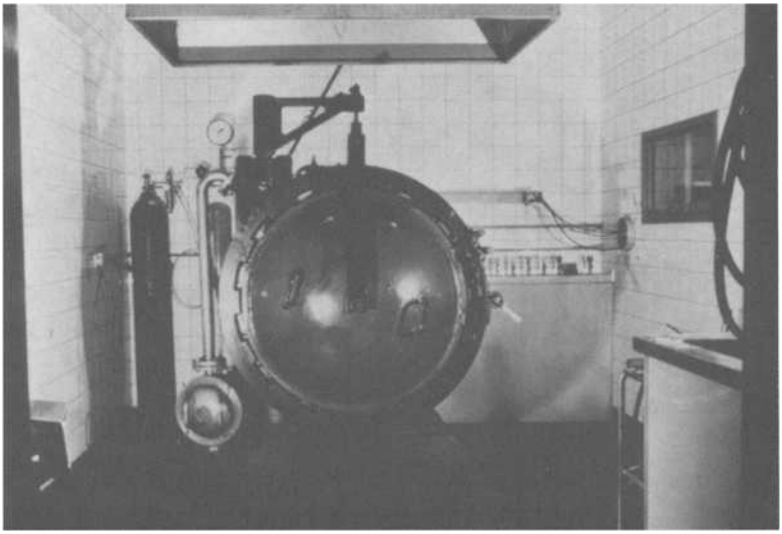


FIG. 3—*One-cubic metre explosion vessel for dust testing.*

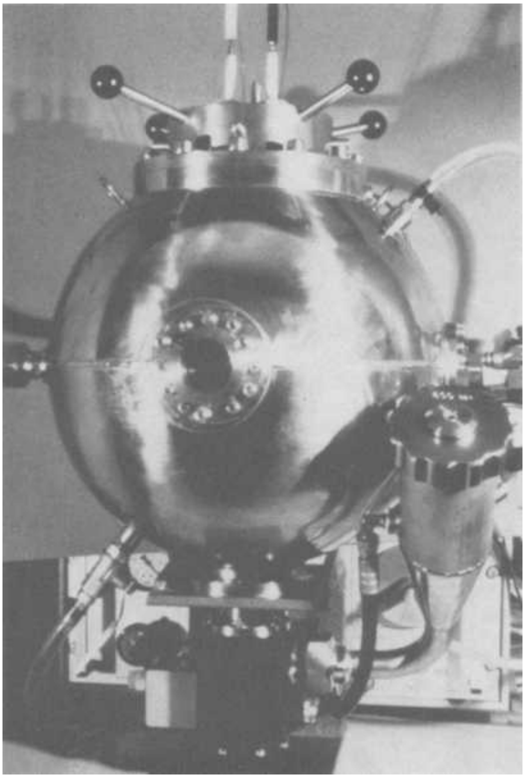


FIG. 4—*Twenty-litre laboratory apparatus for the testing of dusts.*

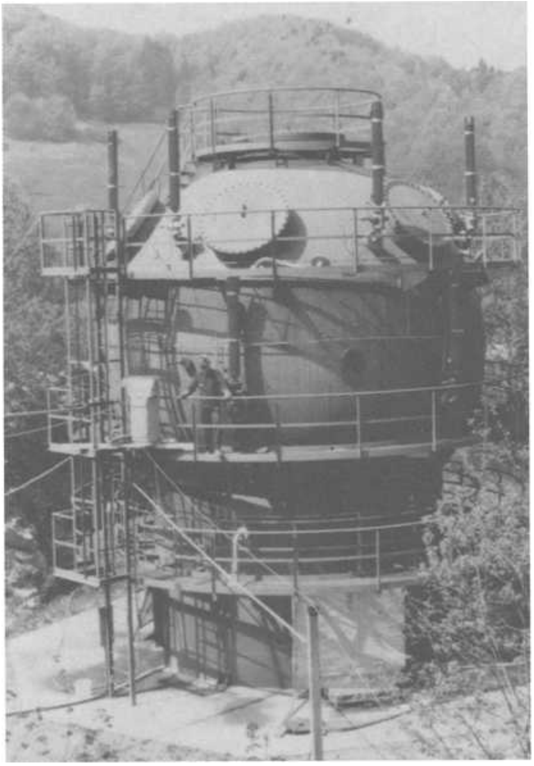


FIG. 5—*Two-hundred-fifty-cubic metre explosion vessel for the testing of dusts.*

The results gained through systematic testing of dusts over the past 20 years [2] have been used to design protective measures against the start and the consequences of dust explosions. This paper will report on such measures.

The VDI Guideline 2263 "Dust Fires and Dust Explosions" [*3*] distinguishes between "preventive explosion protection" which prevents explosions and the "protection through design" which limits consequences of dust explosions to an acceptable level.

Protective Measures

Preventive Explosion Protection

Avoidance of Explosible Dust/Air Mixtures—Mixures of combustible dusts with air can only be ignited within their explosible range, defined by the lower explosible limit (*lel*) and the upper explosible limit (*uel*). The *lel* is in general between 20 and 60 g/m^3, whereas the *uel* lies between 2 and 6 kg/m^3. If dust concentrations can be maintained outside the explosible limits, dust explosions can be prevented. A simple approach which summarily compares the total amount of dust with the total vessel volume may not reflect the actual concentration in all partial volumes because of a possible heterogeneous dust distribution.

For industrial applications, the *lel* is of particular importance. Figure 6 shows the development of the pressure and the rate of pressure rise for lycopodium ignited at the lower level of concentration.

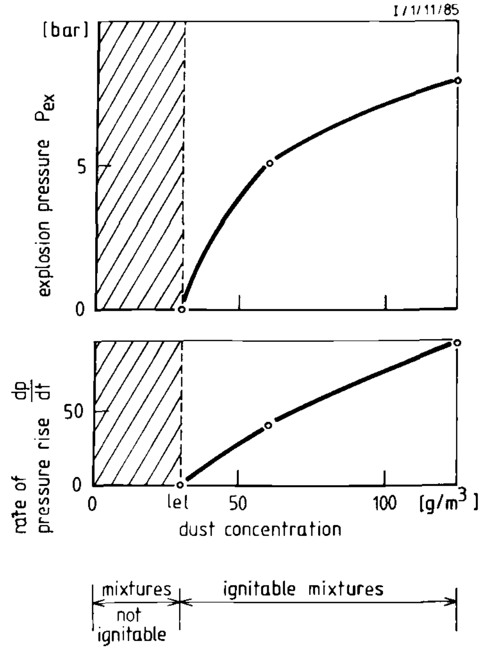


FIG. 6—*Lycopodium: explosion pressure* P_{ex} *and rate of pressure rise* dp/dt *within the range of the lower explosible limit* lel: *—1-m³ vessel,* E = *10 000 J.*

The use of the dust concentration limit as the protective measure is possible only if the dust concentration of the fine particles (median < 63 μm) in the equipment or parts of the equipment is guaranteed to be substantially below the *lel*. Special consideration has to be given to vent systems. Explosible dust/air mixtures can be formed through whirled up dust or the breaking up of dust layers.

Prevention of Explosions by Inerting

Inerting with Nitrogen—Inert gas in sufficient quantities, such as nitrogen introduced into vessels, silos, and mills, will protect such spaces from dust explosions. The oxygen content of air is lowered to such a level that an ignition of the dust/air mixture is impossible. A complete replacement of the oxygen with nitrogen is rarely needed.

The use of such a safety measure requires special knowledge, control of the inerting process, and gastight equipment.

The oxygen concentration that is just below the level to sustain a dust explosion varies with the products and the volume of the test apparatus (Fig. 7). The reason for this is the potent ignition source which is normally used for the explosion testing of dusts (pyrotechnic ignitor with an energy $E = 10\ 000$ J). The limiting oxygen concentrations gained from testing in small volumes are lower in comparison to larger test vessels, which are more representative for practical applications. In general, the oxygen concentration determined in the 1-m³ vessel is 64% higher than the one determined in the 20-L laboratory sphere.

As a safety margin, the maximum allowed oxygen concentration for practical applications is 2% of volume lower than the one found experimentally.

In many cases it is sufficient to maintain an 8% of volume oxygen level for organic dusts. There

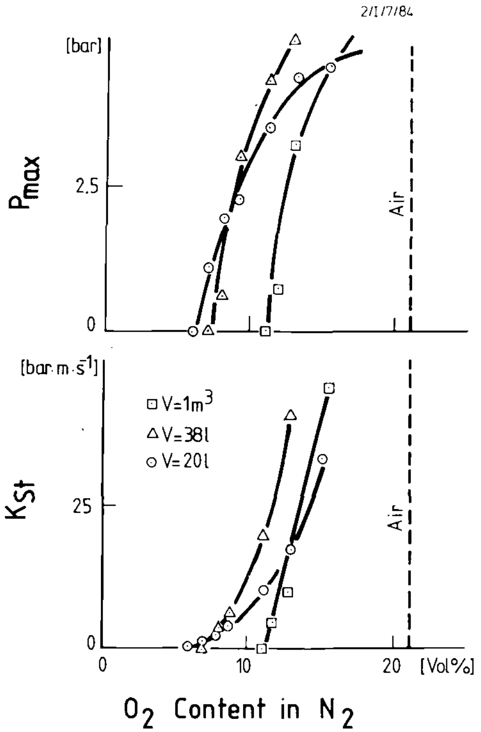


FIG. 7—*Influence of the size of the test vessel on the minimum O_2 requirements of a dust.*

are dusts such as metallic dusts and paraformaldehyde [*3*] which call for a markedly lower oxygen concentration.

The oxygen concentration is practically independent of the initial pressure—the starting pressure of an explosion—but will decrease 1.8% of volume for a 100°C temperature increase (Fig. 8).

With hybrid mixtures, consisting of combustible dust and flammable gas or vapors, the component with the lowest oxygen requirement sets the lowest level of oxygen concentration for the mixture (Fig. 9).

The level of inerting has to be monitored in such a way that the allowed oxygen concentration is not exceeded. This can be done continuously or intermittently. In case of a failure, suitable measures have to be taken:

1. Shut off the equipment if the maximum allowable concentration is exceeded or if the required flow of inert gas cannot be maintained. In general, the shutoff should be automatic.
2. Select a suitable level of alarm which, when exceeded, will trigger countermeasures (automatic or manual).

Inerting will not preclude dust fires. For this, much lower oxygen levels are needed, which have to be determined for each and every case. Inerting is not an efficient way to prevent exothermic reactions.

Inerting Thorough Vacuum—By reducing the pressure P_v below atmospheric pressure, the probability and severity of an explosion can be decreased, either because no explosion can take

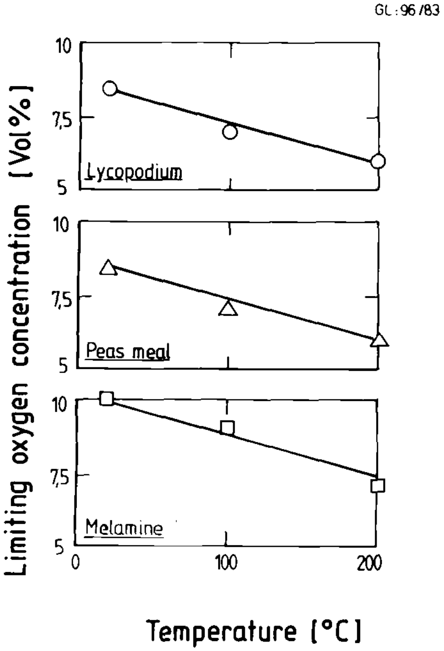


FIG. 8—*Influence of the temperature on the limiting oxygen concentrations for combustible dusts—20-L laboratory apparatus.*

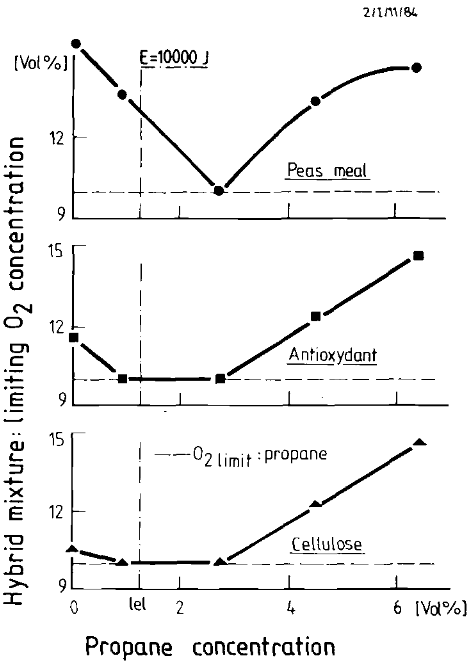


FIG. 9—*Levels of limiting oxygen concentration for hybrid mixtures of combustible dusts and propane—1-m^3 vessel.*

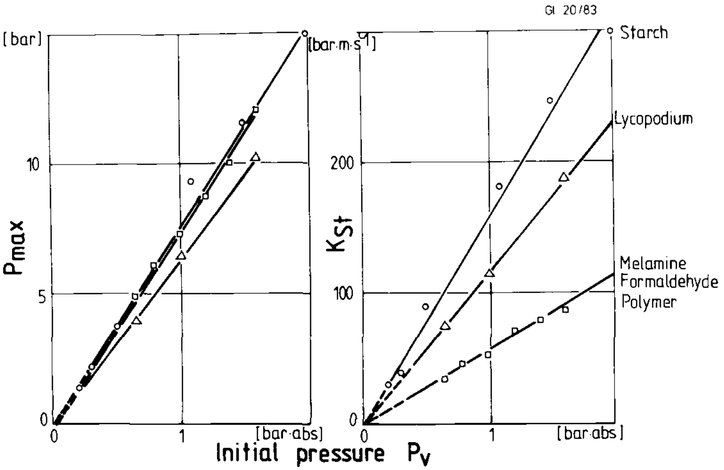


FIG. 10—*Influence of initial pressure* P_v *upon explosion characteristics of combustible dusts—1-m*^{3} *vessel.*

place (P_v < 50 mbar [5000 Pa]) or because the maximum explosion pressure will be less than the atmospheric pressure (P_v < 0.1 bar [10 kPa]) (Fig. 10).

The vacuum must be monitored, and in case of a failure (for example, air entrainment), it must be replaced with another safety measure such as inerting or prevention of effective ignition sources (see later on).

Inerting with Solids—Combustible dusts can be inerted by admixing inert, pulverized solids, mostly in the form of extinguishing powders. In such a case, the minimum ignition energy ($E_{M\ \min}$) requirement of the combustible/inert dust mixture increases with higher inert concentration (Fig. 11). Such a behavior runs parallel to the minimum ignition energy requirement of combustible dust/air mixtures which are inerted with nitrogen.

The minimum concentration of inert matter which is just needed to prevent an explosion from happening depends upon the ignition energy (Fig. 12) and lies in general around 50% by weight.

Prevention of Effective Sources of Ignition

Preliminary Remarks—Dust explosions can be prevented if it is possible to avoid the ignition sources which, because of their characteristics (for example, energy and temperature-time behavior), can ignite dust/air mixtures [*4*]. A distinction has to be made between:

- trivial sources of ignition (for example, welding, grinding, smoking) and
- sources of ignition as a result of mechanical failures leading to (for example, mechanical sparks, hot surfaces, glowing accumulations, electrostatic sparks).

The former can be prevented through organizational measures. If prevention is also possible for the operational sources of ignition, then such a measure is deemed sufficient for all practical purposes as per today's knowledge [*4*]. But the safety measure "prevention of effective sources of ignition" as the sole means to prevent the start of explosions has to be used with expert judgement [*3*]. Every system has to be evaluated with regards to possible sources of ignition. Their elimination has to be guaranteed in a satisfactory manner.

The explosion safety guideline [*5*] enumerates some categories of ignition sources. The following section deals with the important sources of ignition for combustible products.

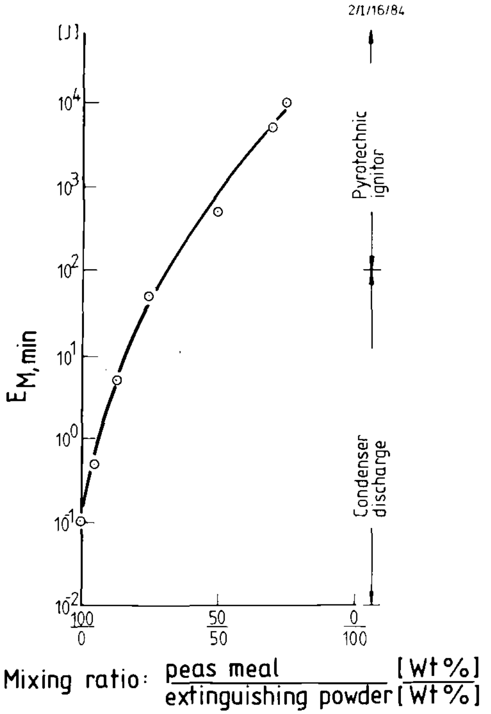


FIG. 11—*Correlation of minimum ignition energy with varying mixtures of combustible dust (peas-meal) with inert powder (tropolar = ammonium phosphate).*

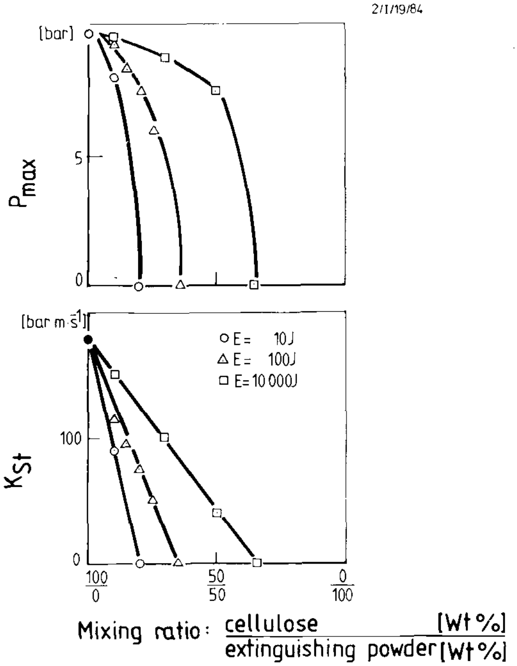


FIG. 12—*Correlation of ignition energy with concentration of cellulose and inert powder (Tropolar), 1-m*^{3} *vessel.*

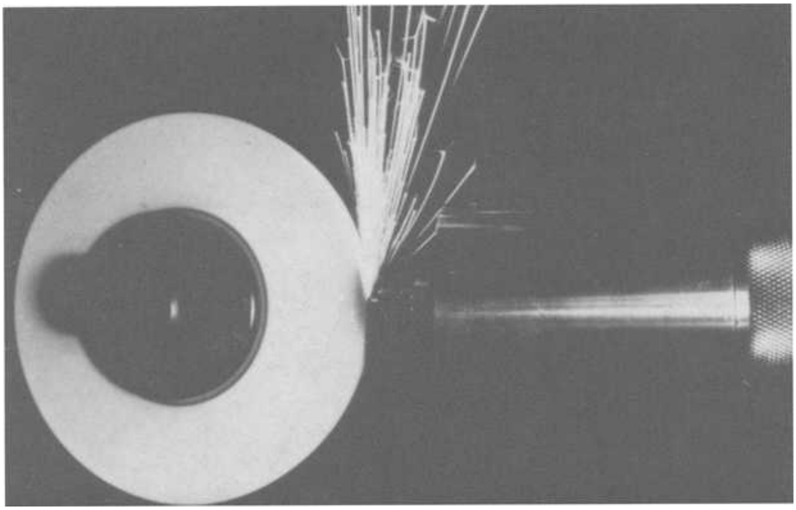


FIG. 13—*Titanium grinding spark:* t_g = *20 ms.*

Mechanical Sparks—Mechanical sparks occur only when the usual metallic materials of construction are moved against each other or against stone at relative velocities $v > 1$ m/s (3 fps). They represent 30% of the ignition sources responsible for actual dust explosions [*6*].

For grinding sparks, which are created through the short contact of construction materials with a rotating, abrasive wheel (Fig. 13), there exists a clear correlation between the ignition temperature T_z of the fuel—combustible dusts and flammable gases—and the electrical equivalent energy E_E (Fig. 14). The value T_z is the auto ignition temperature of the fuel determined in a BAM-oven, whereas E_E is the energy released from a charged condenser over an extended time period which gives the same ignition efficiency as the mechanical spark [*7*]. An ignition of the mixtures can always be expected if the minimum ignition energy requirement of the fuel at a constant ignition temperature is below the value given by a straight line.

Dusts with a low ignition temperature can be ignited through grinding sparks even when the required minimum ignition energy is high; but with a high ignition temperature, a low minimum ignition energy requirement is needed to start an explosion. Titanium/rust impact sparks (Fig. 15) have the same ignition potential as titanium grinding sparks (Fig. 16), whereas aluminum/rust impact sparks are a substantially less efficient ignition source.

In general, the efficiency of the mechanically produced sparks in fuel/air mixtures decreases in the following order:

- flint stone friction and grinding sparks,
- zirconium grinding sparks,
- titanium grinding and impact sparks,
- steel grinding sparks, and
- aluminum/rust impact sparks.

The low ignition efficiency of the steel grinding sparks (Fig. 17) gives no explanation at first for the frequent incidents in steel equipment used in the wood and grain industries [*6*]. But it has been demonstrated that sparks can be generated by rubbing steel against steel for a time cycle t_R of 1 s (Fig. 18). Friction sparks are markedly more efficient than steel grinding sparks. This is due to the higher temperature level of the sliding steel and the correspondingly higher starting temperature of the sparks.

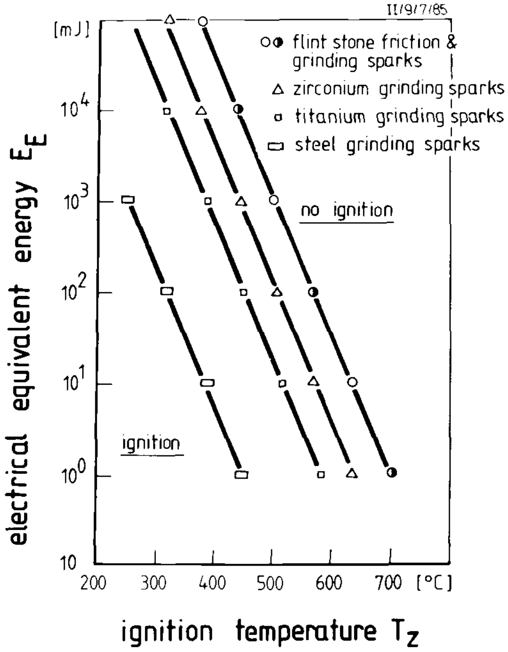


FIG. 14—*Grinding sparks: electrical equivalent energy* E_E *versus ignition temperature* T_z *of fuels*—P_A = *60 N and* v_c = *30 m/s.*

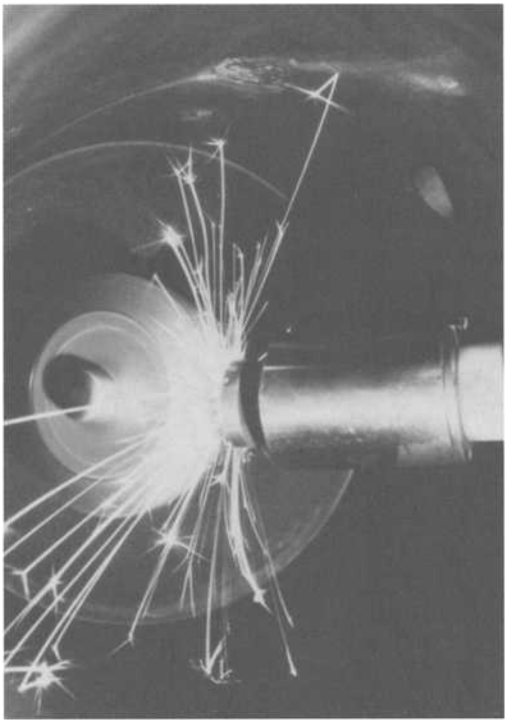


FIG. 15—*Titanium/rust impact sparks.*

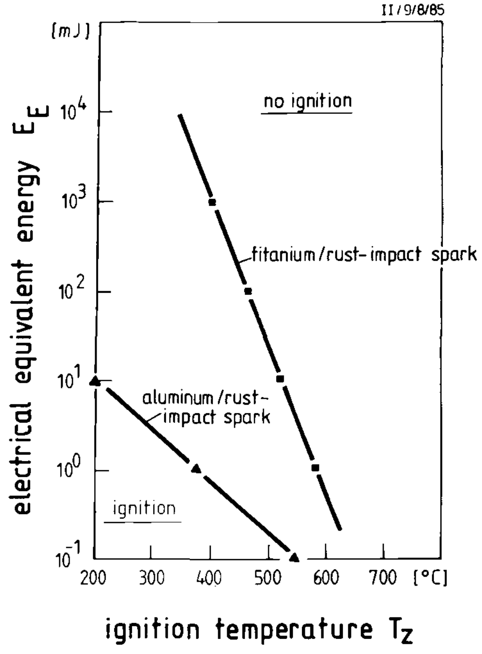


FIG. 16—*Impact sparks: electrical equivalent energy* E_E *versus ignition temperature* T_z—P_A = *60 to 100 N and* v_c = *25 m/s.*

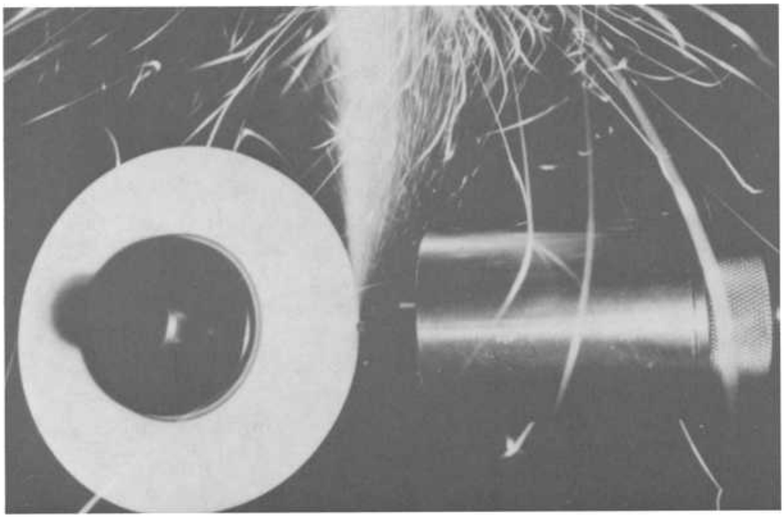


FIG. 17—*Steel grinding sparks*—t_g = *20 ms.*

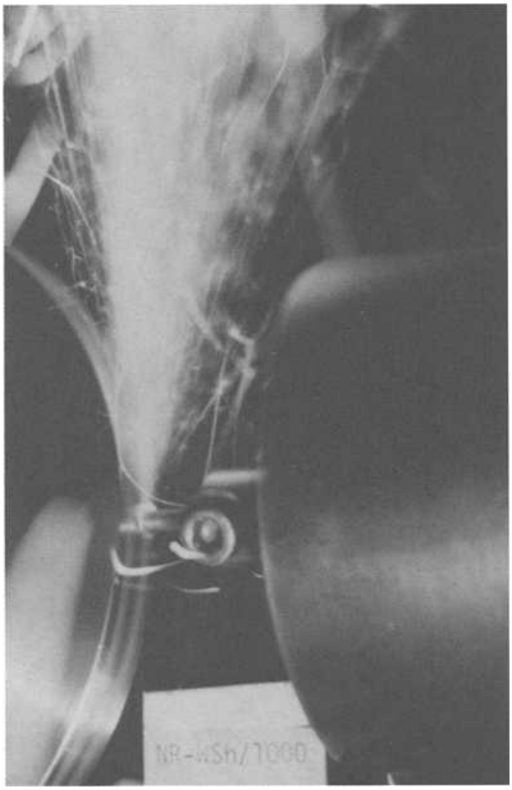


FIG. 18—*Steel friction sparks*—t_R = *1000 ms.*

As proven in Fig. 19, dust mixtures with an ignition temperature of barely 400°C can only be ignited through steel grinding sparks if their minimum ignition energy requirement is low ($E_{M\ \min} \leq 10$ mJ).

However, at the same temperature, steel friction sparks ignite dusts having a minimum energy requirement of $E_{M\ \min} \leq 100$ mJ. Thus the conclusion can be drawn that in practice the friction sparks can be counted on as the major ignition source from all mechanically produced sparks [*8*].

Hot Surfaces, Glowing Accumulations of Particles—Direct contact with hot surfaces can start dust explosions or ignite dust layers [*3*]. In practice, hot surfaces exist on hot equipment, heating devices, driers, steampipes, or electrical equipment. In case of an equipment failure, friction can increase the temperature of equipment beyond its operating level. Temperatures of 1100 to 1300°C can be reached (Fig. 20) and a coal dust/air mixture with an ignition temperature T_z = 500°C will ignite. Stainless steel and carbon steel are the alloys most likely to cause ignition. The temperature at the point of friction and the ignition temperature of the combustible dust will be the determining factors for an ignition.

Dust layers on hot surfaces can also self-ignite and create glowing accumulations which in turn may become sources of ignition for dust/air mixtures.

Static Electricity—Electrostatic charges may, through their form of discharge, pose a threat to explosible dust/air mixtures [*3,9,10*]. Spark discharges (Fig. 21) through charged conductors can

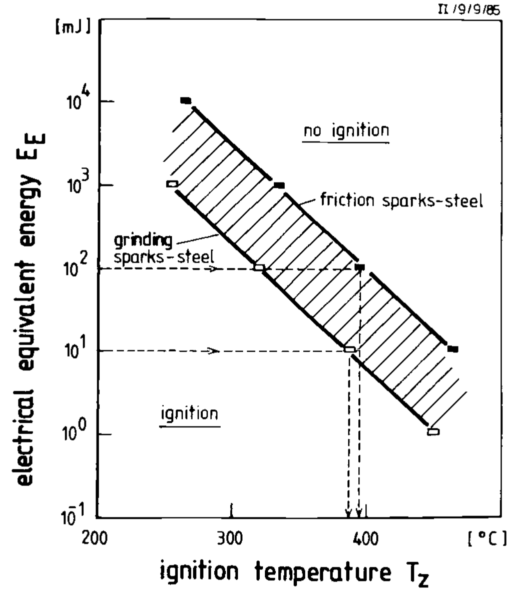


FIG. 19—*Steel grinding and friction sparks: electrical equivalent energy* E_E *versus ignition temperature* T_z *of fuels*—P_A = *60 to 90 N and* v_c = *25 m/s.*

ignite dust/air mixtures if the energy from voltage and capacitance is larger than the minimum ignition energy requirement of the dust.

Based on today's knowledge, a number of dusts can be ignited as easily as the flammable gases butane, propane, propylene, and methane (Fig. 22). To determine the minimum ignition energy requirements of combustible dusts, a condenser is discharged over an extended period of time. Such a discharge is, in general, more efficient in igniting dusts than a regular capacitor discharge [2]. This behavior is to be considered when judging the efficiency of spark discharges in practice.

Brush discharges (Fig. 23) may originate from highly charged nonconductive surfaces (foils, filter fabrics, plastic parts, whirled up dust). They may be observed in various process steps such as milling, sifting, agitating, mixing, separating, or pneumatic conveying. Such a discharge is as efficient in igniting an explosible gas/air mixture as a capacitor discharge over an extended time with an energy content of $E = 4$ mJ. Thus far, there has not been any proof that a brush discharge is also capable of igniting easily ignitable dust/air mixtures.

Propagating brush discharges (Fig. 24) are generated by separating or intensely rubbing together nonconductive layers which are attached to conductive supports (for example, metal). The energy content of such a discharge is 1 J and is capable of igniting dust/air mixtures.

Based on today's knowledge, discharges from conical piles (Fig. 25) are possible if large quantities of coarse, highly chargeable particles are conveyed into silos or vessels at a high velocity. The discharge takes place from the surface of the highly charged pile towards conductive parts. The danger of an explosion is imminent when any fine dust is present. It is assumed that this type of a discharge has been responsible for some past explosion incidents. Based on theoretical considerations, it can be assumed that the available energy is equivalent to <10 mJ produced by a capacitor discharge. At present, additional knowledge is lacking.

If a charged dust cloud is discharged towards a grounded object, a lightning-like discharge can be envisaged.

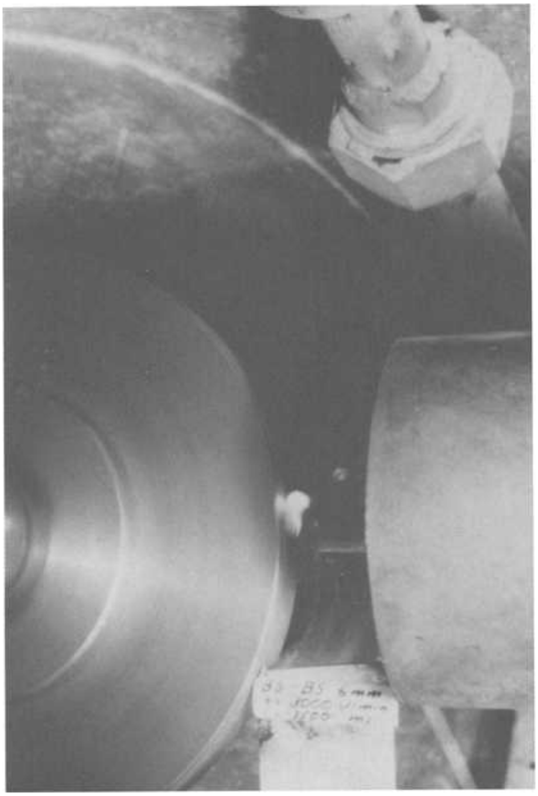


FIG. 20—*Hot surface of a steel pin after rubbing a steel disc*—t_R = *3700 ms and* T = *1290°C.*

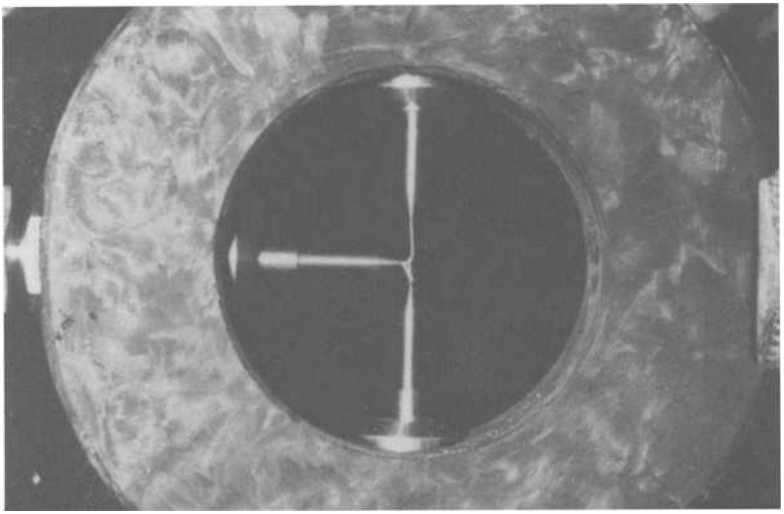


FIG. 21—*Spark discharge extended over time,* E = *1 mJ.*

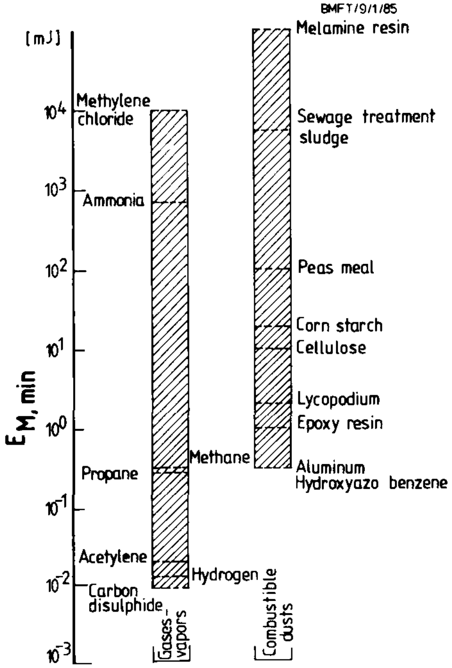


FIG. 22—*Minimum ignition energy: comparison of flammable gases with combustible dusts.*

However, based on today's knowledge, such a discharge is rather unlikely in technical installations. The dimensions, as well as the charging potential, are small compared to nature (Fig. 26). It can be shown experimentally that lightning-like discharges are impossible in equipment with diameters under 3 m.

Explosion Protection Through Design Measures

Preliminary Remarks—If the danger of an explosion cannot be sufficiently reduced by the application of preventive protection, design measures must be used in accordance with the "safety guidelines" [*5*]. All the endangered pieces of equipment have to be designed in such a way that they will withstand the anticipated explosion pressure, which may be equal to the maximum pressure reached in a closed vessel using an accepted test method [*11*, paragraph 12].

In practice, the explosion pressure may be lower than the experimental pressure (as a result of such factors as larger particle size, deviation from optimum dust concentration, elevated temperature, higher dust moisture content, or partial filling of equipment with explosible dust/air mixture). However, the explosion pressure may also be higher (for example, because of higher oxygen concentration or higher initial pressure)!

If the anticipated explosion pressure is higher than the maximum explosion pressure from the test, the anticipated pressure will be the design basis. With lower values either the test or anticipated pressure can be used [*4*].

The following remarks are based on the maximum pressure reached in the closed vessel at standard conditions. The vessels and the equipment which have to be protected can be designed in a pressure or pressure shock resistant [*12*] fashion (Fig. 27).

The explosion pressure resistant vessel or equipment is designed in accordance with the rules and regulations of the pressure vessel code. It will withstand the pressure without deformation.

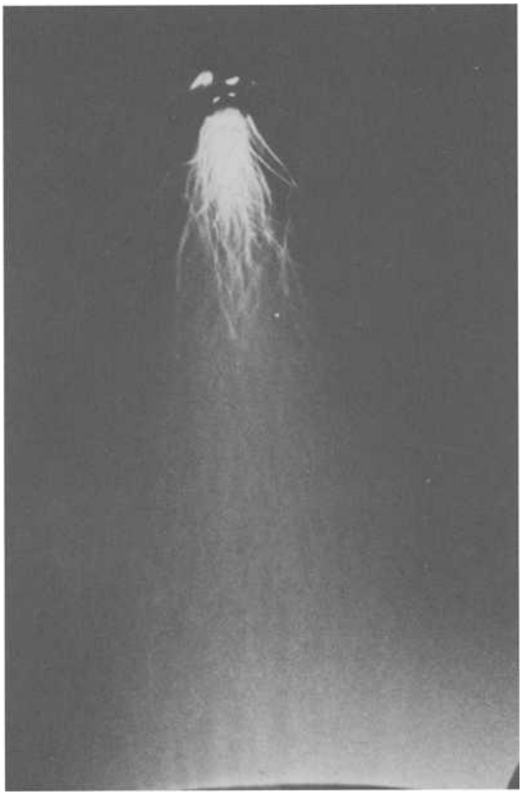


FIG. 23—*Electrostatic brush discharge.*

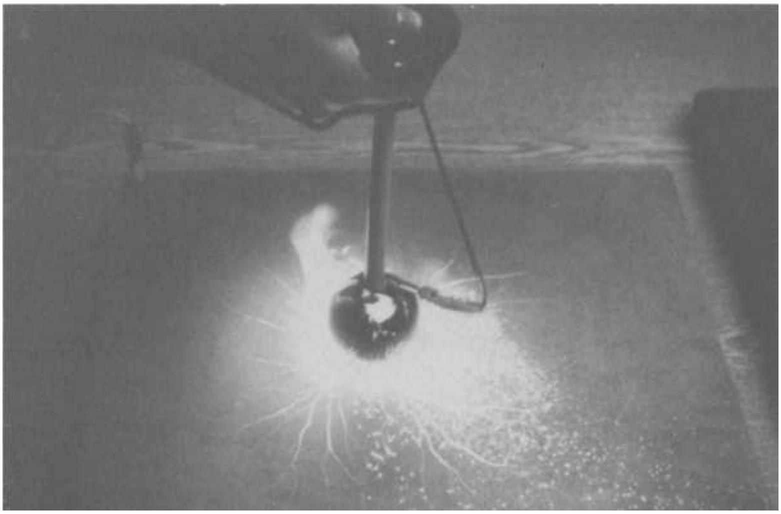


FIG. 24—*Propagating brush discharge.*

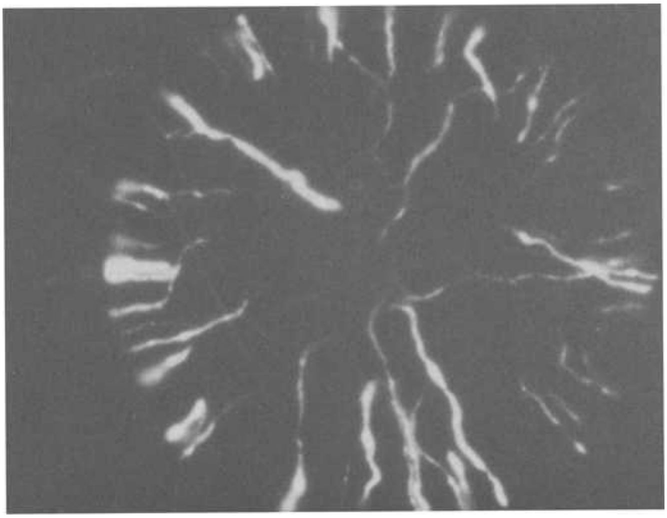


FIG. 25—*Discharge from conical pile.*

Explosion pressure shock resistant vessels will also withstand the internal explosion pressure, but a permanent deformation will be tolerated.

Pressure Resistant Design for the Maximum Explosion Pressure

One method of protecting vessels and equipment from the results of an explosion is the pressure or pressure shock resistant design based on the maximum explosion pressure (Fig. 28). With this

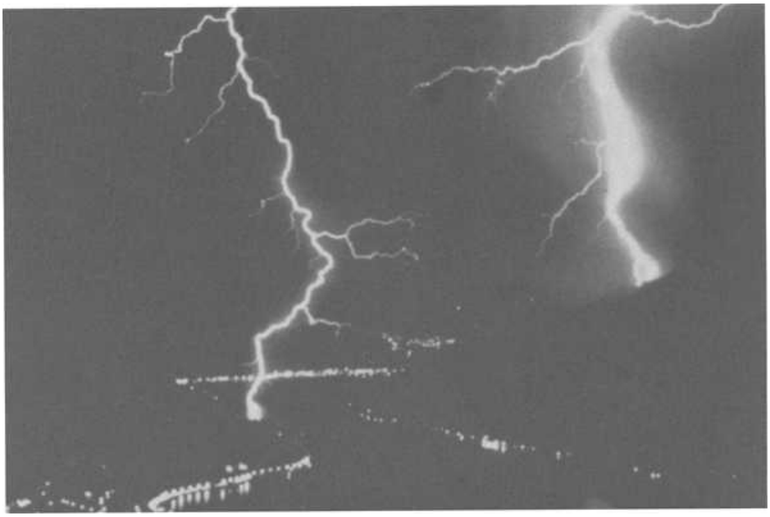


FIG. 26—*Lightning.*

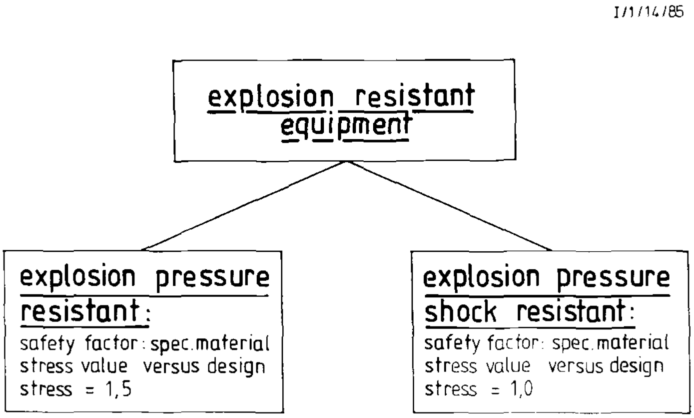


FIG. 27—*Design possibilities for explosion resistant equipment using ductile materials of construction.*

approach, additional design measures are superfluous, except for the technical disengagement of explosions within combined systems (see later on).

Consideration must also be given to the peripheral equipment which also has to withstand the explosion pressure.

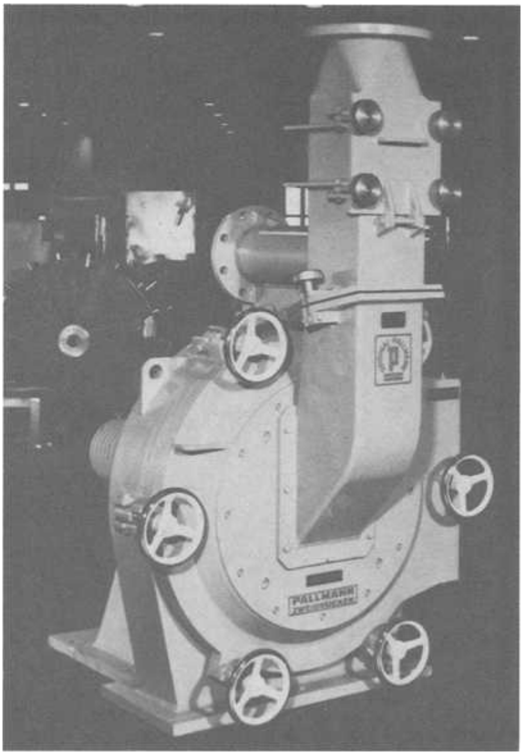


FIG. 28—*Explosion pressure shock resistant mill housing* [12].

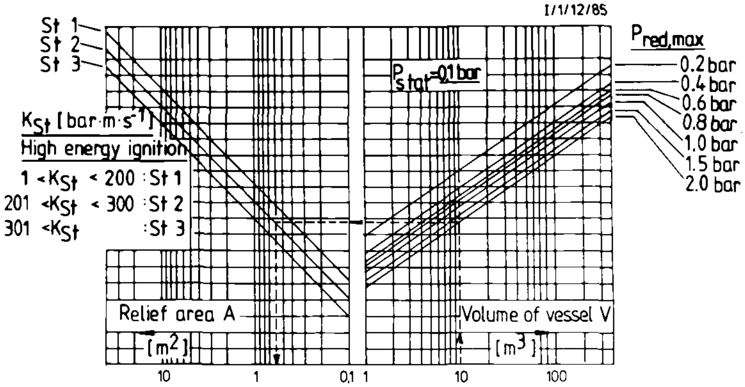


FIG. 29—*Nomogram for the determination of pressure relief areas for dust explosions. Example: static venting pressure* P_{stat} *= 0.1 bar.*

Pressure Resistant Design for a Reduced Maximum Explosion Pressure in Conjunction with Pressure Venting

The term "explosion venting" covers all measures that allow initially closed vessels and equipment to open temporarily or permanently in a safe direction in case of an explosion, thereby preventing the buildup of pressure to an unsafe level. The equipment that will be protected in such a manner has to be designed pressure or pressure shock resistant for the expected reduced maximum explosion pressure $P_{\text{red max}}$.

The VDI Guideline 3673 "Pressure Release of Dust Explosions" [*11*] includes nomograms (Fig. 29) which give the required relief area for known vessel volume, vessel design pressure, and dust explosion class. The same guideline also contains nomograms for the specific dust characteristic K_{St}.

Upon actuation of the relief device, a substantial flame formation has to be expected as a result of the exhaust consisting of combustible dust and combustion gases. If the equipment is inside a production building, the pressure must be vented through ductwork leading to a safe location. The resulting higher pressure has to be taken into account (Fig. 30) and the vessel designed accordingly.

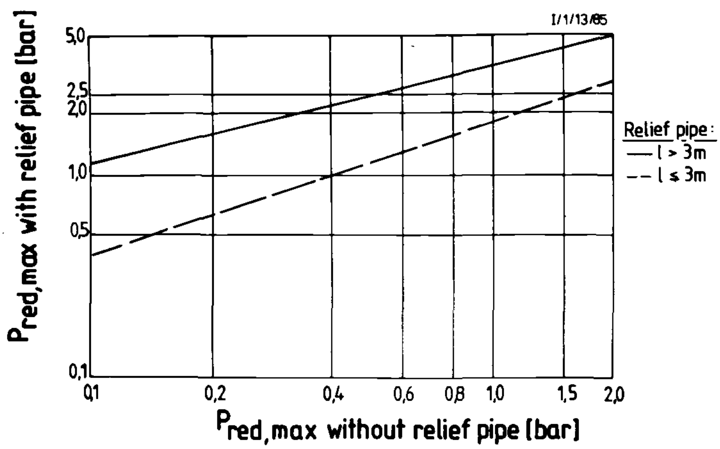


FIG. 30—*Influence of relief pipes on the reduced maximum explosion pressure of combustible dusts.*

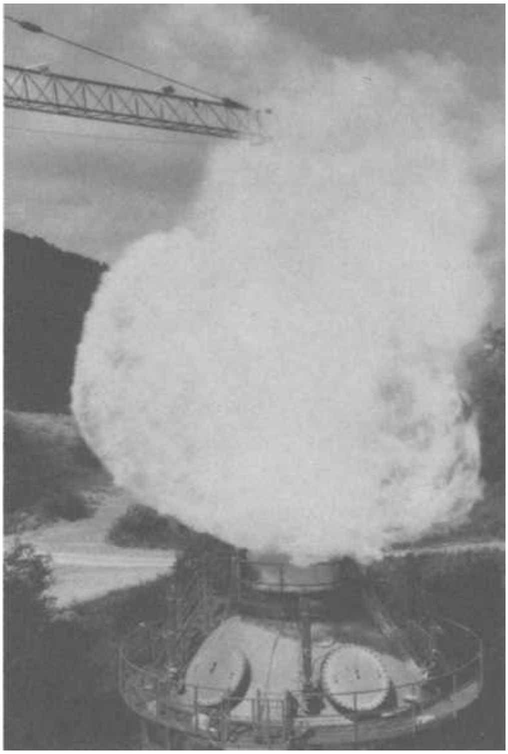


FIG. 31—*Cornstarch dust explosion in a pressure vented 250-m³ vessel.*

When the safety measure "pressure release" is applied, then recoil forces have to be considered [*13,14*]. For relief systems using safety membranes, the following equation applies:

$$F_R = 119\,A\,(P_{\text{red max}} - P_{\text{Atm}})$$

where

F_R = recoil force [kN],
A = relief area [m^2],
$P_{\text{red max}}$ = reduced maximum explosion pressure [bar abs], and
P_{Atm} = atmospheric pressure [bar].

The nomograms in the VDI Guideline 3673 "Pressure Release of Dust Explosions" are valid for dusts having a maximum explosion pressure of 10-bar (1000-kPa) gage. They also assume that the area requirements follow the known "cubic law." Recent tests [*15*] with vented vessels up to 250 m³ (Fig. 31) confirmed this only partially.

For dusts with a slower reaction (K_{St} = 200 bar · m · s^{-1} [20 MPa · m · s^{-1}] Fig. 32), the vent area increases as a function of increasing volume are greater than could be expected from the cubic law. This is also true for faster reacting dusts (K_{St} = 300 bar · m · s^{-1} [30 MPa · m · s^{-1}], Fig. 33) and smaller volumes ($V < 25$ m³). However, for larger volumes ($V \geqslant 25$ m³), the validity of the so-called cubic law is confirmed. This is due to the fact that the area requirements of larger volumes are practically independent of the specific dust characteristic K_{St}. The reason for such a behavior may be found in the fact, that, for a slower developing explosion, lots of unburnt material

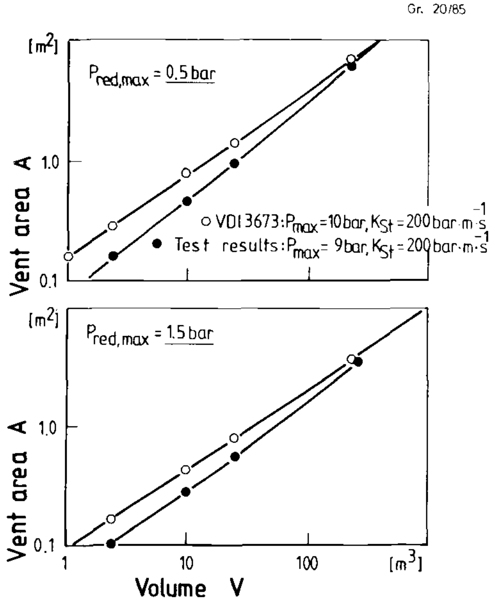


FIG. 32—*Comparison: area requirements of VDI 3673 versus test results* [15]. P_{stat} = *0.1 bar.*

is discharged into the surroundings after actuation of the vent. Such material will be instantly ignited by a following flame. The pressure developed by such a secondary explosion near the relief area will momentarily retard the venting process and therefore increase the reduced maximum explosion pressure.

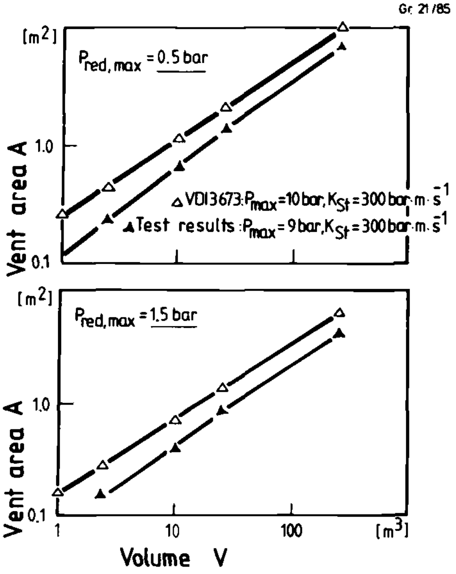


FIG. 33—*Comparison: area requirements of VDI 3673 versus test results* [15]. P_{stat} = *0.1 bar.*

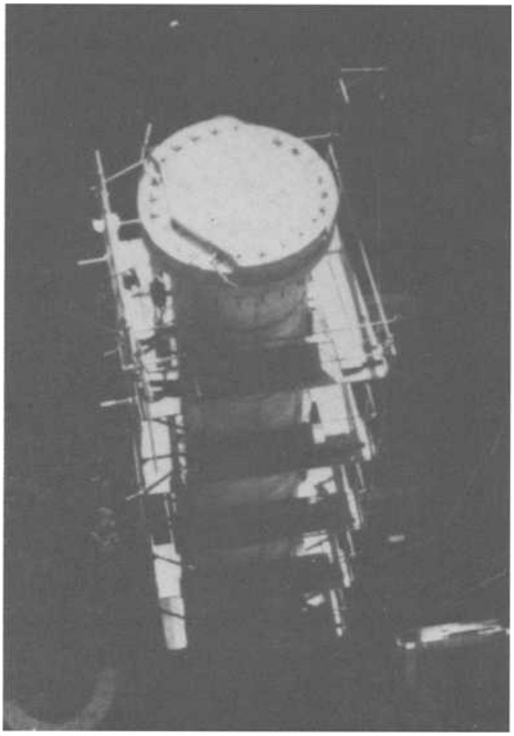


FIG. 34—*Silo with concrete covers for the closure of the vent area.*

Dusts with a maximum explosion pressure of 9 bar (900 kPa) instead of 10 bar (1000 kPa) require a 30 to 50% smaller relief area than called for in VDI Guideline 3673. This is especially true for the more violently reacting dusts (Fig. 33).

If the safety measure "explosion pressure release" is used on silos having a height-to-diameter ratio >5, it is suitable to use the total roof area for pressure venting. However, because of the directional effect of the dust explosion the registered pressure in the silo will be 400% higher than the one experienced in a cubic vessel having the same relief area [*16*]. Therefore, silos have to be built "explosion resistant." The usual concrete covers (Fig. 34) which are often used to close the vent openings on silos reduce the vent efficiency by 70 to 80%, depending upon the design (Fig. 35).

It can be assumed that the turbulence of the dust/air mixture at the moment of ignition will decisively influence the course of an explosion in a silo or a vessel. Therefore, the question is often raised whether the accepted test method for dusts [*11*] reflects the actual turbulence encountered in practice.

A first answer to the question is given by the test results gained from pneumatically filling a 20-m^3 silo having a constant relief area of 0.5 m^2 [*17,18*]. Because of the linear correlation of the air volume at a given product/air ratio and the maximum reduced explosion characteristics, it can be estimated that the VDI values would be reached at an air volume of 21 m^3/min (Fig. 36).

Figure 37 shows the correlation of the relief area "A" with the maximum reduced explosion characteristics for the case of pneumatically conveyed cornstarch and using the VDI method for the preparation of the dust/air mixture. The results from the latter method are slightly higher. At the same time the different results from a pressure vented 20-m^3 cubical vessel can be observed.

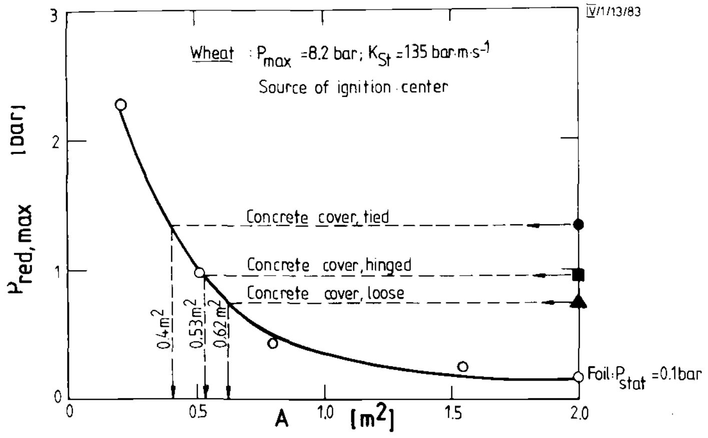


FIG. 35—*Vent efficiency of concrete covers on a silo.*

In summarizing, it can be stated that the VDI dust injection method provides a better dust distribution in comparison to the chosen conditions of the conveying system.

Pressure Resistant Design for a Reduced Maximum Explosion Pressure

Explosion suppression systems are similar to pressure release systems. They prevent the buildup of excessive pressure in vessels which are not designed for the full explosion pressure in case of

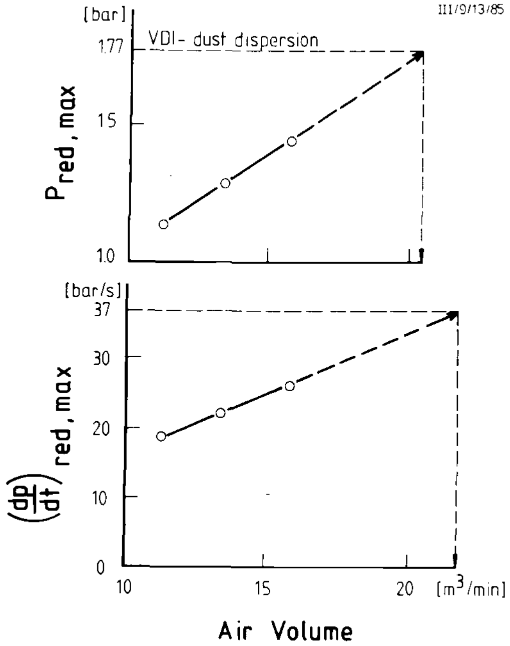


FIG. 36—*20-m^3 silo tested with cornstarch. Influence of air volume on maximum reduced explosion characteristics*—A = *0.5 m^2;* P_{stat} = *0.1 bar; optimum material/air ratio.*

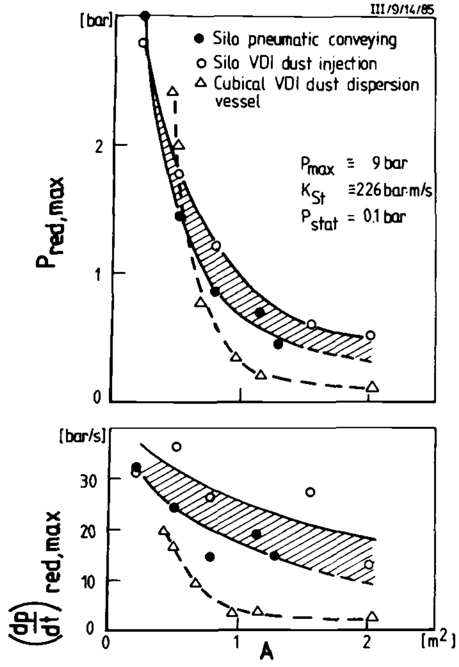


FIG. 37—*20-m³ silo tested with cornstarch. Influence of relief area on the maximum reduced explosion characteristics. Ignition source: center. Comparison of pneumatic conveying versus VDI method.*

a dust explosion. The prerequisite for such a safety measure is a pressure resistant design—in general for 1-bar (100-kPa) gage. Explosion suppression systems consist in principle of pressure detectors which sense a starting explosion plus pressurized extinguishers with valves which are activated by the detectors. The extinguishing medium is distributed rapidly throughout the vessel to be protected and quenches the flames at the onset of the explosion. Until now, only 5.4-L extinguishers were used with fast acting valves (Fig. 38). The pressure of the driving medium-dry nitrogen varies between 60 and 120 bar (6 and 12 MPa), depending upon the system. Extinguishing powder, and in special cases, also water can be used as a suppressant. Basically the application of Halon is also possible. But it has to be remembered that the extinguishing medium may decompose, resulting in higher pressures than with combustible dust alone [*19*]. This can happen with undersized systems or with a delayed discharge. Systematic development of a new suppression system [*20*] consisting of a 45-L extinguisher with a 5-in. (12.7-cm) valve (Fig. 39) led to an 80% savings in the number of extinguishers used on a 250-m³ vessel (Fig. 40). The savings (Fig. 41) result in cost-efficient applications, especially for larger volumes.

In general, suppressant systems are only effective against dust explosions of the dust explosion classes St 1 and St 2.

Technical Disengagement of Explosions Within Combined Systems

Preliminary Remarks—The use of technical disengagement system is always necessary when:

- more than one protective measure is applied or
- vessels are connected by long ducts.

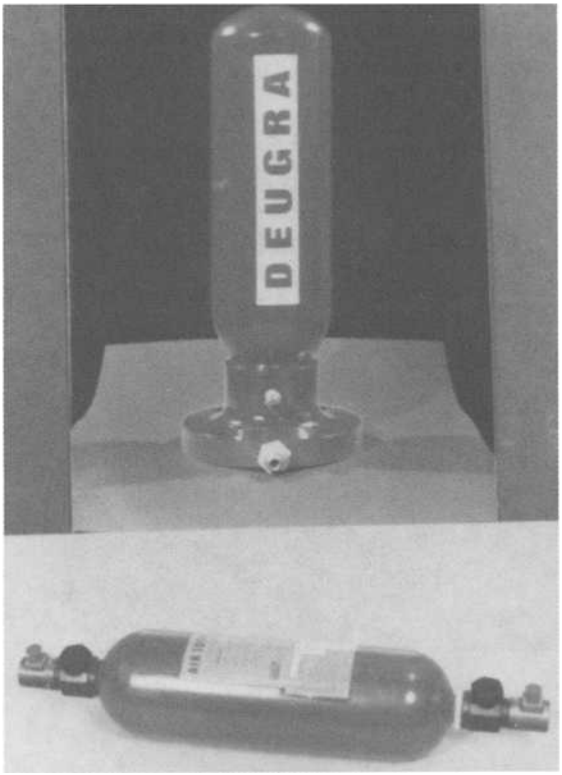


FIG. 38—*5.4-L extinguisher.* Top: *with 3 in. valve.* Bottom: *with ¾ in. valves.*

An example of the first case is the use of "preventive measures" (see earlier) in one section which is connected to another part where "design measures" (see earlier) are used because an ignition source is anticipated and an explosion is imminent.

In the second case, pressure piling and flame jet ignition will result in substantial overpressures. This is especially true if an explosion originates in a larger vessel and then propagates through a pipeline into a smaller vessel [*21*].

Rotary-Vane Feeder—If the technical disengagement is done by a rotary vane feeder (Fig. 42) from a piece of equipment protected through design measures, then such a feeder can also act as a flame arrester if it is designed properly.

Rotary-vane feeders (airlocks) can be used in practice if their pressure resistance as well as their suitability as flame arresters have been documented with dust explosion tests. The test for the suitability as a flame arrester is of utmost importance to assess the effects of the given clearance between the vanes and the housing. For combustible dusts such a gap has to be in the millimetre range, the same as with flammable gases (Fig. 43).

The allowable gap width depends upon the minimum ignition energy requirement and the ignition temperature of the fuel [*22*]. In the case of an explosion, the feeder has to stop automatically. Only this will prevent the start of a secondary fire or an explosion due to glowing accumulations or burning particles.

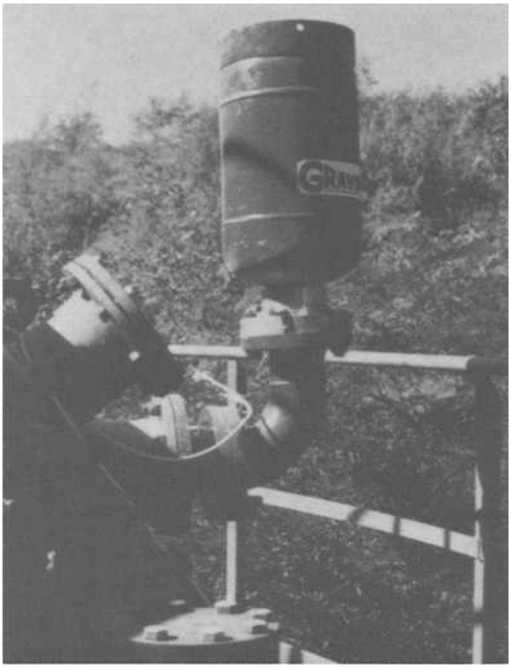


FIG. 39—*45-L extinguisher with 5 in. valve.*

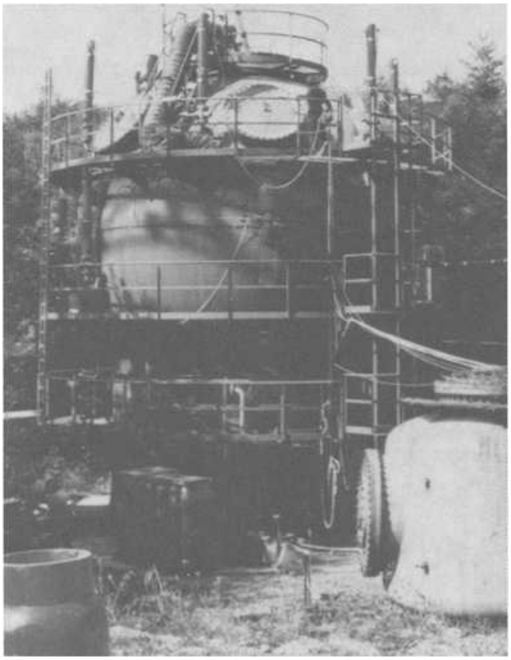


FIG. 40—*250-m³ vessel with ten dust bottles and ten 45-L extinguishers for the suppression of ST2 dust explosions.*

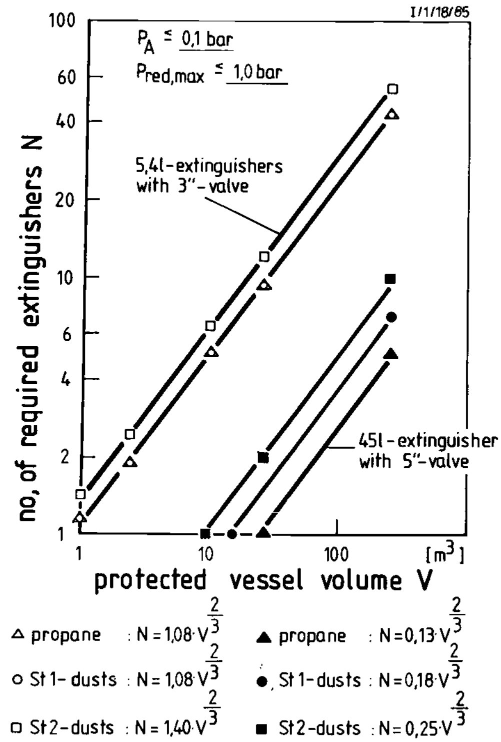


FIG. 41—*Suppressant requirements versus vessel volume. Influence of extinguisher volume and valve size.*

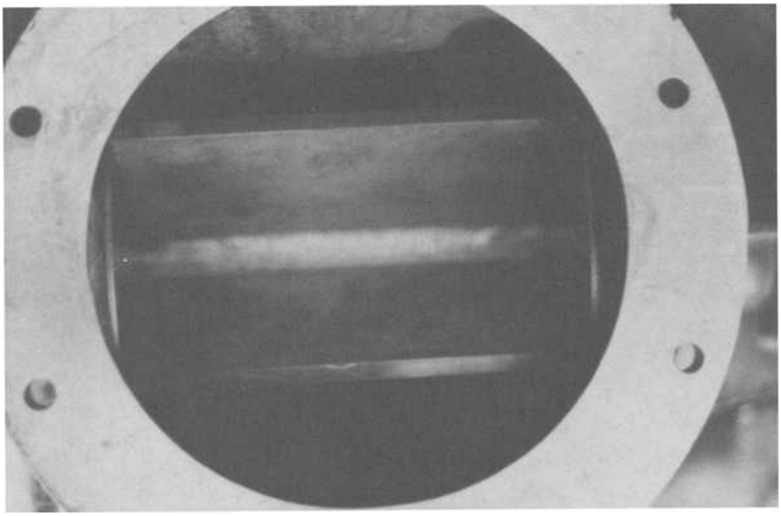


FIG. 42—*Rotary-vane feeder.*

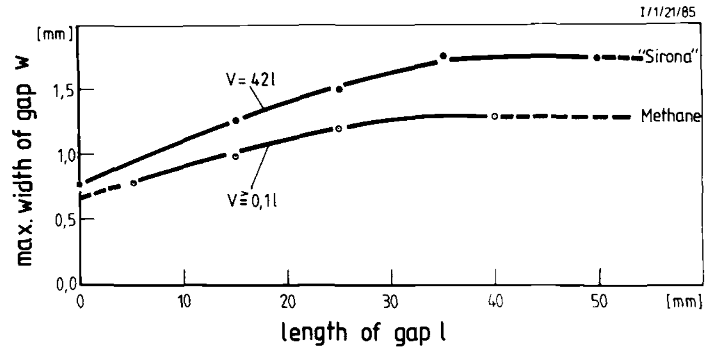


FIG. 43—*Length of gap* (1) *versus width of gap* (w). *Comparison of cornstarch "Sirona" with methane.*

Extinguishing Barrier—The effectiveness of an extinguishing barrier (Fig. 44) depends upon the optical flame detection of a dust explosion in a pipeline. A signal is amplified and used to trigger the explosive activator of the valve on the extinguisher containing a pressurized extinguishing medium. This medium—preferably powder—is injected into the pipeline through the expansion of the driving medium, nitrogen. The medium forms a thick cloud which will extinguish the flame.

There is a specific relationship between the location of the optical detector and the extinguishers which allows the extinguishing medium to contact the flame immediately. The required amount of extinguishing agent depends upon the type of combustible dust, the cross section of the pipeline and the explosion velocity [*19*]. Such a barrier system does not reduce the free area of the pipe.

Rapid Action Valves: Gate or Butterfly Type—As in the case of a flame barrier, an approaching dust explosion is detected by an optical sensor which will activate the closing of a rapid action gate or butterfly valve (Figs. 45 and 46). The time required to shut the valve depends on the size of the valve and the closing mechanism. In general, it is markedly below 50 ms.

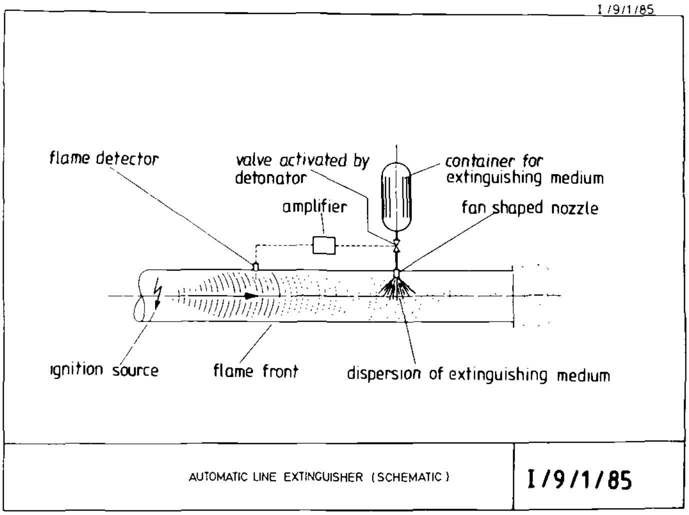


FIG. 44—*Extinguishing barrier (schematic).*

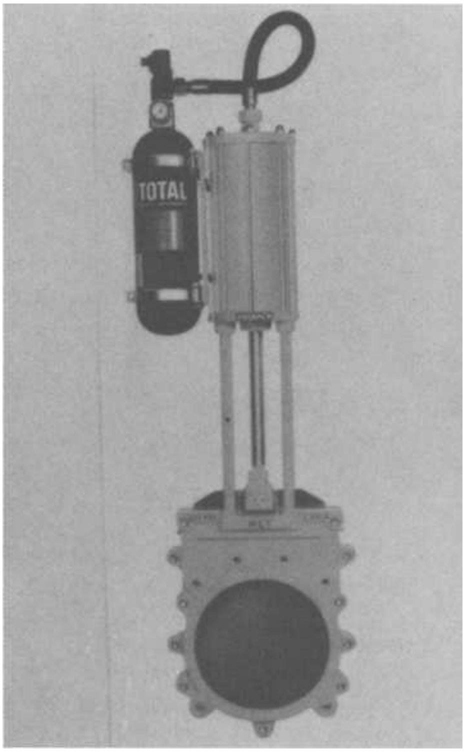


FIG. 45—*Rapid action gate valve.*

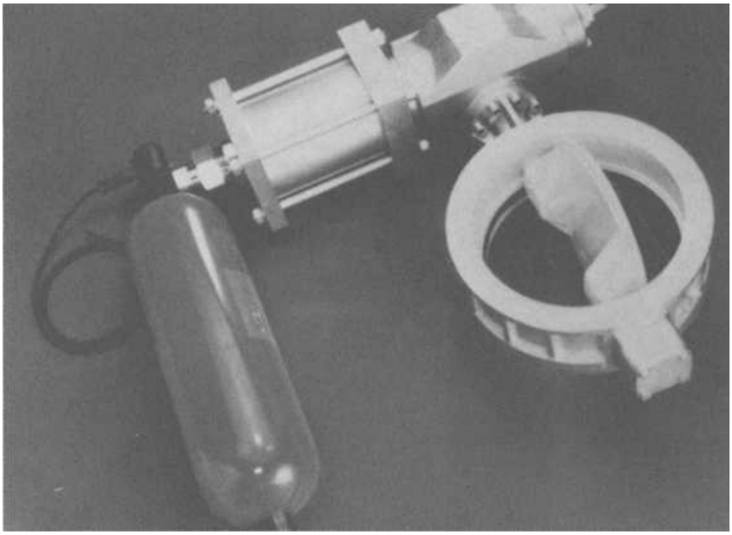


FIG. 46—*Rapid action butterfly valve.*

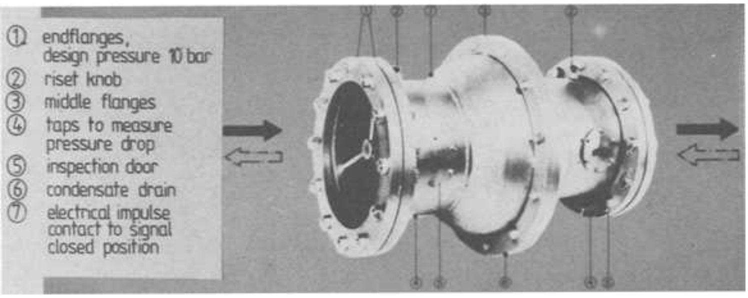


FIG. 47—*Rapid action float valve.*

The effectiveness of the gate and butterfly valves with regard to pressure resistance and ignition breakthrough has to be determined in dust explosion tests.

Rapid Action Valve: Float Type—The technical disengagement of an explosion can also be accomplished with a float-type valve (Fig. 47). The inner part of the valve consists of a float which is supported by bushings and therefore can move axially in either direction. The center positioning is controlled by springs. The force of the spring is designed for a maximum air velocity of 24 m/s, based on the cross section of the pipe [*21*].

In case of an explosion, the valve closes automatically because of the kinetic energy of the pressure wave which precedes the flame front. For the valve to function, the explosion velocity has to be greater than 24 m/s or the pressure differential before and after the float over 0.1 bar (10 kPa).

Upon closing, the float is pressed against a rubber gasket and locked in place by a holding mechanism. The unloading is done externally. This type of valve can only be installed in a horizontal pipeline.

Such valves can also be actuated through compressed nitrogen released instantaneously from a cylinder as soon as a detector senses the oncoming explosion [*19*].

The effectiveness of the valve with regard to pressure resistance and ignition breakthrough is determined in dust explosion tests.

Explosion Diverter—A diverter (Fig. 48) which turns the flow 180° is especially economical for disengaging explosions technically.

The main thrust of the explosion propagating through the longer pipeline ahead of the equipment needing protection will be diverted upwards after the coverplate has lifted. Any restarted explosion, if it occurs at all, will enter the protected equipment at much lower velocities and pressures. Only explosion barriers or fast acting valves will prevent the explosion transfer entirely.

Summary

To counteract the dangers of a dust explosion from dust layers or dust clouds in practice it is important to determine the safety characteristics which quantify these dangers. Based on these characteristics, it can then be decided whether explosion protection is needed for installations which produce, handle, or convey combustible dusts. Protection may be of the preventive type (prevention of dust explosions) or the constructive type (prevention of dangerous explosion results) or a combination of both. In Europe, many laboratories have conducted systematic development work, especially over the past 20 years. Some of the work is still going on, and this paper reports

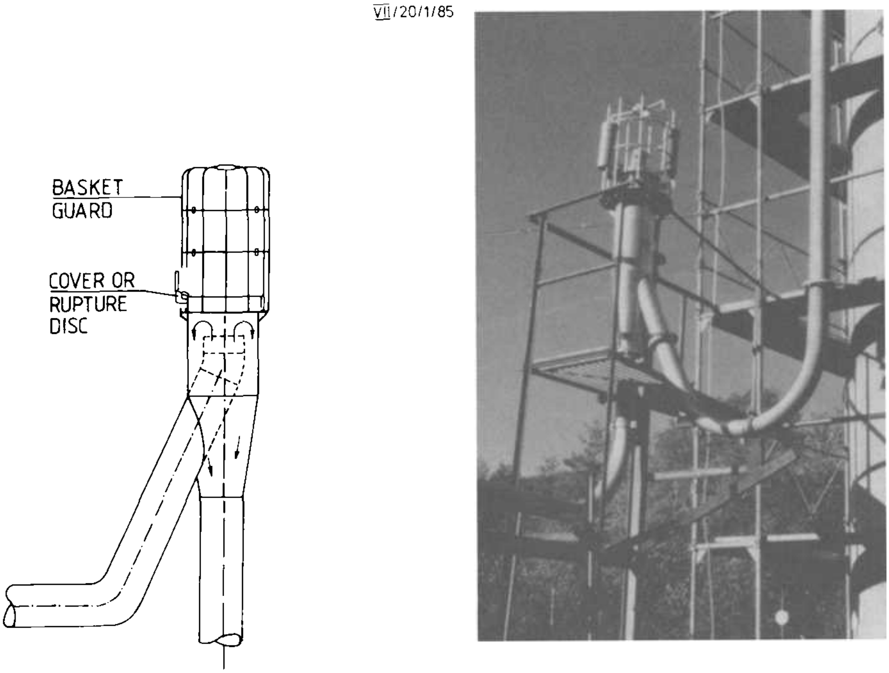


FIG. 48—*Diverter. Left: schematic and right: actual installation.*

on the results and the consequences for dust explosion protection. Based on today's knowledge, no one need be exposed unprotected to a dust explosion because such explosions can be mastered.

References

[1] Bartknecht, W., *Staubexplosionen—Ein historischer Ueberblick,* VDI-Berichte 494, S11-24, VDI Verlag GmbH Duesseldorf, W. Germany, 1984.

[2] Bartknecht, W., "Untersuchung des Explosions-und Zuendverhaltens brennbarer Staeube und hydrider Gemische Schriftenreihe," *Humanisierung des Arbeitslebens,* Band 64, Herausgeber: Der Bundesminister fuer Forschung und Technologie, VDI Verlag GmbH, Duesseldorf, W. Germany, 1985.

[3] VDI-Richtlinie 2263, "Staubbraende und Staubexplosionen," Gefahren-Beurteilung-Schutzmassnahmen VDI-Kommission Reinhaltung der Luft Beuth-Verlag GmbH, Berlin und Koeln, Entwurf Feb. 1985.

[4] Staubexplosiongefaehrdete Maschinen und Apparate: Vorbeugende und Konstruktive Schutzmassnahmen IVSS: Sektion Maschinenschutz Ak6 "Staubexplosionen" D-6800 Mannheim, W. Germany, Entwurf Nov. 1985.

[5] Explosionsschutz-Richtlinien der Berufsgenossenschaft der chemischen, Industrie Ausgabe 03. 1985, Druckerei Winter, Postfach 106140 D-6900, Heidelberg 1, W. Germany.

[6] Kuehnen, G. and Beck, H., Grundlegende Fragen der Sicherheitstechnik bei Staubbraenden und Staubexplosionen, VDI-Berichte 494 S.25-33, VDI Verlag GmbH, Duesseldorf, W. Germany, 1984.

[7] Ritter K., Die Zuendwirksamkeit mechanisch erzeugter Funken gegenueber Gas/Luft-und Staub/Luft-Gemischen, Dissertation Universitaet Fredericiana Karlsruhe (TH), W. Germany, 1984.

[8] Bartknecht, W., Untersuchung ueber das Zuendverhalten von mechanischen Funken in Staub/Luft-Gemischen Jahresbericht, 1984 und 1985, Ciba-Geigy AG, Zentraler Sicherheitsdienst, Fachgruppe Explosions-technik, Basel, Switzerland.

[9] ZH 1/200 Richtlinien zur Vermeidung von Zuendgefahren infolge elektrostatischer Aufladungen, Richtlinie "Statische Elektrizitaet" Carl Heymanns Verlag, D-5000 Koeln, W. Germany.

[10] Maurer, B., Elektrostatische Entladungsvorgaenge als Zuendquelle 9. Internationales Kolloquium fuer die Verhuetung von Arbeitsunfaellen und Berufskrankheiten in der chemischen Industrie CH Luzern, Switzerland, Juni 1984.

[*11*] VDI-Guideline 3673, "Pressure Release of Dust Explosions," VDI-commission Reinhaltung der Luft, Beuth Verlag, Berlin und Koeln, W. Germany, Oct. 1983.

[*12*] Donath, C., Explosionsfeste Bauweise von Apparaturen VDI-Berichte 494 S.161-167, VDI Verlag GmbH, Duesseldorf, W. Germany, 1984.

[*13*] Hattwig, M. and Faber, M., Rueckstosskraefte bei Explosionsdruckentlastung, VDI-Berichte 494 S.219-226, VDI Verlag GmbH, Duesseldorf, W. Germany, 1984.

[*14*] Brunner, M. Y., Bauwerkbeanspruchungen durch Rueckstosskraefte druckentlasteter Staubexplosionen, VDI-Berichte 494 S. 227-232, VDI Verlag GmbH, Duesseldorf, W. Germany, 1984.

[*15*] Bartknecht, W., Druckentlastung von Staubexplosionen in Grossbehaeltern Bundesministerium fuer Forschung und Technologie, Abschlussbericht, Bonn, W. Germany, 1985.

[*16*] Bartknecht, W., "Effectiveness of Explosion Venting as a Protective Measure For Silos," *Plant/ Operations Progress,* Vol. 4, No. 1, Jan. 1985.

[*17*] Bartknecht, W. and Bruderer, R. E., Explosionsablauf von Maisstaerke in einem druckentlasteten 20m^3-Silo bei pneumatischer Befuellung Ciba-Geigy AG, Zentraler Sicherheitsdienst, Fachgruppe Explosionstechnik, Basel, Switzerland, Mai 1985.

[*18*] Radandt, S., Staubexplosionen in Silos: Untersuchungsergebnisse Teil 3, Symposium Heft 14 der Berufsgenossenschaft Nahrungsmittel und Gaststaetten, Knopf-Druck, D6803 Edingen-Neckarhausen, W. Germany, Sept. 1985.

[*19*] Bartknecht, W., Explosionen, Ablauf und Schutzmassnahmen, Springer-Verlag, Berlin, Heidelberg, New York, 2. Auflage S129-125, 1980.

[*20*] Moore, P. and Bartknecht, W., "Suppression of Gas and Dust Explosions in Large Volumes," presented at the 5th International Symposium of Loss Prevention and Safety Promotion in the Process Industries, Cannes, France, Sept. 1986.

[*21*] Czajor, C., Explosionstechnische Entkopplung von Apparaturen, VDI-Bericht 494, S233-238, VDI Verlag GmbH, Duesseldorf, W. Germany, 1984.

[*22*] Schuber, G. Zuenddurchschlagverhalten von Staub/Luft-Gemischen und hybriden Gemischen Zwischenbericht "6" Ciba-Geigy, Basel, Switzerland, 11 Jan. 1985.

Robert G. Zalosh[1]

Review of Coal Pulverizer Fire and Explosion Incidents

REFERENCE: Zalosh, R. G., "**Review of Coal Pulverizer Fire and Explosion Incidents,**"*Industrial Dust Explosions, ASTM STP 958,* Kenneth L. Cashdollar and Martin Hertzberg, Eds., American Society for Testing and Materials, Philadelphia, 1987, pp. 191–201.

ABSTRACT: Reports of 26 coal pulverizer fires and explosions are reviewed in order to elucidate causes and preventive measures. Most of the explosions occurred during pulverizer shutdowns or restarts. The most common ignition scenario involved coal dust accumulations in the mill spontaneously igniting and coming in contact with a flammable coal dust-air suspension during a mill shutdown or restart. Detection of spontaneous combustion by pulverizer outlet temperature alarms (and, to a lesser extent, carbon monoxide analyzers) has not been reliable. Improvements are needed in the detection of incipient mill fires and the effective use of inert gas purges to prevent destructive pulverizer explosions.

KEY WORDS: coal pulverizers, coal dust, fires and explosions, inerting

Coal pulverizer fires and explosions have been a chronic problem at coal-fired power stations and cement plants. The extent of the problem at coal-fired power stations and utility measures being invoked to mitigate it have been documented in a series of papers [*1–4*] presented recently at the Symposium on Coal Pulverizers. The analogous situation in the cement industry has been described in a series of Bureau of Mines and Portland Cement Association workshops and is addressed in the paper by Alameddin and Luzik [*5*] in this Symposium volume.

As a result of the information compiled in these recent papers and symposia, a clearer picture of the pulverizer explosion hazard is emerging. Typical explosion scenarios, as specified, for example, in terms of ignition sources and fuel and oxygen concentrations, are now being identified from incident reports and from in situ measurements. Similarly, the success and limitations of alternative explosion prevention measures are being assessed from actual plant experience and test data.

The intent of this paper is to review these coal pulverizer fire and explosion incident accounts to determine their consistency with current laboratory data on coal dust flammability and explosibility [*6–10*]. An incident database composed primarily of relevant Factory Mutual (FM) loss reports is used along with data on the pulverizer internal environment during normal operations and incipient fires and explosions [*11,12*]. The incident database is presented following a brief synopsis of pulverizer design and operation.

Pulverizer Design and Operation

The three types of coal pulverizers used in the United States are: (1) ball tube mills, (2) bowl mills (also called roller-race mills or vertical spindle mills), and (3) hammermills.

---

[1] Manager, Applied Research Department, Factory Mutual Research Corp., 1151 Boston-Providence Turnpike, Norwood, MA 02062

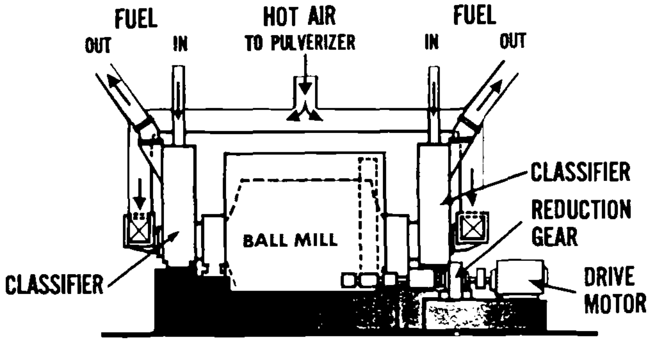


FIG. 1—*Ball tube mill.*

Ball tube mills are rotating horizontal cylinders containing steel or special alloy balls. Coal intermingled with the balls is crushed by the impact and grinding action of the balls as the mill rotates. Hot air flowing through the ball mill carries coal particles to classifiers situated at both ends of the mill (Fig. 1). Large particles rejected in the classifiers are returned to the grinding zone for further size reduction. Small particles passing through the classifier exit the mill through piping leading to burners in direct fired systems and to cyclone collectors in indirect fired (storage bin) systems.

Bowl mills are vertical cylinders containing a rotating bowl in contact with two or more spring-loaded rollers. Coal enters the top of the mill and falls through a central feed pipe leading to the bowl (Fig. 2). Centrifugal force displaces the raw coal toward the outer perimeter where it is crushed between the rollers and a grinding ring in the bowl. Hot air entering the mill under the bowl entrains the crushed coal particles as it flows upward through a narrow opening (called the

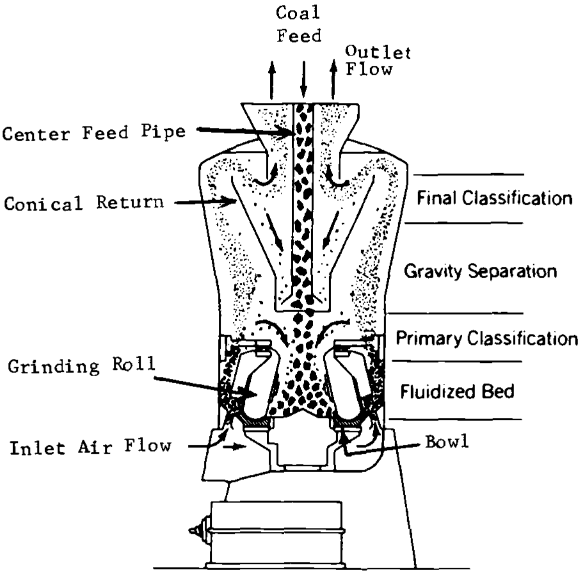


FIG. 2—*Coal recirculation in bowl mill.*

throat) between the edge of the bowl and the pulverizer wall. The coal-air mixture then flows through the classifier at the top of the mill. Smaller particles leaving the classifier are carried in the air flowing out the top of the mill, but the larger particles are returned to the bowl via the conical classifier reject housing.

Hammermills employ swing hammers mounted on rotating shafts to impact the raw coal and pulverize it against an adjustable crusher block. As in the other types of mills, a classifier assembly returns the coarser coal particles for further pulverizing, and allows the finer particles to be entrained into the exhauster flow. Hammermills generally produce larger particles than the other pulverizers and have relatively high power requirements. They are not used as extensively as ball mills and bowl mills in the United States.

Pulverizer coal throughput capacities are typically in the range of 10 to 90 ton/h (2.5 to 23 kg/s). Output size distribution as represented by weight percent through a #200 sieve ranges from 60% through to as much as 90% through. Hot air temperatures in the pulverizer inlet flow range from 300 to 500°F (150 to 260°C), while mill outlet temperatures are typically 140 to 170°F (60 to 77°C).

Startup and shutdown practices vary significantly. A few pulverizing systems are inerted on all startups and shutdowns. Others are inerted during emergency shutdowns, as specified in NFPA 85F-1982 [*13*], but most have no provision for inerting at all (as of 1982 when the survey reported in Ref *1* was conducted). These differences in practice stem from different perceptions of the feasibility of effective inerting as well as differences in cost-effectiveness evaluations. One of the objectives of the following fire/explosion incident review is to assess the current effectiveness of inerting systems and the hazard associated with pulverizer operation without any inerting provision.

Incident Database

The incident database contains information culled from Factory Mutual loss reports describing 26 pulverizer fire and explosion incidents during the past ten years. Three incidents occurred in cement plants and the other 23 occurred in 19 power plants. All but 3 of the incidents occurred in direct fired pulverizer systems.

Table 1 lists the plant code designation, type of pulverizer, operational status at ignition, fire/explosion sequence, and estimated property damage for each incident.

The distribution of incidents among the three types of pulverizers is: bowl/roller mills—13 incidents; ball mills—7 incidents; hammermills—2 incidents; unspecified—4 incidents. The relatively large number of bowl mill incidents is not surprising because there are many more bowl mills than the other two types in the United States. Incident frequencies could not be determined in this loss report database, but a much larger survey generated database compiled by Riley Stoker [*1*] indicated that bowl mills had roughly the same fire frequency (about 1.3 fires per year per mill) as ball mills, but about twice the explosion frequency (0.34 explosions per year per bowl mill). According to Carini et al. [*1*] the latter difference is probably not statistically significant in view of all the other factors that influence pulverizer explosion frequency.

The data on mill operational status at ignition indicate a remarkably high occurrence of restart and shutdown incidents, as shown in Fig. 3. Furthermore, all but one of the restart/shutdown incidents were explosions or explosions followed by fires. This contrasts with the two normal operations incidents, which were both fires. Implications of this data are discussed later in terms of flammability and explosibility conditions within the mill.

High temperature alarms based on mill exit air temperatures were triggered in three of the four emergency shutdown incidents and in one other incident involving a reduced coal feed rate. However, high temperature alarms did not trigger in at least seven other incidents in which they were installed. The alarm threshold, which varied from 161 to 203°F (72 to 95°C), did not seem to be the deciding factor as to whether or not the alarm would trigger. This result is consistent

TABLE 1—*Pulverizer incident tabulation.*

Incident	Year	Plant[a]	Type of Mill	Status at Ignition	Fire/Explosion Sequence	Property Damage (k$)
1	75	P-1	bowl	restart	explosion	110
2	75	P-2	bowl	operating	fire	50
3	76	P-3	hammer	operating	fire	6
4	77	P-4	?	idle	exp-fire	200
5	78	P-5	bowl	n. shutdown	exp-fire	1 438
6	79	P-6	bowl	restart	exp-fire	1 000
7	79	P-7	bowl	intermittent	explosion	100
8	79	C-1	bowl	intermittent	explosion	150
9	79	P-8	ball	restart	explosion	100
10	80	P-9	ball	e. shutdown	fire-exp	350
11	80	P-10	hammer	n. shutdown	exp-fire	15 000
12	80	P-11	bowl	n. shutdown	explosion	70
13	80	P-9	ball	restart	explosion	25
14	80	P-9	ball	n. shutdown	explosion	25
15	80	P-12	ball	n. shutdown	explosion	100
16	81	P-12	ball	n. shutdown	explosion	50
17	83	P-13	bowl	restart	explosion	170
18	83	P-14	?	?	explosion	250
19	83	C-2	ball	coal feed jam	exp-fire	150
20	83	P-15	bowl	e. shutdown	explosion	135
21	83	P-16	bowl	n. shutdown	explosion	20
22	83	P-17	?	?	fire	275
23	83	C-3	bowl	e. shutdown	exp-fire	45
24	84	P-18	?	e. shutdown	exp-fire	150
25	84	P-15	bowl	restart	explosion	120
26	84	P-19	bowl	cutback	fire	80

[a] Plants are identified by code: P or C designate power or cement plant, and the number designates a specific company or organization for each type of plant.

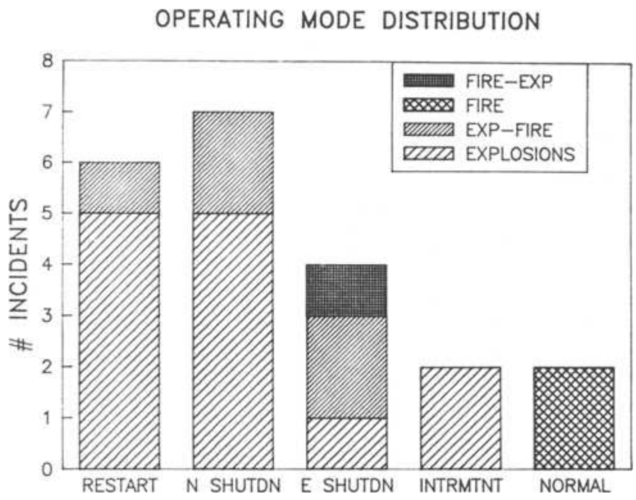


FIG. 3—*Incident operating status at ignition.*

TABLE 2—*Inert gas purge systems in incidents.*

Inert Gas	Available, Incidents	Used at Ignition, Incidents
Steam	6	2
Carbon Dioxide	5	0
None	12	NA
Unknown	3	NA

with the Riley Stoker data [1] which indicated that the frequency of mill fires was not statistically dependent upon the temperature threshold of the alarm. The Riley Stoker survey did indicate that a temperature detection system that compares mill outlet temperature to mill inlet air temperature is reported to be more effective than detection on the basis of outlet temperature alone.

Table 2 shows the distribution of inert gas systems involved in these incidents. At least half the incidents occurred in facilities without any available inert gas purge for the pulverizer. In the eleven incidents where a steam or carbon dioxide purge was available, the purge was not being used at ignition in nine of these incidents. The most cited reasons for the purge not being used at ignition were: equipment malfunction preventing its activation, and operator belief that it was not necessary because either they did not realize there was a problem, or they thought the problem had been eliminated by earlier use of the inerting or extinguishing system. (Some examples of these incidents are briefly described in the illustrative incident narratives below.)

Table 3 shows the property damage distributions for the four fire/explosion sequences. Incidents involving an explosion followed by a fire incur, on average, an order-of-magnitude more property damage than the other three sequences. The postexplosion fires are usually due to flames being vented from ruptured air ducts which are weaker than the pulverizer and the burner feed pipe. Incidents involving a pulverizer fire leading to an explosion also, on the average, produce significantly more property damage than either explosions alone or fires alone.

Since these tabulations are based on insurance company loss reports, they do not reflect the numerous minor fires and "puffs" often not reported to Factory Mutual. One indication of the difference between the Factory Mutual database and the broader electric utility database described in Ref *1* is that the FM database contains about three times as many explosions as fires, while the Riley Stoker database in Ref *1* has about four times as many reported fires as explosions. This would imply that many of the pulverizer fires are easily extinguished before they produce damage exceeding the deductible allowance for insurance claims.

Another inherent limitation of the FM database is that the reports usually do not contain information on the type of coal used. The Riley Stoker survey [1] indicated that pulverizers with subbituminous coals had twice the fire and explosion frequencies as those with bituminous coals.

TABLE 3—*Property damage in fire/explosion sequence.*

Fire/Explosion Sequence	Incidents	Property Damage (k$) Avg	Max	Min
Explosion	14	102	205	20
Fire	4	103	275	6
Explosion-Fire	6	2971	15 000	45
Fire-Explosion	2	275	350	200

Illustrative Incidents

The following incident narratives are offered to provide additional insight into pulverizer fires and explosions with current prevention, detection, and inerting measures (see Table 1).

Incident 10

This pulverizer explosion occurred in a direct fired system with four 90 ton/h capacity ball tube mills. Subbituminous western coal is dried and crushed to nominal ¾-in. (1.9-cm) size before entering the mills. As in most pulverizers, the operator can adjust inlet air temperature and flow rate by the positions of dampers in the hot air and tempering air ducts leading to the mill. Mill diagnostics available to the operator include mill inlet and outlet air temperatures, classifier inlet temperature, coal depth, and air flow rates. A carbon monoxide analyzer is also usually available, but was down for repairs during the incident. Manually operated steam inerting and water spray systems are available for emergencies in which mill temperatures cannot be controlled merely by coal and hot/tempering air flow rates.

The sequence of events leading to the explosion began about 2 p.m. the preceding day when the inlet temperature to Mill 3 started to climb (see Fig 4). By 6:37 p.m. the inlet and outlet temperatures were well above the normal range (200 to 250°F [93.3 to 121.1°C]), and the differential pressure indicator in the mill inlet air duct registered zero air flow. Steam inerting was initiated at this time, as indicated in Fig. 4, but mill temperatures continued to rise. At 10:15 p.m. the mill deluge system was activated for 2.5 min. Coal feed to the mill was stopped at 10:55 p.m., and the mill was again deluged, this time for 10 to 15 min. Mill temperatures returned to normal at this point, and both the steam inerting and the water deluge systems were shut down.

An inspection of the air ducts at 11:10 p.m. revealed that the tempering air duct damper was actually completely shut despite a control room reading indicating fully open. Repairs to this damper and to another faulty damper in the hot air duct were completed by 11:38 p.m. Steam

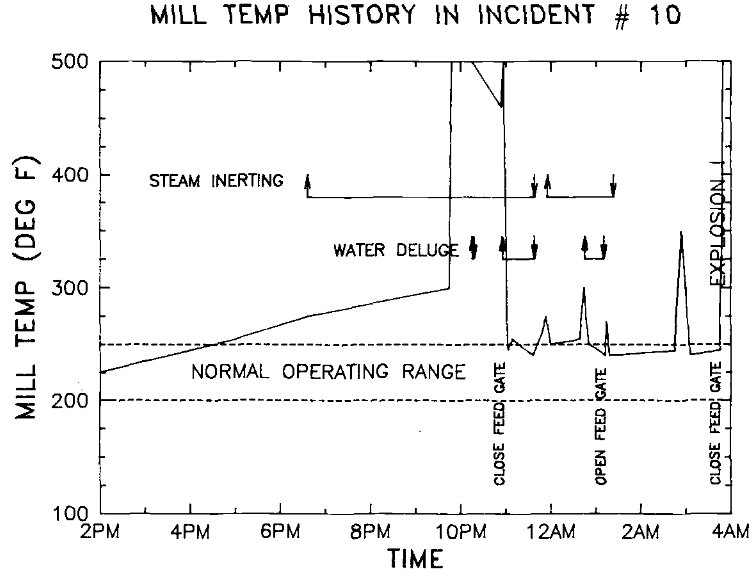


FIG. 4—*Mill temperature history in Incident 10.*

inerting was discontinued at this time with the expectation that air flows could now resume control of mill temperatures. This was only partially successful (see Fig. 4), and another period of steam inerting and water deluge was needed.

When the coal feed gate was opened at 1:23 a.m. to restart coal flow into the mill, a mild "puff" occurred as evidenced by spikes in the air flow differential pressure readings and by visual observation of coal dust leakage/blowing. This leakage grew worse over the next 2 h (even though mill temperatures were successfully controlled by the air flow dampers), so that the coal feed gate was closed to begin shutting down and stripping the mill. At 3:46 a.m. mill temperatures started to increase substantially, and air dampers were adjusted accordingly. Steam inerting was restarted at 3:53 a.m. but an explosion occurred 1 min later. The explosion ruptured coal-air ducts leading from the mill classifiers to the boiler, and also caused a fire involving fuel oil escaping from a broken burner igniter line.

Incident 23

This incident occurred in an indirect fired pulverizing system equipped with a carbon monoxide monitor and a carbon dioxide inerting system. Shortly after a high temperature (147 °F [64°C]) alarm sounded in the control room, a mill emergency shutdown was initiated. This includes coal feed and pulverizer shutdown along with carbon dioxide purge and water spray activation. The shutdown was successful in that temperatures, which had continued to rise above 200°F (93.3°C), decreased almost to the normal operating range (130 to 135°F [54.4 to 57.2°C]) after a period of 3 h (Fig. 5). At this point, however, the operator jogged (momentarily started) the pulverizer. Within seconds, an explosion occurred and a fire ensued in both the pulverizer and the cyclone collectors connected to the pulverizer outlet.

Investigation following the incident showed that the carbon dioxide tank had been emptied by repeated purges during the 3 h shutdown. A faulty tank gauge did not alert the mill operators to the deplenished carbon dioxide supply. Inspection of the bowl mill revealed a 12-in. (30-cm) deep

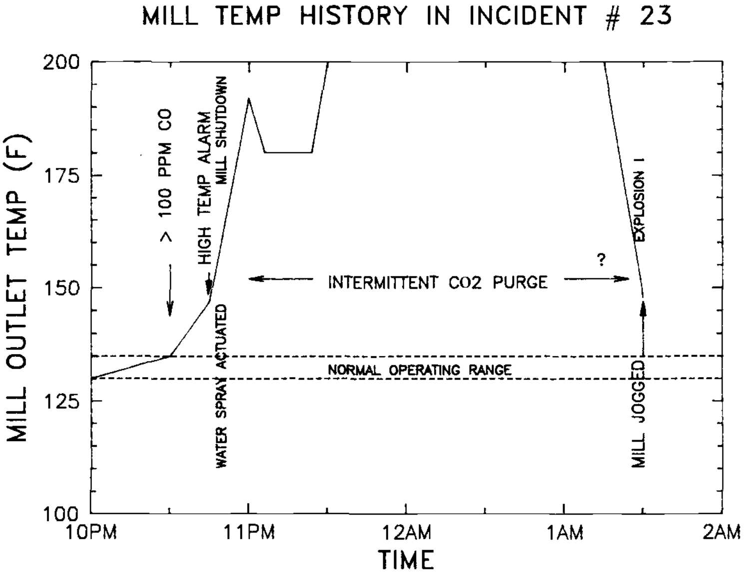


FIG. 5—*Mill temperature history in Incident 23.*

accumulation of coal dust which apparently had been smoldering during the shutdown period. This was confirmed by the carbon monoxide monitor record which showed concentrations exceeding 100 ppm during, and for a 15–min period preceding, the shutdown. When the pulverizer was jogged, sone hot coal probably contacted and ignited coal dust dispersed above the bowl and in the mill outlet ducting.

Pulverizer Explosibility Analysis

Are these reports of pulverizer fires and explosions consistent with laboratory data on coal dust–air mixture flammability limits and criteria for spontaneous combustion of coal deposits? Lower explosive limits for coal dust in air have been reported to range from 0.05 kg/m^3 [*9*, p. 207] to 0.13 kg/m^3 [*6*] depending on the type of coal (particularly percentage of volatiles) and the test apparatus employed. Upper limits in air are reported [*7*] to be in the range 2.0 to 4.0 kg/m^3 depending on coal particle size (10 to 50 μm) and effective ignition energy. The lower limit increases asymptotically as oxygen concentrations decrease to the reported [*6,10*] limit value of 12 to 14% by volume, depending on coal volatility, inert diluent gas, temperature, and ignition source strength. According to recent data reported by Wiemann [*10*], there is a corresponding but more pronounced reduction in the upper limit as oxygen concentrations are reduced to these limit values. Wiemann also reports that oxygen limit concentrations typically decrease by about 0.14% by volume for each 10°C (50°F) increase in mixture temperature.

Pulverizer coal dust concentrations cannot readily be measured directly but steadystate outlet concentrations can be calculated from the design coal feed rates and air flow rates. Results for six different pulverizers in the FM incident database are shown in Table 4. In each case (with the possible exception of Plant P-11), the steadystate outlet concentration is well within the lower and upper flammability limits cited above. In fact, outlet concentrations in two pulverizers are very close to the value (0.30 kg/m^3) found by Gardner et al. [*14*] to produce the highest pressures and flame speeds (in some cases bona fide detonations) for coal dust explosions in pipes connected to mock pulverizers.

Actual mill outlet concentrations at ignition probably differ from those in Table 4 because in all but four of these incidents, the coal feed to the pulverizer was shut off or significantly reduced at the time of ignition. The time lag between coal feed shutoff and ignition varied from a few seconds to at least 16 min. Air flow rates were 100% full flow in most restart incidents, but were either shut off or well below full flow in many shutdown incidents.

Pulverizer oxygen concentrations during mill operation are somewhat lower than 21% because of the water vapor generated during coal heating and pulverizing. Oxygen concentrations are not usually measured, but data for a few plants have been reported in Ref *11*. Oxygen concentrations during normal operation of the pulverizers tested were in the range of 16 to 19%. Thus coal dust

TABLE 4—*Pulverizer outlet fuel concentrations.*

Plant	Coal Feed Rate, kg/s	Air Flow, m^3/s	Outlet Concentration, kg/m^3
C-1	1.9	7.1	0.27
C-3	7.6	10.1	0.75
P-6	2.5	7.1	0.35
P-11	13.9	7.1	1.96
P-12	6.3	6.2	1.02
P-15	17.0	24.1	0.71

concentrations can occasionally approach upper limit (oxygen limited) conditions in some cases, but most mills operate within the flammable range.

In view of the flammable conditions that exist during normal operations of most pulverizers, the question of ignition sources in the mill must be addressed. Although pulverizer explosions have occasionally been ignited by sparking and hot spots associated with tramp metal entering the mill, most ignitions are apparently due to spontaneous combustion of coal deposits in the mill. According to the analysis and testing of Lawn et al. [*8*], the "onset" air temperature for the self-heating of pulverized coal beds can be as low as 65°C (150°F) for a 20-cm-deep fuel bed. Bureau of Mines data [*15,16*] obtained in an adiabatic heating oven (tantamount to an infinitely deep bed) demonstrate that bituminous and subbituminous pulverized coal beds begin self-heating at temperatures in the range of 30 to 135°C (86 to 275°F) depending on moisture and oxygen content. Comparing these values to the corresponding values reported in the preceding illustrative incidents, it is not surprising that there have been numerous coal pulverizer fires and explosions due to spontaneous combustion.

A closer look at the spontaneous ignition data of Lawn et al. [*8*] reveals why, indeed, there have not been many more pulverizer fires and explosions, and what can be done to avoid these conditions in future operations. Their data clearly demonstrate that spontaneous combustion onset temperatures increase sharply as the depth of the coal bed decreases (Fig. 6). Mill outlet temperatures and coal deposit thicknesses in some of the reported incidents are also shown in Fig. 6 to indicate that spontaneous combustion is most likely to be an ignition source for relatively deep deposits or incidents in which steam purges simultaneously heat and moisten the coal deposits.

According to pulverizer operators [*3,4*], coal dust accumulations in bowl mills often occur at the air duct inlet to the mill. This is a particularly dangerous location because air inlet temperatures are significantly higher than average/outlet mill temperatures, and smoldering coal accumulations can burn there for a long time before outlet temperatures reach the alarm threshold. These operators have made modifications to that area of the mill/duct to avoid these accumulations.

Notwithstanding these and other mill design modifications to avoid chronic coal dust accumulations, occasional smoldering coal dust accumulations in the mill are inevitable. If an emergency

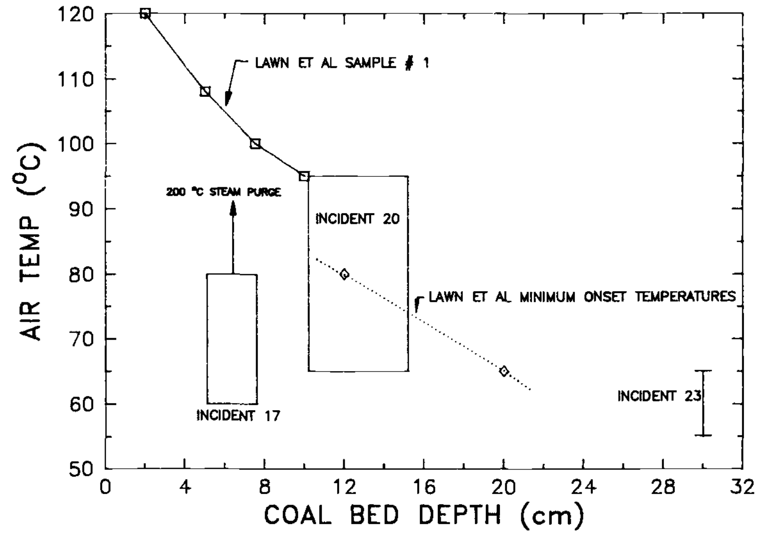


FIG. 6—*Comparisons of coal bed depths and temperatures in three incidents with minimum spontaneous heating temperatures reported by Lawn et al.* [*8*].

shutdown is conducted without an inert gas purge, the process of stripping the mill of coal may allow some of the smoldering accumulation to be dislodged and ignite the coal dust–air mixture which may still be in the flammable range near the mill outlet. This scenario is even more likely during a mill restart with a residual smoldering coal deposit. According to the FM incident database, these are the most likely scenarios for pulverizer explosions.

Inerting during all shutdowns and restarts is the only responsible alternative to verifying that the mill is free of any smoldering accumulations and residue. Of course, inerting requires verification measurements also. The two illustrative incidents included in this paper and other reported difficulties in implementing adequate steam inerting capability [*3*,*12*] indicate that additional work remains before the coal pulverizer fire/explosion hazard can be eliminated or generically controlled.

Conclusions and Recommendations

This analysis of coal pulverizer fires and explosions has shown that reported incidents are consistent with laboratory data on the flammability and explosibility of coal dust. Pulverizer fires occur often because mill inlet air temperatures are close to or above the onset temperatures for spontaneous combustion of deep coal dust accumulations. If, as is often the case, these incipient fires are detected (usually by temperature readings or observation of glowing hot metal, occasionally by carbon monoxide detectors in the mill), they can be extinguished by inerting or by deluging with water or, as a far less desirable alternative, by reducing mill temperatures with cool tempering air flows. When these fires are not detected, or when they are mistakenly believed to be extinguished, mill shutdowns and restart cause smoldering coal residue to be dislodged and ignite flammable coal dust–air suspensions in the mill and mill outlet lines.

Although the current understanding of pulverizer fire and explosion scenarios is being applied in making improvements and modifications to pulverizer design and operation, additional laboratory and full-scale data on flammability and detectability would be quite useful. In particular, data on spontaneous combustion onset temperatures in partially oxygen vitiated air flows are needed. Pulverizer fire detection and diagnostics have to be improved (possibly via infrared detectors or more reliable gas analyzer design and operation) or, more likely, have to be made cost-effective and reliable for routine use during pulverizer operation.

References

[*1*] Carini, R. C., Hules, K. R., and Broske, D. R., "Historical Trends in the Occurrence of Fires and Explosions in the U.S. Pulverized Coal Fired Utility Industry," presented at the Symposium on Coal Pulverizers, sponsored by the Electric Power Research Institute (EPRI), Nov. 1985 (see also Final Report on EPRI Research Project 1883-1, May 1986).

[*2*] Zalosh, R. G., "Influence of Startup/Shutdown/Emergency Procedures of Pulverizer Fire and Explosion Incidents," presented at the Symposium on Coal Pulverizers, sponsored by the Electric Power Research Institute, Nov. 1985.

[*3*] Keele, K. and Peterson C. A., "Coal Mill Fires & Explosions Experience Summary," presented at the Symposium on Coal Pulverizers, sponsored by the Electric Power Research Institute, Nov. 1985.

[*4*] Beckman, B. R., "Availability Improvement at KCPL" presented at the Symposium on Coal Pulverizers, sponsored by the Electric Power Research Institute, Nov. 1985.

[*5*] Alameddin, A. N. and Luzik, S. J., "Coal Dust Explosions in the Cement Industry," in this volume, pp. 217–233.

[*6*] Hertzberg, M., Cashdollar, K. L., and Lazzara, C. F., "The Limits of Flammability of Pulverized Coals and Other Dusts," in *Eighteenth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, PA, 1981, p. 717.

[*7*] Deguingand, B. and Galant, S., "Upper Flammability Limits of Coal Dust–Air Mixtures," in *Eighteenth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, PA, 1981, p. 705.

[*8*] Lawn, C. J., Street, P. J., and Baum, M. M., "Spontaneous Combustion in Beds of Small Fuel Particles," in *Eighteenth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, PA, 1981, p. 730.

[*9*] Field, P., *Dust Explosions*, Elsevier Scientific Publishing, New York, 1982.

[*10*] Wiemann, W., ''Influence of Temperature and Pressure on the Explosion Characteristics of Dust/Air and Dust/Air/Inert Gas Mixtures,'' in this volume, pp. 33–44.

[*11*] Jewett, S. Y., Robertson, J. W., and Woolbert, G. D., ''An Advanced Coal Mill Monitoring System for Fire and Explosion Prevention,'' presented at the Symposium on Coal Pulverizers, sponsored by the Electric Power Research Institute, Nov. 1985.

[*12*] Cannon, J. N., Germane, G. J., Holst, S., Carr, D., Clark, D., and Smoot, L. D., ''Transient Characterization of Pulverized Coal Mills with Steam Inerting; Summary Report Part VIII,'' Brigham Young University Combustion Laboratory Report, Dec. 1983.

[*13*] ''Standard for the Installation and Operation of Pulverized Fuel Systems,'' National Fire Protection Association Standard 85F-1982.

[*14*] Gardner, B. R., Winter, R. J., Moore, M. J., Broske, D., and Carini, R., ''Some Explosion Tests on Typical American Coals,'' presented at the Symposium on Coal Pulverizers, sponsored by the Electric Power Research Institute, Nov. 1985.

[*15*] Kuchta J. M., Rowe, V. R., and Burgess, D. S., ''Spontaneous Combustion Susceptibility of U.S. Coals,'' Bureau of Mines R.I. 8474, 1980.

[*16*] Smith A. C. and Lazzara C. P., ''Spontaneous Combustion Studies of Coal,'' presented at the 1984 Fall Technical Meeting of the Eastern Section of the Combustion Institute, Dec. 1984.

Richard C. Carini[1] *and K. R. Hules*[1]

Coal Pulverizer Explosions

REFERENCE: Carini, R. C. and Hules, K. R., "**Coal Pulverizer Explosions,**" *Industrial Dust Explosions, ASTM STP 958,* Kenneth L. Cashdollar and Martin Hertzberg, Eds., American Society for Testing and Materials, Philadelphia, 1987, pp. 202–216.

ABSTRACT: In 1981 the Electric Power Research Institute (EPRI) began a research program to study pulverized coal fires and explosions in the U.S. utility industry. Historical trends resulting from an industry-wide survey and experimental results of explosion-related testing are discussed. The survey indicates that explosive events are occurring at a rate of approximately one explosion for each unit every three years resulting in an industry cost of one billion dollars annually. The historical trends show that although coal type has a large influence on explosion frequency, it is not the only significant factor in setting explosion hazard levels. Laboratory experiments were performed in full-scale test rigs that allowed triggering and monitoring of coal system explosions on demand. Ignition events that remained within the coal pipe created only weak pressure rise, while ignition events within the simulated pulverizer volume created explosions exceeding 70 bars (7000 kPa). These experiments showed that explosion characteristics depend on dust concentration, ration of pulverizer volume to coal pipe area, as well as coal type.

KEY WORDS: pulverizers, fires, explosions, fire prevention safety, coal fired boilers

In 1981 the Electric Power Research Institute (EPRI) sponsored a research program to study pulverized coal fires and explosions in the U.S. utility industry. Historical trends resulting from an industry-wide survey and experimental results of explosion-related testing are discussed. The survey conducted by Riley Stoker Corporation (Riley) indicates that explosive events are occurring at a rate of approximately one explosion for each unit every three years resulting in an industry cost of one billion dollars annually. The historical trends show that although coal type has a large influence on explosion frequency, it is not the only significant factor in setting explosion hazard levels. Laboratory experiments were performed by the Central Electricity Generating Board (CEGB) and Fenwal, Inc. (Fenwal). Full-scale test rigs that were used allow triggering and monitoring of coal pulverizer system explosions on demand. Ignition events that remained within the coal pipe created only weak pressure rise, while ignition events within the simulated pulverizer volume created forces exceeding 70 bars (7000 kPa). These experiments showed that explosion characteristics depend on dust concentration, ratio of pulverizer volume to coal pipe area, as well as coal type.

The Survey Approach

The survey used a questionnaire, telephone conversations, and plant visits to gather data and observations from utility personnel. Descriptions of pulverizer systems, unit hardware, and characterization of the coal were sought by the survey.

In this paper the term "explosion" encompasses both severe puffs (structure deformation) and true explosions (containment breaching). The term "unit" designates a utility steam generator and its auxiliaries.

---

[1] Manager of administrative services, Research & Development, and senior staff engineer, Research & Development, respectively, Riley Stoker Corp. P.O. Box 547, Worcester, MA 01613.

The results of the survey indicate that the frequency of explosions is increasing. The average survey value of 0.31 explosions per year per unit shows a rise over previous averages [*1*]. Adjusted for the entire pulverizer coal fired utility industry, there is almost one explosive event each day. Even though a small percentage are of the containment breaching type, the other events have the potential of being true explosions. In addition, there is a wide range of explosion frequencies from plant to plant. Some units reported explosion-free operation while a few units reported as high as three explosions per year. It must be emphasized that the survey reflects the situation at the end of 1981 and some of the values may no longer apply. Since the survey, many plants have made modifications which have lowered their problem occurrences.

Survey Database

The database consists of data for 1678 pulverizers at 361 steam generating plants belonging to 76 separate utilities. Table 1 shows some sample data and statistics.

The database was analyzed using a statistical approach to categorize a plant's particular configuration with respect to explosion frequencies. Categories useful for industrial applications cover the follow areas:

Pulverizer System Characteristics
- Pulverizer system operation mode
- Pulverizer generic type
- Pulverizer operation mode
- Pulverizer capacity
- Number of pulverizers per unit
- Pulverizer age

Fuel Characteristics
- Coal type
- Coal volatile content
- Coal moisture content
- Coal ash content

Survey Trends

The analysis of the database shows that the explosion hazard level is not simply a function of small numbers of plant characteristics. If all units in the industry are viewed as a single group, there is no single parameter or group of parameters that distinguishes the high risk units from the low [*2*]. For all utility units, the categories noted above are statistically equivalent and equally poor for differentiation. Therefore, viewing explosion susceptibility as a function of a single category is ineffective.

In spite of the poor correlations, understanding the interaction of plant characteristics at a simple level of analysis is of value for a discussion of trends at a higher level of analysis. Figures 1 and 2 show the data for each of the characteristics. It is important to note that, because of the general nature of this phase of the discussion, not all units will follow or agree with the overall trends. Recognizing the statistically weak influence of these parameters, the following trends were observed:

1. *Pulverizer system operation mode:* Bin storage units have twice the explosion frequency as direct fired units. Differentiation of the direct fired units by coal type shows that subbituminous-

TABLE 1—*Sample database population statistics.*

Item	Minimum	Maximum	Average
Pulverizer age (years)	1	44	19.00
Pulverizer capacity (tons/hour)	3	100	31.50
Pulverizers per boiler	2	12	4.75

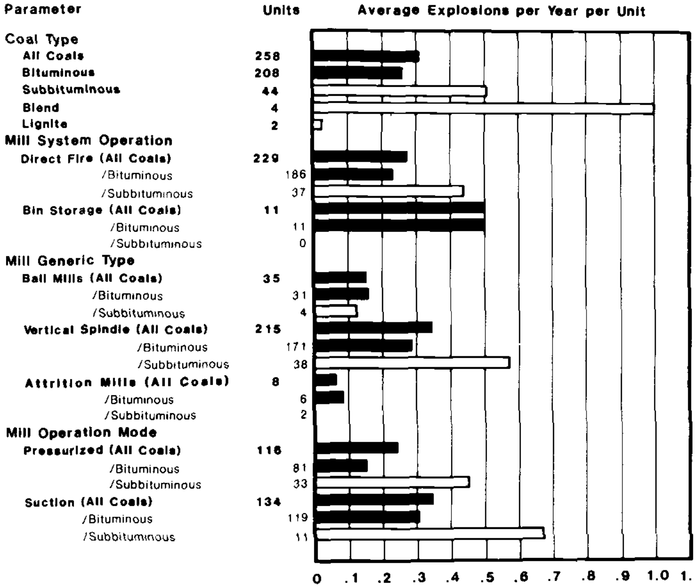


FIG. 1—*Average explosions per year per unit for four classification-type parameters.*

fired units have explosion frequencies twice as high as those of the bituminous fired units (Fig. 1).

2. *Pulverizer generic type:* The explosion frequency for vertical spindle pulverizers is about twice that of the ball pulverizers and about five times that of the attrition pulverizers. With bituminous coals the vertical spindle pulverizers show a higher explosion frequency while the ball and attrition pulverizers have equivalent lower frequencies. Also, subbituminous grinding vertical spindle pulverizers have about twice the explosion frequency of bituminous grinding vertical spindle pulverizers (Fig. 1).

3. *Pulverizer operation mode:* The suction operation pulverizers have a slightly higher explosion frequency than pressurized pulverizers. The trend is reemphasized by the coal type. Subbituminous coals accentuate the difference (Fig. 1).

4. *Pulverizer capacity:* Generally, explosion frequency is independent of pulverizer capacity. However, by separating bituminous and subbituminous coal fired systems a slight trend is observed. Units firing bituminous coals have a reduction in explosion frequency with an increase in pulverizer capacity. Units firing subbituminous coals experience an increase in explosion frequency with an increase in pulverizer capacity (Fig. 2*a*).

5. *Number of pulverizers per unit:* Explosion frequency increases with an increasing number of pulverizers per unit. Once again coal type produces two opposing conditions. Units firing bituminous coals show a slight decrease in explosion frequency with increasing number of pulverizers per unit. However, subbituminous fired units show a sharp increase in explosion frequency with increasing number of pulverizers per unit (Fig. 2*b*).

6. *Pulverizer age:* Explosion frequency appears to be independent of pulverizer age. Explosion frequency has a slight decrease with pulverizer newness for bituminous coals. Conversely, explosion frequency increases with pulverizer newness for subbituminous coals (Fig. 2*c*).

7. *Coal type:* The subbituminous coals have explosion frequencies of about twice those of bituminous coals. The explosion values of lignite coals were ignored due to the extremely small population (Fig. 1).

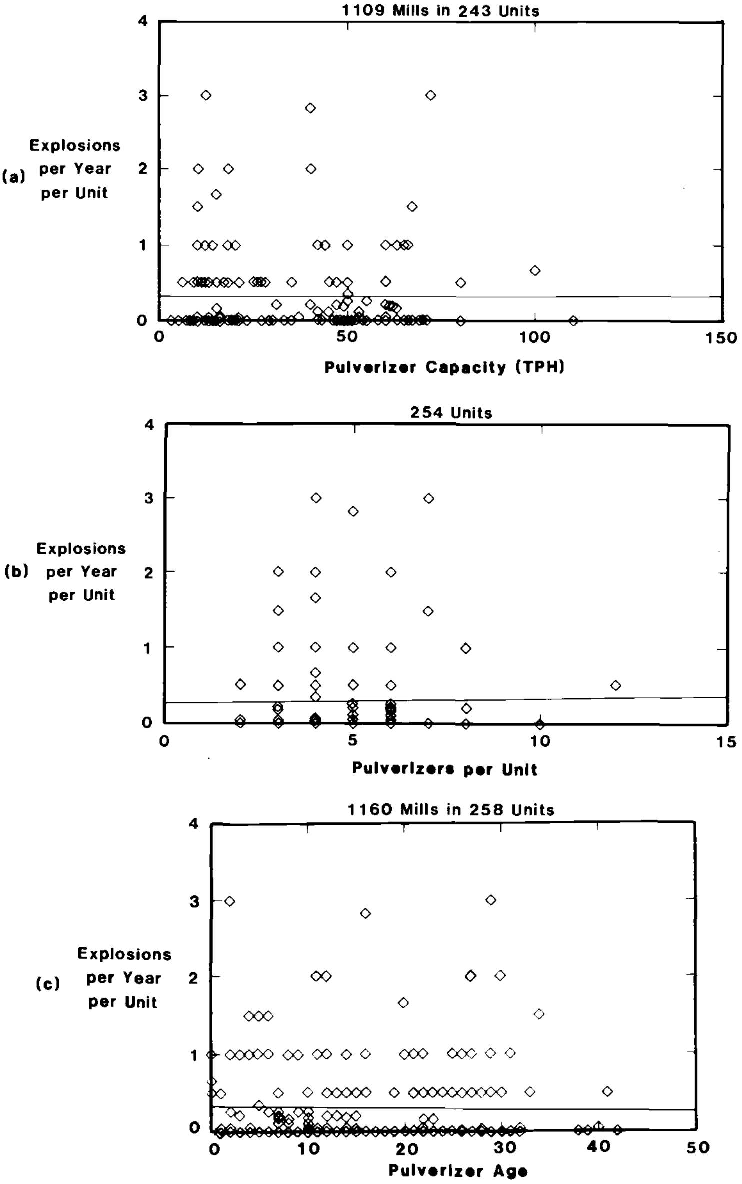


FIG. 2—*Explosions per year per unit for six range-type parameters.*

8. *Coal volatility:* Explosion frequency increases with an increase in volatility content, but this trend is as weak statistically as the other categories (Fig. 2*d*).

9. *Coal moisture:* Explosion frequency remains unchanged with increase in moisture of the as received coal. Overall, there is a connection between moisture and pulverizer age. The newer units have a trend toward using higher moisture coals (Fig. 2*e*).

10. *Coal ash:* Explosion frequency is higher for medium ash coals than for low and high ash

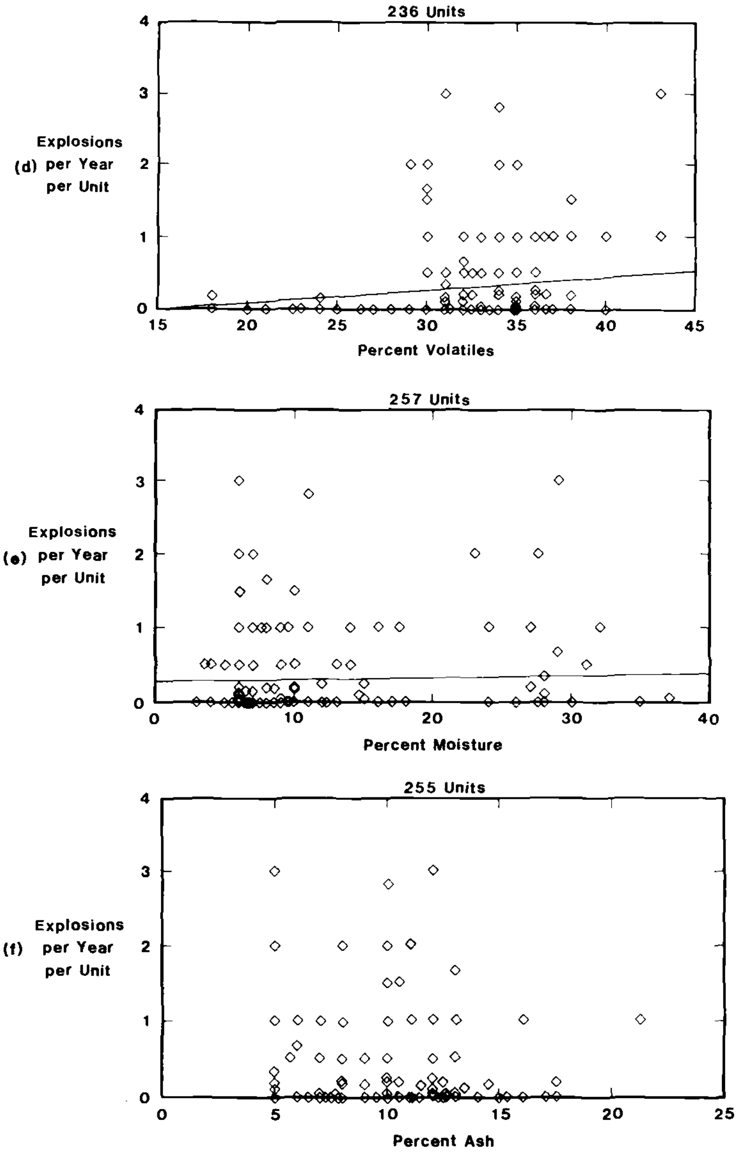


FIG. 2—*Continued.*

coals. This trend is dominated by the units firing high volatile, low moisture, subbituminous coals. These coals fall into the medium ash group and appear to have higher than normal explosion frequency (Fig. 2*f*).

The trends discussed above are statistically weak and should be considered as introductory material to fire and explosion problems. A better level of analysis does not focus on the frequency of events but rather focuses on the interrelationship of fires, explosions, and plant characteristics. A major finding is that explosions do not occur in proportion to the number of fires at a unit. Rather, a unit falls into one of four modes:

Mode 1, low fire and low explosion frequency (78% of units), the desirable pattern, contains units with all types of plant characteristics indicating that there are no intrinsic barriers to safe operation for any plant. However, this mode does contain a significantly higher proportion of the database's oldest units. The trend that older units have fewer fires and explosions than newer units is interpreted as indicating that longer periods of operating and maintenance experience with a particular unit produce a safer facility. Thus, more attention to improved operating procedures and maintenance practices can make any plant safer.

Mode 2, high fire and low explosion frequency (9% of units), tends to be characterized by base loaded units; middle aged, large capacity, pressurized mills; and medium volatile, high ash, subbituminous coals.

Mode 3, low fire and high explosion frequency (7% of units), tends to be characterized by base loaded units; newer units; suction mills and vertical spindle mills in general; medium volatile coals, high moisture coals, low ash coals, and subbituminous coals.

Mode 4, high fire and high explosion frequency (6% of units), the smallest of the groups, tends to be characterized by units with a larger number of mills; vertical spindle mills; medium volatile coals, high moisture coals, high ash coals, and subbituminous coals.

The survey cannot distinguish between explosion experience before and after installation of inerting systems [*3*]. However, because inerting agents are used to prevent something from happening, explosion frequency can be used to gauge the effectiveness of inerting agents in preventing explosions. Four inerting agents including "None" were identified in the survey. Figure 3 shows the explosion frequency for carbon dioxide, nitrogen, and steam, as well as the groups "None" and "Unknown." "None" are units reporting no inerting agents. The group "Unknown" are the units that left the entry blank. Both "Unknown" and "None" contain units of low and high frequencies.

Almost 90% of the "None" and "Unknown" categories are comprised of units firing bituminous coals, while the steam group contains almost 95% subbituminous coal users. Historically, the steam group is experiencing approximately 1.5 times as many explosions as the group that is

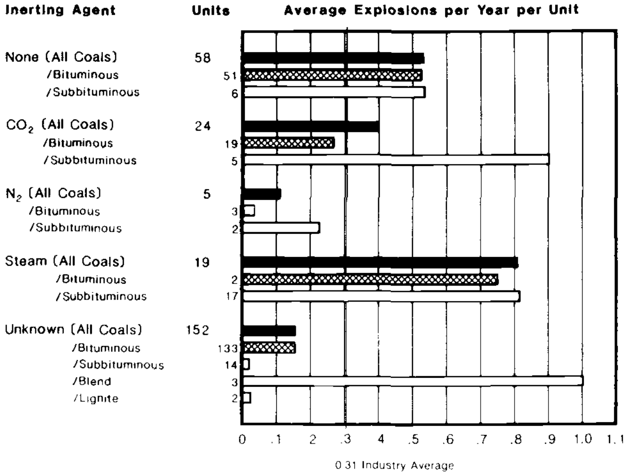


FIG. 3—*Average explosion per year per unit versus three inerting agents used by U.S. utilities.*

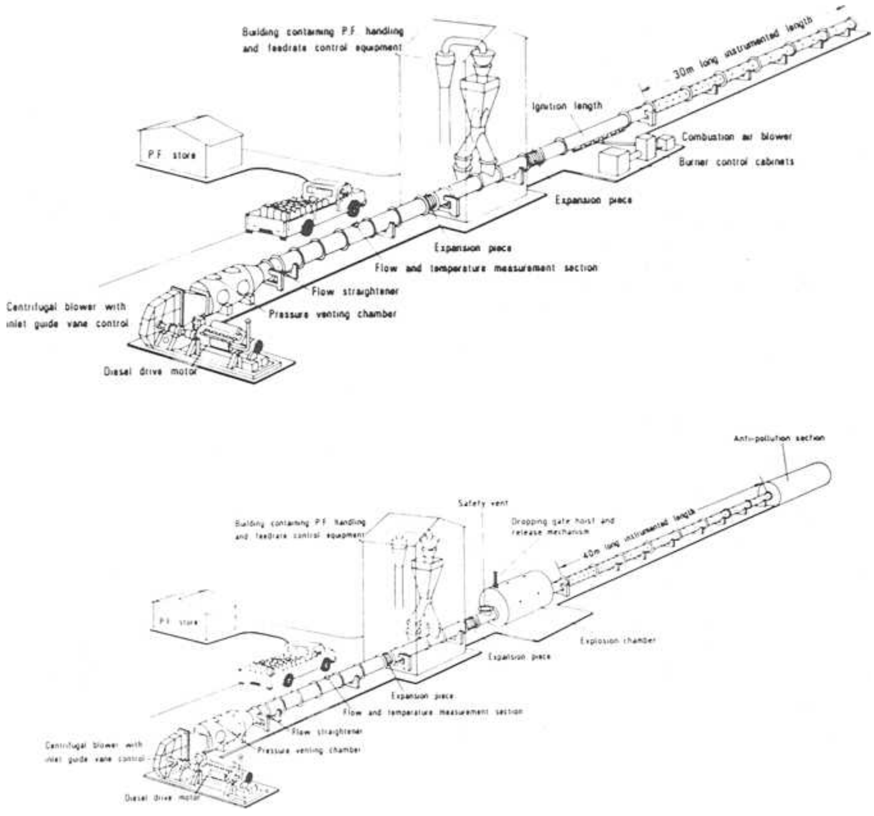


FIG. 4—*The CEGB explosion test facility:* (top) *pipeline fire configuration and* (bottom) *mill fire configuration.*

doing nothing. The group using carbon dioxide is similar to "None" and has half the explosion frequency of steam.

Laboratory Experiments

To obtain an understanding of explosion origin and growth, full-scale coal pipe and simulated pulverizer tests were conducted at the CEGB Explosion Test Facility in Foulness, England [*4*]. The controlled conditions kept the interaction of variables at a manageable level while simulating field conditions which would produce damaging or lethal explosions in field hardware. The laboratory setting permitted detailed measurements to be made for understanding growth mechanisms of pulverized coal system explosions. Additional experiments with inerting agents were conducted at Fenwal in Ashland, MA [*5*]. Inerting is the release of an agent into a region with explosive conditions in order to render the environment nonexplosive. The process is distinct in methods and goals from suppression and extinguishing. All pressures reported in the text, tables, and figures are gage.

Full-Scale Explosion Tests

Figure 4 is a schematic of the CEGB explosion test facility built to focus on the origin and propagation of explosions in coal pipes. The test programs carried out at CEGB were divided into

TABLE 2—*Coal characteristics for coals used in the explosion tests.*

Coal	Moisture Content		Pulverized, Dry Basis			Heating Value, kJ/kg	Ash Free Heating Value, kJ/kg
	Raw, %	Pulv., %	Volatiles, %	Ash, %	Fixed Carbon, %		
Pennsylvania bituminous	4.3	1.5	18.2	18.8	63.0	23 020	28 350
Oklahoma bituminous	3.8	1.5	38.6	12.1	49.3	30 620	34 835
North Dakota lignite	32.8	13.1	41.5	10.5	48.0	24 400	27 263
Wyoming subbituminous	27.9	17.3	41.3	7.1	51.6	28 030	30 172

three series. The first two series concerned pipeline fires as possible trigger ignitions for explosions using intense, localized fire sources and large, persistent fire sources. The third test series used the combined pulverizer volume coal pipe geometry with the ignition source within the pulverizer volume. The simple straight pipe layout shown in the figures reduced the number of interacting parameters influencing the initial testing. The program apparatus had a maximum instrumented length of 41 m (135 ft) when the simulated pulverizers were used as shown in Fig. 4*b*. Four coals covering a wide range of characteristics were selected for testing [5]. Table 2 gives the proximate analyses, and Table 3 gives the size distributions of the pulverized coals.

Explosion Testing Using Pipeline Fire Ignition Sources

The 0.45-m^3 (16-ft^3) T-injector shown in Fig. 5 simulates a sudden eruption of a coal pipe fire when used in the arrangement shown in Fig. 4*a*. Figure 6 plots the maximum pressure recorded at a transducer versus the location of the transducer and includes tests with and without suspended coal dust for the same strength of the T-injector source.

The figure shows that the observed low pressure levels are the result of the T-injector charge bursting into the pipe rather than any combustion of the coal dust mixtures. Because these tests provide a good simulation of actual coal pipe conditions, it is possible to conclude that vigorous but short lived fire events originating in the coal pipe would not trigger a detonation in that coal pipe.

Figure 7 is a schematic of the "burning bed" ignition source used to simulate large, persistent pipeline fires. This gas fired ignitor is 25 cm (10 in.) wide and adjustable in length up to a maximum of 5 m (16.4 ft). The firing rate produced a heat flux of 363 kW/m^2 (115 kBtu/h·ft^2 which was sufficient to keep the grate at surface temperature between 700 and 900°C (1300 and 1650°F). This condition corresponds roughly to a bed of coke burning at 1000°C (1830°F) [*4*].

Figure 8 presents the results of this series of tests as a plot of peak pipeline pressure versus

TABLE 3—*Size Distribution of Coals Used in the Explosion Tests.*

Coal	British Grind	Mass % Through Sieve				
		% −18	% −35	% −60	% −140	% −200
Pennsylvania bituminous	SF 250	100	100	100	98.6	88.1
Oklahoma bituminous	SF 250	100	100	100	97.4	88.9
North Dakota lignite	SF 250	100	100	100	98.9	89.7
Wyoming subbituminous	SF 250	100	100	100	97.1	85.8
Wyoming subbituminous	M 190	100	99.8	96.2	69.1	52.4
Wyoming subbituminous	CM 100	99.9	85.7	55.5	24.5	15.9

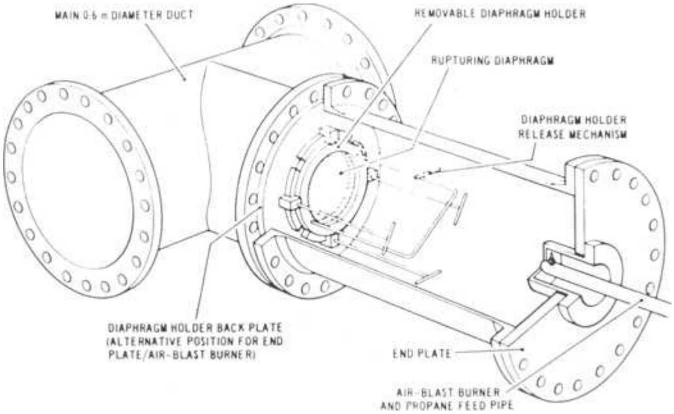


FIG. 5—*The CEGB "*T*-injector" flame ignition source.*

coal pipe air velocity. The figure shows a strong influence of pipe air velocity, coal type, and coal grind on the relatively low pressures created by the burning bed ignitor. The most reactive coals were fine grinds (roughly 90% through 200 mesh) of the Oklahoma bituminous and Wyoming subbituminous samples. The lines in Fig. 8 for these two coals indicate that pressures generated by coal pipe fires were almost linearly proportional to air velocity for a given coal type. The coal type fixed the proportionality constant [5]. The peak pressures remained small over the wide range of velocities tested. Typical design velocities in U.S. plants fall in the middle of the range shown in Fig. 8 where the peak generated pressures would be below 0.7 bar (70 kPa). The test results

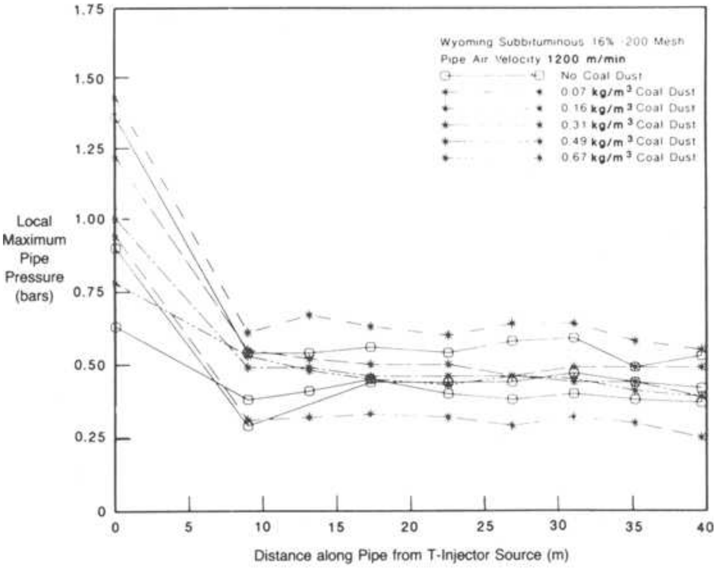


FIG. 6—*Local maximum pipe pressure versus position along the coal pipe for explosion testing using the* T*-injector source in the coal pipe.*

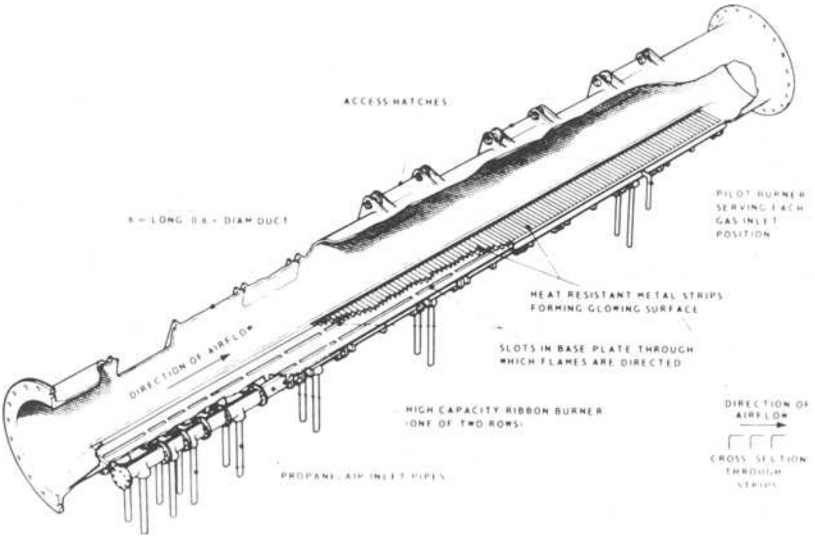


FIG. 7—*The CEGB "burning bed" ignition source.*

indicate that pipeline fires will not trigger detonation in the pipe. However, Fig. 8 does indicate that pipeline fires may give rise to low level pressure events which may reach the burners and furnace.

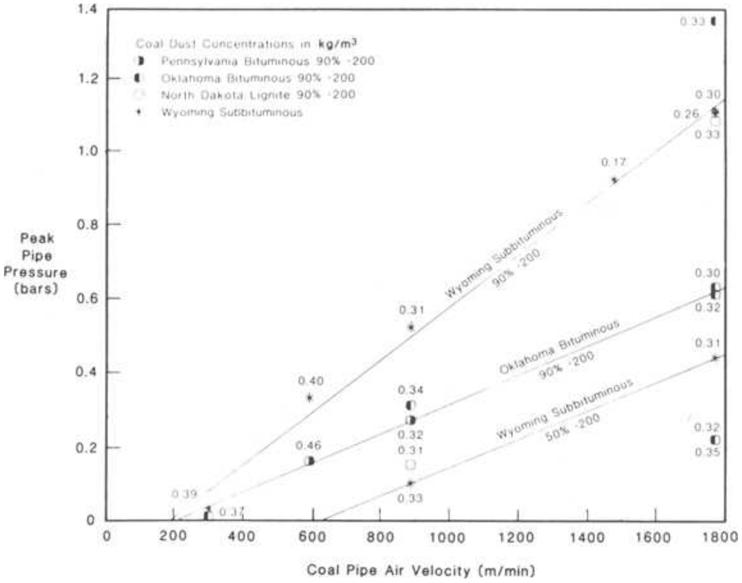


FIG. 8—*Peak pipe pressure versus coal pipe air velocity for explosion testing using the burning bed ignition source.*

Explosion Testing Using Pulverizer Fire Ignition Sources

The last series of CEGB experiments added the remaining major coal system component, the volume representative of a full sized pulverizer as shown in Fig. 4*b*. The vessel volume of 21 m^3 (742 ft^3) in full form and 15 m^3 (530 ft^3) in reduced form preserved the vessel–coal pipe interface and venting characteristics of a generalized pulverizer rather than a specific type. The ignition source was moved back upstream into the pulverizer volume. Two types of ignition sources were used in various locations relative to the pulverizer coal pipe interface:

1. The T-injector was attached to the middle of the vessel and charged with approximately 91 g (0.2 lb) of finely ground coal dispersed in the injector and triggered with a 26-kJ (5-Btu) chemical ignitor. This ignition source represents a small but vigorous dispersed cloud of burning coal particles which could enter a pulverizer from an external fire.
2. Two 26-kJ (5-Btu) chemical ignitors, the energy equivalent of approximately 2.75 g (0.02 oz) of coal, gave a reproducible source of modest energy release rate.

Figures 9, 10, and 11 plot the maximum pipe pressure, maximum vessel pressure, and maximum flame velocity, respectively, as functions of coal concentration. Prominent are the high values for peak pressure in the pipe (up to 81 bars [8100 kPa]), peak pressure in the pulverizer (up to 7 bars [700 kPa]), and flame speed in the pipe (up to 2850 m/s). These results are impressive because energy sources as small as a teaspoonful of burning coal triggered a detonation while large pipeline fires produced low level pressure events. The vessel/pipe explosion tests may be summarized as:

1. The origin and growth of an explosion requires the interaction of events in a vessel/pipe geometry containing a dust suspension. The word "vessel" signifies that any properly sized volume (that is, pulverizer, classifier, or fan) connected to a coal pipe may host the originating ignition source. A fire of even modest size and intensity enters a dust laden vessel and ignites the contents. The vessel pressure and flame fronts vent into a dust laden coal pipe. The pressure wave

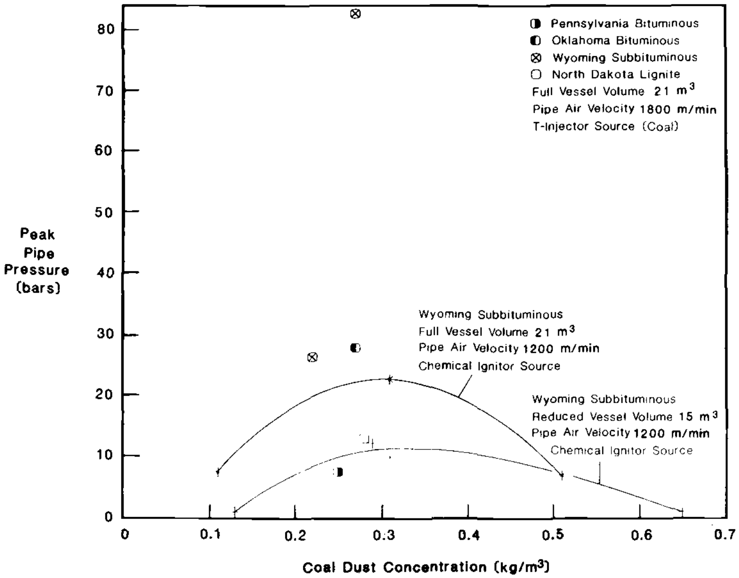


FIG. 9—*Maximum pipe pressure versus coal dust concentrations for explosion testing using the combined vessel/pipe geometry and vessel ignition.*

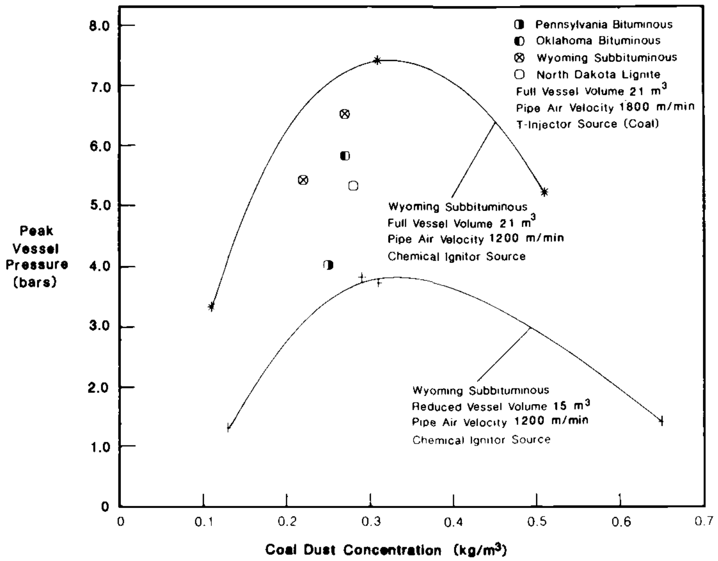


FIG. 10—*Maximum vessel pressures versus coal dust concentrations for explosion testing using the combined vessel/pipe geometry and vessel ignition.*

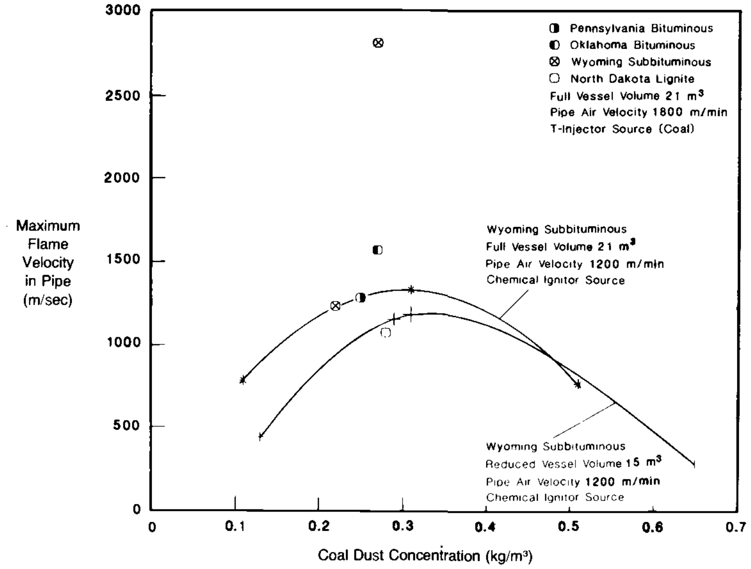


FIG. 11—*Maximum flame speed versus coal dust concentration for explosion testing using the combined vessel/pipe geometry and vessel ignition.*

turbulence appears to enhance the burning and speed of the flame front in the pipe. Pipe pressure rises to several hundred psig as the pressure wave pulls the flame front into itself downstream in the pipe. If the flame front catches up with the pressure wave, they coalesce into a burning shock front (that is, detonation) with almost instantaneous rates of pressure rise, supersonic speed, and pressure levels exceeding 80 bars (8000 kPa). Longer coal pipe runs may produce higher pressure levels.

2. When the detonation pressure wave or shock front hits an obstruction or termination condition in the pipe, a large reflected pressure wave radiates upstream toward the vessel with the triggering fire. This return wave can pressurize the vessel to over 7 bars (700 kPa).

3. Fine grinds of coal with dust concentrations near 0.3 kg/m^3 (0.3 oz/ft^3) produce the largest pressures and flame speeds. Higher and lower dust concentrations produce weaker events.

4. A reduction in the ratio of vessel volume to coal pipe area reduces the peak values of pressure and flame speed in an event. As vessel volume decreases, the venting of vessel pressure and flame from a trigger fire is less intense producing a less intense explosion. A 28% reduction in vessel volume reduced peak explosion pressures 50%.

Laboratory Steam Inerting Tests

Fenwal conducted a series of experiments on steam inerting. The goal was to determine the minimum quantity of steam needed to prevent an event in a pulverizer isolated from coal pipes and air ducts and filled with a reactive coal dust cloud. Oklahoma bituminous coal ground to 75% through 200 mesh was injected into a 2-m^3 (67-ft^3) vessel to form a uniform cloud of 0.4-kg/m^3 (0.4-oz/ft^3) coal concentration in the 120°C (250°F) vessel air. Specific amounts of steam were bled into the vessel. A nitrocellulose ignitor was triggered 0.3 s after the steam was introduced into the vessel.

The results of these tests are given in Table 4. Repeated tests at 18% steam by volume failed to produce an event, whereas lesser amounts of steam failed to inert the vessel. It was concluded that a minimum steam volume of 18% provided a nondetonation environment in the simulated isolated pulverizer. However, underinerting with steam appears to lead to a more explosive condition in the mill. One hypothesis is that small amounts of steam participate in gasification reactions with coal to produce highly combustible and explosive gaseous species. Another

TABLE 4—*Steam inerting test results.*[a]

Percent Steam by Volume	Steam Pressure, mm Hg	Explosive Event	Maximum Pressure, bar (kPa)
5	38	yes	3.93 (393)
10	76	yes	3.93 (393)
12	91	yes	3.99 (399)
13	99	no	. . .
13	99	yes	4.48 (448)
14	106	yes	4.69 (469)
15	114	no	. . .
15	114	yes	4.61 (461)
16	122	no	. . .
16	122	yes	4.69 (469)
18	137	no	. . .
18	137	no	. . .

[a] All tests with Oklahoma bituminous, 98% < 50 mesh, 72% < 200 mesh, 0.40 kg/m^3.

hypothesis is that the addition of steam may increase the turbulence in the vessel. Therefore, the 18% minimum value shown above is related specifically to this experiment. Further testing is necessary to determine whether or not this is practical for field application.

Conclusions

The conclusions stated in this report are derived from statistical analysis of the survey process and laboratory testing. The survey results indicate that there is no single condition or combination of conditions that is always present in explosion situations. The laboratory testing results are to be considered general in nature and are not directed at any specific plant. The creation of explosions evolves from a complicated interaction of variables and the conclusions are not absolute and contain exceptions. Therefore initiation of any pulverizer system modifications without a thorough analysis may produce results directly contrary to those desired.

There were two general conclusions reached in the study. First, not all fires cause explosions, however all explosions were initiated thermally. Second, all explosions were reported to occur during startup, shutdown, feed interruption, or other transient conditions.

Coal Type

The type of coal is a major factor in explosion frequencies. Units using subbituminous coals show twice the frequency of explosions as units with bituminous coals. Firing a subbituminous coal does not indicate a hazardous situation by itself. There are many utilities operating with subbituminous coals that are reporting explosion frequencies below the norm. However, when joined with the other characteristics, subbituminous coals appear to exaggerate any sensitive condition. The survey sampling with lignite is too small to allow any evaluation. The blending of coals, though it cannot be used statistically, does indicate possible operational problems. Blends that are not homogeneous force pulverizer operation to react to changes in fuel characteristics. Follow-up interviews revealed that units that have converted to washed coal, for economic or environmental reasons, have had a marked decrease in explosions as a side benefit.

Fuel changes should not be made until after a complete analysis of the fuel has been made to determine the coal's reactivity. Because the characteristics of the coal show one of the strongest influences on explosion frequency, any changes in coal supply would have an effect on a plant's frequency of explosions.

Pulverizer Systems

Direct fired systems have exhibited half the explosion frequency of bin storage systems. Because flue gas is used as the pneumatic transport medium in bin storage systems, the plants may assume an inert gas is present. However, load changes, leakage in the system, or malfunctioning dampers can increase oxygen concentrations to levels suitable for explosions.

The experiments show that the size relationship of pulverizer, classifiers, crushers, and fans to coal pipes is crucial in explosion origin and growth. The relative sizes determine whether or not a detonation can occur as well as the magnitude of the resultant forces. Detonation evolution requires a change in volume and must originate in a pulverizer system component other than a coal pipe. While a fire is located in a coal pipe, it cannot trigger a detonation. However, if the fire moves and enters a piece of equipment of different size and venting characteristics, then the probability of an explosion increases. The relocation of a fire to other components of a pulverizer systems such as the classifier, crusher, fan, or pulverizer can create a detonation.

Pulverizer Age

Plants with more operating experience have lower explosion frequencies. However, complicating this statement are the facts that unit capacity, number of pulverizers, and pulverizer capacity are smaller for older units than newer units. The type of coal and type of operation are additional factors affecting experience. There is a correlation of lowered explosion frequencies with improvements in maintenance and operating procedures. Interviewers reported that plants that have instituted improved maintenance or operating procedures have lowered their frequencies of explosive events. Also, equipment manufacturers periodically modify their recommended maintenance procedures and replacement parts. It is important that plants with concerns review their maintenance and operating procedures and periodically contact the equipment manufacturers.

Pulverizer Type and Operation Mode

The survey results show vertical spindle pulverizers have experienced twice the explosion frequency of ball pulverizers and three times the frequency of attrition pulverizers. Pressurized pulverizer operation shows a lower frequency of explosions than suction pulverizer operation for all pulverizers. Characteristics beyond the pulverizer type are involved. Many vertical spindle pulverizers are in suction operation and grind subbituminous coals. The interrelationships of various factors make it impossible to determine how sensitive pulverizers are to coal types.

Inerting Systems

The survey responses showed that less than one fifth of all units use inerting systems. Comparing all other units to the units with inertants, plants without inerting systems have lower explosion frequencies. With every inerting agent the frequency of explosions is higher with subbituminous coals. The information on inertants is not conclusive, but does reveal concerns that require further investigation. If it is determined that an inerting system is necessary, additional instrumentation and controls are required. Extensive training is required to ensure full understanding of the system by operational and maintenance personnel. Inerting is no guarantee of elimination of explosions, but with extreme care the frequency of explosions may be reduced.

In summary, the experiments confirm that explosions cannot occur while equipment is in a fuel-rich state. This implies that at full fuel capacity flow conditions an explosion cannot occur. However, unnoticed disruptions in fuel flow can reduce the fuel-rich condition in one or more of the system components. In addition, testing indicates that the more powerful the ignition source the richer the mixture that can support an explosion. Detection and control of small fires reduces the risks of explosions for all operating conditions.

References

[*1*] "Coal Pulverizer Fires and Explosions: Detection, Prevention, and Control," preliminary draft. Electric Power Research Institute, Palo Alto, CA, Oct. 1984.

[*2*] Carini, R. C., Hules, K. R., and Broske, D. R., "Historical Trends in the Occurrence of Fires and Explosions in the United States Pulverized Coal Fired Utility Industry," presented at the EPRI Symposium on Coal Pulverizers, Denver, CO, Nov. 1985.

[*3*] Carini, R. C., Hules, K. R., Santanam, C. B., Broske, D. R., and Gillis, J. P., "The Relative Effectiveness of Different Agents in Dealing with Coal Pulverizer Fire and Explosion Prevention," presented at the Coal Technology Conference, Houston, TX, Nov. 1984.

[*4*] Gardner, B. R., Winter, R. J., Moore, M. J., Broske, D. R., and Carini, R. C., "Some Explosion Tests on Typical American Coals," presented at the EPRI Symposium on Coal Pulverizers, Denver, CO, Nov. 1985.

[*5*] Carini, R. C., Hules, K. R., and Broske, D. R., "Experimental Results of Pulverized Coal System Fire and Explosion Testing," presented at the EPRI Symposium on Coal Pulverizers, Denver, CO, Nov. 1985.

Amin N. Alameddin[1] *and Steven J. Luzik*[2]

Coal Dust Explosions in the Cement Industry

REFERENCE: Alameddin, A. N. and Luzik, S. J., "**Coal Dust Explosions in the Cement Industry,**" *Industrial Dust Explosions, ASTM STP 958,* Kenneth L. Cashdollar and Martin Hertzberg, Eds., American Society for Testing and Materials, Philadelphia, 1987, pp. 217–233.

ABSTRACT: The number of coal fired industrial systems and utility power plants is rapidly increasing because of the high cost and uncertain availability of fuel oil and natural gas. For many cement producers in the United States, the conversion from fuel oil and natural gas to pulverized coal has been difficult, frustrating, and in a few cases, very costly. This study deals mainly with coal safety requirements in the cement industry which accounts for a very small percentage of coal usage in pulverized coal firing systems. It also deals with the safety requirements associated with coal grinding, drying, blending, transporting, and storing. Case histories investigated by the Mine Safety and Health Administration (MSHA) will be discussed, and recommendations will be made for future fire and explosion prevention.

KEY WORDS: coal dust, fires and explosions, cement plants, coal fired systems, safety

To achieve the goal of safe, efficient, and economical coal firing system designs, both users and regulatory personnel must have an understanding of the hazards involved in coal fired systems and the nature of the problems involved in the use of pulverized coal.

The potential for fires and explosions connected with the use of coal is uniquely different from other fuels. Knowing and understanding the hazards involved are the first steps in developing safer systems.

History

In the 1960s a large number of cement and electric utility power plants converted from coal as their primary fuel to either fuel oil or natural gas. The use of fluid fuels was economical and provided a clean, relatively simple firing system. In addition, the use of fluid fuels met the Environmental Protection Agency (EPA) standards for clean air. Since the 1973 oil embargo the steep rise in the cost of oil has caused many plants to convert back to the use of pulverized coal as their primary fuel for the firing systems.

At the present time the majority of cement plants are using coal as the primary fuel. For startup of kilns, boilers, and furnaces the use of liquid fuels is still a common practice.

---

[1] Mining engineer, Safety and Health Technology Center, Mine Safety and Health Administration, P.O. Box 25367, Denver, CO 80225.

[2] Supervisory chemical engineer, Industrial Safety Division, Bruceton Safety Technology Center, Mine Safety and Health Administration, Pittsburgh, PA.

Phenomena of a Coal Dust Explosion

To understand fully the hazards of using pulverized coal as a fuel in a cement plant, one must become familiar with the factors that typically enter into the development of an explosion. A typical pulverized coal fuel system must process bulk coal into a form that can be efficiently utilized as a fuel to heat the kiln for calcining the raw materials (clay, limestone, and so forth) into clinker (see Appendix). This is usually accomplished by grinding and drying the bulk feed in a pulverizer so that the coal emerging from the pulverizer will consist of 70 to 80% particulate that will pass through a 200-mesh U.S. screen sieve (that is, particles with a diameter of 74 μm or less). High temperature air from the clinker cooler is often used to dry the coal and convey it from the pulverizer to the burning pipe in the kiln. The coal pulverizer is one of the most hazardous pieces of equipment from a fire and explosion viewpoint because fuel and oxygen for combustion are always present.

A dust explosion is often described as a rapid burning of combustible particulate within a confined area, which results in the generation of intense heat and corresponding pressure rise. If not vented adequately, the rise in pressure caused by the rapid buildup of heat can cause damage to the confining vessel and the surroundings. The following factors must be present to cause a dust explosion:

(1) the presence of dust in suspension in a concentration above its flammable limit,
(2) sufficient oxygen to enable combustion of the fuel,
(3) a source of energy to ignite the fuel, and
(4) a certain degree of confinement of the suspended dust mixed with oxygen.

Factors Affecting Dust Fire/Explosion Probability

Factors that influence the dust fire/explosion probability include the following:

1. *Fuel*—Bituminous coal is the fuel typically used in a pulverized fuel system. All U.S. bituminous coals and coal dust passing through a 200-mesh sieve having a diameter of (74 μm or less) present a dust explosion hazard.

The minimum explosive concentration is the minimum quantity of dust in suspension that will propagate an explosion if exposed to an ignition source of sufficient magnitude. For high-volatile bituminous coals, the minimum explosive concentration lies between 50 and 100 g/m^3 (0.05 to 0.1 oz/ft^3) [*1*,*2*]. A coal pulverizer under normal grinding conditions will, in most cases, be loaded with a concentration of coal dust above this minimum concentration. The upper explosive limit is not well-defined but is above 4000 g/m^3 (4.0 oz/ft^3) [*3*].

2. *Oxygen*—the drying and conveying air in the pulverizer contains sufficient oxygen to support combustion of a coal dust cloud above its lower flammable limits. If coal containing a high percentage of moisture is being dried, the drying air will be diluted with water vapor which will result in a reduction of the oxygen level in the air. This reduction may reduce the rate of pressure rise and maximum pressure generated if an explosion occurs but will not prevent an ignition unless the overall oxygen concentration is reduced to about 13% (for bituminous coals under a strong ignition source).

3. *Ignition sources*—Many possible ignition sources may be present in a pulverized fuel system. Frictional sparks can be generated within the pulverizer itself by tramp iron or other foreign objects which may find their way into the system. Also, hard inclusions in the coal, such as pyrites or rock, may be a source. The action of these materials against one another or moving parts in the mill may produce sufficient heat and sparks to initiate a fire or an explosion. Broken damper plates or fan blades from fans or ducting may also create frictional sparks which can ignite coal dust clouds or accumulations. The high temperature of the drying air often can provide enough heat to

ignite coal accumulations in the mill under certain conditions. Feeding hot coals from storage piles into the pulverizer may also provide an ignition source. Defective electrical equipment is yet another possible source.

The minimum ignition temperature of a coal dust cloud can range anywhere from 425°C for dried lignites to 800°C for certain anthracite coals [*4*]. Bituminous coals typically ignite somewhere between 500 to 625°C [*2,4*]. The minimum ignition temperature for the generation of a smouldering fire in a coal dust layer is much lower, however, and certain bituminous coals may be ignited at temperatures as low as 160°C [*5*]. The electrical energy required to ignite a bituminous coal dust cloud is on the order of 60 mJ and increases with increasing turbulence of the dust cloud [*2*].

4. *Self-heating of dusts*—Another important phenomenon which may lead to fire or explosion in a pulverized fuel system is that a spontaneous combustion, or self-heating. Spontaneous combustion occurs when a pile or accumulation of coal, over a period of time, begins to auto-oxidize and leads to a runaway exothermic reaction accompanied by the evolution of heat and/or flame. The principal factors that affect spontaneous combustion are as follows (this listing comes mainly from Ref *5*):

(a) *Rank*—Tendency to self-heat increases with decreasing rank. Coals are classified by rank in accordance with the ASTM Classification of Coals by Rank (D 388). Lignites and subbituminous coals are most susceptible to spontaneous heating.

(b) *Air flow rate*—Sufficient to maintain high oxygen concentrations on the coal surface, but not high enough to remove heat by convective cooling, will increase the tendency toward spontaneous heating.

(c) *Particle size*—The smaller the coal particle, the greater the exposed surface area and the tendency to undergo spontaneous heating.

(d) *Moisture content of the coal and the air*—At temperatures below 100°C, the rate of heat generation by moisture absorption exceeds the rate of heat generation by oxidation. Lower rank coals, if predried and subjected to moist air, are most susceptible to self-heating because of the above effect.

(e) *Temperatures*—The rate of oxidation is a direct function of temperature. The higher the temperature, the faster the rate at which coal reacts with oxygen.

(f) *Impurities in the coal*—Presence of sulfur mineral pyrite and marcasite may accelerate spontaneous heating. Generally, the pyrite content must exceed 2% before it has a significant effect.

(g) *Pile geometry*—Size, depth, and shape of the stored coal pile is another factor that affects spontaneous combustion.

Coal rank, particle size, air permeability, geometric size of the pile, and moisture content of the coal and the air are the most important factors.

5. *Coal selection*—Use of coal as a fuel in cement or power plant operations can present special problems to a plant operator because of the wide range of coals and quality of coal available on the market. To ensure safe operation of a pulverized coal fuel system, operating parameters will change as the type of coal or blend of coals is varied. It may be difficult to predict the behavior of a particular coal in the system in regard to the fire and explosion hazard involved. Selection of safe and efficient inlet and outlet air temperatures in the pulverizer, to ensure safety in the event of a planned or unplanned shutdown, is often a result of trial and error. The experience of the operator in dealing with various types or blends of coal is often a key factor in the prevention of fires and explosions in pulverized coal fuel systems.

As previously mentioned, the tendency of coal to undergo self-heating is inversely related to the rank of the coal. Self-heating increases with decreasing rank. ASTM has developed a standard procedure for the ranking of coals (ASTM D 388). Coals having 69% or more fixed carbon on a dry mineral, matter-free basis are classified according to fixed carbon value. Coals having less than 69% fixed carbon are classified according to their calorific values on a moist, mineral-matter-free basis.

It is sometimes difficult to predict the tendencies of blends of coals to undergo self-heating, and experimental testing may be necessary to accurately predict the behavior of these blends under plant conditions.

Laboratory Testing

Select laboratory testing is routinely carried out to investigate cement plant explosions involving pulverized coal dust. Samples of dust taken from the pulverizer are screened, and a particle size distribution profile is obtained. A proximate analysis test provides information on volatile matter and fixed carbon content of the particular coal sample. U.S. coals, having a volatile ratio (also known as moisture, ash free [maf] volatility) of 12% or more [5], present a dust explosion hazard.

$$\text{Volatile Ratio, \%} = \frac{\text{\% Volatile Matter}}{(\text{\% Volatile Matter} + \text{\% Fixed Carbon})} \times 100$$

The minimum explosive concentration is also determined to indicate the lower flammability limit of the sample and provides an indication as to whether or not the sample is ignitible by an inductive spark ignition source. This test is carried out in a 1.2-L Hartmann tube apparatus [*6*]. If the particular sample is not ignitible by spark ignition source, tests are conducted in a 20-L vessel [*1*] using stronger ignition sources.

Results of these tests are incorporated into the investigative report and provide legal documentation of the explosibility properties of the coal being used at the particular facility where the explosion took place.

Coal Fired Systems

There are three types of coal fired systems used in cement plants.

1. *Direct Fired System* (Fig. 1) is the simplest to operate, control, and maintain. It has the lowest equipment cost and is the safest system in terms of dust explosion probability. Coal is pulverized in the mill and is fed with the primary air or hot drying gases directly into the kiln. The main source of air or hot drying gases is from the clinker cooler, the kiln, or preheater exhaust.

The system has one major disadvantage in that all the air required to dry the coal is blown directly into the kiln. The primary air, which is usually high in moisture and low in temperature (about 79.4°C [175°F]), feeding directly into the kiln can adversely reduce the overall efficiency of the kiln and its ability to make good clinker. Another disadvantage is that the coal dust fines–air mixture flowing through the high-speed fan blades can cause impurities or foreign objects to be lodged in the fan and ductwork. This may cause a serious frictional ignition problem that can lead to an explosion. The foreign objects or impurities can also cause fan blade wear resulting in a serious maintenance problem.

2. *Semidirect fired system* (Fig. 2) was developed to overcome some of the disadvantages inherent with the direct fired system. In this system the pulverized coal and the transporting gases or air leaving the coal mill are separated by means of a cyclone. The cyclone collects the pulverized coal at its bottom but allows the air to pass freely out its top. The air is recirculated back to the coal mill as makeup air after it is separated from the pulverized coal. The coal remains in the cyclone hopper until it is discharged by the rotary feeders. Two advantages are that the mill system fan operates in a partially closed loop and that the coal feed is controlled by the rotary feeders and not by the primary air flowing through the coal pulverizer. The volume of air flowing through

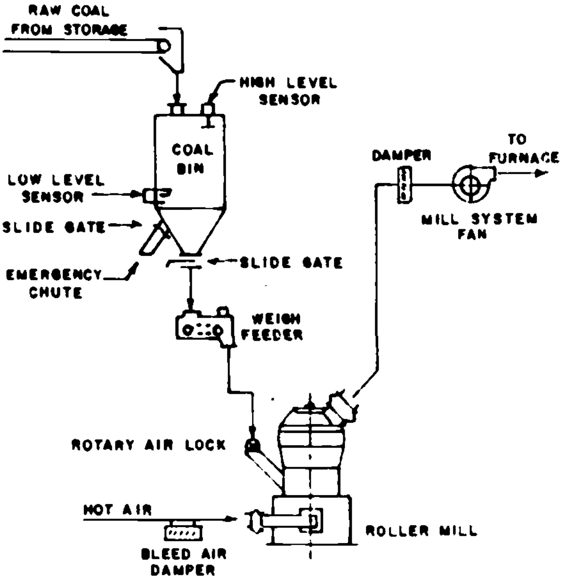


FIG. 1—*Direct fired system.*

the coal mill and directly to the kiln or burner can be reduced, increasing the thermodynamic efficiency of the system.

However, this system has a number of disadvantages. During the separation process in the cyclone, some of the coal fines are inevitably carried out of the cyclone top with the recirculating air. These coal fines are less damaging to the mill system fan blades than in the direct system but

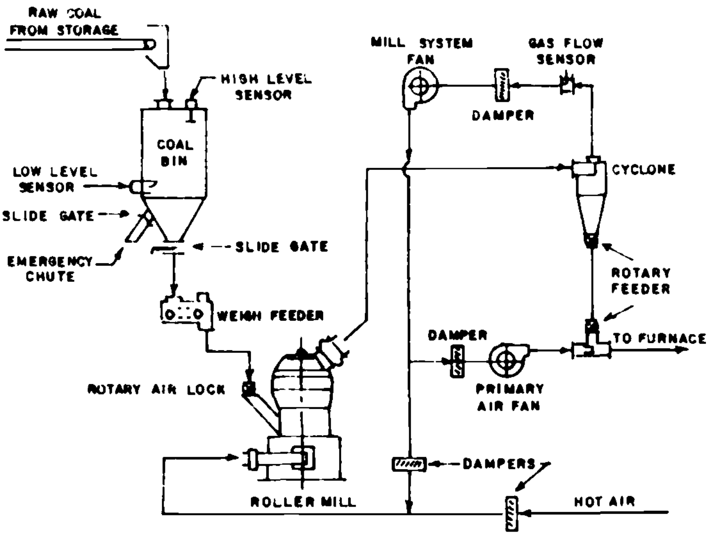


FIG. 2—*Semidirect fired system.*

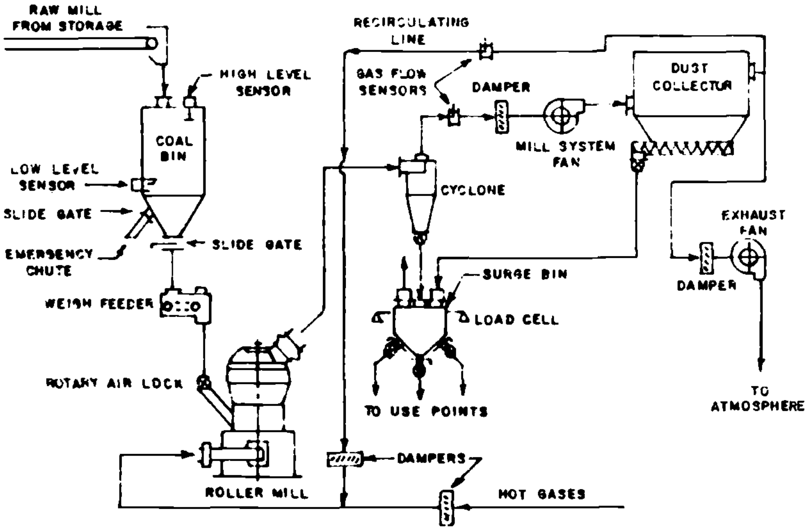


FIG. 3—*Indirect fired system.*

constitute a more serious fire and explosion hazard. Moisture from the coal in the recirculating loop can accumulate and settle in the circuit leading to coal agglomeration, plugging, and other problems. One other major disadvantage is that the cyclone storage capacity is rather small, so a mill shutdown will soon cause a coal feed shutdown and result in kiln cooling and system shutdown unless some other fuel source is available for firing the system.

3. *Indirect fired system* (Fig. 3)—In this system the hot air circulating loop, used for drying the coal and transporting it through the coal mill and into the cyclone, is completely separated from the system that transports the pulverized coal to its use points. The system provides for storage of large quantities of pulverized coal in a silo or bin (surge bin), usually with a three-day maximum capacity, so that the coal firing can be maintained even during a mill shutdown. One important feature of this system is that none of the drying and transporting air in the recirculating loop, from the pulverizer to the cyclone to the baghouse dust collector and back to the pulverizer, is used to transport the coal fines to the firing points. The drying and transporting air vents the coal moisture directly to the atmosphere via an exhaust fan. There is a filter baghouse dust collector in the recirculating loop downstream from the cyclone which prevents the coal fines from being recirculated back to the pulverizer or accumulating anywhere in the loop. The baghouse dust collector feeds its fines directly to the surge bin. Since the drying air circuit is completely separated from the coal-firing circuit, clean and dried exhaust gas may be used as inert gas in the recirculating loop instead of air. This allows the use of a much greater proportion of high-temperature secondary air to primary air in the kiln resulting in a more efficient combustion regime.

The disadvantages of an indirect system include higher capital costs and greater danger of coal dust explosions than with direct or semidirect fired systems as a result of the added handling and storage requirements of the pulverized fuel. The presence of the baghouse dust collector and surge bin would add to the coal dust explosion hazards.

Coal Storage Systems

There are two main types of coal storage systems used in the cement industry.

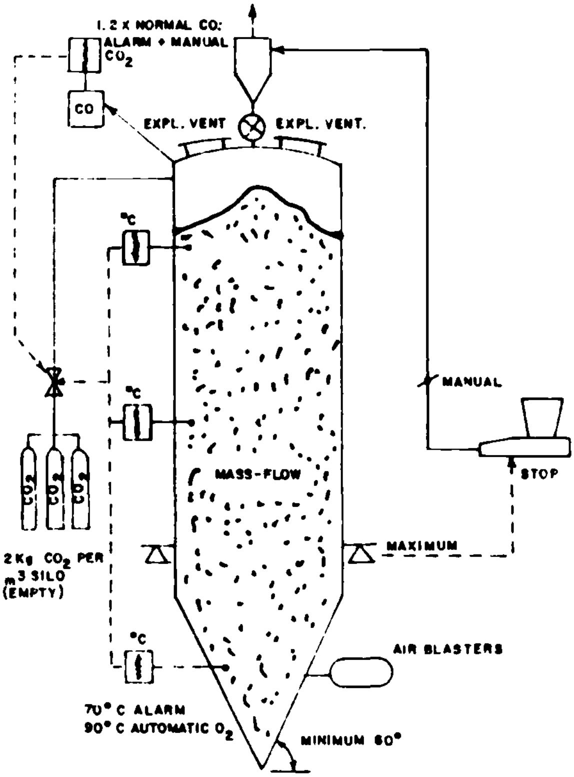


FIG. 4—*Coal bin.*

1. *Coal bin or silo* (Fig. 4)—Bins are usually constructed of steel, but concrete is also used. Bins are circular, square, or rectanglar in cross section and generally designed for a three- or four-day capacity. The hoppers should be designed for mass flow to eliminate static coal deposits. The bin outlet should be large enough to prevent arching or plugging. All bins should be self-cleaning, and internal surfaces should be kept free of stiffeners, weld strips, or flange surfaces.

For explosion venting design, many factors must be considered. The National Fire Protection Association (NFPA) Guide for Explosion Venting (NFPA 68, see Appendix) should be used in evaluating each installation. Explosion venting provides relief for explosion force build-up inside the bin and limits the damage should an explosion ever occur.

2. *Coal stockpiles* can either be in the open or under a covered storage shed area. The storage site selected should be located away from any heat source, well drained, free from standing water, and preferably on a dry, high ground area. The storage area should be cleared of all foreign materials such as wood, rags, waste oil, or other materials having low ignition temperatures. Coal should be spread in horizontal layers and piled so as to ensure effective ventilation to dissipate heat or packed firmly to ensure the minimization of communicating voids containing air.

Problem Areas in the Coal-Firing System

The uniqueness of coal and the variability of coal properties from area to area make the present engineering technology and the latest state of the art for buildings and operating facilities for safe fueling of cement kilns difficult. Almost every operator using a coal dust-fired kiln will acknowledge that the installation has certain physical features that make the operation inherently hazardous and that he or she operates the facility cautiously and, during certain critical situations, with a degree of uncertainty.

Most coals used in the firing of kilns have the tendency for spontaneous ignition in accumulated piles. The following factors also can create hazardous conditions:

1. *Storage of coal*—If the coal is stored improperly on stockpiles, it can self-ignite creating a serious fire hazard. However, in coal silos or bins, where coal heating is already in progress, the added confinement may cause a serious fire and explosion hazard.
2. *Handling of coal within the firing system*—Western coal is more friable than eastern coal. It fractures more easily in handling, conveying, and stockpiling and produces a higher percentage of fines which contribute to the dust accumulation. Dust accumulations increase the risk of fire and explosion. However, western coals have a higher moisture content, but they tend to dehydrate which causes fissures and subsequent degradation of lump size. Also, western coal has a higher tendency for spontaneous combustion. Volatile gases resulting from thermal decomposition when the coal is heated can cause a serious explosion in a confined area such as a silo or surge bin. Coal with high moisture content will need a higher coal mill inlet temperature for drying purposes.
3. *Accumulations of coal dust during system operation*—During operation of the coal pulverizer and the coal-dust-handling facilities, coal fines can collect at dead areas within the pulverizer and at bends in ducting. Given certain conditions coal fines could create a fire and explosion hazard.
4. *Unplanned shutdowns*—Unplanned shutdown of the coal firing system can be due to power failure, system fan failure, kiln shutdown, or coal feed shutdown causing mill shutdown. If the problem causing the unplanned shutdown persists and the coal in the mill cannot be moved, a fire may occur creating a critical situation which will result in an explosion during startup. Many of the fires and explosions in the coal processing installations have occurred following an unplanned shutdown. Most fires have occurred in the pulverizers, baghouses, or in bins during idle periods. Most explosions have occurred in the pulverizer or in the cyclone immediately after restart of the system.
5. *Debris in the pulverizer*—Debris or foreign material entering the system with the coal feed to the pulverizer can create a hazardous condition. Tramp iron in the pulverizer can cause high-temperature sparks capable of initiating a dust explosion. If foreign material becomes lodged within the system, it will alter the design air flow and can cause dead spots where coal dust may accumulate.
6. *Baghouse dust collector*—The baghouse is one critical area where the cement industry using indirect and semidirect systems has experienced many fires. Freshly ground, high-temperature coal fines that escape from the cyclone enter the baghouse for final separation from the drying air circuit. This coal is highly susceptible to autoxidation. The likelihood of a fire as a result of spontaneous combustion is increased during idle periods within the system where the coal can also degas volatile constituents which can contribute to fire or explosion. Static electricity in the baghouse can provide a source of ignition also, and proper grounding methods and use of semiconductor bags are essential to minimize the hazard.
7. *Pulverized coal surge bins*—The coal surge bin where freshly ground coal is stored prior to delivery to the burner is a critical area in the system. The primary hazard associated with the surge bin is fire from spontaneous combustion or a related phenomenon during shutdown periods. The risk is increased as a direct function of the amount of coal stored in the bin in any given period of time.

Case History of Accident Investigations

A total of 26 fire and explosion accidents were investigated by MSHA inspection personnel from 10 June 1977, through 4 Feb. 1985, in cement plants throughout the United States. In most cases, the inspection personnel required technical assistance from the Safety and Health Technology Center in Denver, Colorado, or from the Safety Technology Center in Bruceton, Pennsylvania.

During a typical investigation technical information was collected on the system operating parameters which included the system flow sheet, quantity of air, coal dust samples, types of coal, and so forth. The coal samples were sent to the Safety Technology Center in Bruceton for laboratory testing for composition, particle sizes, and explosibility of the dust. The tests completed in the Bruceton Laboratory were all based on several ASTM standards (see Appendix).

All 26 incidents occurred in the coal fired systems. In most cases there was substantial damage to equipment, building, and operating facilities. In addition, some of the incidents caused severe personnel injuries which included second- and third-degree burns and one fatality.

The Ad Hoc Committee on Coal System Safety of the Portland Cement Association (PCA) had compiled 13 fires and explosions that occurred in the indirect fired systems at cement plants. About half of the incidents involved fires and/or explosions in the filter baghouse of the indirect-fired systems. The other half involved the cyclone dust collectors and pulverizer coal mills.

The Ad Hoc Committee concluded that there was a trade-off between operating efficiency, fuel costs, and safety. Lower rank coal requires high mill inlet temperatures, and the use of indirect systems has improved the firing efficiency and fuel consumption but has increased the fire and explosion hazards.

The following accidents in coal fired systems and coal storage facilities of cement plants have been investigated.

Explosion date: 4 April 1978—New York

A combustible gas and coal dust explosion occurred in the kiln. The dust buildup was attributed to incomplete combustion, excessive coal feed, temperature too low to sustain combustion, or a combination of all three. The successive startup and shutdown cycles during the early operating stages, while the coal feed was kept to a minimum, may also have contributed to the dust buildup.

There were no injuries to personnel but there was extensive damage to the dust and breech chamber at the kiln feed end and to the ductwork leading from the multicyclone to the electric precipitator.

Recommendations: To investigate the application of a total hydrocarbon analyzer, equipped with flame-out alarm and automatic fuel shut-off.

Explosion date: 16 Oct. 1979—-Montana

A coal dust explosion occurred inside No. 1 mill exhaust fan housing. As a result of one or a combination of kiln puffs (minor explosions), the system fan damper failed, one piece fell into the inlet of the exhauster and could have hit or rested on the rim of the whizzer wheel or on the inlet ductwork. The other half could have lodged itself in a section of the ductwork or possibly even in the mill converter head, temporarily blocking off the mill air flow. This blockage would account for the pressure rise indicated by the control room charts. The piece lying at the inlet of the exhauster and hitting the whizzer wheel could also explain the rattling metallic noise reported.

Two persons received second- and third-degree burns. There was extensive damage to the mill exhaust fan (Figs. 5 and 6).

Conclusions: The following conditions were believed to have existed before the explosion:

1. Coal feed was 97% minus 200 mesh.
2. Air temperature at the fan outlet was 65.6°C (150°F) and was dropping.
3. Transport air velocity was low allowing the settling of coal fines to the bottom of the burner pipe.

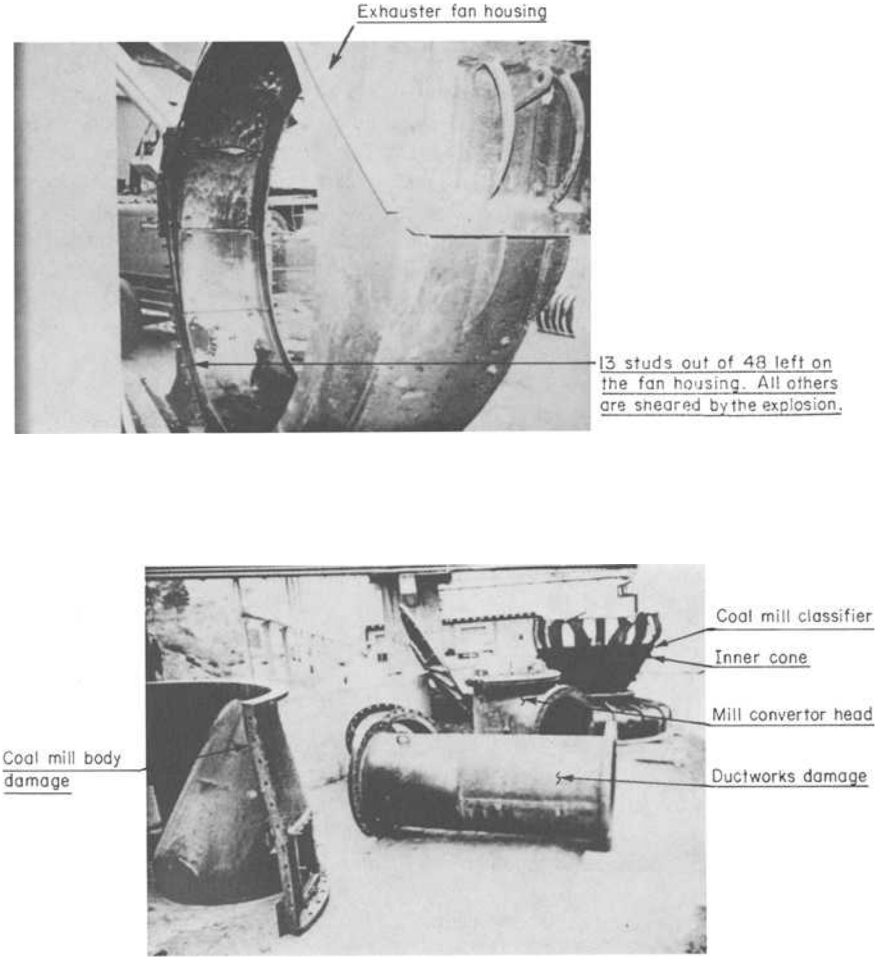


FIG. 5—*Explosion damage to coal mill component parts, ducting, and exhaust fan housing.*

4. Operator reduced the coal feed rate to 50% of the original rate thus creating a fuel to air ratio that was at the lower explosive limit.

5. Damper section failure at the fan inlet resulted in metal contact with the fan blades. This failure provided a probable ignition source (friction causing sparking). The other section was found in the inside of the inner cone of the bowl mill.

Explosion date: 6 Feb. 1981—Pennsylvania

The explosion was the second (the first was on 2 May 1980) that occurred during the restart of the plant following an unintentional power failure.

Both explosions occurred immediately after the coal mill circulation fan was restarted.

There were no personnel injuries. The major damage was confined to the cyclone.

Recommendations: The principal hazard resulting from a power stoppage is the heat buildup in the base of the coal mill. It was recommended that the plant should provide cooling in this area

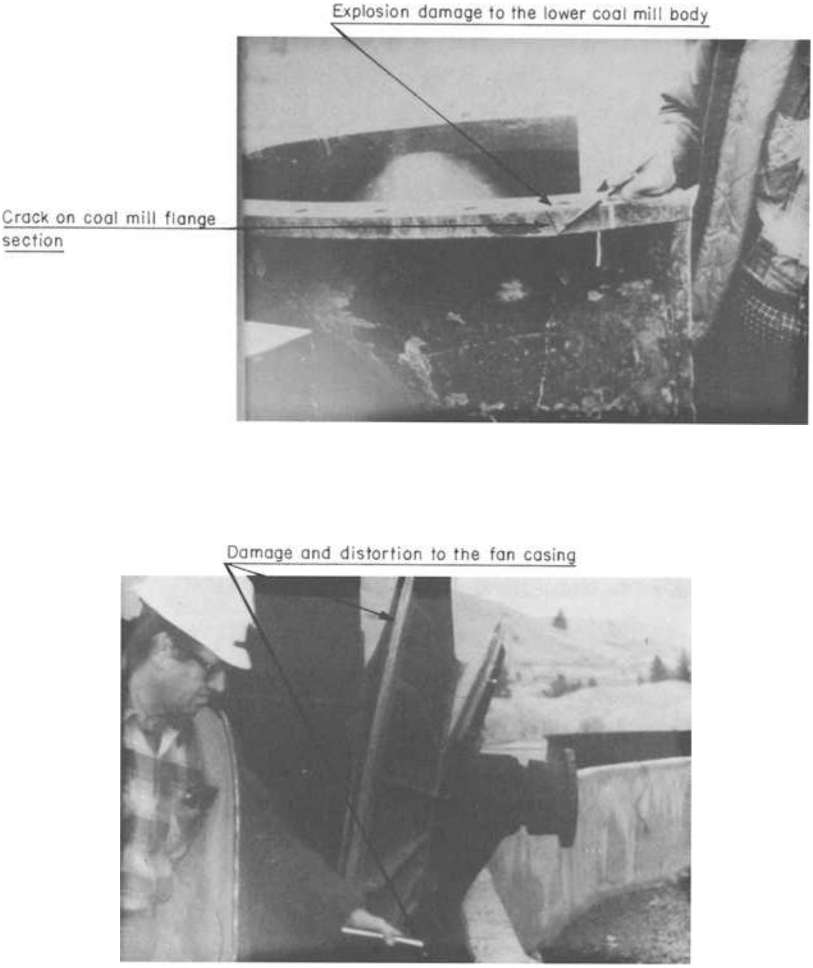


FIG. 6—*Explosion damage and distortion to fan casing and to the lower section of the mill.*

after a power loss. An immediate automatic injection system consisting of high-pressure water through fog nozzles was installed. Another safety measure that was recommended was an explosion-suppression system to be installed in the cyclone. In this system pressure sensing devices are used to actuate pressurized cylinders of fire suppression agents.

Explosion date: 18 July 1984—California

An explosion occurred in a coal bin. Fire was initiated by spontaneous combustion. Carbon dioxide application from the top was insufficient to prevent the development of an explosive atmosphere in the confined space above the coal. When a smoldering fire burns for a considerable time without being detected, the buildup of volatile gases can produce an explosive mixture resulting in an explosion.

There were no injuries to personnel, but there was extensive damage to the bin top and to the conveyor housing feeding the bin (Figs. 7–9).

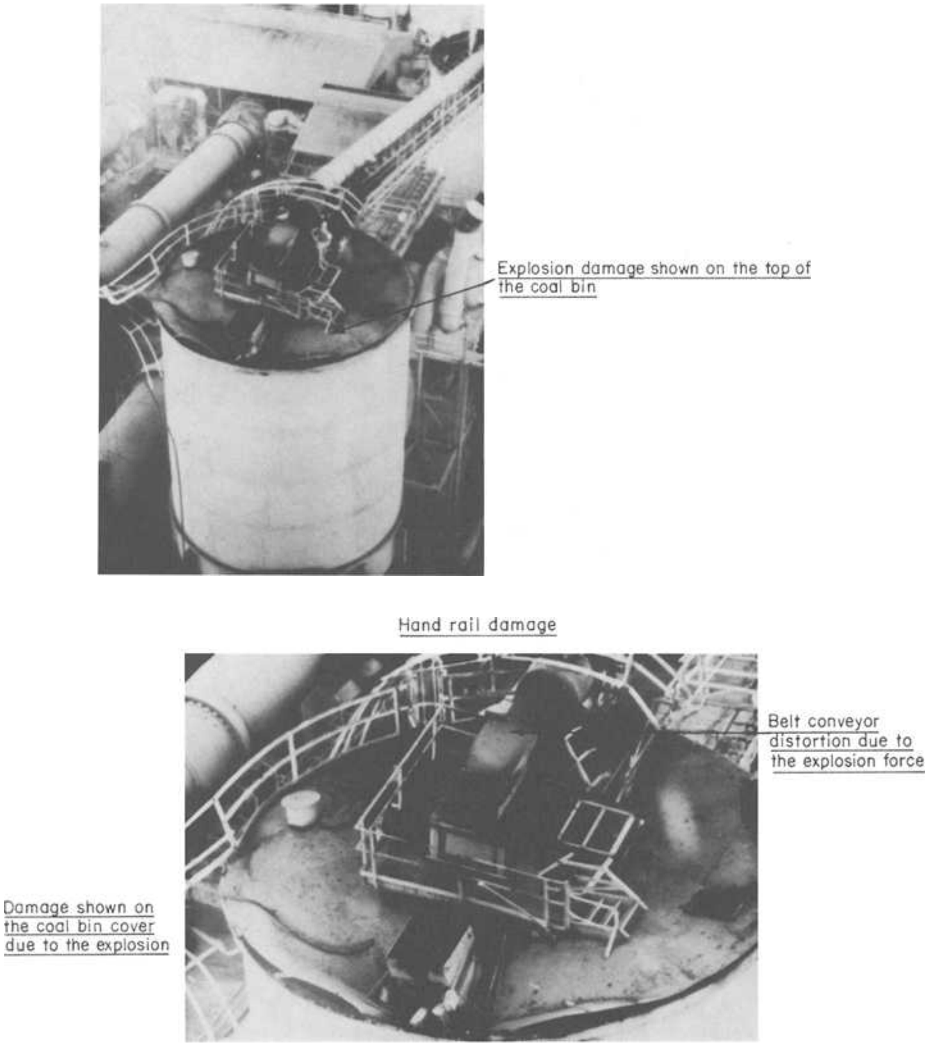


FIG. 7—*Explosion damage to equipment and structures on top of coal bin.*

Recommendations: The bin must be tightly constructed to reduce air leakage to a minimum. The application of carbon dioxide (CO_2) should be applied near the bottom and at the top of the bin to produce a small positive pressure inside the bin preventing leakage of air into the bin. An effective carbon dioxide inerting system should be developed for handling similar conditions in the future. A weak wall construction system was suggested for covering a sizeable area on the top of the bin for future installations (see also Fig. 4 for other recommendations).

Explosion date: 23 Jan. 1985—New York

Three employees were injured, one fatally, when they were thrown off the platform as a result of an explosion in the Bowl Mill.

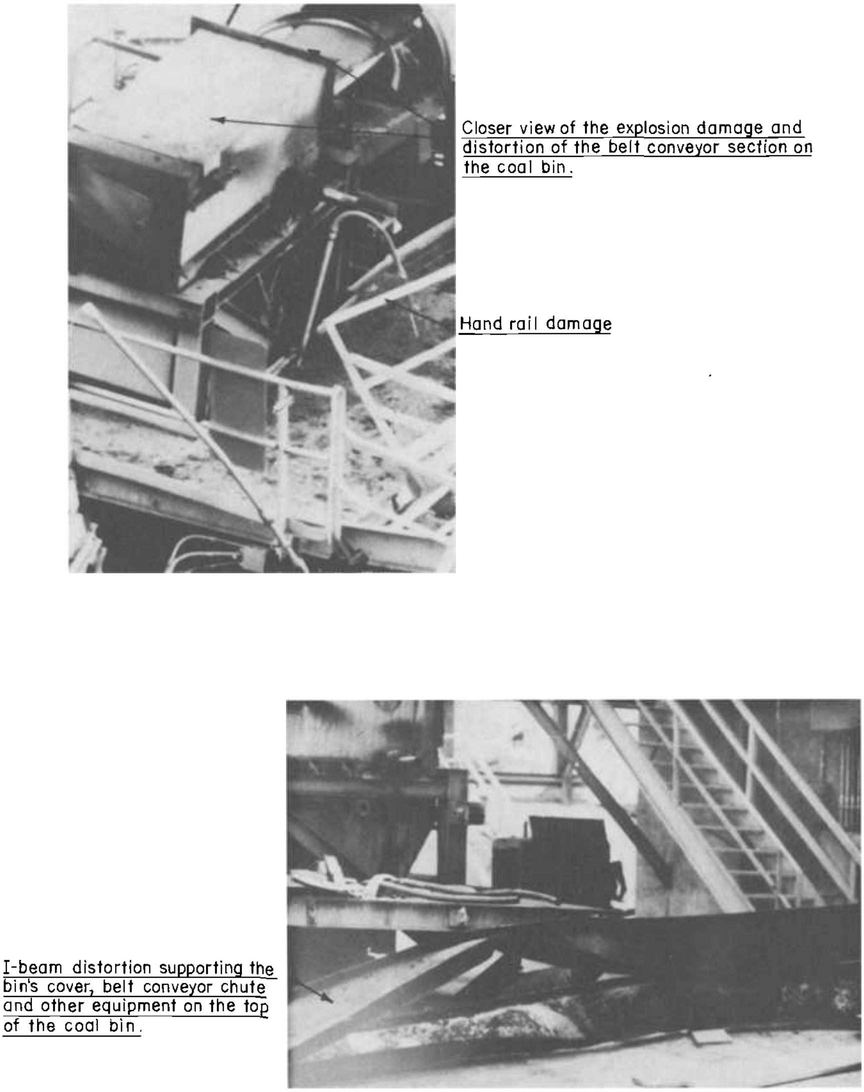


FIG. 8—*Explosion damage to conveyor section on coal bin top and to the bin I-beam support.*

The Bowl Mill was shut down as a result of abnormalities in the mill operation and an unusually large amount of rejects from the coal mill reject chute. A foreman and two repairmen climbed on a platform and proceeded to remove the stud nuts securing the mill (west) inspection door. One repairman removed seven of the eight stud nuts and tried to break the seal by forcing it with a screwdriver. An explosion forced the inspection door open throwing the three persons to the floor. The explosion forces caused extensive mechanical damage to the primary air fan in addition to fatally injuring one person (Fig. 10).

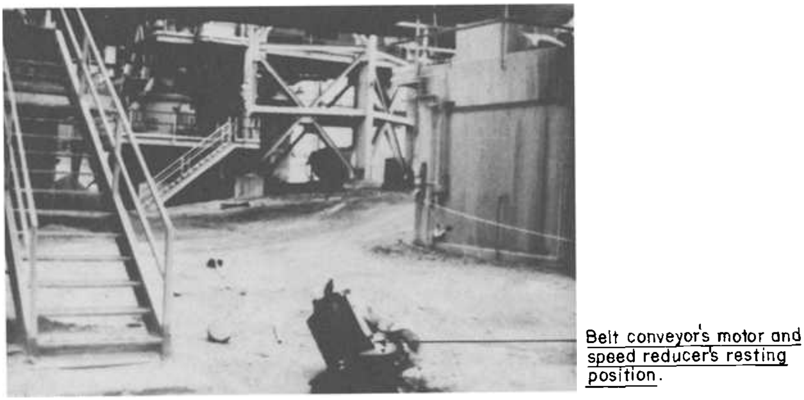


FIG. 9—*Final resting position of conveyor motor and speed reducer after the explosion (about 45.72 m [150 ft] away from the bin).*

Explosion date: 18 June 1985—New Mexico

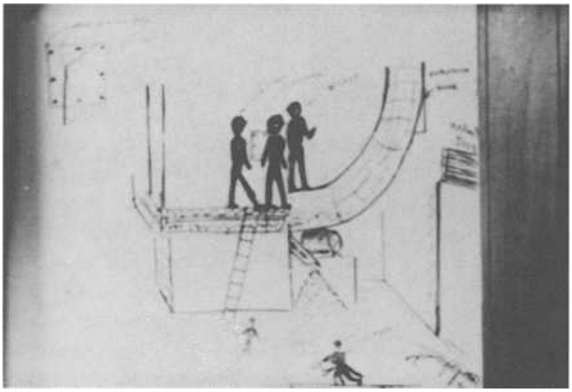
An explosion occurred in the coal grinding mill circuit during a scheduled shutdown of a cement kiln.

There were no injuries to personnel, but property damage and disruption of production resulted. Physical damage was limited to the 914.4-mm (36 inch) diameter hot air supply pipe which had separated at the welded joint, bent and distorted coal screw feeder covers, the hot air inlet damper (badly bent), and minor distortion of the cold air inlet control damper.

Prevention and Recommendations

The following special precautions are necessary to ensure safe operation of coal fired systems:

1. Elimination of one or more legs of the Fire Triangle or Explosion Pentagon
   (a) *Inerting*
      (1) Use of oxygen-deficient air in the pulverizers (indirect system) under normal operating conditions.
      (2) Use of rock dust, carbon dioxide, or water systems in the pulverizers and dust collectors when shutdown occurs (taking into consideration that rock dust could contaminate the coal).
      (3) Inerting with water sprays and steam when overtemperature conditions are observed. Care must be taken to prevent the development of a dust cloud which may then explode.
   (b) *Removal of ignition sources*
      (1) Use of magnets and metal detection to remove tramp iron from the system.
      (2) Cutting and welding operations should be carried out in accordance with recognized safety codes or guidelines (American Welding Society, American National Standards Institute [ANSI], NFPA).
      (3) Electrical components should meet the National Electrical Code and NFPA requirements and appropriate NFPA dust explosion codes (see Appendix).
      (4) Hot coal from storage areas should be discarded and not fed into the pulverizer. Particular care should be exercised during startup and shutdown.
      (5) Proper control measures should be instituted to prevent spontaneous combustion.
      (6) Grounding of dust collector bags or use of semiconductor bags to prevent static electricity discharge.



Sketch of a mill explosion showing the location of people before and after.

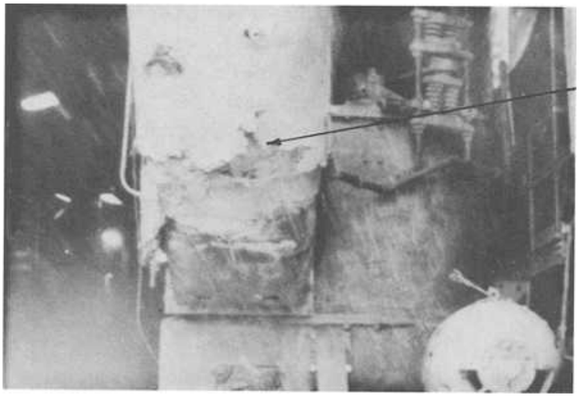


FIG. 10—*Explosion damage to mill ducting, insulation, and the inspection door.*

(7) Smoking and open heat sources should be prohibited in hazardous areas of the plant.

2. Good housekeeping

(a) Prevention of dust accumulations by control of spillage, leakage, and degradation of coals to fines during handling and resultant dust buildups.

(b) Cleaning and removal of extraneous combustible materials from the workplace.

(c) Design, implementation, and maintenance of dusttight equipment.

3. Equipment design

(a) Small compact design of pulverizers, cyclones, dust collectors, and storage bins with a minimum of dead space.

(b) Elimination of dead spots, ledges, corners, or other areas where dust can accumulate in equipment or ducting.

(c) Storage bins designed with proper discharge angles and smooth internal surfaces and vibrators to facilitate removal of the coal.

   (d) Auxiliary electric power systems available to operate key pieces of equipment in the event of a power failure.

   (e) Use of overtemperature and overpressure controls to warn of a potentially dangerous situation.

   (f) Fire and/or explosion suppression systems can be installed on pieces of equipment susceptible to fires and/or explosions.

   (g) Detection equipment can be installed to monitor carbon monoxide (CO) buildup in the pulverizer, cyclone, storage bin, or dust collector. The design of the carbon monoxide monitoring system is based on the fact that CO buildup is related directly to the oxidation rate of the coal. An analysis system is needed to compare the CO content of the incoming and outgoing mill air and indicate the difference. The principal advantage of this system is that it can detect CO buildup and, therefore, may give the operator sufficient lead time to adjust operating conditions, apply fire extinguishing measures, and, if necessary, shut down the mill to prevent an explosion.

   (h) The use of explosion venting design should be considered for controlling the explosion damage.

4. Education and training. Written procedures should
   (a) Be specific to prevent any variations in the interpretation and application by different operators.
   (b) Be readily available to all operating personnel.
   (c) Contain the necessary information for system checkout, warmup, and shutdown including short-term, long-term, and emergency operating conditions.
   (d) Be modified immediately when operational changes are deemed necessary.
   (e) Be reviewed regularly with all operators to prevent gradual changes in the actual operating practices. A safety meeting or group training session is helpful for this review and updating.
   (f) Be established for fire fighting with periodic drills
5. Preventive maintenance
   (a) A routine maintenance program should be developed for pieces of equipment sensitive to breakdown, such as motors, dampers, and fan blades.
   (b) Periodic inspections should be carried out to ensure that key pieces of equipment are in good operating condition.

APPENDIX A

Glossary

ash inorganic residue remaining after ignition of combustible substance, as determined by prescribed test methods

calorific value (heat of combustion) heat produced by combustion of a unit quantity of a solid or liquid fuel when burned at constant volume in an oxygen bomb calorimeter

clinker fused product of a kiln which is ground to make cement

coal bin (coal silo or coal bunker) container, circular in cross section, used to store run-of-mine coal. It is placed ahead of the coal pulverizing mill in the coal fired system

coal surge bin bin used for storing pulverized coal approximately 200-mesh (74 μm or less)

explosion pentagon the three elements present in the fire triangle plus two additional elements necessary for explosion—suspension of fuel within the flammable limits and confinement

fire triangle the three elements necessary for a fire—fuel, heat (ignition sources), and oxygen

fixed carbon solid residue, other than ash, obtained by destructive distillation, as determined by prescribed methods. It is principally carbon but may contain appreciable amounts of sulfur, hydrogen, nitrogen, and oxygen

proximate analysis determination, by prescribed methods, of moisture, volatile matter, ash, and fixed carbon (by difference)

pulverized fuel solid fuel reduced to such a size that more than 50% will pass through a 200-mesh U.S. sieve (74 μm or less)

rank term used to classify coals according to their degree of metamorphism, or progressive alteration, in the natural series from lignite to anthracite

run-of-mine raw coal as it is delivered by mine cars, skips, or conveyors and prior to treatment of any sort. It is usually the average grade of coal or ore produced in a mine

ultimate analysis the determination, by prescribed methods, of carbon, hydrogen, sulfur, nitrogen, ash, and oxygen (by difference)

APPENDIX B

Standards

The following standards are applicable to this paper:

ASTM Standards

D 121-78	Standard Definitions of Terms Relating to Coal and Coke
D 197-82	Standard Method of Sampling and Fineness Test of Pulverized Coal
D 311-30	Standard Method of Sieve Analysis of Crushed Bituminous Coal
D 388-82	Standard Classification of Coals by Rank
D 3172-73	Standard Method for Proximate Analysis of Coal and Coke
D 3176-84	Standard Method for Ultimate Analysis of Coal and Coke

Other Standards

NFPA 68-1978	Guide for Explosion Venting
NFPA 69-1978	Standard for Explosion Prevention Systems
NFPA 70	National Electrical Code
NFPA 85E-1985	Prevention of Furnace Explosions in Pulverized Coal-Fired Multiple Burner Boiler-Furnaces
NFPA 85F-1982	Installation and Operation of Pulverized Fuel Systems

References

[1] Cashdollar, K. L. and Hertzberg, M., "20-1 Explosibility Test Chamber for Dusts and Gases," *Review of Scientific Instruments,* Vol. 1, No. 1, April 1985, pp. 596–602.

[2] Nagy, J., Dorsett Jr., H. G., and Cooper, A., "Explosibility of Carbonaceous Dusts," BuMines RI 6597, Pittsburgh, 1965.

[3] Hertzberg, M., Cashdollar, K. L., et al., "Inhibition and Extinction of Coal Dust and Methane Explosions," BuMines RI 8708. Pittsburgh, PA,

[4] Conti, R. S., Cashdollar, K. L., et al., "Thermal and Electrical Ignitibility of Dust Clouds," BuMines RI 8798, Pittsburgh, 1983.

[5] Kim, A. G., "Laboratory Studies on Spontaneous Heating of Coal," BuMines I.C. 8756, 1977.

[6] Dorsett, H. G., Jacobson, M., et al., "Laboratory Equipment and Test Procedures for Evaluating Explosibility of Dusts," BuMines RI 5624, Pittsburgh, 1960.

Willy J. Geysen,[1] *Ronnie Belmans,*[2] and Louis Scheys[3]

A Sugar Dust Explosion and Some Measures to Limit Its Consequences

---

REFERENCE: Geysen, W. J., Belmans, R., and Scheys, L., "**A Sugar Dust Explosion and Some Measures to Limits Its Consequences,**" *Industrial Dust Explosions, ASTM STP 958,* Kenneth L. Cashdollar and Martin Hertzberg, Eds., American Society for Testing and Materials, Philadelphia, 1987, pp. 234–242.

ABSTRACT: A dust explosion in a Belgian sugar refinery is described. Using the factory characteristics and the sugar dust parameters as encountered in this plant, and taking into account the results of the accident investigation carried out by the authors, preventive and protective measures are worked out. Adaptions of the installation are proposed and explosion vents in silos, bucket elevators, and dust collectors are introduced. Furthermore, attention was paid to electrical grounding, dustproof electrical equipment, isolation of the equipment with rotary valves, indirect input, and compartmentalization of different production lines. The preventive equipment maintenance program was adapted to minimize spark generation hazards. New regulations were introduced, among others a general no-smoking rule and a general open flame and hot work permit.

KEY WORDS: sugar dust explosion, dust explosion, preventive measures

In 1982, two serious explosions occurred in sugar refineries, one in the north of France and one in Belgium.

The explosion investigation was carried out by the first author (Kath. Univ. Leuven) acting as a forensic science expert designated by the attorney in charge.

In consequence of this explosion, the management of the Tiense Suikerraffinaderij (Belgium) decided to embark on a significant program in all their sugar refineries as an effort to control the damage of possible explosions. The third author acted as a major safety advisor in setting up this program.

The program consists on the one hand of preventive measures such as improved housekeeping and a general hot work permit introduction, and on the other hand of protective measures such as modification in the sugar handling equipment and installation.

Factory Characteristics

The explosion of October 1982 occurred in the granulation building where sugar with 1% moisture is completely dried.

The granulation phase of the complete sugar production process is shown in Fig. 1.

---

[1] Chairman, Electric Power and Industrial Applications Division, Electrical Engineering Department, Katholieke Universiteit Leuven, Kard. Mercierlaan 94, B-3030 Leuven-Heverlee, Belgium.

[2] Research fellow supported by the Belgian National Scientific Research Foundation, Laboratory for Electrical Machines and Drives, Katholieke Universiteit Leuven, Kard. Mercierlaan 94, B-3030 Leuven-Heverlee, Belgium.

[3] Safety engineer, Suikerraffinaderij Tienen, Aandorenstraat 1, 3300 Tienen, Belgium.

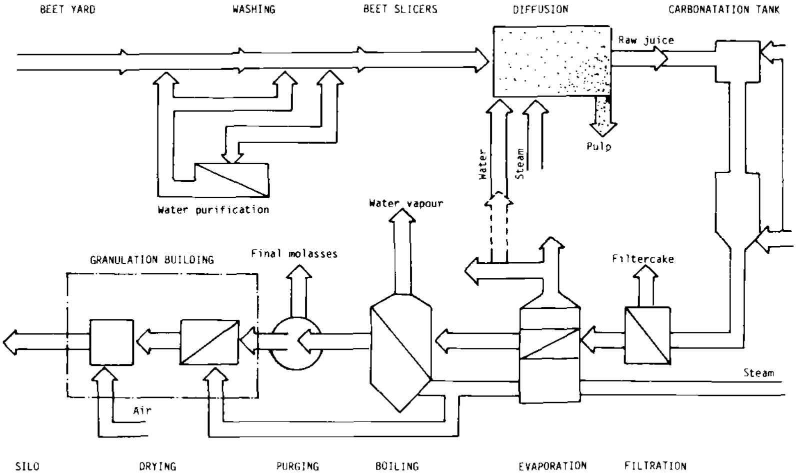


FIG. 1—*Granulation phase of the sugar production process.*

The equipment in the granulation building consists of:

- a rotating hot air drier,
- screens,
- six 100-ton (91-Mg) daily production silos,
- bucket elevators,
- belt conveyors,
- screw conveyors, and
- chair conveyors.

One out of these six 100-ton (91-Mg) silos is composed of two 50-ton (45-Mg) silos in series.

The granulation building is 30 m high with four floors and a mezzanine on the fourth level. It has a metal joist construction.

The material damage of the explosion was significant with major damage on the fourth level:

- two 50-ton (45-Mg) aluminum silos in series were ripped open, these silos were empty at the time of the explosion;
- two stainless steel silos were slightly damaged;
- all three of the bucket elevators were pressurized at the bottom and completely ripped apart on the third level; no damage was noticed at the top of the elevators;
- the dust collector and the main suction pipe were damaged; and
- the metal panel walls and the building roof were either blown away or dented.

On Fig. 2 a view on the granulation building after explosion is shown.

Sugar Dust Parameters

Dust explosions mostly happen in different phases. Often three major ones may be distinguished. The initial explosion is generally very small, but this first explosion creates a bigger dust cloud which causes a bigger explosion. This second explosion may result in a still bigger dust cloud accompanied by a blast if the cloud is partially confined.

In the accident investigation after the explosion it was clearly demonstrated that these three phases did occur in the explosion under consideration.

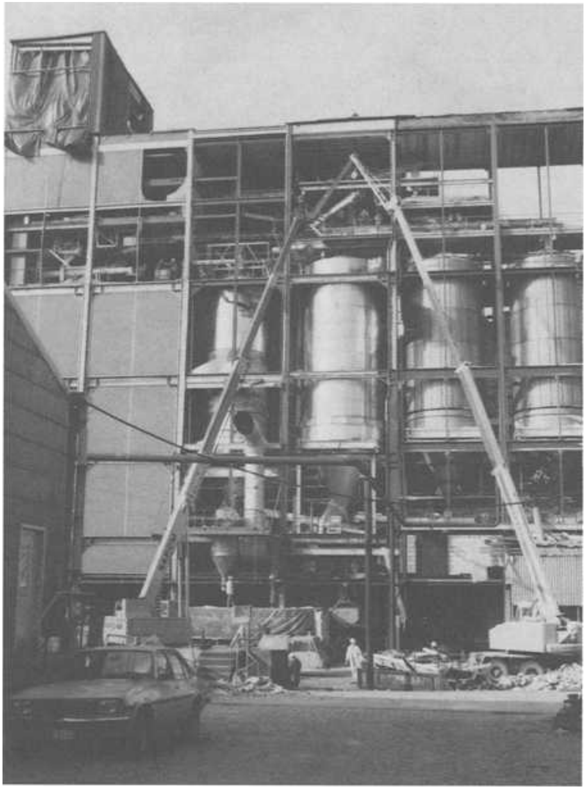


FIG. 2—*Granulation building after the explosion.*

To obtain an explosion, the sugar dust must be in the correct environment. The different parameters should have their ideal value, and in addition these parameters should interact with one another.

The parameters given in Table 1 and Figs. 3 and 4 are obtained from the measurements and the theoretical analysis carried out by Dr. S. Radandt of the Berufsgenossenschaft für Nahrungsmittel und Gaststätten (FRG) and by Dr. A. Beck of the Berufsgenossenschaftliches Institut (FRG). The tests were performed using sugar dust samples from the factory where the explosion took place. To find the maximum pressure, a sphere having 1-m^3 volume was used. The pressure rise was obtained using a 1.2-dm^3 vertical glass tube. A detailed description of the test procedures is found in Ref *1*.

TABLE 1—*Granulation density distribution of sugar dust samples.*

Size, µm	Weight Percent Less Than			
	8204390/1	8204390/2	8204390/3	8294390/4
500	61	63	37	77
250	16	29	6	26
125	6	5	3	8
63	4	2	2	2
32	0	1	1	1

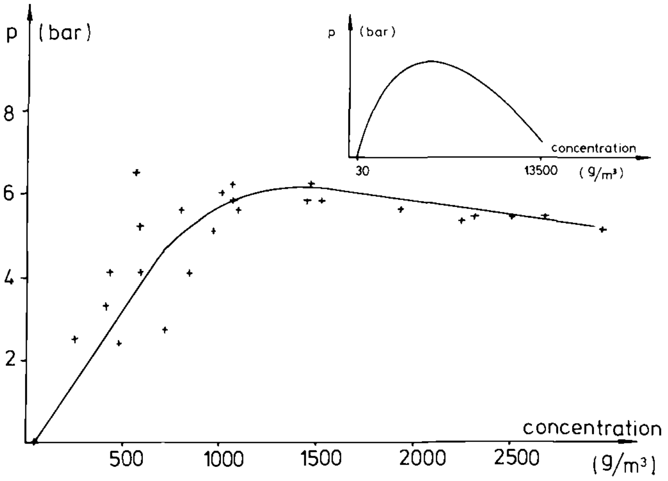


FIG. 3—*Maximum pressure as function of the concentration. The small figure shows the results of the theoretical extrapolation.*

The most important parameter is the concentration of the dust in milligrams/cubed metres, combined with the size of the sugar particles.

The theoretical extrapolation of the experimental results shows that the lower explosion limit under which no dust explosion is possible is 30 g/m^3, a very low value which is obtained in almost any equipment, also in "empty" silos. The upper explosion limit is 13.5 kg/m^3 which is difficult to obtain (Fig. 3).

The smaller the particle, the better the explosion is initiated and the higher the pressure builds up. The largest particle size above which an explosion is unlikely is about 500 μm [2].

The complete granulation density distribution of the samples is shown in Table 1.

According to the test results, the maximum absolute pressure developed varies between 5.5 and 6.6 bar (550 and 660 kPa) for concentrations from 600 up to 2000 g/m^3.

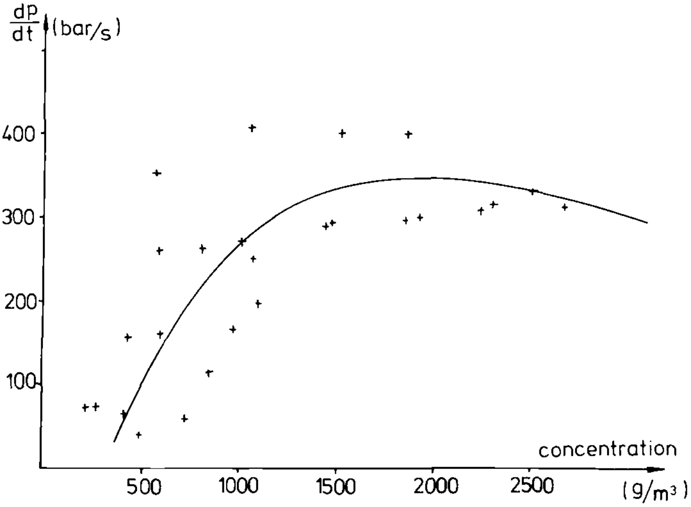


FIG. 4—*Rate of pressure rise as function of the particle size.*

Even at concentrations of 400 g/m^3, a pressure of 4 bar (400 kPa) is obtained.

The rate of pressure rise was 420 bar/s (42 MPa/s) for concentrations from 1100 to 1900 g/m^3. The concentration of 400 g/m^3 resulted in a pressure rise of 160 bar/s (Fig. 4).

The normalized pressure rise rate (K_{St}) value based on these results is nearly 110.

All these values correlate with the literature on sugar dust explosions studied in the Federal Republic of Germany [*3*] and France [*4*].

Humidity has an adverse effect on sugar dust explosions. The higher the humidity, the more energy is needed to initiate combustion. In normal conditions, the minimum explosion energy for sugar dust is about 30 mJ (Fig. 5) [*2*].

The addition of inert materials such as calcium carbonate, mica, and chalk decreases the final explosion pressure. This addition method, however, cannot be used in the food industry.

The oxygen content in the atmosphere is also quite important. An explosion can occur even in 9% oxygen, a highly reduced content compared with the normal value of 21% [*5*]. Inerting with nitrogen is a possibility to suppress an explosion. However, this method depends on the equipment in which the dust is handled, and is not common in the food industry in general.

Accident Investigation

The explosion in the Belgian sugar plant killed four people and injured some twenty more. It also caused major damage to the installations.

The accident happened in mid-afternoon during normal operations. From the damage pattern and the questioning of all the eyewitnesses, the investigators could clearly show that the final explosion occurred in the two 50-ton (45-Mg) silos and that this final explosion caused major structural and personal damage.

However, in spite of a careful pressure analysis of the installation and a detailed duct damage investigation, it could not be definitely concluded where the original explosion or smoldering occurred.

Although welding activities were being carried out in two locations on the moment of the explosion, the investigation could probably eliminate the causal relationship of welding processes with the explosion. No substantial deviation of the installation from the technical regulations could be seen.

From this analysis, the authors tried to deduce some feedback information to prevent such accidents in the future. They also studied the international literature covering this kind of accident. From this comparison, they tried to deduce some useful information regarding the use of good practice codes.

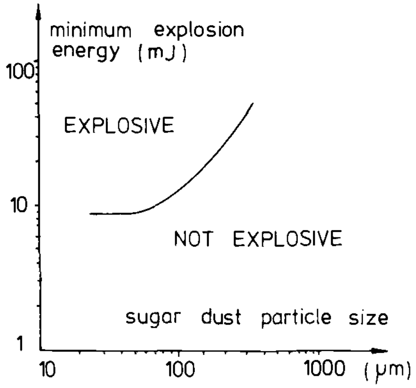


FIG. 5—*Minimum explosion energy as function of the particle size.*

Prevention and Protection Measures

Based on theoretical knowledge, and according to the philosophy of the explosion guidelines edited by the German BG Chemie, a series of explosion preventive and protective measures have been taken.

The most significant damage normally does not result from the initial explosion, but from the subsequent explosions. It is therefore important to minimize or better still to eliminate dust accumulations in the building. Dust is liberated at transfer points in conveying systems and in grinders, where sugar is dumped into equipment and where the equipment is not dustproof. Consequently, the tightness of the equipment is imperative. An adequately sized dust collecting system at suction points where dust is liberated is also necessary.

Where these precautions are insufficient, manual cleaning is a must. Dust accumulations of 1 mm thickness could already be sufficient to cause a disaster.

New plants should be designed to be easy to clean and excess dust accumulation should be prevented by ensuring that joints and inspection hatches are leakproof. Where possible, plants should operate under a slight negative pressure. All open parts, such as bagging points and charging openings should be fitted with dust exhausts.

Statistics show that a very common cause of accidents involving dust clouds is the use of power equipment, welding torches, and sparking tools without proper precautions. The minimum explosion energy needed to start sugar combustion is very low and can be obtained with a spark resulting from welding and cutting, friction, static electricity, electrical equipment, smoking, and so forth. Therefore, a general program to avoid occurrence of ignition sources has been set up. A general smoking prohibition, a general hot work permit, thorough earthing of the electrical installation, and a general avoidance of hot spots and hot surfaces are just part of this program.

From statistical data we know that equipment especially subject to dust explosions are:

- bolting mills,
- silos and bins,
- bucket elevators, and
- dust collectors.

As it is impossible to limit the dust concentration within this equipment, an explosion can occur in specific circumstances. When unexpected ignition sources occur, protective measures must be provided to limit the consequences of such an explosion. There are three ways to realize this protection: one can contain the pressure, one can release it, or one can choose another type of equipment. For example, the equipment can be arranged so that bucket elevators are not needed and that the transfer is done by ordinary conveyors. However, this application is limited since the slope of a conveyor belt cannot exceed 18°. The design of pressure resistant equipment is generally very costly and is only applied on small machines if no other means are possible. Another protective method is to limit the developed pressure by an explosion suppression system. Inerting with a nitrogen atmosphere is another possibility, if the equipment arrangement and the production process permit this. All these protective methods, however, have a limited application range as a result of practical problems and financial aspects.

The most frequently used protective method is the installation of explosion vents on the equipment. The dimensions of these vents are calculated in accordance with German VDI guidelines and American NFPA standards.

Sugar handling equipment cannot be used in the open air because of humidity. On the other hand, the explosion vents have to release the pressure outside the buildings because the release of a pressure wave inside the building might cause considerable damage and possibly create secondary explosions.

It is therefore imperative that the equipment be located close to an exterior wall to minimize the length of the ducts of these explosion vents. This length should not exceed 3.0 m, so as to avoid the detonation hazards of longer ducts.

One elevator in our sugar refinery is 38 m high, 0.64 m wide, and 1.47 m long, which results in a volume of 35.75 m^3. According to the nomogram in VDI, eight explosion panels of 0.8 m^2 over the entire length of the elevator are needed to release the pressure.

The elevator itself withstands a pressure of 0.7 bar (70 kPa) and the vents release at 0.1 bar (10 kPa). The ducts on these vents which guide the explosion into the open air should withstand the residual reduced pressure after an explosion, which in our case is estimated at 0.2 bar (20 kPa).

Other preventive actions designed to limit the frequency and the consequences of an explosion in a bucket elevator are:

- electrical grounding,
- dustproof casing,
- belt slipping prevention through an adequate rotation fail switch,
- rotary valves on feed and discharge chutes,
- antistatic belts,
- the interior of the elevator panels should not be treated with aluminum based paint to minimize violent sparking in the event of mechanical impact,
- air flow switches on the top and bottom explosion vents to stop the elevator, and
- an anti run-back device.

During the installation of explosion vents on the small silos located inside the granulation building, special problems were encountered:

- their volume was less than 200 m^3,
- the explosion vents could not be installed on their sides, and
- the distance from the building roof was about 4 m.

Five explosion vents of 0.8 m^2 each have been installed in the roof of the silo. The vents release at 0.1 bar (10 kPa) while the silo itself can withstand 2.3 bar (230 kPa). A 5-m-high chimney was installed on top of the silo to convey the explosion pressure into the open air.

Additional preventive actions for silos are:

- rotary valves on feed and discharge pipes,
- electrical grounding, and
- dustproof construction.

We have already mentioned that an adequately sized dust collecting system is necessary. Such a system consists of ducts and filters. The ducts as well as their expansion joints withstand 9 bar (900 kPa). Because of static electricity, the flanges of both pipes have to be grounded by bridging the joint. The filter units should be isolated from the other equipment to avoid the transmission of an explosion (Fig. 6). This is done by means of an indirect input connection. The supply pipe extends to above the filter, and the dust laden air is drawn into the filter through this bypass. A membrane is installed on the bypass to release the pressure of an eventual explosion.

The dust collector itself is equipped with explosion vents in accordance with VDI guidelines. The design of these vents has to take into account the possibility of underpressure. The dust is extracted from the filter unit by rotary valves and a screw conveyor.

Bag-type filters equipped with explosion vents are also used at our plant and the bags are made of antistatic cloth. Grounding is needed to avoid static electricity.

Conclusions

In conclusion, we would like to list the different protective measures taken in the Tienen sugar plants after the explosion that occurred in 1982.

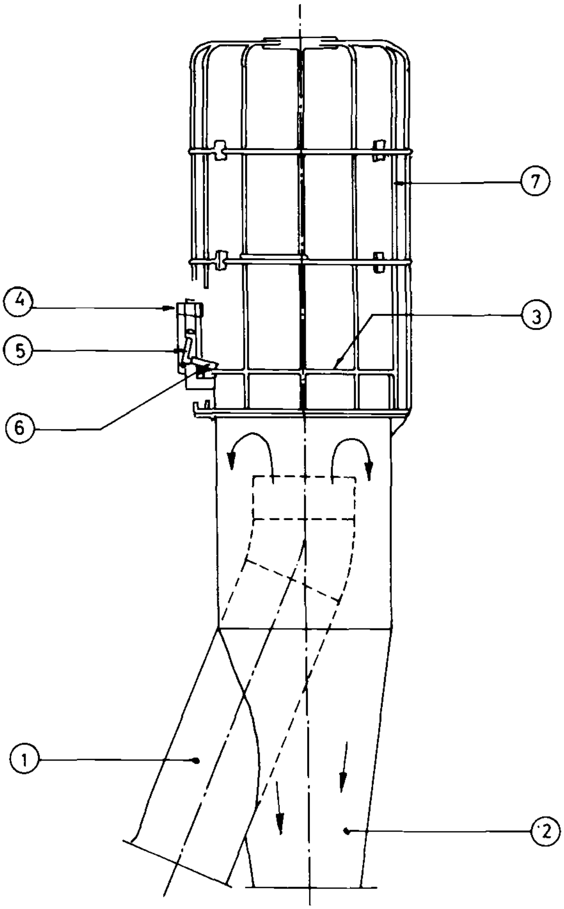


FIG. 6—*Filter unit:* (1) *from the dust collector,* (2) *towards the filter,* (3) *explosion vent or pressure relieve valve,* (4) *regulation screw,* (5) *transmission spring,* (6) *lock, and* (7) *garding.*

(1) a high standard of housekeeping, including dustproof equipment, an adequate dust collecting system, and additional manual vacuum cleaning;

(2) a preventive equipment maintenance program to minimize the spark generation hazards;

(3) electrical grounding to prevent static electricity;

(4) dustproof electrical equipment;

(5) a general no-smoking rule within the plant;

(6) a general open flame and hot work permit;

(7) explosion vents installed in silos, bucket elevators, and dust collectors; and

(8) isolation of the equipment with rotary valves, indirect input, and so forth also including the compartmentalization of the different production lines with each having individual silos, elevators, and dust collectors.

For financial reasons, as well as by comparison with most of the known sugar factories in Europe, the Tienen Group did not install equipment for fast explosion suppression because such a system would only bring an asymptotic contribution to safety in our sugar plants.

These preventive and protective measures have been instituted based on a hard lesson learned from an accident investigation, after much human harm and material damage.

By these actions we hope to be able to prevent or at least to control the damage of future possible explosions at our sugar refinery.

References

[*1*] Kühner, G., Beck, H., and Glienke, "Forschungsbericht Staubexplosionen. Brenn- und Explosionskenngrössen von Stäuben," Schriftreihe des Hauptverbandes der gewerblichen Berufsgenossenschaften e.V., Bonn, F.R.G.

[2] Edwards, R. E., "Sugar Dust Explosion Variables," *The Sugar Journal,* Feb. 1970, pp. 21–26.

[*3*] Bartknecht, W., *Explosionen,* Springer Verlag, Berlin-Heidelberg-New York, 1980.

[*4*] Pinneau, J., Giltaire, M., and Dangeaux, J., "Surpression des explosions par extincteurs déclenchés," INRS Note 1267-100-80, 1980, France.

[5] Radandt, S., "Staubexplosionen in Silos für Nahrungsmittel, Futtermittel, Getreide und Oelsaten—Untersuchungsergebnisse Teil 1," *Berufsgenossenschaft Nahrunsmittel und Gastätten, Symposium Heft 9,* 1981.

C. William Kauffman[1]

Recent Dust Explosion Experiences in the U.S. Grain Industry

REFERENCE: Kauffman, C. W., "**Recent Dust Explosion Experiences in the U.S. Grain Industry,**" *Industrial Dust Explosions, ASTM STP 958,* Kenneth L. Cashdollar and Martin Hertzberg, Eds., American Society for Testing and Materials, Philadelphia, 1987, pp. 243–264.

ABSTRACT: After the explosions of December 1977 intense scrutiny was given to the occurrence of fires and explosions in grain handling and processing facilities in the United States.

The conditions leading to fires and explosions in these facilities—fuel, oxidizer, ignition, mixing, and confinement—had been identified immediately following World War I.

At the beginning of this decade the National Academy of Sciences investigated 14 explosion incidents, reported on the findings, and made recommendations concerning accident prevention. As the decade has progressed, however, these fires and explosions have continued with reports of investigations being available for some major incidents. The continuing critical factor in these explosions is the massive uncontrolled accumulations of fuel. In the effort to eliminate this industrial hazard, the U.S. Department of Labor has issued Draft Final Standards pertaining to safety hazards in grain-handling facilities. It is clear that it is technically feasible to eliminate fire and explosion hazards from the grain and agricultural products industry because these events do not occur as a result of unknown, unpreventable causes.

KEY WORDS: dust explosions, primary explosions, secondary explosions, grain elevators

Over 200 years have elapsed since the first report of a dust explosion in a Turin flour mill in 1785 [*1*]. However, in spite of the intervening 2 centuries of continued explosions and study of the problem, it still manages to command scientific, economic, and political attention [*2*]. Sound scientific explanations of the conditions necessary for the occurrence of these explosions and the many physical processes that govern their propagation have been developed [*3–7*]. Indeed, the explosibility testing of dusts has through 75 years of experience become routine for the U.S. Bureau of Mines which has issued hundreds of publications on the subject [*8*]. It has even become the subject of several commonly available textbooks [*9–13*].

To those investigators working in the dust explosion area it is indeed a mystery why these explosions need to continue occurring. A solution to this problem was practically demanded by the U.S. agricultural industry after December 1977, when 5 grain elevator explosions in 8 days killed 59, injured 48, and destroyed 2.5% of the nation's export elevators. To disseminate the already existing information concerning agricultural dust explosions, the U.S. Department of Labor mailed a hazard alert describing the explosion dangers in facilities handling agricultural products [*14*], to 15 000 grain handling facilities and the National Academy of Sciences hosted an international colloquium on the subject [*15*]. However, to verify that an adequate understanding of agricultural dust explosions did exist, the U.S. Departments of Agriculture and Labor supported the formation of the Panel on the Causes and Prevention of Grain Elevator and Mill Explosions under the auspices of the National Academy of Sciences. As elucidated in the 4 reports issued by the Panel [*5,16–18*], no new scientific reasons for the occurrence of agricultural dust explosions

---

[1] Associate professor, Department of Aerospace Engineering, The University of Michigan, Ann Arbor, MI 48109-2140.

were discovered, and recommendations were made to deal with the problem. A similar examination of this dust explosion problem was conducted by the National Institute of Occupational Safety and Health [*19*].

As it was thought, based upon the findings of the National Academy of Sciences and National Institute of Occupational Safety and Health, that the reasons for the occurrence of agricultural dust explosions were well known it was deemed that perhaps federal safety regulations could have an effect on decreasing the frequency and severity of these explosions. Such regulations have been employed in the coal mining industry with apparent success [*20*]. Dust explosibility tests have shown that coal dust presents less of an explosion hazard than almost all of the usual agricultural dusts. A proposed rule was issued by the Occupational Safety and Health Administration (OSHA) early in 1984 [*21*]. To establish a docket, hearings were held in four different locations during that year, and in addition written comments were accepted. Draft final standards were submitted to the Office of Management and Budget in March 1986. While these standards cover many items relating to safety in grain-handling facilities they also deal with the dust explosion problem, addressing, for example, housekeeping, allowable dust accumulations, control of ignition sources, and, in a limited context, suppression systems and venting.

These regulations have been criticized by both those who want and those who oppose the concept of regulations because of, among other things, the alleged economic implications of compliance, the suspected allowance of explosive amounts of fuel, and the reported limited scope of facility applicability. However, even should the regulations contain some deficiencies they do attempt to address the dust explosion problem which continues to persist in the agriculture and agricultural products industry.

History of Agricultural Dust Explosions in the United States

In 1923 Price and Brown published a definitive treatise on dust explosions [*3*]. Until that time the subject of dust explosions had not received serious consideration. A large number of explosions had been occurring in mines and industrial plants where no explosive gases were present. As a result of a series of coal mine explosions in 1907 the U.S. Geological Survey began to investigate these disasters, and in 1910 this group became the U.S. Bureau of Mines which in 1913 investigated an explosion in a feed grinding plant in Buffalo, New York. After the investigation the grain and milling industry showed considerable interest in the prevention of future disasters. As a result of the ensuing cooperation and the considerable interest in avoiding the loss of essential food supplies during World War I, a permanent continuing program concerning dust explosions in mills and elevators was established by the Bureau of Chemistry in the U.S. Department of Agriculture. Their book was a result of this work. In this publication they report on the combustion and ignition properties of dusts, the control of ignition sources, the prevention of dust–air mixtures, the collection of dust, equipment design including light construction, and protective regulations, and they give a review of explosions. For explosions in the grain and grain processing industry the book includes explosion data for 63 years from 1860 to 1922. During this period of time they report 119 incidents, 215 deaths, and 271 injuries. This gives an average of 1.8 incidents/year, 3.4 deaths/year, and 4.6 injuries/year. On the average each incident produced 2 deaths and 3 injuries.

This work became the basis of the National Fire Protection Association (NFPA) Committee on Dust Explosion Hazards, which subsequently prepared codes for the prevention of dust explosions in occupancies and processes involving combustible dusts. The 1942 edition of the National Fire Code for the Prevention of Dust Explosions [22] lists dust explosion data from 1898 to 1942 (see Table 1). For the agricultural products industry there were 365 incidents, with 334 deaths and 679 injuries. Normalizing this gives 8.1 incidents/year, 7.4 deaths/year, and 15.1 injuries/year. In

TABLE 1—*Record of dust explosions in the United States (to 1 Sept. 1942).*[a]

Classifications	Total Explosions	Explosions with Injury or Fatality	No. Killed	No. Injured	No. Explosions with Reported Losses	Amount of Losses, dollars
Grain elevators	150	59	115	281	138	24 531 218
Woodworking plants	100	42	30	132	73	2 713 613
Feed and cereal mills	90	37	63	222	79	7 351 510
Flour mills	87	25	28	46	62	4 548 300
Starch and corn products	38	18	128	130	32	5 384 826
Cork dust	37	7	6	28	34	181 190
Pulverized coal	26	14	21	26	24	92 359
Sugar refineries	25	4	12	31	14	1 622 300
Fertilizer plants	26	5	7	20	14	852 450
Malt houses	23	2	2	18	18	747 500
Metal dusts	36	21	49	76	32	1 684 165
Sulfur dusts	23	7	2	39	15	80 095
Bark dust	14	1	0	2	13	587 600
Coffee and spice dusts	11	2	5	13	9	201 700
Cotton mills	13	4	2	4	8	78 950
Paper dust	7	0	0	0	7	395 000
Phonograph record dust	6	1	0	1	5	36 400
Pitch and resin dust	15	7	14	57	12	2 098 472
Rubber dust	7	3	11	2	6	30 300
Miscellaneous	46	20	24	78	38	2 510 992
Totals	780	279	519	1206	633	55 728 940

[a] Ref. *22*.

1957, NFPA published details of dust explosions in the United States and Canada since 1860 [*23*]. In the U.S. agriculture and agricultural products industry there were 510 incidents resulting in 390 deaths and 997 injuries (see Table 2). This gives an annual average of 5.25 incidents, 4.0 deaths, and 10.2 injuries. In Canada the data date from 1916 so a period of 41 years must be used to normalize the data. During this period there were 31 incidents with 72 deaths and 93 injuries resulting from agricultural dust explosions. This gives an annual rate of 0.75 incidents, 1.7 deaths, and 2.26 injuries. Again each incident produces multiple deaths and injuries. However, the annual rate is smaller than in the United States.

For the above mentioned databases, data pertaining only to grain elevators are also reported, and the results are as follows. From 1898 to 1921 Price and Brown list 34 incidents, 67 deaths, and 60 injuries giving yearly averages of 1.4 incidents, 2.8 deaths, and 2.5 injuries. For 1898 to 1942 NFPA gives 150 incidents, 115 deaths, and 281 injuries giving yearly averages of 3.26 incidents, 2.5 deaths, and 6.1 injuries. For the broader base of 1898 to 1956 in the United States, NFPA gives 203 incidents, 134 deaths, and 427 injuries for a yearly average of 3.5 incidents, 2.3 deaths, and 7.36 injuries. In Canada for the period 1919 to 1956 there were 19 incidents, 47 deaths, and 73 injuries. The resulting annual average is 0.5 incidents, 1.23 deaths, and 1.92 injuries. Thus is can be recognized that there are fewer explosions and less human damage in the grain elevator industry than in the entire agricultural products industry.

Another effort to analyze the frequency of agricultural dust explosions was made in 1980 by the U.S. Department of Agriculture (USDA) [*24*], but the data are restricted to grain elevators, and this report relies heavily on the earlier extensive work of Verkade and Chiotti [*25*]. Data totals for the 21-year period beginning in 1958 are 250 incidents, 164 deaths, and 605 injuries (see Fig. 1). This gives annual averages of 11.9 incidents, 7.8 deaths, and 28.8 injuries. These figures are substantially higher than those given by any of the historical databases, and it has been argued

TABLE 2—*Record of dust explosions in the United States (to 31 Dec. 1956).*[a]

Classifications	Total Explosions	Explosions with Injury or Fatality	No. Killed	No. Injured	No. Explosions with Reported Losses	Amount of Losses, dollars
Bark dust	15	1	. . .	2	14	1 029 200
Coal dust	55	17	30	32	50	901 609
Pulverized						
Other	8	3	. . .	5	7	714 345
Coffee and spice dusts	12	2	5	13	9	201 700
Cork dust	40	8	6	29	37	196 290
Cotton dust	18	6	6	12	13	263 570
Feed and cereal dusts	134	52	69	305	115	11 365 572
Fertilizer dusts	28	6	7	21	16	873 450
Flour dust	106	35	33	90	82	8 449 595
Grain dust	203	80	134	427	188	41 993 107
Malt dust	26	2	2	18	21	1 811 150
Metal dusts	80	38	108	198	59	3 196 915
Miscellaneous dusts	52	25	26	92	43	2 844 220
Paper dust	9	. . .	. . .	. . .	8	470 000
Phonograph record dust	6	1	. . .	1	5	36 400
Pitch and resin dusts	5	4	12	47	5	2 055 300
Plastic dusts	35	10	19	71	28	1 071 332
Rubber dust	15	4	13	2	14	564 600
Seed and seed products dusts	11	4	9	6	10	2 363 300
Starch and corn products dusts	56	26	145	169	49	7 905 776
Sugar dust	29	6	12	33	18	1 728 950
Sulfur dust	33	7	2	39	23	103 745
Wood dust	147	54	38	158	118	10 379 141
Totals	1120	391	676	1770	932	100 585 267

[a] Ref *23*.

that it is biased by the data from the year 1977 in which an unusual amount of personal injury occurred. Also using this same database an attempt was made to identify the ignition sources of the dust explosion as well as the location of the primary explosion (see Tables 3 and 4). It is significant that the most probable ignition source and the most probable location for the primary explosion are unknown. Because so many of the details concerning the events leading up to a dust explosion in a grain elevator had not been accurately reported, it was decided that accident investigation should play an important role in any future studies of the problem.

Activities of the Panel on the Causes and Prevention of Grain Elevator and Mill Explosions

With the support of the U.S. Department of Labor and the U.S. Department of Agriculture, a panel was instituted in November 1978 to determine the "causes" of dust explosions in grain elevators and mills and what actions could be taken to prevent the occurrence of such explosions. To make the required detailed studies the ten-member panel and the eleven liaison members were further divided into subpanels—one of which was concerned with explosion investigation. The task defined for this group was to arrive at the scene of an explosion as rapidly as possible after its occurrence and attempt to determine the sequence of events which led up to it and to describe the events during it [*16*]. The actual incidents were chosen by the Occupational Safety and Health

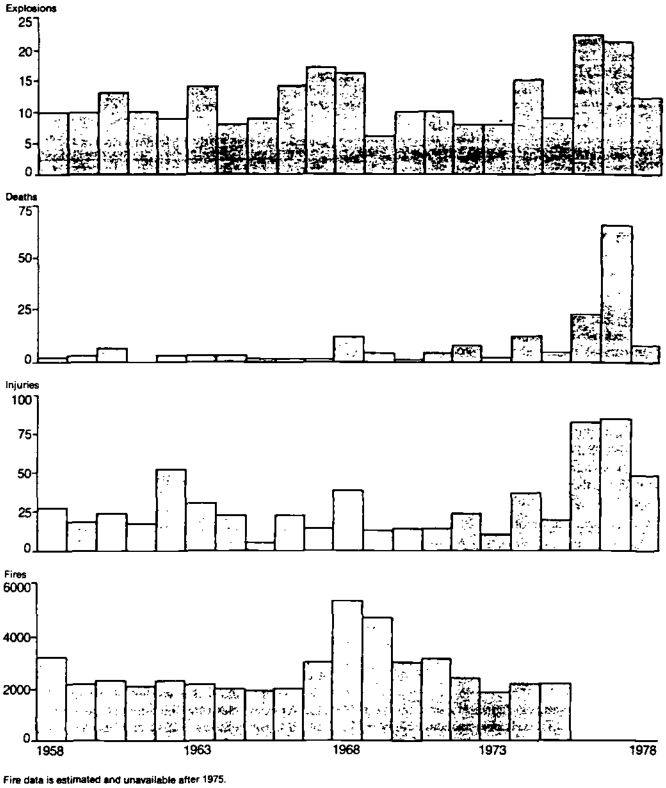


FIG. 1—*Explosions, deaths, injuries, and fires in grain-handling facilities in the last 21 years [24].*

Administration based upon deaths and injuries. During the tenure of the panel the explosion investigation subpanel visited the sites of fourteen grain elevator or mill explosions or both (see Table 5). After each event a summary of the findings was reported to the entire panel, and this no doubt had considerable influence on the two reports issued by the panel concerning the prevention of these dust explosions [*5*,*17*]. Detailed reports for all fourteen incidents were published [*18*,*26*]. These investigations showed that it is indeed possible to describe in detail the events leading up to and during the occurrence of a dust explosion in a grain handling facility. Such success requires only that a team of qualified investigators—personnel trained in explosions, grain elevator operation, operations analysis and human factors, and dust control—arrive at the site of an explosion within a few hours of its occurrence, and that they have free access to the remains and witnesses. In all fourteen of the explosions it was possible to identify the five components necessary to support a successful dust explosion—fuel, oxidizer, ignition, mixing, and confinement—with the exception of the ignition source at the Corpus Christi explosion where two different ones seemed equally likely. Table 5 gives for each case the location of the primary explosion, the ignition source, and other data. These results concerning the causes of such dust explosions are quite definite as compared to the large percentage of unknowns in USDA data.

It may be noted that both electrical and mechanical devices are important ignition sources, and in one case there was a chemical ignition source. Conspicuous by its absence is welding and cutting work, perhaps because this has been such a common ignition source in the past, and it is commonly considered to be a hazardous activity in grain handling facilities. The location of the

TABLE 3—*Probable ignition sources.*[a]

Ignition Source	No. of Facilities	Percentage of Facilities
Unknown	103	41.2
Welding or cutting	43	17.2
Electrical failure	10	4.0
Tramp metal	10	4.0
Fire other than welding or cutting	10	4.0
Unidentified foreign objects	9	3.6
Friction from choked leg	8	3.2
Overheated bearings	7	2.8
Unidentified spark	7	2.8
Friction sparks	7	2.8
Lightning	6	2.4
Extension cords caught in legs	4	1.6
Faulty motors	4	1.6
Static electricity	3	1.2
Fire from friction of slipping belt in let	3	1.2
Leaking flammable vapor	3	1.2
Smouldering grain or meal handled	2	0.8
Smoking material	2	0.8
Lighted firecracker	1	0.4
Volatile chemical escaped from soybean processing	1	0.4
Fire from cob pile outside facility	1	0.4
Heating system	1	0.4
Pocket of gas in bin ignited	1	0.4
Extinguishing fire	1	0.4
Leak in gas pipe ignited	1	0.4
Electric control panel exploded	1	0.4
Slipping conveyor belt	1	0.4
Sample size	250	100.0

[a] Ref *24*.

primary explosion was almost always in a tightly confined area, especially bucket elevators. But, the ignition of a confined propane leak in two cases acted as the primary explosion.

The occurrence of secondary explosions is also noted in Table 5. The secondary explosions, of course, result from the layers of dust that are widely distributed through a facility. These are the explosions of consequence in an actual scenario and that this is indeed the situation may be verified from the data in Table 6 where losses, fatalities, and injuries are segregated according to primary and secondary explosions. On the average, 85% of the deaths and 89% of the injuries resulted from these layered dust explosions. These data should make it quite clear that accumulations of layered dust which support the secondary explosions are extremely hazardous.

Recent Explosion History

After the publication of their survey document in 1980 [*24*], the USDA continued to keep track of agricultural dust explosions by information relayed to them by USDA employees, OSHA, newspapers, and trade publications. Table 7 lists incidents reported since 1979 through the first quarter of 1986 with the facility, location, date, and number of deaths and injuries given. In this 7¼-year period 154 incidents resulting in 49 deaths and 224 injuries are reported. On a yearly basis this amounts to 21.9 incidents, 6.75 deaths, and 30.89 injuries. The temporal distribution of these data may be seen in Figs. 2 through 4 which are simply a continuation of Fig. 1. Certainly 1976, 1977, and 1981 were not good years with regard to the results of dust explosions in grain

TABLE 4—*Probable location of primary explosion.*[a]

Location of Primary Explosion	No. of Facilities	Percentage of Facilities
Unknown	58	23.2
Bucket elevator	58	23.2
Hammer mills, roller mills, or other grinding equipment	17	6.8
Storage bins or tanks	13	5.2
Headhouse	9	3.6
Adjacent or attached feed mill	8	3.2
Basement	4	1.6
Processing equipment	3	1.2
Dust collector	3	1.2
Tunnel	2	0.8
Distributor heads	2	0.8
Passenger elevator or manlift shaft	2	0.8
Grain drier	2	0.8
Outside and adjacent to facility	2	0.8
Pellet collector	2	0.8
Conveyor system	2	0.8
Receiving pit	2	0.8
Other handling equipment	2	0.8
Processing plant	1	0.4
Down spout	1	0.4
Corn tester	1	0.4
Feed room	1	0.4
Sampler	1	0.4
Storage room	1	0.4
Boiler or feed mill	1	0.4
Electrical switch	1	0.4
Auger conveyor	1	0.4
Electric panel	1	0.4
Sample size	250	100.0

[a] Ref *24*.

handling facilities, although the maximum number of reported incidents occurred in 1980. The 3 years with the large number of personal injuries are years in which there were incidents at an export elevator. Note that 1983 seems to represent the year during which conditions were relatively safest. It is also perhaps appropriate to view the current trends with respect to the events of the comparatively recent past. In 1978 there was considerable dissemination of information [*14,15,27*] with regard to the dust explosion hazard in facilities handling agricultural products. In 1978 and 1979 the frequency of these events decreased. However, in 1980 and 1981 there was again an increase. In 1982 the National Academy of Sciences released the results of their study and in 1983 there was a decrease in incidents—and the first occurrence since 1961 of no deaths reported resulting from an agricultural dust explosion. However, in 1984, 1985 and the first quarter of 1986 this trend was reversed. Certainly during the summer of 1984, when the hearings on Proposed Rule Making by the U.S. Department of Labor were being held, there should have been a heightened awareness of this explosion problem.

After the two explosions of 7 April 1981, on-site investigations were no longer conducted by the National Academy of Sciences. In some situations, investigations were conducted by fire marshals or OSHA compliance officers, and their findings furnish some of the details relating to the accident. For others, only very sketchy information is available. Practically no details are known about the fatal explosions at Critic Mills, Bay State Milling, and Central Soya. A little

(Text continued page 255)

TABLE 5—*Elevator explosion data.*[a]

Elevator Location	Date	Time	Fatalities	Injuries	Estimated Loss, dollars[b]	Dust Cloud	Ignition Source	Secondary Explosion
Lexington, NE	1/23/79	9:00 a.m.	1 employee	1 employee	$ 110 000	bucket elevator	belt friction	yes
Abilene, KS	3/23/79	12:25 a.m.	none	1 employee	40 000	headhouse	fire, light fixture	yes
Montevideo, MN	9/14/79	9:15 a.m.	1 employee	2 employees 1 trucker	85 000	basement	belt friction	no
Morgan, MN	10/23/79	3:05 p.m.	none	1 employee	45 000	bucket elevator boot pit	fire, light fixture	yes
St. Joseph, MO	4/21/80	1:15 p.m.	1 employee	3 employees 1 inspector	2 000 000	grain shipping bin	electrical arc	yes
New Bern, NC	5/8/80	1:15 p.m.	1 trucker	1 employee	210,000	bucket elevator	belt friction	yes
Baltic, SD	5/28/80	10:40 a.m.	1 trucker 1 contractor	1 trucker 3 contractors	130 000	propane in basement	match	yes
St. Paul, MN	6/10/80	10:53 a.m.	none	4 employees 6 truckers 3 inspectors	270 000	basement tunnel	electrical arc	yes
Fonda, IA	7/15/80	3:30 p.m.	none	none	30 000	bucket elevator	fire, welding	no
Hendricks, MN	9/30/80	9:30 p.m.	1 employee 1 contractor 1 trucker's son	1 employee 2 truckers 1 contractor	210 000	propane in basement	water heater	yes
Omaha, NE	11/12/80	9:45 p.m.	none	none	1 480 000	headhouse	fire, unapproved space heater	yes
Beatrice, NE	2/27/81	9:00 a.m.	none	1 inspector 1 trucker	80 000	first floor hallway	electrical arc	yes
Corpus Christi, TX	4/7/81	3:10 p.m.	9	30	30 000 000	bucket elevator	friction at head pulley or smoldering grain	yes
Bellwood, NE	4/7/81	4:15 p.m.	1 employee 1 trucker	1 employee	2 500 000	bucket elevator	friction at head pulley	yes

[a] Ref 27.

[b] Property loss estimate does not include grain loss.

	Property Loss, dollars[b]			Fatalities			Injuries		
Location	Primary	Secondary	Total	Primary	Secondary	Total	Primary	Secondary	Total
Lexington, NE	30 000	80 000	110 000	none	1 employee	1 employee	none	1 employee	1 employee
Abilene, KS	20 000	20 000	40 000	none	none	none	none	1 employee	1 employee
Montevideo, MN	30 000	55 000	85 000	1 employee	none	1 employee	2 employees 1 trucker	none	2 employees 1 trucker
Morgan, MN	2 000	43 000	45 000	none	none	none	none	1 employee	1 employee
St. Joseph, MI	20 000	1 980 000	2 000 000	none	1 employee	1 employee	none	3 employees 1 inspector	3 employees 1 inspector
New Bern, NC	30 000	180 000	210 000	1 trucker	none	1 trucker	none	1 employee	1 employee
Baltic, SD	35 000	95 000	130 000	1 contractor	1 trucker	1 trucker 1 contractor	3 contractors	1 trucker	1 trucker 3 contractors
St. Paul, MN	30 000	240 000	270 000	none	none	none	none	4 employees 6 truckers 3 inspectors	4 employees 6 truckers 3 inspectors
Fonda, IA	30 000	none	30 000	none	none	none	none	none	none
Hendricks, MN	35 000	175 000	210 000	none	1 employee 1 contractor 1 trucker	1 employee 1 contractor 1 trucker	none	2 employees 2 contractors 3 truckers	2 employees 2 contractors 3 truckers
Omaha, NE	1 230 000	250 000	1 480 000	none	none	none	none	none	none
Beatrice, NE	30 000	150 000	180 000	none	none	none	1 inspector	1 trucker	1 inspector 1 trucker
Corpus Christi, TX	30 000	29 970 000	30 000 000	none[c]	9	9	none[c]	30	30
Bellwood, NE	30 000	2 470 000	2 500 000	none	1 trucker 1 employee	1 trucker 1 employee	none	1 employee	1 employee
Total	1 582 000	35 710 000	37 290 000	3	17	20	7	58	65

[a] Ref *26*.

[b] Property loss estimate does not include grain loss.

[c] See Ref *26* for details.

TABLE 7—*Explosion incidents 1979–1986.*

Date	Facility	Location	Injuries	Fatalities
1/23/79	Lexington Mill & Elevator	Lexington, NE	1	1
1/25/79	Farmers Marketing Assn.	Denver, CO	0	0
3/23/79	Farmers Grain Exchange	Abilene, KS	1	0
3/30/79	The Ralston Purina Co.	Richmond, IN	1	0
4/10/79	ADM	N. Kansas City, MO	6	0
5/3/79	Good Seed & Grain Co.	Hamburg, IA	1	0
7/7/79	Riley Co.	Irena, SD	0	0
7/17/79	Nashua Equity Coop.	Nashua, IA	1	0
7/18/79	National Feed Co.	Spokane, WA	0	0
8/21/79	Brock Grain Co. d/b/a Tangeman Grain Co.	Talmage, NE	0	0
9/14/79	Pillsbury Company	Montevideo, MN	3	1
9/27/79	Hiawatha Grain Co.	Minneapolis, MN	1	0
10/10/79	Kasbeer Farmers Elevator Company Coop.	Kasbeer, IL	0	0
10/14/79	Cargill, Inc.	Grinnell, IA	0	0
10/23/79	Morgan Elevator Co.	Morgan, MN	2	0
10/29/79	Cargill, Inc.	Grinnell, IA	1	0
11/18/79	Lamberton Wabasso Farmers Elevator	Lamberton, MN	0	0
12/15/79	United Seed Co.	Ralston, NE	0	0
12/17/79	Missouri Farmers Assn.	Mexico, MO	0	0
Totals		19	18	2
1/5/80	Farmers Elevator Co.	Minneapolis, KS	1	0
1/10/80	Schwab Grain Co., Inc.	La Crosse, KS	0	0
1/18/80	Nutrena Feed Mill	Grand Island, NE	0	0
1/22/80	New Washington Equity	New Washington, OH	3	0
1/24/80	Ntl. Starch/Chem. Corp.	Indianapolis, IN	0	0
2/1/80	Land O'Lakes Feedmill	Minneapolis, MN	9	2
2/8/80	ADM West Plant	Decatur, IL	0	0
2/28/80	Ocheyedan Coop Elev.	Ocheyedan, IA	0	0
2/28/80	Peavy Co. Elevator	E. Grand Forks, MN	0	0
3/5/80	Goodpasture Export	Galena Park, TX	0	0
3/18/80	Shawnee Milling Co.	Shawnee, OK	0	0
4/21/80	Pillsbury Co. Elevator	St. Joseph, MO	0	1
4/22/80	Missouri Farmers Assn.	Mexico, MO	0	0
5/5/80	Sully Coop Exchange	Sully, IA	3	0
5/8/80	New Bern Oil/Fertil. Co.	New Bern, NC	0	1
5/9/80	Choska Alfalfa Co.	Haskell, OK	2	0
5/9/80	Princeton Grain Co.	Princeton, NE	0	0
5/10/80	NPC, Incorporated	Eden, NC	0	0
5/28/80	Baltic Farmers Coop	Baltic, SD	3	2
5/29/80	Rocky Ford Land Co.	Rocky Ford, CO	0	0
6/10/80	Farmers Union Gr. Term.	St. Paul, MN	13	0
7/1/80	Huisings Grain, Inc.	Casey, IL	0	1
7/2/80	Ralston Purina	Wichita, KS	2	0
7/8/80	McNabb Grain Co.	McNabb, IL	0	0
7/8/80	Farmers Grain Co.	Green Valley, IL	0	0
7/15/80	Cargill, Inc.	Fonda, IA	0	0
7/15/80	Pillsbury, Inc.	Madisonville, KY	1	0
7/21/80	Packer River Terminal	S. St. Paul, MN	2	0
7/22/80	Anheuser-Busch	Jacksonville, FL	0	0
8/18/80	Murphy Products	Longview, TX	0	0
8/21/80	Missouri Valley Grain	Marshall, MO	0	0
8/30/80	Egg Belt, Inc.	Des Moines, IA	0	0
9/2/80	Ohio Farmers Grain Co.	Fostoria, OH	0	0

TABLE 7—*Explosion incidents 1979–1986 (continued).*

Date	Facility	Location	Injuries	Fatalities
9/5/80	Mississippi River Grain	Gulf Port, IL	0	0
9/30/80	Farmers Elevator Co.	Hendrick, MN	1	3
9/30/80	Hartland Elevator	Hartland, MN	1	0
10/4/80	Fairleigh Feedyards	Scott City, KS	0	0
10/6/80	Kinnie, Ltd.	Holyoke, CO	1	0
10/12/80	Naples Terminal	Naples, IL	0	0
10/21/80	Cassen Mills	Signourney, IA	0	0
10/27/80	Victoria Elevator Co.	Minneapolis/St. Paul, MN	0	0
11/12/80	Naples Terminal Elev.	Naples, IL	0	0
12/11/80	Consolidated Coop	Brewster, MN	0	0
12/17/80	Allied Feed Mills	Fort Worth, TX	0	0
12/18/80	Lincoln Grain, Inc.	Atchison, KS	0	0
Totals		45	42	10
1/3/81	Gibson Co. Farm Bureau	Princeton, IN	1	0
2/4/81	Peavey Company	Alton, IL	1	0
2/27/81	Southeast Nebraska Coop	Beatrice, NE	3	0
3/19/81	S. Soo Grain Co.	S. Sioux City, NE	0	0
4/7/81	Goldkist Feed Mill	Valdosta, GA	0	0
4/7/81	Conagra, Inc.	Amboy, IN	0	0
4/7/81	Bellwood Farmers Coop	Bellwood, NE	1	2
4/7/81	Corpus Christi Public	Corpus Christi, TX	30	9
4/15/81	Beverly Elevator Co.	Beverly, NE	0	0
4/15/81	Pillsbury Company	Roberts, IL	0	0
4/30/81	Bob Gottsch Feed Yard	Elkhorn, NE	3	0
5/21/81	Inola Elevator	Inola, OK	5	0
8/17/81	Perma Delta Rice Mill	Greenville, MS	1	0
8/21/81	Pendleton Grain Grower	Pendleton, OR	1	0
9/4/81	Louisberg Grain & Feed	Sterling, CO	5	0
9/9/81	LaPorte Coop Elevator	LaPorte City, IA	1	0
9/24/81	Mid America Commodities	Farmer City, IL	2	0
9/24/81	Madison Farmers Elev.	Madison, SD	4	0
10/6/81	Garnac Elevator	San Diego, CA	0	0
10/8/81	Gold Proof Elevator	Louisville, KY	1	0
11/6/81	Del-Mar Industries, Inc.	Longview, TX	3	2
Totals		21	62	13
1/5/82	MFA	Caruthersville, MO	0	0
2/4/82	Producers Grain	Corpus Christi, TX	0	0
3/9/82	Riceland Food, Inc.	Helen, AR	0	0
3/10/82	Continental Grain	Reserve, LA	0	0
3/14/82	Feeders Grain Storage	Tarkio, MO	0	0
4/1/82	Critic Mills	Bealstown, IL	2	1
4/8/82	Southern State Feedmill	Winchester, KY	2	0
4/20/82	Agri Industries	Council Bluffs, IA	24	5
5/25/82	Central Soya	Henderson, KY	0	0
6/9/82	Farmers Coop	Newman Grove, NE	0	0
7/12/82	Farmers Export	Philadelphia, PA	4	0
10/8/82	Henkel, Inc.	Keokik, IA	0	0
11/16/82	Raymond Coop Grain Elev.	Raymond, NE	2	5
11/22/82	Young Grain Co.	Newburg, IN	0	0
Totals		14	34	11
1/8/83	Parr Grain Co.	Parr, IN	1	0
1/13/83	Indian Head Grain	Lubbock, TX	1	0
3/9/83	Lyford Gin Assn.	Lyford, TX	3	0
4/18/83	Hutton Grain Co. Elev.	Vincennes, IN	1	0
4/28/83	Franklin Grain Elev.	Franklin, IL	1	0
5/26/83	Tenco	O'Kean, AR	1	0

TABLE 7—*Explosion incidents 1979–1986 (continued).*

Date	Facility	Location	Injuries	Fatalities
7/7/83	Cooksville Grain Co.	Cooksville, IL	1	0
8/29/83	Ralston Purina Feedmill	Shrevesport, LA	1	0
9/1/83	Underwood Farms	Fullerton, NE	0	0
11/2/83	Poitz, Inc.	Yuma, CO	0	0
11/28/83	Prairie Grain, Inc.	East Bernard, TX	0	0
12/1/83	Rivards Quality Seeds	Argyle, MN	2	0
12/28/83	Darwin Coop Elevator	Darwin, MN	2	0
Totals		13	14	0
1/20/84	Lubbock Feed Lots Mill	Lubbock, TX	1	0
2/4/84	Epstein-Harris Feed Yard	Fort Morgan, CO	1	0
2/12/84	Norman-Heartwell Grain	Norman, NE	0	0
2/20/84	Owensboro Grain Co.	Owensboro, KY	1	0
2/25/84	Castlewood Farmers Elev.	Castlewood, SD	1	0
3/14/84	Chester Farmers Grain	Chester, NE	0	0
3/15/84	Monroe Grain Co.	Monroe, NE	2	0
5/11/84	Lake Lillian Farmers Co.	Lake Lillian, MN	4	2
5/30/84	Blue Valley Coop	Tamora, NE	0	2
6/8/84	Archer Daniels Midland	Decatur, IL	3	1
6/26/84	Community Grain Co.	Galesville, IL	1	0
7/31/84	Juniata Farmers Coop	Juniata, NE	0	0
8/28/84	Pettibone Elevator	Pettibone, ND	0	0
9/16/84	St. Elmo Terminal Elev.	Paulina, LA	0	0
9/19/84	Con Agra, Inc.	Knoxville, TN	11	3
9/21/84	Indiana Grain	Logansport, IN	0	0
11/18/84	Bay State Milling	Clifton, NJ	2	1
12/4/84	St. Charles Elevator	Destrehan, LA	0	0
12/7/84	Haveman Grain Co., Inc.	Murray, NE	2	0
12/26/84	Southwest Grain Coop	Dickson, ND	0	0
Totals		20	29	9
1/2/85	Farmers Coop Business	Shelby, NE	2	0
1/17/85	Farmers Coop Grain Assn.	Stromsberg, NE	0	0
1/25/85	Bunge Corp.	Old Shawneetown, IL	0	0
2/6/85	Early & Daniel	Cincinnati, OH	0	0
2/18/85	Comstock Farmers Elev.	Comstock, MN	3	0
3/12/85	Farmers Coop Elevator	Muleshoe, TX	0	0
4/2/85	Davenport Grain Co.	Davenport, NE	2	0
5/3/85	Martin Grain, Inc.	Taylor Ridge, IL	0	0
5/15/85	Shickley Grain Co.	Shickley, NE	1	0
6/3/85	Galva Coop Grain & Supp.	Galva, IL	0	0
6/12/85	ADM	Clinton, IA	1	0
7/29/85	Agri Export Elevator	Galena Park, TX	0	0
8/7/85	Pillsbury	Browns, IL	1	0
10/15/85	Carroll Cty. Farm Bu.	Flora, IN	2	0
10/15/85	Buffalo Lake Farmers Co.	Buffalo Lake, MN	1	0
11/2/85	Farmers Coop Grain Assn.	Marion, SD	4	3
11/2/85	Mid-State Terminal	Ottawa Lake, MI	0	0
11/3/85	Halford Feedlot	Colby, KS	1	0
11/9/85	Central Soya	Baltimore, MD	1	1
11/27/85	Producers Rice Mill	Stuttgart, AR	1	0
11/29/85	Cargill	Dayton, OH	0	0
12/9/85	DeKalb Co. Farm Bureau	Waterloo, IN	0	0
12/31/85	Hubinger	Keokuk, IA	0	0
Totals		23	20	4
1/3/86	Snyder Elevator	Elizabeth Town, IN	0	0
1/6/86	Ralston Purina	Wichita, KS	4	0
1/10/86	Dudley Feed Lot	St. John, KS	0	0
2/19/86	Southeast Nebraska Coop	Beatrice, NE	1	1
2/25/86	Dudley Feed Lot	St. John, KS	0	0

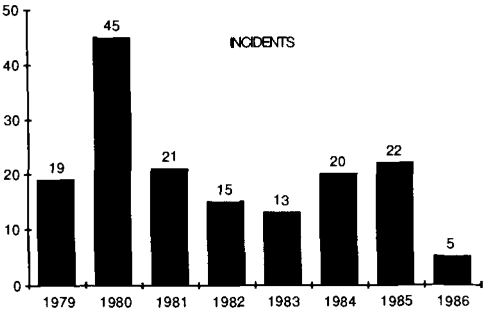


FIG. 2—*Dust explosion incidents in grain-handling facilities reported to USDA, 1979 to 1986.*

more information is known with regard to some of the other explosions involving fatalities. At Del-Mar Industries a new roof was being put on and hot work was being performed by an outside contractor. At Archer Daniels Midland, a choke had occurred early in the day and, as a result, a piece of burning belting was deposited in a baghouse of the dust control system which resulted in a fire and the subsequent explosion. For six additional fatal explosion cases considerably more detailed information is available.

At 4:30 p.m. Central Standard Time (CST) on 16 Nov. 1982, a grain elevator explosion occurred at the Raymond Co-op Grain Elevator, Raymond, Nebraska, killing five people, including three elevator employees and two customers, and injuring an employee and a customer. Additionally, the explosion caused $250 000 in property damage. The wooden elevator had a 428 000-bushel (15 082 = m^3) storage capacity and a general store. At the time of the explosion rail cars were being loaded, a truck had just dumped a load of milo, and grain-drying operations had just terminated. The propane supply for the grain dryer was located 100 ft (30.5 m) away across a driveway and a 1.25-in. (3.17-cm) buried plastic pipe was used to transport the propane. The buried depth of the pipe ranged from 18 in. (45 cm) to 3 ft (0.9 m). For several days preceding the explosion the odor of propane was reported by elevator workers. After the explosion the pipe was found to be cracked. Walls for the dump pit and the office basement were located near the propane line. The leaking propane apparently migrated along the pipe and into the basement where an operating oil furnace was located. One witness reported that the explosion appeared to go from the ground up. Layered dust accumulation then apparently supported secondary explosions after the occurrence of the primary propane explosion. A similar scenario was seen twice during the

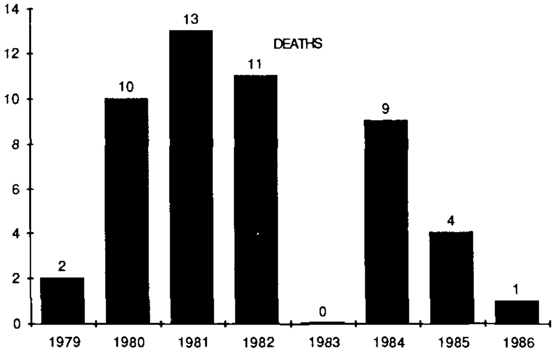


FIG. 3—*Dust explosion deaths in grain-handling facilities reported to USDA, 1979 to 1986.*

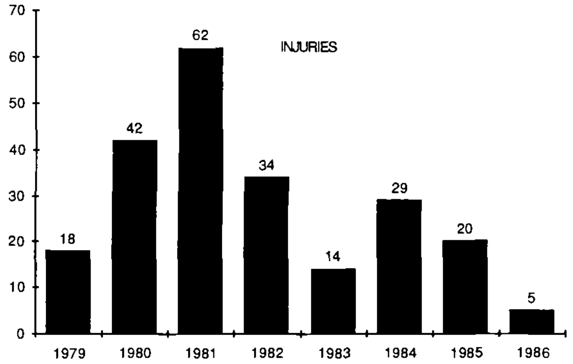


FIG. 4—*Dust explosion injuries in grain-handling facilities reported to USDA, 1979 to 1986.*

National Academy of Sciences investigations. The National Grain and Feed Association had issued a special warning pamphlet concerning the special hazards of propane usage and possible synergistic consequences.

At 1:25 p.m. Central Daylight Time (CDT) on 30 May 1984, an explosion occurred at the Blue Valley Co-op, Tomara, Nebraska, which resulted in the deaths of two workers and did $250 000 in property damage to the facility which consisted of eight concrete silos of recent construction. At the time of the accident a grain truck was being unloaded. Earlier in the day at approximately 12:15 p.m., a fire had been discovered in the waste products dropped from the top of the elevator by the screener, which was being used to clean grain. This fire was extinguished by elevator employees who were also fire department members using a department truck. Care was exercised to make sure that all of the fire had been dealt with in the refuse pile which was at ground level. Witnesses to the explosion reported that fireballs were seen both at the top of the elevator in the vicinity of the three bucket elevators and at the truck dump area on the ground level. Extensive damage occurred in the basement area due to the explosion of the number two bucket elevator. Investigators found a severely overheated and partially destroyed bearing in the head pulley of bucket elevator number two which had spewed burning grease and hot metal into the product stream. Evidence of a fire was also found in the screener whose discharge had previously supported a fire. Because of the positive pressurization system in the basement of the elevator and a recent cleaning, there apparently was little layered dust and no subsequent secondary explosions. The venting of the explosion of the bucket elevators onto the work floor area did most of the damage. As recognized previously, bucket elevators are a likely location for primary explosions and bearings may be an ignition source.

On 2 Nov. 1985 at 6:10 p.m. CST, during harvest season unloading of corn, an explosion occurred at the Marion Farmers Co-op Association elevator in Marion, South Dakota, killing two elevator employees and one farmer while injuring four others. The 275 000-bushel (9 691-m^3) elevator was of concrete construction and built in 1978. The explosion was the result of the failure of a chain drag conveyor, which had jammed and caused the drive motor to overheat, starting a fire. The elevator was reported to be heavily layered with dust which supported the fire and the subsequent secondary explosion. The basement explosion then propagated into one of the concrete silos which was split open. As had been previously noted in the National Academy of Science investigations it is possible for a primary explosion to occur outside of the product-handling stream.

The Bluffs Elevator Company, located in Council Bluffs, Iowa, exploded at 2:10 p.m. CST on 20 April 1982, killing 5 employees and injuring 24, including numerous Union Pacific Railroad

FIG. 5—*Council Bluffs, IA—Explosion.*

employees who were working outside of the elevator. The major portion of the facility was of old wooden construction with a capacity of 1.2 million bushels (42 286.8 m^3). This portion contained 6 bucket elevators and the remainder of the operating equipment. Surrounding this structure were 7 concrete silos constructed in 1979 with a storage capacity of 1.0 million bushels (35 239 m^3). At the time of the explosion trucks were being unloaded and railcars were being loaded. Preceding the accident a new conveying system had been installed for the truck dump, significantly increasing the capability for unloading. The bucket elevators were vintage equipment and reported to be in a state of poor repair. The storage bins were of the open top design allowing the escape of copious quantities of dust. Immediately preceding the explosion an effort was being made to start another bucket elevator and difficulty was being experienced. A witness saw smoke coming from the headhouse. An explosion followed which was reported to have been seen first in the lower levels. The air blast produced was significant, doing structural damage up to approximately 1 mile (1.6 km) distance. A photograph immediately after the passage of the shock wave at approximately ½ mile (0.8 km) distance was made (Fig. 5). Close examination shows many large masses of debris still airborne. Figure 6 shows the intense ensuing fire from a smaller distance. Because of the complete destruction of the rubble and the death of pertinent witnesses, data concerning the ignition source and the primary explosion are circumstantial. It is highly likely that a choke had developed in the bucket elevator, and that it was being jogged in order to start it. This subsequently led to a burn-through of the belt and its droppage. The primary explosion subsequently vented out into the dusty basement, and the secondary explosions then propagated upward through the facility. An unusual result of this explosion was an ensuing court case in which a jury awarded damages amounting to $2.6 million for the wrongful death of 2 employees [*28*].

In Lake Lillian, Minnesota, on 11 May 1984, the Lake Lillian Farmer's Elevator Company grain elevator and feed mill suffered an explosion at 11:10 a.m. which resulted in two deaths, an employee and a farmer, and four injuries, two employees, a trucker, and a farmer. The concrete

FIG. 6—*Council Bluffs, IA—Fire.*

elevator and mill were constructed in 1951 and had an internal storage capacity of 150 000 bushels (5 286 m^3) with an additional 280 000 bushels (9 867 m^3) in exterior bins. The physical damage to the facility amounted to less than $100 000. Immediately preceding the accident, corn was being ground in the feed mill portion of the facility using a mill which consisted of two rotating steel disks. Witnesses reported that the mill began to run rough, and that an explosion was seen coming out of the product handling system as well as the basement area onto the mill work floor. The explosion then propagated through the product handling system into the upper level of the mill where a secondary explosion occurred and vented with little structural damage through the large window area. It further propagated via spouting to the headhouse of the main elevator complex where yet another secondary explosion occurred which again vented with minimal property damage through the large window area. Figure 7 shows the minimal structural damage to the mill and elevator buildings. Upon disassembly a structural failure was seen to have occurred in one of the steel disks in the corn mill. A peripheral portion of the disk, of perhaps 2 $in.^2$ (13 cm^2) in area, had come loose (see Fig. 8). It passed through the mill itself no doubt introducing copious quantities of sparks and hot metal into the discharging product stream which was passing into a small bucket elevator. As shown in Fig. 9 there was sufficient layered dust present to support secondary explosions.

Beginning at approximately 11:40 a.m. on 19 Sept. 1984, an explosion and subsequent fire did significant damage to the ConAgra feed manufacturing facility in Knoxville, Tennessee, and caused the deaths of three employees and eleven injuries. The mill and warehouse portion of the facility were of late nineteenth century brick and timber construction and the elevator portion was a concrete structure erected in 1920. At the time of the incident feed was being manufactured in the mill and stored in the warehouse. In the elevator corn was being ground using a rotating steel disk mill on the work floor and then classified using a screener located in the headhouse. The explosion initiated in the elevator structure itself and secondary explosions in the elevator basement and

FIG. 7—*Lake Lillian, MN—Elevator structure.*

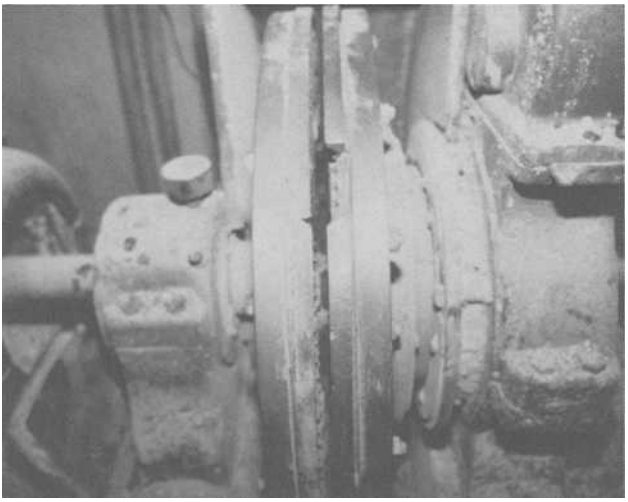


FIG. 8—*Lake Lillian, MN—Ignition source.*

FIG. 9—*Lake Lillian, MN—Layered dust on floor.*

work floor areas and in the headhouse propelled ignition sources into the adjoining mill and warehouse buildings. The headhouse was totally destroyed by the secondary explosion (see Figs. 10 and 11). These explosions were fueled by layered dust such as that shown on the work floor and on equipment in Figs. 12 and 13. While the product handling system clearly showed the effects of a primary explosion, the ignition source could not be clearly identified. Two items which had been previously identified as ignition sources in other incidents—a corn cracker (Lake Lillian, MN) and a classifier (Peachtree City, GA, plastic resins plant)—were present in this system. The fatalities in this case were a direct result of the missiles produced by the fragmentation of the headhouse during its secondary explosion. This results from inadequate venting of the confining

FIG. 10—*Knoxville, TN—Original structure.*

FIG. 11—*Knoxville, TN—Damaged structure.*

structure. The volume of this headhouse was 1396 m^3, and the window area was 31.2 m^2. Using standard NFPA venting data [*29*], treating the building as a vessel, and using available data for the failure of glass, p (static activation), and the failure of concrete, p (reduced explosion), a minimum required venting area of 40 m^2 is calculated which exceeds by approximately 30% the amount available. Structural failure would have appeared to have been inevitable.

These results may be contrasted with a headhouse explosion in which successful venting

FIG. 12—*Knoxville, TN—Layered dust on floor.*

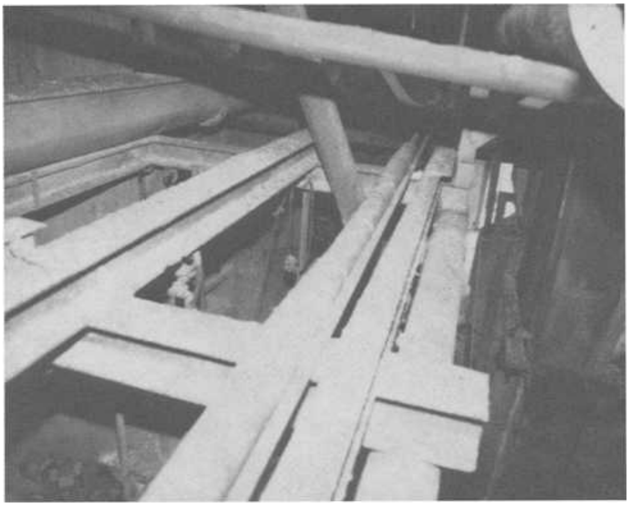


FIG. 13—*Knoxville, TN—Layered dust on equipment.*

occurred. Such was the case at the St. Joseph, Missouri, Pillsbury Co. elevator explosion of April 1980 reported on elsewhere [*26*]. Here the volume was calculated as 3429 m^3, and the window area was 294 m^2. Using the same assumptions as above, the required venting area is 80 m^2, which is much less than that available. As might be expected, the only damage done to the Pillsbury headhouse structure was to the windows and large roll-up doors. There were no concrete fragments producted by failure of the concrete structure.

Based upon the reports available, the recent incidents show considerable commonality with the fourteen incidents that were investigated in great detail by the National Academy of Sciences. A successful agricultural dust explosion still requires the presence of each component from the well known dust explosion pentagon—fuel, oxidizer, ignition, mixing, and confinement.

It is perhaps worthwhile to note that on 19 Feb. 1986, an explosion occurred at the Southeast Nebraska Co-op, Beatrice, Nebraska, killing one employee and injuring another. One of the fourteen explosions investigated by the National Academy of Sciences occurred at the same facility on 27 Feb. 1981, and injured three employees. At that time, members of the investigating subpanel noted layered accumulations of dust with depths up to several feet. This same elevator had also exploded in August 1962, injuring five. In fact, since 1958, twenty-seven elevators have been involved in repeat explosions, with the Archer Daniels Midland elevator in Decatur, Illinois, experiencing six.

Conclusions

The physical conditions required to produce an agricultural dust explosion are well understood. These conditions exist in many facilities handling agricultural commodities and products. Accident investigations conducted show the presence of these conditions, the sequence of events leading up to the accident, and the propagation path of the combustion process during the explosion. Additionally, they have shown that it is the secondary explosion resulting from layered dust that causes the significant damage. When the accident statistics are summarized as in Table 8 it may be noted that an understanding of the physical requirement for such explosions has not decreased their frequency of occurrence or their consequences. It may be that the combination of litigation

TABLE 8—*Summary of average annual accident statistics.*

Source	Incidents	Deaths	Injuries
Price & Brown			
Agriculture	1.8	3.4	4.6
Elevators	1.4	2.8	2.5
NFPA 1943			
Agriculture	8.1	7.4	15.1
Elevators	3.26	2.5	6.1
NFPA 1957			
Agriculture USA	5.25	4.0	10.2
Elevators USA	3.5	2.3	7.36
Agriculture Canada	0.75	1.7	2.26
Elevators Canada	0.5	1.23	1.92
USDA 1980			
Elevators	11.9	7.8	28.8
USDA 1986			
Elevators	21.9	6.75	30.89

awards and settlements, insurance costs, and federal regulations will prove to be effective in the termination of these agricultural dust explosions.

Acknowledgments

This work was supported by the Department of Health and Human Services, National Institute of Occupational Safety and Health under Grant OH01122-06. The author would like to express his sincere appreciation to Ralph P. Regan of the U.S. Department of Agriculture and to Thomas H. Seymour of the U.S. Department of Labor for the valuable information which they have furnished. Robert W. Wesley of the University of Michigan also contributed with regard to the venting calculations.

References

[*1*] Morozzo, C., "Account of a Violent Explosion Which Happened in a Flour Warehouse at Turin, December the 14th, 1785 to Which are Added Some Observations on Spontaneous Inflammations," *Repertory of Arts and Manufacturers*, Vol. 2, 1795, pp. 416–433.

[*2*] USDA Grain Storage, Handling, and Processing Safety Coordinating Subcommittee Annual Report, Fiscal Year 1985, U.S. Department of Agriculture, Office of the Secretary, Jan. 1985.

[*3*] Price, D. J. and Brown, H. H., *Dust Explosions—Theory and Nature of, Phenomena, Causes and Methods of Prevention*, National Fire Protection Association, 1923.

[*4*] Kauffman, C. W., "Agricultural Dust Explosions in Grain Handling Facilities" in *Fuel-Air Explosions*, SM Study No. 16, University of Waterloo Press, Waterloo, Ontario, 1982, pp. 305–348.

[*5*] "Prevention of Grain Elevator and Mill Explosions," Panel on Causes and Prevention of Grain Elevator Explosions, National Materials Advisory Board, National Academy of Sciences, NMAB 367-2, 1982.

[*6*] Tezok, F., Kauffman, C. W., Sichel, M., and Nicholls, J. A., "Turbulent Burning Velocity Measurements for Dust/Air Mixtures in a Constant Volume Spherical Bomb," presented at the 10th International Colloquium on Dynamics of Explosions and Reactive Systems, University of California, Berkeley, CA, Aug. 1985.

[*7*] Srinath, S. R., Kauffman, C. W., Nicholls, J. A., and Sichel, M., "Flame Propagation Due to Layered Combustible Dusts," presented at the 10th International Colloquium on Dynamics of Explosions and Reactive Systems, University of California, Berkeley, CA, Aug. 1985.

[*8*] Spratten, H. J., "List of Publications Issued by the U.S. Bureau of Mines—July 1, 1910 to January 1,

1960 with Subject and Author Index," U.S. Bureau of Mines Special Publication, U.S. Government Printing Office, 1960.

[9] Palmer, K. N., *Dust Explosions and Fires*, Chapman and Hall Ltd., London, 1973.

[*10*] Bartknetcht, W., *Explosions, Course Prevention Protection*, Springer-Verlag, Berlin, Heidelberg, New York, 1981.

[*11*] Field, P., *Dust Explosions*, Vol. 4: "Handbook of Powder Technology," Elsevier Scientific Publishing Company, New York, 1982.

[*12*] Cross, J. and Farrer, D., *Dust Explosions*, Plenum Press, New York, 1982.

[*13*] Nagy, J. and Verakis, H. C., *Development and Control of Dust Explosions*, Marcel Dekker, New York, 1983.

[*14*] Bingham, E., "Grain Elevator Industry Hazard Alert," Occupational Safety and Health Administration, 5 Jan. 1978.

[*15*] *International Symposium on Grain Elevator Explosions*, Vols. 1 and 2, National Materials Advisory Board, National Academy of Sciences, NMAB 352-1,2, 1978.

[*16*] "The Investigation of Grain Elevator Explosions," Panel on Causes and Prevention of Grain Elevator Explosions, National Materials Advisory Board, National Academy of Sciences, NMAB 367-1, Sept. 1980.

[*17*] "Pneumatic Dust Control in Grain Elevators—Guidelines for Design Operation and Maintenance," Panel on Causes and Prevention of Grain Elevator Explosions, National Materials Advisory Board, National Academy of Sciences, NMAB 367-3, 1982.

[*18*] "Guidelines for the Investigation of Grain Dust Explosions," Panel on Causes and Prevention of Grain Elevator Explosions, National Materials Advisory Board, National Academy of Sciences, NMAB 367-4, 1983.

[*19*] "Occupational Safety in Grain Elevators and Feed Mills," U.S. Department of Health and Human Services, National Institute of Occupational Safety and Health, Publication No. 83-126, Sept. 1983.

[*20*] McAteer, J. D., *Miner's Manual*, Center for Law and Social Policy, Washington, DC, undated.

[*21*] "Grain Handling Facilities; Safety Hazards; Proposed Rulemaking," U.S. Department of Labor, Occupational Safety and Health Administration, 29CFR Parts 1910 and 1917, Federal Register, 6 Jan. 1984.

[*22*] "National Fire Codes for the Prevention of Dust Explosions," National Fire Protection Association, 1943.

[*23*] "Report of Important Dust Explosions," National Fire Protection Association, 1957.

[*24*] "Prevention of Dust Explosions in Grain Elevators—An Achievable Goal," A Task Force Report, U.S. Department of Agriculture, 1980.

[*25*] Verkade, M. and Chiotti, P., *Literature Survey of Dust Explosions in Grain Handling Facilities: Causes and Prevention*, Iowa State University, 1976.

[*26*] Kauffman, C. W. and Hubbard, R. F., "An Investigation of Fourteen Grain Elevator Explosions Occurring between January 1979 and April 1981," Directorate of Safety Standards Program, Occupational Safety and Health Administration, May 1984.

[*27*] "Grain Industry Guidelines to Increase Fire and Explosion Safety," National Grain and Feed Association, 5 Jan. 1978.

[*28*] "Grain Dust Explosion: Inadequate Dust Control: Failure to Provide Ignition Prevention Equipment: Wrongful Deaths: Punitive Damages," *Law Reporter*, Oct. 1985, p. 305.

[*29*] "Guide for Explosion Venting," NFPA No. 68, National Fire Protection Association, 1978.

Rolf K. Eckhoff[1]

A Differentiated Approach to Sizing of Dust Explosion Vents: Influence of Ignition Source Location with Particular Reference to Large, Slender Silos

---

REFERENCE: Eckhoff, R. K., "**A Differentiated Approach to Sizing of Dust Explosion Vents: Influence of Ignition Source Location with Particular Reference to Large, Slender Silos,**" *Industrial Dust Explosions, ASTM STP 958,* Kenneth L. Cashdollar and Martin Hertzberg, Eds., American Society for Testing and Materials, Philadelphia, 1987, pp. 265–280.

ABSTRACT: The rate of heat generation during combustion of a dust cloud in a vented industrial enclosure is influenced by several factors, including some that are entirely dependent on the actual industrial process. The key role played by the location of the ignition source in relation to the vent opening is emphasized. Recent experiments in a top-vented 236-m^3 silo of length/diameter (L/D) = 6 revealed that the maximum explosion pressure increased by almost two orders of magnitude, with ignition at the silo bottom as opposed to at the top. The need for a new differentiated approach to dust explosion vent sizing is emphasized. In future, simple, general nomographs and formulas will have to be replaced by methods tailoring the vent to suit each specific application within an overall context of risk assessment. The lack of correlation between explosion violence predicted by existing closed bomb tests, and explosion violence in realistic full-scale experiments also calls for a differentiated approach to the violence testing problem.

KEY WORDS: dust explosions, explosion violence, explosion venting, explosibility tests, ignition sources, dimensioning, risk assessment

Background

Various precautions can be taken to reduce dust explosion hazards in industry. The importance of eliminating potential ignition sources has been stressed frequently, and this of course still remains a major issue. However, it is normally considered that trying to eliminate ignition sources alone does not provide sufficient protection. In addition, in case an explosion should nevertheless be initiated, it is necessary to ensure that destructive effects are minimized.

Because of its favorable features both technically and economically, *venting* has become a widely used means of obtaining this additional protection. Nevertheless, the conclusion drawn by Palmer [*1*] more than ten years ago still seems to have considerable validity: "The technical literature on venting of dust explosions is chaotic in that it is inadequate, fragmentary and to some extent contradictory." However, although the status is still confusing, signs of a slowly developing clarification are detectable. A useful updated summary of existing knowledge has recently been produced by Schofield [*2*]. The most important step forward is the growing understanding of the need for a more differentiated approach to dust explosion vent sizing. It is necessary to account for all the variables that will have a significant influence on the violence of a dust explosion in any specific situation [*3*].

---

[1] Chief scientist, Chr. Michelsen Institute, Fantoftvegen, 38, N-5036 Fantoft, Bergen, Norway.

Nature of the Vented Dust Explosion

The maximum overpressure P_{max} in a vented enclosure, in which a dust explosion takes place, will always be the net result of two simultaneous, competing processes:

- burning of the dust, causing release of heat and thus pressure increase, and
- flow of the unburnt and burning dust cloud and combustion products through the vent opening, causing the pressure to decrease.

If we consider a given enclosure provided with a given vent, the influence on P_{max} of the burning rate of the dust will be as indicated schematically in Fig. 1.

Clearly, being able to quantify the rate of heat release that will actually occur in a specific situation is the key issue. However, predicting this quantity from theory is an extremely demanding task, and a satisfactory theoretical model of the dust explosion venting process in practical industrial situations has not yet been developed. On the other hand, the main factors that influence the rate of heat release, are known:,

(1) chemical composition of dust, including moisture;

(2) chemical composition and initial pressure and temperature of the gas phase;

(3) distributions of particle sizes and shapes in the dust that determine the specific surface area of the dust in the fully dispersed state;

(4) degree of dust dispersion or agglomeration of dust particles that determine the effective specific surface available to the combustion process in the dust cloud in the actual industrial situation;

(5) distribution of dust concentration in the actual cloud;

(6) distribution of initial turbulence in the actual cloud;

(7) possibility of in situ generation of high turbulence levels by rapid flow of still unburnt dust cloud, induced by the expansion of the burnt part of the cloud; and

(8) possibility of flame front distortion by other mechanisms than turbulence, that is, by acoustic wave interactions.

Factors 1, 2, and 3 can be assessed accurately in laboratory tests provided that representative samples are available. However, Factors 5 to 8 are determined solely by the actual industrial dust

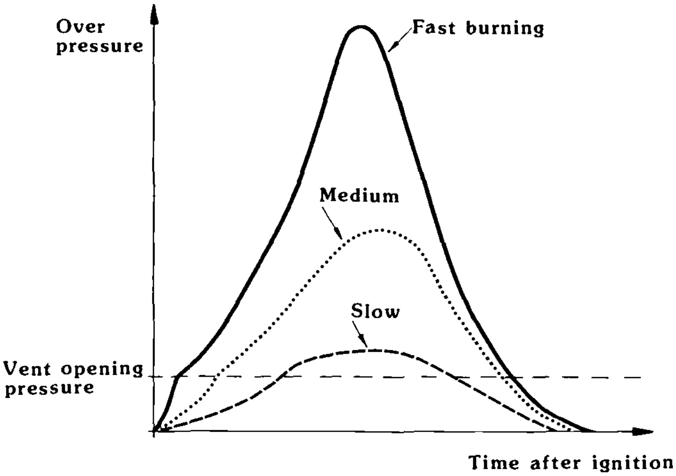


FIG. 1—*Illustration of the influence of the dust cloud burning rate on the maximum pressure generated in a dust explosion in a given enclosure provided with a given vent.*

cloud generation process and the geometry of the confinement. Factor 7 can be strongly influenced by the location of the ignition source, and this is a main concern of the present paper.

The so-called "cubic law," $K_{St} = (dP/dt)_{\max} \cdot V^{1/3}$ = constant, for explosions in closed vessels of various volumes, where P = explosion overpressure at time t and V = the vessel volume, is quoted quite frequently in technical literature on dust explosions. However, it is often overlooked that this law is only valid if *all* the Factors 1 to 8 are the same in the different volumes, and the flame thickness is small compared to the vessel size [*4*].

How Can Dust Clouds Be Generated and Ignited in Industrial Plants? Some General Considerations

Cloud Generation

The ways in which dust clouds are generated in industry depend on several factors. First there is an influence of the type of enclosure. Some typical ways in which dust clouds are generated in various categories of enclosure are:

- turbulent flow of dust in pipes for pneumatic transport and dust extraction;
- mechanical generation of turbulent clouds in mills and bucket elevators;
- pneumatically generated turbulent clouds in air jet mills, filter boxes, cyclones, storage silos, fluidized beds, and spray driers;
- dust layers on internal surfaces of various types of process equipment dispersed by mechanical shaking or blasts from preceding explosions in other plant units; and
- dust deposits on external surfaces of process equipment, beams, shelves, floors, and so forth blown into suspension in workrooms by the blast from a local "primary" explosion in a process unit ("secondary" explosions).

However, for any given specific category of enclosure, such as bucket elevators or cyclones, the dust cloud generation process will vary with the type of dust and other specific features of the industrial process. Furthermore, even for one specific process unit in a specific industrial plant processing a specific powder or dust, the dust cloud generation process will vary with time as a result of inevitable, and most often unpredictable, process variations. The implications of this for vent design are discussed later.

Ignition

The identification of likely ignition sources and their likely locations is the other main problem in assessing the violence of the explosion generated by a given dust cloud structure. The location of the ignition source can strongly influence the violence of a vented dust explosion as a result of variations in explosion induced flame instabilities and turbulence. Normally, the maximum explosion pressure in a vented explosion of a given dust cloud in a given enclosure will be lower if ignition occurs close to the vent opening than if the ignition point is far upstream of the vent. This difference is particularly marked in elongated structures, such as pipes, mine galleries, bucket elevators, and slim silos of length/diameter (L/D) > 5.

Realistic Large-Scale Experiments are Needed: Examples of Previous Work

Background

Attempts have been made in the past to develop theories for predicting sizes of dust explosion vents. However, in view of the vast complexity of the problem, in particular with respect to predicting real dust cloud structures and their combustion rates, it is not surprising that none of these attempts have proved successful in describing real industrial situations. For this reason, the only feasible approach at present seems to be full-scale experimentation using dust clouds generated in the same ways as clouds are generated in industry [*5,6*].

The need to work with realistic dust cloud generation mechanisms, when investigating dust explosion phenomena for design purposes, has long been appreciated in the coal mine explosion research. Experiments under conditions of realistic dust cloud generation have been conducted in large-scale mine galleries in many countries [*7*]. Generating the dust cloud in the way that would be operational in a real accidental explosion has been considered an important and inherent part of the problem.

Vented Dust Explosions in a Cyclone Plant Working Under Conditions of Realistic Dust Cloud Generation

This most significant and interesting investigation has been described by Palmer [*1*]. Further details are given by Tonkin and Berlemont [*8*]. The cyclone itself had a total volume of about 1.2 m^3, and was integrated in a closed loop dust circulation system, consisting of a fan for feeding air and dust through a 30-cm-diameter duct to the cyclone. Dust that accumulated in the bottom part of the cyclone was discharged continuously through a rotary lock into an intermediate hopper just below the cyclone, from which it was refed into the air stream that recirculated from the cyclone exhaust to its inlet. The annular top surface of the cyclone was provided with several sector shaped vents, and in addition, a circular vent was located just above the exhaust opening.

The dust/air suspension was normally ignited in the duct, about 1.5 m upstream of the cyclone inlet. This would imply that the ignition of the dust in the cyclone itself was accomplished by a fairly large flame jet entering through the inlet. It seems reasonable to consider this ignition mode as rather severe with respect to causing violent explosions, as compared to a point source within the cyclone itself. On the other hand, it may be argued that more violent explosions would have resulted in the cyclone experiments had ignition taken place further upstream in the dust feeding duct than at 1.5 m from the cyclone inlet.

Experiments were performed with cork dust, English flour, and a phenol-formaldehyde resin dust. The dust concentration in the inlet air stream to the cyclone was typically of the order of 300 g/m^3, which was the concentration that generally gave the highest pressures in the vented explosions. The air velocity in the duct was normally about 8 m/s.

The results of the cyclone experiments are given in Fig. 2. For vent areas of at least 0.06 m^2, the three dusts tested gave very similar explosion overpressures for a given vent area. This is interesting in view of the fact that $(dP/dt)_{max}$ measured in the Hartmann bomb was quite different for the three dusts, namely 450 bar/s (45 MPa/s) for the phenol-formaldehyde, 200 bar/s (20 MPa/s) for the cork, and 125 bar/s (12.5 MPa/s) for the flour. Lack of correlation between explosion violence in real industrial situations and the $(dP/dt)_{max}$ from the closed bomb tests in common use was also experienced in 500-m^3 silo experiments [*9*]. The general problem of using $(dP/dt)_{max}$ as a criterion of expected explosion violence in real situations has been discussed elsewhere [*4,10*].

The VDI 3673 Guideline [*11*] divided combustible dusts into three explosion classes based on the measured rate of pressure rise in a 1-m^3 vessel. Class St1 is for dusts with $0 < K_{St} \leq 200$ bar · m/s (20 MPa · m/s), Class St2 is for $200 < K_{St} \leq 300$ bar · m/s (30 MPa · m/s), and Class St3 is for $K_{St} > 300$ bar · m/s (30 MPa · m/s). By assuming that all three dusts would be classified as St1 in the context of the VDI 3673 code [*10*], it is possible to make a tentative comparison of the vent area requirements of this code and the data from the cyclone experiments. Figure 2 shows the quite dramatic difference in area requirements. Over the range where comparison is possible, Nomograph 7a of VDI 3673 [*11*] requires at least five times as large vent areas as those found in the realistic experiments. In defense of the VDI 3673, it could be argued that St1 dusts comprise

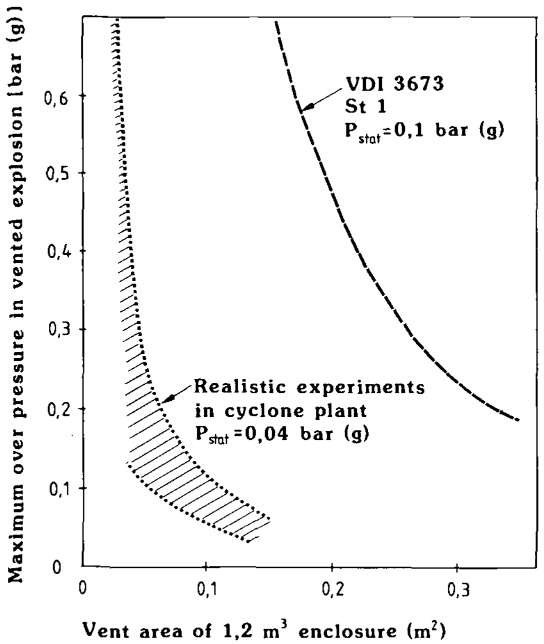


FIG. 2—*Comparison of VDI 3673* [11] *vent area requirements for explosion of a St1 dust in an enclosure of 1.2-m³ volume, and vent area/pressure correlations obtained in realistic dust explosion experiments in a 1.2-m³ cyclone. Hatched area covers data for three different dusts (cork, English flour, and phenol-formaldehyde) and a variety of vent configurations.* P_{Stat} *denotes the overpressure at which the vent cover gives way under quasistatic conditions.*

K_{St} values of up to 200 bar · m/s (20 MPa · m/s). Therefore, if K_{St} of the three dusts in question were significantly lower than 200, the St1 line in Fig. 2 might be too conservative. For reasons discussed elsewhere [*4*], the correlation between $(dP/dt)_{max}$ in the Hartmann bomb and the West German K_{St} is not very good, but a conversion factor of 0.4 seems to be a reasonable average value. This would mean that 450 bar/s (45 MPa/s) in the Hartmann bomb, the value measured for the phenol formaldehyde dust, corresponds to K_{St} = 180 bar · m/s (18 MPa · m/s), which is close to the upper limit of the St1 class.

It is easy to suggest a number of likely reasons why VDI 3673 is unrealistically conservative in the specific case discussed. The dust dispersion in the U.K. experiments may not have been complete, and the air circulation in the cyclone may have been so intense that it caused partial quenching of the combustion process. Finally, in a working cyclone, there are per definition steep dust concentration gradients, as opposed to the homogeneous concentration aimed at in idealized dust explosion tests.

However, the concern from the point of view of industrial safety is to focus at the dust cloud characteristics that would be encountered in a cyclone in practice. Under no circumstances does it seem likely to encounter the type of clouds used in the experiments providing the data basis of the VDI 3673 venting code.

Venting of Dust Explosions in an Industrial Bag Filter Unit

In a recent paper, Lunn and Cairns [*12*] report on a series of dust explosion experiments in an industrial bag filter unit. The experiments of interest in the present context were conducted during normal operation of the filter, which was of the air pulsed, self-cleaning type. Four different dusts were used, and K_{St} values according to the West German standard were determined by the 20-L sphere test developed by Bartknecht and coworkers [*13*]. The ignition source was located in the hopper below the bag section. In most of the experiments the vent was located in the top surface of the filter housing. Hence, to get to the vent, the flame had to propagate all the way up from the hopper and through the congested filter bag section. In a few experiments, however, the vent was located in the rear wall of the filter housing, not far from the point of ignition.

The results from the dust filter explosion experiments with realistic dust cloud generation are summarized in Table 1, together with the corresponding VDI 3673 predictions. Table 1 first shows that all the pressures measured in the actual filter were lower than the corresponding VDI 3673 predictions. Secondly, Table 1 confirms lack of correlation between the VDI 3673 ranking of expected pressures according to the K_{St} values from the 20-L sphere tests, and the ranking actually obtained. The third, and in the present context, particularly important conclusion is that location of the vent near the point of ignition resulted in much lower pressures than those generated with the vent in the top surface. This is in accordance with the expected trend, but the data provide a valuable quantification of the effect in an industrial bag filter.

Venting of Dust Explosions in an Elongated 8.6-m³ Empty Vessel

Lunn and Cairns [*11*] also report on some interesting dust explosion experiments in a vented 8.6-m^3 empty cylindrical vessel of 7.6-m length, 1.2-m diameter, and thus L/D = 6.3. The same four dusts were used as in the filter experiments just described. The dust clouds were generated by releasing the dust from a bottle pressurized with nitrogen. The ignition source was located on the horizontal vessel axis, 3 m from the closed end, that is, at about 40% of the distance from the closed to the open end, and it was activated 2 s after onset of release of dust from the pressurized bottle.

These experiments were not, strictly speaking, "practical." However, they are of substantial practical interest, because they demonstrate, when related to the filter experiments, the practical significance of the discussion in the Nature of the Vented Dust Explosion section above. Some results are shown in Fig. 3.

Figure 3 first shows that all of the measured pressures are higher than those predicted by the VDI 3673 code. This is in accordance with the restriction given in VDI 3673, of the nomographs not being applicable to elongated vessels of L/D > 5. However, the most striking feature of Fig. 3 is the lack of correlation between the measured maximum pressures and those predicted by the VDI 3673 nomograph. The present paper does not permit any lengthy specific discussion of

TABLE 1—*Maximum pressures measured during dust explosions in an industrial 6.7-m³ bag filter unit* [12]. *All pressures in bar(g). Comparison with VDI 3673 predictions* [11].[a]

Dust Type	K_{St}, bar · m/s	Vent Location: Roof	Vent Location: Rear Wall	VDI 3673 [*10*] Pressure Predictions
Polyethylene	138	0.14	0.02[b]	~0.15
Phenolic resin	140	. . .	0.02[b]	~0.15
Toner dust	169	0.09	. . .	0.23
Aspirin	190	0.14	. . .	0.30

[a] 1 bar = 100 kPa.

[b] Plastic vent cover of static opening pressure of 0.1 bar(g) probably weakened by heat from initial dust flame.

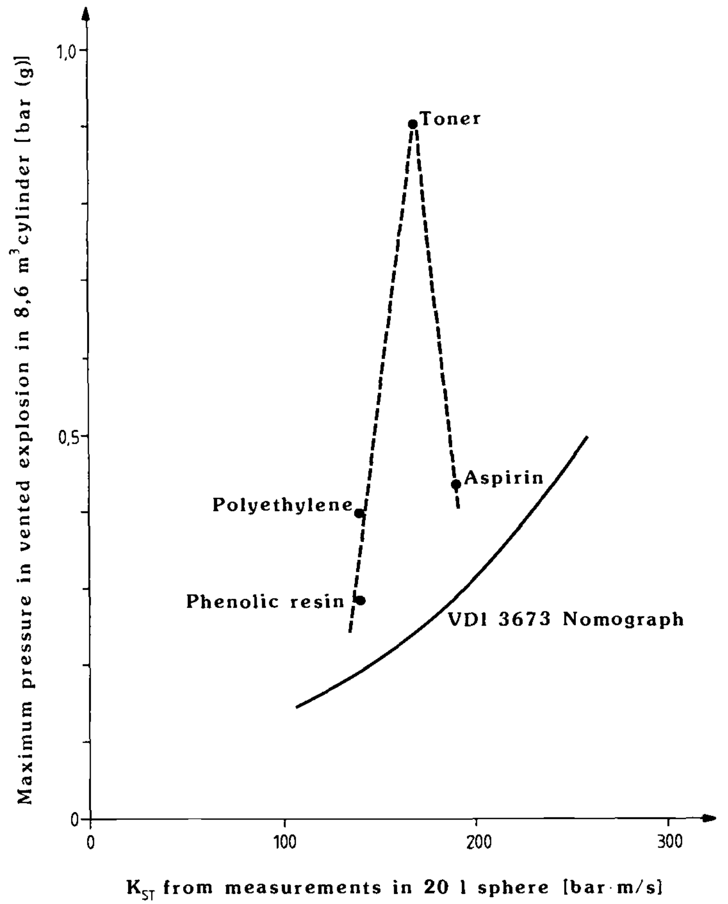


FIG. 3—*Experimental explosion pressures measured by Lunn and Cairns* [12] *in a cylindrical vessel of volume 8.6* m^3 *and L/D* ≈ 6*, and with one end fully open for venting (A = 1.1* m^2*). Ignition 3 m from closed end, on the vessel axis. Comparison with VDI 3673 nomograph data* [11].

possible reasons for this, but the parameters playing the key roles are most certainly among those listed in the Nature of the Vented Dust Explosion section above.

A particularly important finding is that the toner dust gave the lowest top venting pressure of the four dusts in the filter unit test, but the highest pressure in the 8.6-m^3 vessel test. In view of the fact that the toner dust was the finest one, and therefore the most cohesive of the four dusts, substantially different degrees of dust dispersion in the two enclosures probably are the main reason for this apparent inconsistency (Factor 4 in the list in the Nature of Vented Dust Explosion section).

The L/D of about 6 of the 8.6-m^3 explosion vessel is very close to that of the large silo discussed in the next section. No doubt, the high pressures recorded in the 8.6-m^3 vessel were a result of ignition taking place relatively far from the vent. It is not unlikely, however, that ignition even farther away from the vent would have generated still higher pressures. On the other hand, ignition close to the vent would certainly have generated much lower pressures than the VDI 3673 predictions.

Recent Vented Dust Explosion Experiments in a 236-m³ Silo in Norway

During Spring 1985, a series of maize starch explosions were conducted in a new experimental 236-m³ steel silo outside Bergen, Norway on behalf of National Grain & Feed Association, Washington, DC [*14,15*].

The silo has a height of 22 m and a diameter of 3.7 m, and hence L/D = 6. The vent opening is located in the 10.7-m² circular top surface, and its size can be varied in steps of 0.23 m², from 0.23 to about 9 m². The shape of the vent opening can also be varied at will. If desired, a given venting area can also be distributed on several smaller openings.

When L/D becomes as large as 6, the top vented silo is starting to behave as a one-end-open pipe, and the explosions will exhibit acceleration features typical of duct and gallery explosions. Figure 4 gives an overview of some results obtained with the most explosible dust clouds that could be produced by the pneumatic dust injection method used, in the absence of significant initial turbulence in the cloud at the moment of ignition. The average dust concentration at the moment of ignition was typically about 400 to 500 g/m³.

Figure 4 highlights the central issue of the present paper, the strong influence on the maximum explosion pressure of location of the ignition source in relation to the vent. As can be seen, the VDI 3673 [*11*] recommendations for vessels of L/D < 5 agree quite well with the pressures obtained with ignition at 7.5 m above the silo bottom (at about 35% of the distance from bottom to top). Ignition further down, however, gave higher pressures, by a factor of two, than the VDI

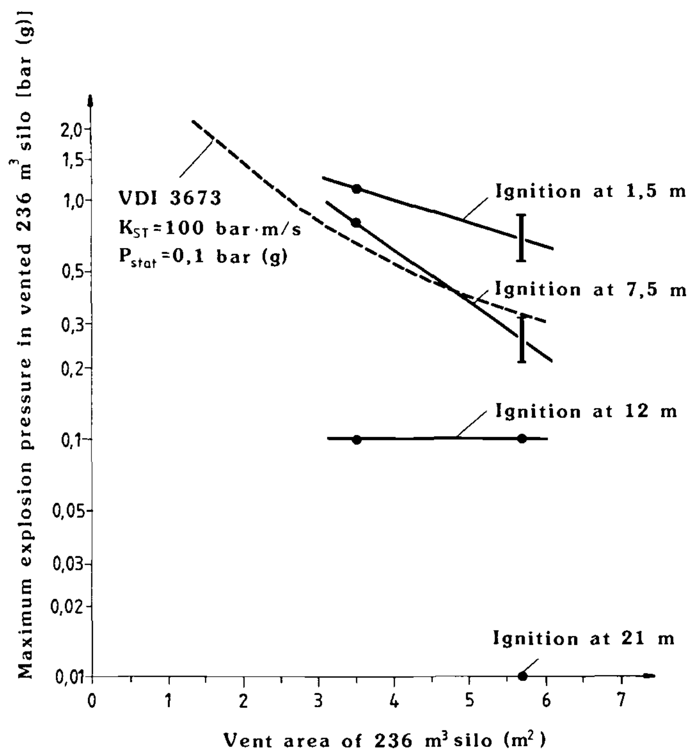


FIG. 4—*Explosion pressures measured by Eckhoff et al.* [14,15] *during maize starch explosions in a cylindrical steel silo of volume 236 m³ and L/D = 6, and with a vent opening in the top surface. Influence of the location of the ignition point. Comparison with VDI 3673 predictions* [11], *for vessels of L/D < 5.*

3673 values, whereas ignition in the upper half of the silo generated much lower pressures than the VDI 3673 predictions.

Potential Ignition Sources, Their Probable Locations, and Associated Dust Generation Processes in Large Storage Silos

Flame Jets

Analyses of accidental dust explosions involving silos indicate that most often the silo explosion is a secondary event, following a primary explosion in, for example, a bucket elevator or a grinder. For this reason, flame jets entering the silo from the outside through available openings seem to be a likely type of ignition source for silo explosions.

It has been suggested that some silo explosions in the past may have been initiated by a flame jet from a violent explosion below the silo that entered the silo through the discharge spout at the bottom. This suggestion implies first that the discharge spout is open, or can be blown open by an explosion below the silo. Secondly, it implies that the explosible dust cloud in the silo is large enough to generate a significant explosion pressure. An initially open discharge spout would normally imply that the silo is empty, apart from dust layers on the wall and roof. If the dust cloud is to be generated from such layers, it must be dispersed either by mechanical vibrations or by an air blast preceding the flame jet.

The scenario that the silo spout at the bottom is open at the same time as the silo is being filled from the top seems rather unlikely for normal operational reasons. One could nevertheless in theory envisage a situation where a dust explosion propagated in the tunnel below the silo at the same time as filling of the silo with dust from the top had just started with the bottom spout left open by mistake. In such a case, strong worst-case explosions could occur that no normal silo would be able to withstand, even if generous venting was provided. However, one must consider whether an accidental coincidence of the three events necessary to create this situation would be credible.

Whether or not it is likely that a closed bottom spout can be blown open by an overpressure from below also needs to be considered. In addition to blowing the spout open, the overpressure must also be able to lift any bulk material stored in the silo.

Another mechanism for generating and igniting dust clouds in silos from below could be that a dust explosion in the tunnel generates and compresses a dust cloud ahead of the flame, so that an unburnt explosible dust cloud at higher than atmospheric pressure is pushed into the silo through any open bottom spout, and subsequently ignited inside the silos by the flame jet that follows it. If the size of the spout opening and the pressure drop across it are known, the amount of dust cloud entering the silo per unit time can be estimated. However, it does not seem obvious that large volumes of unburnt cloud can be generated in the silo in this way before the flame reaches the spout.

A more likely situation would be that the dust cloud was generated in the empty silo by dispersion of dust layers on the internal surface of the wall and roof. Dispersion of a 1-mm layer of grain dust on the internal wall of a 7-m-diameter silo would give an average dust concentration of about 300 g/m^3 in the silo. Dispersion of such dust layers could be due to mechanical shaking caused by preceding explosions elsewhere in the plant. If an explosion had first occurred in the tunnel below the silo, ignition at the silo bottom could be accomplished by a flame jet entering the silo through the open bottom spout.

It is nevertheless felt that the most likely scenario for flame jet ignition is a jet entering the silo in the top region, either through a dust extraction opening or through the product feeding system. This is likely both because these openings would be open during dust filling, and because the origin of dust explosions in grain elevators and flour mills is often either the milling and grinding system or mechanical transport units such as bucket elevators.

As shown in the preceding section, top ignition in a large slim silo, provided with a reasonable size vent at the top, only generates very low explosion pressures, of the order of a few tens of millibars, even with a large, effective ignition source, and with the entire silo filled with a worst-case concentration dust cloud.

Electrostatic Discharges

Over the years the question of whether electrostatic discharges are likely initiators of dust explosions in industry has been discussed repeatedly. A recent series of papers [*16–19*] seems to provide some valuable conclusions.

In his excellent survey paper, Glor [*16*] considers six categories of electrostatic discharges:

- spark,
- brush,
- corona,
- propagating brush,
- 'Maurer' discharges, and
- lightning discharges.

A spark discharge occurs when an electrically conducting body at high potential drains its excess charge to earth across a suitable spark gap. Such discharges can initiate dust explosions. However, as long as all metal items are earthed, this kind of discharge will not occur.

Brush discharges occur between a curved, earthed electrode (radius of curvature 5 to 50 mm) and a charged nonconducting body (plastic, rubber, or dust). According to Glor, no ignition of a dust cloud by a brush discharge has yet been conclusively demonstrated, not even in sophisticated laboratory tests on very sensitive dusts. Corona discharges occur under similar conditions as brush discharges, but the earthed electrode has to be a sharp edge or spike. The energies will be much lower than of brush discharges, and the possibility of igniting dust clouds by corona discharges can therefore be ruled out.

Propagating brush discharges will normally have much higher energies than brush discharges. They occur if a double layer of charges of opposite polarity is generated across a nonconducting surface. For example, if powder were transported pneumatically in a nonconducting plastic pipe provided with an external earthed metal shield, such discharges might occur if the two sides of the plastic pipe wall were short-circuited, either by perforation or at the pipe end. In his report of past gas and dust explosions caused by electrostatic discharges, Lüttgens [*17*] mentions one dust explosion, which occurred in Germany, 15 years ago, and was initiated by a propagating brush discharge. Powder was transported pneumatically in a plastic pipe outdoors, and the earthed conducting shield on the outer surface of the pipe was generated by rainwater and snow!

Propagating brush discharges may be generated during pneumatic filling of steel silos having an internal nonconducting coating. Therefore, the use of such silos for storing ignition sensitive powders or dusts should be avoided.

Yong Fang Yu [*18*] investigated charge buildup in natural agricultural dusts transported pneumatically in a 6-m-long earthed steel pipe. He was unable to generate stored energy levels higher than 0.2 mJ in the collecting container. During these experiments he also attempted unsuccessfully to ignite the cloud in the collecting container by an incendiary capacitive spark of about 1-J energy. The probable reasons for this low incendivity were high flow velocity and strong turbulence in the dust cloud in the container.

As regards dust explosions in silos, the types of electrostatic discharges discussed so far will most probably occur in the top part of the silo. This means that should an ignition occur, against all odds, and the silo is provided with a reasonably sized vent in the roof, the explosion will be mild.

The fifth type of possible electrostatic sparks discussed by Glor are the 'Maurer' discharges (first discovered by Dr. B. Maurer). Such discharges can be generated if nonconducting powders are conveyed into a large container, for example, a silo, and the charged particles settle in a heap. However, under realistic industrial conditions only particles of large diameters (1 to 10 mm) and high specific electrical resistivity can generate spark discharges in this way. Further, the equivalent ignition energy of this type of discharge has been estimated to be about 10 mJ. This means that most agricultural dusts would not be ignited.

Finally, Glor discusses the lightning type discharge, and concludes that there is no evidence that such discharges have occurred in dust clouds generated in industrial operations.

Thorp et al. [*19*] investigated the hazard of electrostatic ignition of sugar dust clouds inside storage silos in a full-scale pneumatic conveying and storing facility. They were able to draw some low-energy spark discharges from the charged dust cloud, which were incapable of causing ignition. In fact, these spark discharges were not even able to ignite a propane/air mixture with a minimum ignition energy of less than 1 mJ.

From 1979 to 1984, National Grain & Feed Association, Washington, DC, conducted a comprehensive investigation of the electrostatic discharge ignition hazard in the grain industry [*19*]. The investigation comprised electrostatic charging of grain conveying belts, earthing characteristics of grain facilities, and electrostatic hazards inside storage silos. The main conclusion was that ignition as a result of electrostatic discharges in the type of industrial plant considered is rather unlikely. However, low absolute air humidity, low grain humidity, and lack of proper earthing can make the hazard significant.

Smoldering Combustion Nests

In recent investigations, Pinkwasser [*21*][2] studied the possibility of dust explosions being initiated by smoldering lumps ("nests") of powdered material conveyed through the process system. The object of the first investigation [*21*] was to see under which conditions smoldering material that had entered a pneumatic conveying line would be "extinguished" in the dilute-phase and dense-phase conveying modes. In the case of >1-kg/m^3 pneumatic transport of screenings and flour, the temperature of a 10-g smoldering nest had dropped to a safe level after a conveying distance of only a few metres. In the case of lower dust concentrations, 0.1 to 0.9 kg/ m^3, that is, within the explosible range, the smoldering nest could be conveyed for an appreciable distance, but no ignition was ever observed in the conveying line.

In a second investigation,[2] smoldering, mechanically stable nests of 700°C were allowed to fall freely through a 1-m-tall column containing dust clouds of 0.1 to 1.0 kg/m^3 of wheat flour or wheat starch. Ignition was never observed during free-fall. However, in some tests, ignition occurred immediately after the nest had come to rest at the bottom of the test column. In view of the discussion in the previous section, this clearly is a somewhat alarming conclusion.

To generate further insight into this important problem area, Chr. Michelsen Institute (CMI) investigated the possibility of dust cloud ignition by falling smoldering nests in the large 236-m^3 silo during Spring 1986 [*22*].

Metal Sparks from Impact

A comprehensive two-year research program at CMI, sponsored by National Grain & Feed Association, USA, has just been completed [*23*]. The main question considered was under what conditions ignition of dust clouds by heat from accidental single impacts is at all possible. It now appears that ignition of clouds of natural organic dusts by single accidental impacts is considerably

---

[2] Th. Pinkwasser, "Igniting Power of Smoldering Nests During Free Fall Through an Explosible Dust Cloud," personal communication to R. K. Eckhoff.

less likely than hitherto believed by many, provided the sparking metal is not titanium or zirconium. However, metal sparks from grinding and cutting operations can initiate explosions in clouds of organic dusts [*20*].

Concluding Remark

In this section, various possibilities of generation and accidental ignition of dust clouds in large storage silos have been discussed. The discussion is not intended to be conclusive, but rather to illustrate the type of analysis needed for identifying likely modes of dust cloud generation and likely types of ignition sources and their probable locations.

Risk Analytical Nature of the Practical Vent Sizing Problem

Distribution of Expected Explosion Violence

Let us consider a specific process unit in a specific industrial plant where one or more specific combustible materials are produced or handled or both in powdered or granular form. The process unit can be a mill, a fluidized bed, a bucket elevator, a cyclone, a storage silo, or any other enclosure in which explosible dust clouds may occur.

Assume that the plant can be operated for one million years from now with no systematic changes in technology, operating and maintenance procedures, knowledge and attitudes of personnel, or in any other factor that might influence the distribution of ways in which dust clouds are generated and ignited. One can then envisage that a certain finite number of explosion incidents will occur during the million-year period. Some of these will only be weak "puffs," whereas others will be more severe. Some may be quite violent. Because we assume that "status quo" conditions are reestablished after each incident, the incidents will be distributed at random along the time axis from now on and a million years ahead.

Influence of Vent Size on Distribution of Expected Explosion Pressures

Let us assume that the process unit considered is equipped with a vent opening. The expected maximum pressure P_{max} generated in vented explosions in the enclosure will by and large decrease with increasing vent size. This is illustrated in Fig. 5. If the vent area is unnecessarily large (A_1), the distribution of expected explosion pressures will be well below the maximum acceptable pressure P_{red}. On the other hand, if the vent is very small (A_3), a considerable fraction of all explosions will generate pressures exceeding the maximum acceptable one. In the case of A_2, the vent size is capable of keeping the majority of all explosion pressures below P_{red}. (Note that for $P_{max} > P_{red}$, Fig. 5 illustrates the hypothetical pressures that would have been generated had the enclosure been sufficiently strong to withstand the explosions.)

Acceptable Residual Risk Determines Necessary Vent Size

In case the fraction of the explosions that generates $P_{max} > P_{red}$ represents a reasonable risk, A_2 in Fig. 5 will constitute an adequate vent size for the case in question. However, the decision as to whether the fraction of expected destructive explosions is acceptable depends on several considerations.

The first is the expected total number of incidents of ignition of a dust cloud in the enclosure in the one-million-year period. This number is strongly influenced both by the standard obtained with respect to elimination of potential ignition sources and the control of dust. If these standards are comparatively low, the overall chance of a cloud ignition will be comparatively high.

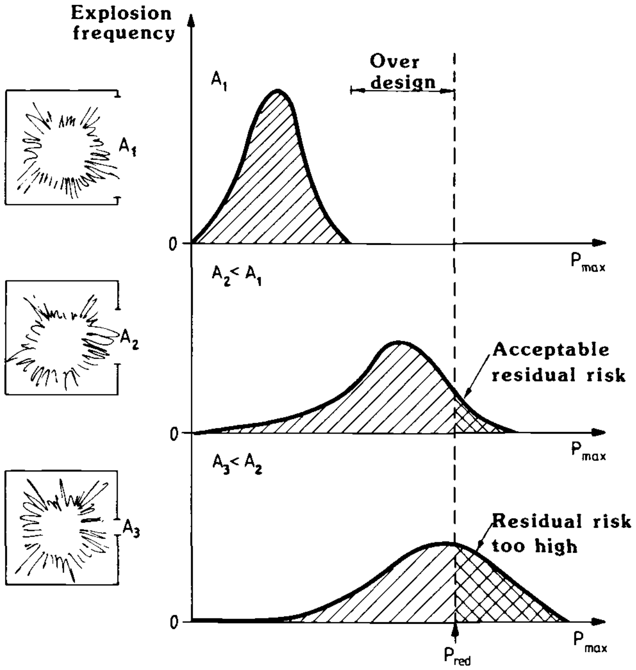


FIG. 5—*Distributions of maximum explosion pressures in a given process unit, fitted with vents of different sizes, generated by the same one-million-year population of explosions. The unit of explosion frequency is number of explosions per million years and unit of pressure. The areas under the frequency curves then give the total number of explosions in one million years, and should therefore be the same for the three cases.*

Consequently it will be necessary to require that the *fraction* of all expected explosions that will not be taken care of by a vent be comparatively small to ensure that the expected *number* of destructive explosions is kept at an acceptable level. Therefore, if the probability of dust cloud ignition is low, one can rely on a smaller vent than if the standard of dust control and the efforts to eliminate ignition sources are inadequate.

Risk is defined as the product of the expected number of a specific type of undesired events in a given reference period and the *consequence* per event. When assessing the maximum acceptable number of destructive explosions in the one-million-year period, that is, the maximum acceptable number of explosions of $P_{max} > P_{red}$, it is therefore necessary to estimate the expected consequences of the explosions that the vent in question will not handle in a safe way. This includes both possible threats to human life and health, and possible damage to property.

In principle, it is possible to reach such a high standard of explosion prevention that the total number of expected explosions in the one-million-year period is of the same order as the acceptable number of destructive explosions. For example, it may turn out that a vent capable of handling less than half of the explosions would be adequate. However, the safety increase provided by such a vent would be marginal, and it is questionable whether installing it would be advisable.

Influence of Process or Product Changes on the Explosion Violence Distribution

Figure 5 illustrates the "random" variation of the expected explosion pressure for a specific process unit in a specific plant, handling a specific dust. However, if dust chemistry or particle size distribution is significantly changed, the distributions of P_{max} will also change. For example, if particle size is increased, and a systematic reduction of combustion rate results, all three distributions will be shifted towards lower P_{max} values. The small vent area A_3 may then turn out to be sufficient. Alternatively, the average running conditions of the process could be altered in such a way that a significant systematic change in the dust cloud turbulence or concentration within the process unit would result. This would also cause the distributions in Fig. 5 to change, rendering the original vent size either too small or unnecessarily large.

The "Worst Credible Case"

The discussion in the previous sections has disclosed the central problem in prescribing an adequate vent size for a given purpose: *identification of the "worst-case" explosion to be designed for,* that is, the worst case that has a significant probability of occurring.

In the West German VDI 3673 venting code [*11*], the choice of "worst case" seems rather conservative with respect to dust concentration, turbulence level, and degree of dust dispersion. In defense of this approach it has been argued [*24*] that the venting code ensures safe venting under all circumstances encountered in practice. However, extreme conservatism may not be the optimal solution. Excessive overdesign of vents quite often imposes significant, unnecessary practical problems and costs both in finding a suitable vent location that does not conflict with other concerns, and in designing the vent cover arrangement. Furthermore, providing a large vent opening can significantly reduce the strength of the process unit to be vented, necessitating complicating reinforcement for maintaining the original strength. VDI 3673 does not seem to permit a reduction in vent size if the probability of ignition is low.

In some cases, when faced with these rigid requirements, industry simply concludes that venting is not applicable to their problem at all, and no vents are provided. This situation is not uncommon in the case of large storage silos in the grain, feed, and flour industry. The alternative venting philosophy outlined in the present paper implies that even a modestly sized vent may add significantly to the safety standard of the plant by being capable of providing adequate relief for the majority of the expected explosions.

In addition, it should be emphasized that even the VDI 3673 code may in certain circumstances of dust cloud generation predict too small vent openings. This was demonstrated in a maize dust explosion experiment in a vented 500-m^3 silo [*3*], when the dust cloud was in an active state of jet generated turbulence at the moment of ignition. This clearly is a further relevant argument for seeking an alternative approach to vent sizing, based on the philosophy of risk assessment.

Conclusions

1. The rate of heat release in a dust explosion in a given vented enclosure is not determined only by the chemistry and particle size distribution of the dust and by the chemistry, temperature, and pressure of the gas phase. In addition, the degree of dust dispersion and the distributions of dust concentration and turbulence in the actual cloud play central roles in determining the rate of heat release, and hence the maximum pressure that will occur in the enclosure during the vented explosion. The role of in situ generated flame instabilities and high-rate turbulent combustion is strongly influenced by the location of the ignition source with respect to the vent.

2. Realistic full-scale experimental investigations of vented dust explosions in industrial enclosures have indicated limited applicability of the West German vent sizing code VDI 3673. In particular, the substantial influence of the location of the ignition source on the maximum explosion pressure has been confirmed. The probable nature and location of potential ignition sources for initiation of dust explosions in various industrial enclosures in practice therefore require careful consideration.

3. Further full-scale dust explosion experiments in various types of vented process units, in which the dust clouds are generated and ignited in the same ways as in realistic industrial situations are needed. Only such tests can adequately determine the explosion violence and the necessary vent sizes to be associated with a given dust in a given industrial situation.
4. A differentiated approach to dust explosion vent sizing must be adopted, which pays appropriate attention to the marked influence on the necessary vent area of the actual dust cloud generation, ignition, and flame propagation processes. It is necessary to discuss and agree upon which dust cloud formation and ignition processes and associated combustion rates should, under various circumstances in industry, be regarded as the "worst cases" that the vents to be designed should be able to accommodate. In future, simple, general nomographs and formulas will have to be replaced by methods that tailor the vent arrangement to suit each specific application, within an overall context of risk assessment.
5. The lack of correlation between explosion violence predicted by existing closed bomb tests, and explosion violence in realistic full-scale experiments, also calls for a differentiated approach to the violence testing problem.

Acknowledgments

The author wishes to express CMI's sincere gratitude to the National Grain and Feed Association (NGFA) for substantial financial support of several dust explosion related research program at CMI. Sincere thanks are also due to the Swedish Fire Research Board, BRANDFORSK, and the Norwegian Council for Scientific and Industrial Research, for granting most valuable financial contributions.

References

[*1*] Palmer, K. N., *Dust Explosions and Fires,* Chapman and Hall, London, 1973.

[*2*] Schofield, C., *Guide to Dust Explosion Prevention and Protection. Part 1—Venting,* The Institution of Chemical Engineers, U.K., 1984.

[*3*] Eckhoff, R. K. and Fuhre, K., "Dust Explosion Experiments in a Vented 500 m^3 Silo Cell," *Journal of Occupational Accidents,* Vol. 6, 1984, p. 229.

[*4*] Eckhoff, R. K., "Use of $(dP/dt)_{max}$ from Closed-Bomb Tests for Predicting Violence of Accidental Dust Explosions in Industrial Plants," *Fire Safety Journal,* Vol. 8, No. 2, 1984/1985, p. 159.

[*5*] Eckhoff, R, K., *Current Dust Explosion Research at CMI. Fuel-Air Explosions,* J. H. S. Lee and C. M. Guirao, Eds., University of Waterloo Press, 1982, p. 657.

[*6*] Eckhoff, R. K., Fuhre, K., Henery, M. J., Pedersen, G. H., and Thorsen, H. G., "Maize Starch Explosion Experiments in a Vented 500 m^3 Storage Bin," Fire and Explosion Research Report ESV-83-068, prepared by Chr. Michelsen Institute, Bergen, Norway, for National Grain and Feed Association, Washington, DC, CMI-Report 823307-1, Feb. 1983.

[*7*] Cybulski, W., "Coal Dust Explosions and their Suppression," English translation published by Foreign Scientific Publ. Dept. of National Center for Scientific, Technical and Economical Information, Warsaw, Poland, 1975.

[*8*] Tonkin, P. S. and Berlemont, F. J., "Dust Explosions in a Large-Scale Cyclone Plant," Fire Research Note 942, Fire Research Station, July 1972.

[*9*] Eckhoff, R. K., "Relevance of Using $(dP/dt)_{max}$ Data from Laboratory-Scale Tests for Predicting Explosion Rates in Practical Industrial Situations," VDI-Berichte 494, 1984, p. 207.

[*10*] Eckhoff, R. K., "Measurement of Explosion Violence of Dust Clouds," in Proceedings of International Symposium on Explosion Hazard Classification of Vapors, Gases and Dusts, Publication NMAB-447, National Academy Press, Washington, DC, 1987, p. 181.

[*11*] VDI-Richtlinie 3673, Druckentlastung von Staubexplosionen, Verrein Deutscher Ingenieure, Düsseldorf, 1979.

[*12*] Lunn, G. A. and Cairns, F., "The Venting of Dust Explosions in a Dust Collector," *Journal of Hazardous Materials,* Vol. 12, 1985, pp. 87–107.

[*13*] Bartknecht, W., *Explosionen, Ablauf und Schutzmassnahmen,* Springer-Verlag, 1978, pp. 43–45. (English translation; *Explosions, Course, Prevention, Protection,* Springer-Verlag, 1981.)

[*14*] Eckhoff, R. K., Fuhre, K., and Pedersen, G. H., "Vented Maize Starch Explosions in a 236 m^3 Experimental Silo," Fire and Explosion Research Report ESV-86-070, prepared by Chr. Michelsen Institute for National Grain and Feed Association, Washington, DC, CMI-Report 843307-2, Dec. 1985.

[*15*] Eckhoff, R. K., Fuhre, K., Pedersen, G. H., "Dust Explosion Experiments in a Vented 236 m^3 Silo Cell," paper presented at 5th International Symposium on Loss Prevention and Safety Promotion in the Process Industries, Cannes, France, 15–19 Sept. 1986.

[*16*] Glor, M., "Hazards Due to Electrostatic Charging of Powders," *Journal of Electrostatics,* Vol. 16, 1985, p. 175.

[*17*] Lüttgens, G., "Collection of Accidents Caused by Static Electricity," *Journal of Electrostatics,* Vol. 16, 1985, p. 247.

[*18*] Yong Fang Yu, "On the Electrostatic Charging of Some Finely Divided Materials in Modern Agricultural Pneumatic Transport Systems," *Journal of Electrostatics,* Vol. 16, 1985, p. 209.

[*19*] Thorpe, D. G. L., Singh, S., Cartwright, P., and Bailey, A. G., "Electrostatic Hazards in Surface Dust in Storage Silos," *Journal of Electrostatics,* Vol. 16, 1985, p. 193.

[*20*] Anway, A., "Summary of Static and Metal Sparking Research," Fire and Explosion Research Report SMS-86 . . . , National Grain & Feed Association, Washington, DC.

[*21*] Pinkwasser, Th., "Extinguishing Nests of Smouldering Material in Pneumatic Conveying Systems," paper given at a dust explosion conference in Paris, 24–26 April 1985, organized by APRIA, Paris.

[*22*] Alfert, F., Eckhoff, R. K., Fuhre, K., Pendersen, G. H., and Mills, J., "Initiation of Dust Explosions in Silo Cells by Smouldering Nests," CMI Report 863380-1, Dec. 1986.

[*23*] Pedersen, G. H., "Initiation of Dust Explosions by Heat Generated During Single Impact Between Solid Bodies," Fire and Explosion Research Report SMS-86-054, prepared by Chr. Michelsen Institute for National Grain and Feed Association, Washington, DC, CMI-Report 833310-2, 1986.

[*24*] Donat, C., "Auswahl und Bemessung von Druckentlastungseinrichtungen für Staubexplosionen," *Staub-Reinhalt Luft,* Vol. 31, 1971, p. 154.

Peter E. Moore[1]

Suppression of Maize Dust Explosions

REFERENCE: Moore, P. E., "**Suppression of Maize Dust Explosions,**" *Industrial Dust Explosions, ASTM STP 958*, Kenneth L. Cashdollar and Martin Hertzberg, Eds., American Society for Testing and Materials, Philadelphia, 1987, pp. 281–293

ABSTRACT: The results of a systematic series of maize (corn) dust explosion suppression trials in vessel volumes of 6.2, 10, and 25 m^3 are presented. Tests are reported for explosions of both medium and high turbulence dust clouds. The four suppressants, Halon 1011, ammonium phosphate powder, water, and halon/powder hybrid, were tested. The ammonium phosphate powder proved to be significantly more effective than the other suppressants. In the case of highly turbulent maize dust explosions, the halon suppressant catastrophically failed to suppress the incident. Suppression effectiveness is shown to be more dependent on the speed of deployment of the suppressant agent than on the absolute concentration delivered into the vessel. Thus, deployment of suppressant from a larger number of smaller suppressors results in a lower suppressed explosion pressure. The criteria for the limits of effectiveness of a given suppression system are defined and the experimental results compared with a theoretical estimate of the expected suppressed explosion pressure. It is shown that there is a reasonable correspondence between the theoretical estimate and corresponding experimental measurement and concluded that a theoretical model can be used as a basis for the design of effective explosion suppression systems for industry.

KEY WORDS: dust explosions, explosion protection, explosion suppression, suppressants, maize dust

The explosion hazard represented by maize (corn) dust is just one of the numerous dust explosion hazards that plague industry.

The potential explosion intensity of any dust is defined by the explosion rate constant K, which is determined from a measurement of the maximum rate of pressure rise $(dP/dt)_{\max}$ in a closed vessel of volume V in accordance with a standard test procedure (ISO 6184/1 or VDI 3673):

$$\text{Explosion Rate Constant} \quad K = (dP/dt)_{\max} \cdot V^{1/3}$$

Dusts are thus classified into explosion classes listed in Table 1.

Maize starch fines represent one of the severest dust explosion threats falling into the upper limit of the dust explosibility classification, St1, under conditions of moderate turbulence, and very capable of exploding with an intensity more akin to the upper limit of the dust explosibility

TABLE 1—*Explosion classes for dusts.*[a]

Dust Explosion Class	Explosion Rate Constant K
St0	does not explode
St1	$K \leq 200$ bar · m · s^{-1}
St2	$200 < K \leq 300$ bar · m · s^{-1}
St3	$K > 300$ bar · m · s^{-1}

[a] 1 bar = 100 kPa.

---

[1] Manager—Explosion Technology Group, Graviner Ltd., Poyle Rd., Colnbrook, Slough, SL3 OHB U.K.

classification, St2, when ignited under conditions of extreme turbulence. Thus, maize starch dust provides a realistic explosion threat against which to evaluate the efficacy of explosion suppression measures.

This paper presents the results obtained in a series of full scale explosion suppression trials using various suppression system hardware and alternative suppressants, and contrasts these results with the expected performance of such systems based on a simple thermodynamic model. Tests were undertaken in closed vessels with volumes of 6.2, 10, and 25 m^3 to provide a base to extend explosion suppression up to the larger volume of 250 m^3 which is reported elsewhere [*1*].

Explosion Suppression Technology

To suppress an explosion it is necessary to detect it and to discharge rapidly sufficient suppressant into the growing fireball such that all flame is extinguished before the explosion pressure developing inside the component results in component deformation or rupture. Thus, an explosion suppression system is comprised of:

- explosion detector(s) (typically pressure detectors for dust explosions),
- explosion suppressor(s) (high rate discharge extinguishers), and
- a control unit [provides the electrical energy to actuate the suppressor(s)].

The effectiveness of any suppression system is dependent on a large number of factors, any one of which could make the difference between a "good" suppression and the catastrophic failure of the suppression system to arrest the explosion. Unlike fire extinguishing, explosion suppression is NOT simply a matter of deploying a sufficient concentration of an appropriate agent. The prevalent factors are:

- the nature of the explosible fuel;
- the explosibility parameters of the fuel: maximum explosion pressure P_{max}, explosibility rate constant K;
- plant component volume and geometry;
- turbulence;
- detection threshold pressure (P_A);
- choice of suppressant: its effectiveness against the defined fuel;
- number and geometric deployment of explosion suppressors;
- suppressor capacity;
- suppressant charge;
- suppressant propelling agent pressure (P_{N2}); and
- suppressor outlet(s) size.

The pressure/time curve of an unsuppressed and a suppressed explosion in a closed vessel is shown in Fig. 1. The reduced (suppressed) explosion pressure P_{RED} defines the system effectiveness. Provided that P_{RED} is below the plant component's pressure shock resistance P_s, the explosion suppression system can be considered suitable for the application. Suppressants in common usage include halogenated hydrocarbons (halons), dry powders, and hybrid mixtures thereof.

Explosion Suppression Theory

Consider, as an example, the effectiveness of a liquid halon suppression system. The first effect is that of a cold, finely dispersed liquid spray entering the combustion wave and abstracting energy as it vaporizes. Subsequently, the vaporized halon can participate in homogeneous gas phase radical scavenging chain terminating reactions of the type:

$$\dot{H} + CH_2ClBr \longrightarrow CH_2\dot{C}l + HBr$$

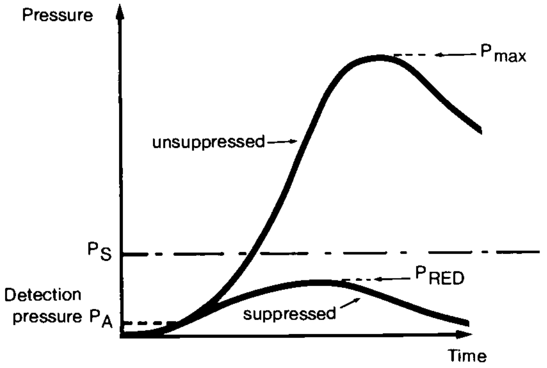


FIG. 1—*Pressure/time history of unsuppressed and suppressed explosions.*

which compete with the chain propagation reactions:

$$H_2 + O\dot{H} \longrightarrow H_2O + \dot{H}$$
$$\dot{H} + O_2 \longrightarrow O\dot{H} + \dot{H}$$
$$\dot{O} + H_2 \longrightarrow \dot{O}H + \dot{H}$$

The observation [2] that the halon concentration required to render a flammable vapor/air mixture nonflammable is proportional to the halon molar heat capacity and not dependent on its chemical specificity can be interpreted as evidence for a limiting adiabatic flame temperature, below which the combustion wave cannot be sustained. Thus, one criteria for suppression is to reduce the combustion kernal temperature to below this limiting temperature.

This hypothesis identifies the need to deliver greater than a critical mass of suppressant M_θ into the enveloping fireball for effective suppression:

$$M_\theta = \frac{\Delta Q}{H_\theta}$$

where ΔQ is the excess energy content of the fireball and H_θ is the heat abstraction capacity of the suppressant.

Calculation of this critical mass, which is time dependent, demands consideration of such factors as:

- thermochemistry and kinetics of combustion reactions,
- energy density of explosion kernal at the instant of interaction with suppressant,
- perturbation of the combustion wave arising from the discharge of suppressant,
- suppressant droplet size distribution,
- thermodynamics and physical kinetics of droplet vaporization, and
- residence times of suppressant droplets in the combustion zone.

It has been shown [3] that this simple theoretical treatment correlates well with experimental results of explosion suppression systems. Thus, for a given explosion hazard and explosion suppression system, it is possible to calculate the mass of suppressant required, as a function of time from ignition, to ensure effective suppression of the explosion threat in the plant component. Superimposition of the effective suppressant delivery into the combustion zone (defined by vessel geometry, suppressor locations, and suppressor discharge characteristics) enables the instant of suppression t_{RED}, and thus the corresponding suppressed explosion pressure P_{RED}, to be calculated.

Three possible outcomes can be envisaged from such an analysis (see Fig. 2):

Effective suppression—suppressant delivery overtakes suppressant requirement and the resultant maximum suppressed explosion pressure P_{RED} is estimated.

Unreliable suppression—suppressant delivery coincides with suppressant requirement.

Failed suppression—suppressant delivery lags behind suppressant requirement.

It is important to recognize that an explosion suppression system will either arrest the enveloping explosion or the system will fail. In a failed suppression, the combustion wave will be perturbed by the suppressant, but will continue to propagate until all of the oxygen or fuel is essentially consumed—the resultant internal explosion pressure will be of similar magnitude to the unsuppressed fuel/air explosion pressure $P_{\max}$. In the specific case of halon suppressant, should a failed suppression result, the halon suppressant will be elevated above its autoignition temperature [*4*], and will then participate in the combustion process giving rise to a higher internal explosion pressure than the corresponding unsuppressed explosion pressure $P_{\max}$ and the generation of very toxic halogen acid reaction products. Figure 3 illustrates the three criteria that can result in a failed suppression:

Too Late—activation of the suppressors is too late as a result of either too high a detection pressure or the use of explosion suppressors with a slow opening valve.

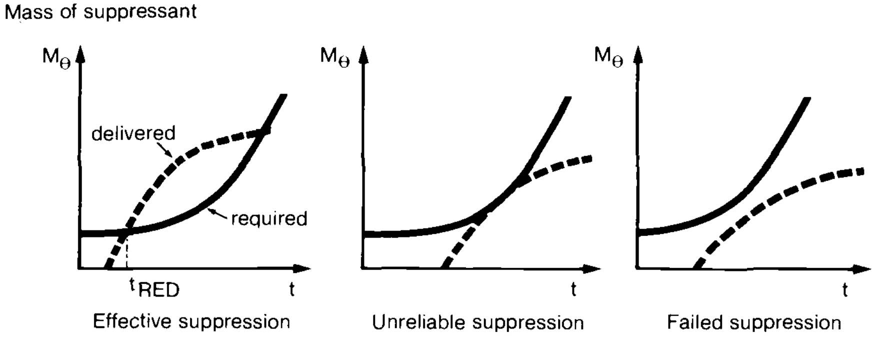
Too Slow—the rate of release of suppressant into the volume is too slow such that suppressant delivery never overtakes suppressant requirement. This will result from the incorrect choice of suppressors, or from the use of a small number of large suppressors rather than a large number of small suppressors.

Too Little—an insufficient concentration of suppressant is deployed into the plant component.

Thus, it can be summarized that effective suppression demands early detection and the rapid deployment of a sufficient concentration of an effective suppressant.

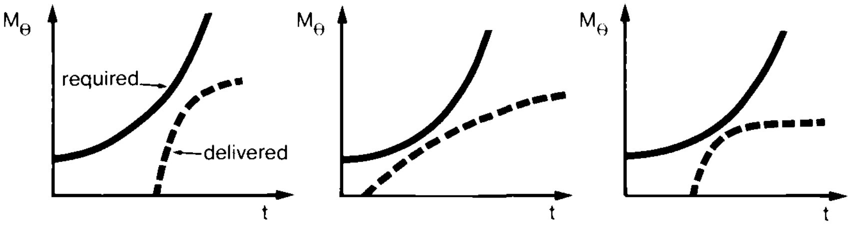
Unsuppressed Control Maize Dust Explosions

The 6.2-, 10-, and 25-m^3 explosion test apparatus are shown in Fig. 4. The vessels are designed to withstand the full pressure load of an unsuppressed explosion. A maize dust sample with an explosibility rate constant $K = 200$ bar · m · s^{-1} (20 MPa · m · s^{-1}) (St2) was used in this research program. Dust explosions were produced in each of these vessels by pneumatically dispersing a preweighted sample of the dust into the vessel volume, and igniting that dust cloud after a predetermined ignition delay t_V. The shorter the ignition delay t_V, the more turbulent is the dust suspension at the instant of ignition. The maize dust was dispersed in the test vessels from



Effective suppression Unreliable suppression Failed suppression

FIG. 2—*Suppression efficiency.*



Too late Too slow Too little

FIG. 3—*Causes of failed suppression.*

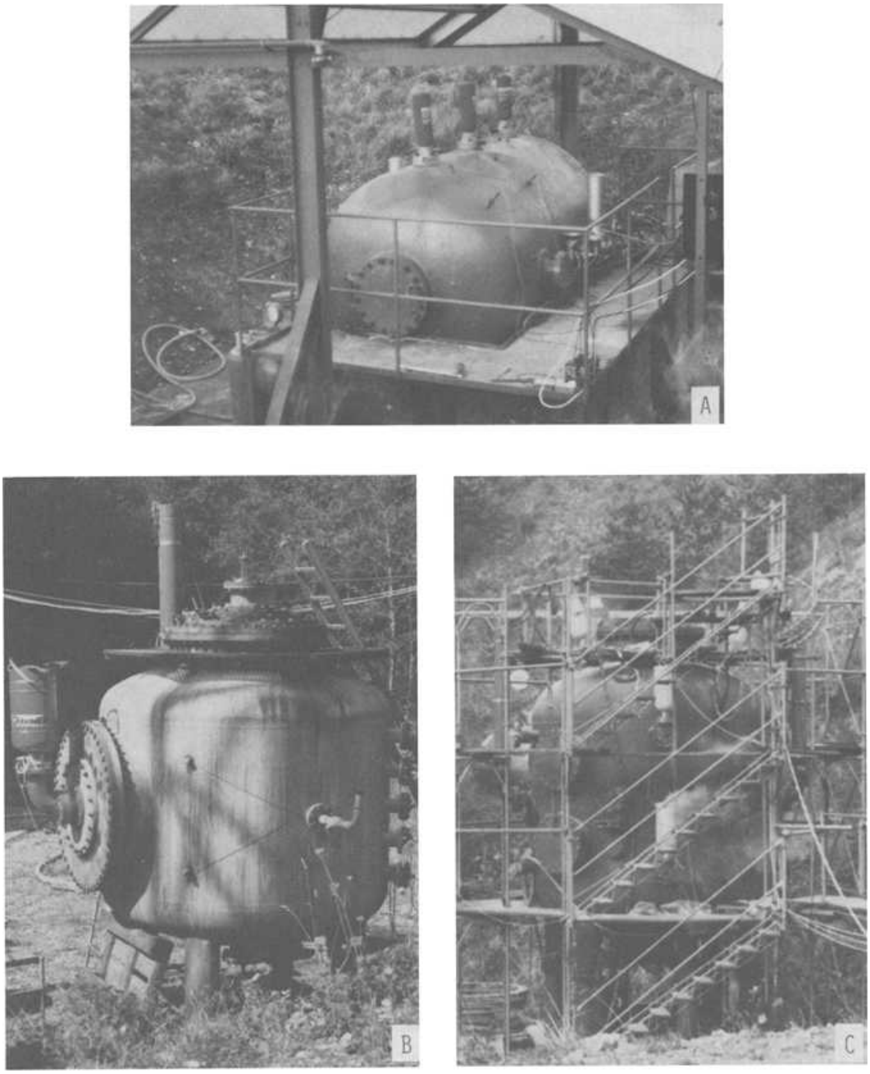


FIG. 4—*Test vessels* (a) *6.2-m³ cylinder,* (b) *10-m³ cylinder, and* (c) *25-m³ cylinder.*

reservoir(s) fitted with a high speed valve and a dispersion nozzle. The size and number of dust reservoirs were dependent on the vessel volume (see Table 2).

The explosibility rate constant K is defined from the cubic law as:

$$K = (dP/dt)_{\max} \cdot V^{1/3}$$

where $(dP/dt)_{\max}$ is the maximum recorded rate of pressure rise in the vessel volume V.

The time taken to disperse the most explosible charge of maize dust ($\sim$500 g/m^{-3}) into all three vessels was $\sim$0.6 s. This resulted in a measured K value of $\sim$200 bar · m · s^{-1} (20 MPa · m · s^{-1}), representing the upper limit of the dust explosibility Class St1. Maize dust explosions representative of the upper limit of the dust explosibility Class St2 ($K \sim$ 300 bar · m · s^{-1} [30 MPa · m · s^{-1}]) were attained in the three vessels using an ignition delay $t_V \sim$ 0.45 s. These two levels of maize dust explosion intensity, St1 and St2 limits, were chosen as a base to evaluate the efficacy of explosion suppression measures against maize dust hazards.

Explosion Suppression Systems Evaluated

The explosion suppression systems used in this research program comprised a single membrane pressure detector, high rate discharge (HRD) explosion suppressors, and an electrical control unit. Four types of HRD suppressors were used:

(1) 5.4-L capacity with a single 76-mm-diameter outlet,
(2) 20-L capacity with a single 76-mm-diameter outlet,
(3) 45-L capacity with a single 76-mm-diameter outlet, and
(4) 45-L capacity with a single 127-mm-diameter outlet.

The suppressors were charged with liquid or powder suppressant and pressurized with dry nitrogen to a predetermined pressure P_{N2}. The suppressor release mechanism was based on a steel diaphragm and explosive pack fitted with a detonator and appropriate linear shaped charge. Upon receipt of a signal from the membrane pressure detector, the control unit fires the detonator and the shaped charge plasma cuts the steel diaphragm. This opens in less than a millisecond leaving an unimpeded outlet for the propelling agent to expel the suppressant. Each HRD suppressor was fitted with a "pepper pot" hemispherical nozzle to disperse the suppressant into the volume to be protected. Tests were undertaken with four alternative suppressants against the two intensities of maize dust explosion:

MAP—mono-ammonium phosphate based powder—$NH_4H_2PO_4$,
halon—chlorobromomethane (Halon 1011)—CH_2BrCl,
water—(with wetting agent additive)—H_2O, or
hybrid—50:50 MAP/halon.

TABLE 2—*Maize dust reservoir characteristics.*

Test Apparatus	Dust Reservoirs
6.2-m^3 cylinder (2.6:1 aspect)	3- by 5-L canisters each fitted with a 19-mm Ø valve and perforated spray ring
10-m^3 cylinder (1:1 aspect)	1- by 50-L canister fitted with a 76-mm Ø valve and "pepper pot" nozzle
25-m^3 cylinder (1:1 aspect)	2- by 50-L canisters each fitted with a 76-mm Ø valve and "pepper pot" nozzle

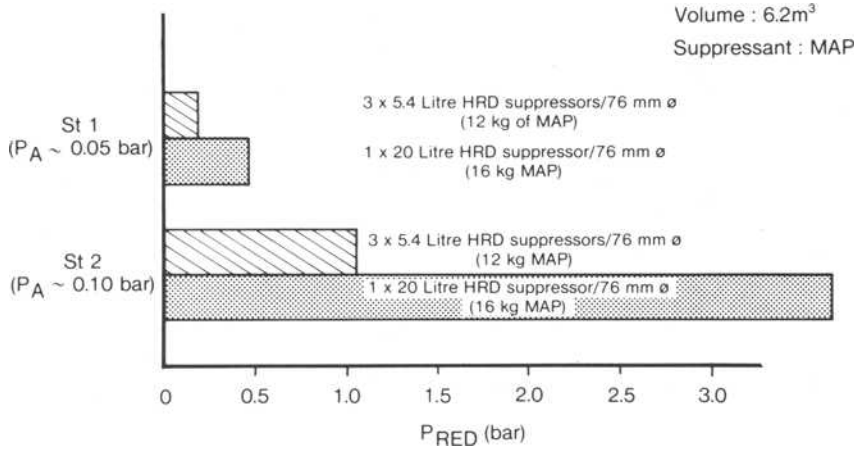


FIG. 5—*6.2-m^3 explosion suppression trials—various suppressors.*

Suppression of Maize Dust Explosions

Comparison of Suppression Systems

The relative effectiveness of the four HRD explosion suppressor types was experimentally determined in a series of maize dust explosion suppression trials using the powder mono-ammonium phosphate suppressant.

The results presented in Fig. 5 contrast the effectiveness of three 5.4-L/76-mm 0 HRD suppressors with a single 20-L/76-mm 0 HRD suppressor against St1 and St2 maize dust explosions in a vessel volume of 6.2 m^3. Although the larger suppressor deployed 25% more suppressant, the higher discharge rate of the three smaller suppressors resulted in lower suppressed explosion pressures. The results presented in Fig. 6 contrast the effectiveness of suppression systems using 20-L/76-mm 0 HRD suppressors, 45-L/76-mm 0 HRD suppressors, and 45-L/127-mm 0 HRD suppressors against similar explosions in the 25-m^3 vessel. Again, the rapid deployment of suppressant proves more important than the concentration of suppressant attained—35 kg of suppressant deployed from a single 127-mm 0 HRD suppressor having similar effectiveness to 105 kg of the same suppressant deployed from three 76-mm 0 HRD suppressors of the same capacity.

The suppressor propelling agent pressure P_{N2} affects both the suppressant discharge rate and the effective throw of the suppressant cloud. For St1 maize dust explosions, Fig. 7 shows that a reduction in the propelling agent pressure from 60 to 20 bar (6 to 2 MPa) results in a very significant increase in the suppressed explosion pressure P_{RED}.

The experimental results reported in this section demonstrate that there is a complex relationship between the suppressant charge, suppressor propelling agent pressure, and the number of suppressors required to provide effective suppression of a given explosion. For explosions of the intensity of maize dust, the rapid deployment of suppressant is more important than the absolute suppressant concentration provided that more than a minimum concentration is attained.

Comparison of the Effectiveness of Various Suppressants

A comparison of the effectiveness of halon, MAP, and water suppressants against St1 and St2 maize dust explosions in the 6.2-m^3 vessel is shown in Fig. 8, using the relatively low detection pressure of 0.05 bar (5 kPa). All three suppressants demonstrate similar effectiveness against an

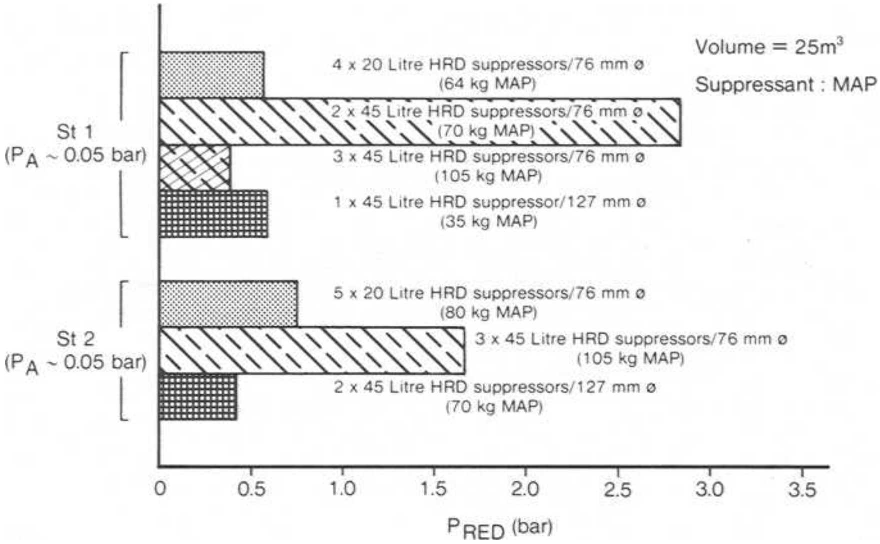


FIG. 6—*25-m³ explosion suppression trials—various suppressors.*

St1 hazard, whereas water proved somewhat ineffective and halon catastrophically failed to suppress the St2 explosion. Comparable tests in the 25-m³ vessel are presented in Fig. 9. In this case halon and water were marginally more effective than the MAP powder against the St1 explosion, but again halon catastrophically failed to suppress the St2 explosion. The "failed" suppressed explosion pressure was higher than the corresponding unsuppressed maize dust explosion pressure, and an extensive cloud of toxic halon pyrolysis products issued out from the vessel gaskets (see Fig. 10). Tests with halon/MAP hybrid suppressant in the 25-m³ vessel (see Fig. 11) also resulted in failed suppression, although the volume of toxic gases released was much less.

Figure 12 presents the results of the explosion suppression trials against St1 maize dust explosions with halon, water, and powder suppressants in the 6.2- and 25-m³ vessels. The influence of the detection pressure P_A on the measured suppressed explosion pressure P_{RED} is indicated for the

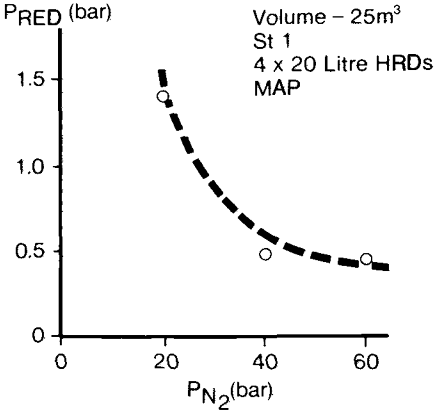


FIG. 7—*Influence of suppressor propelling agent pressure* P_{N2}.

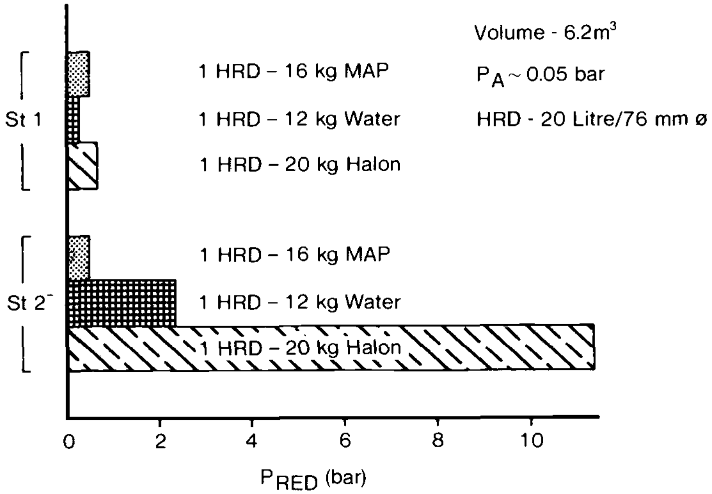


FIG. 8—*6.2-m³ explosion suppression trials—various suppressants.*

three suppressants. It is evident that the border between effective suppression and catastrophic failure is very marginal for halon suppressant against St1 maize dust explosions, whereas water and MAP powder suppressants have a significant operational range of effectiveness against this hazard.

Discussion and Implications

The results presented above have demonstrated some of the aspects of explosion suppression technology and underline some of the difficulties in assessing the efficacy of a given system. The conclusions about suppression systems and suppressants are, in practice, colored by other constraints prevalent to system applications. Powder suppressant is very effective at suppressing maize dust

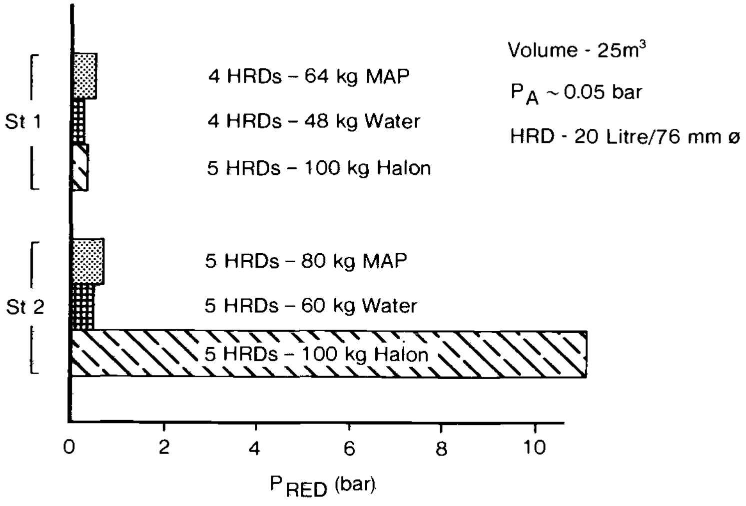


FIG. 9—*25-m³ explosion suppression trials—various suppressants.*

FIG. 10—*Failed suppression showing release of pyrolyzed halon.*

explosions, and since it mixes with the product, it also inerts the hazardous space against reignition—provided that appropriate plant shutdown measures are taken. However, the powder suppressant will contaminate the product. Water suppressant is also very effective, but the water droplets rapidly fall out of suspension after suppressing the explosion, thus providing only minimal reignition protection. Halon is a vaporizing liquid that does not contaminate the product and leaves the hazardous space inert, again provided that the plant is immediately shut down—but its use against explosions of the violence of maize starch cannot be recommended. The observed relative effectiveness of the suppressants reflect calculated values of the critical mass $M_\theta \simeq 8.5$ kg/m^3 for halon and 3.0 kg/m^3 for MAP.

It is interesting to compare test results with calculated reduced explosion pressures P_{RED} derived using the mathematical model which has been outlined above and described elsewhere [5]. Table

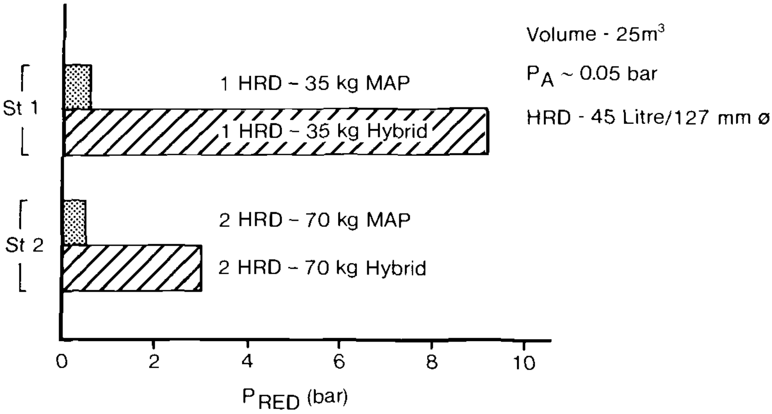


FIG. 11—*25-m^3 explosion suppression trials with "hybrid" suppressant.*

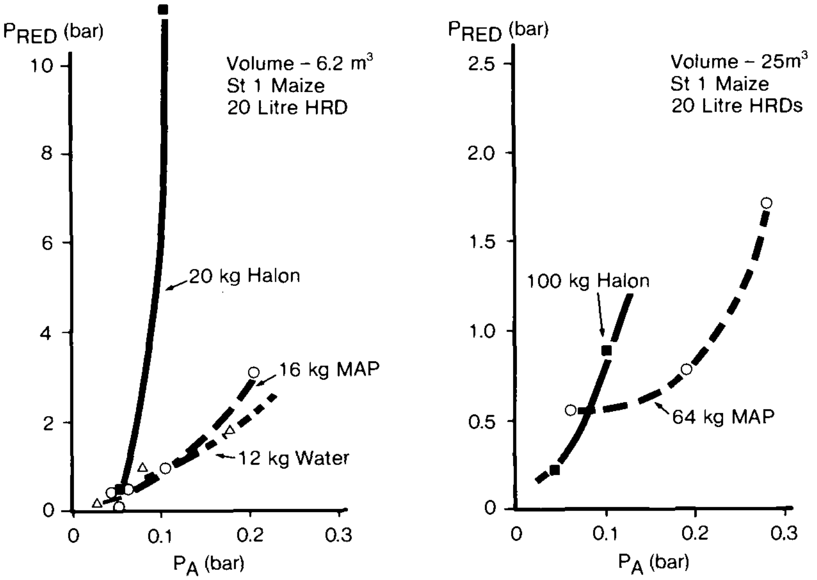


FIG. 12—*St1 dust explosion suppression trials—influence of* P_A.

3 compares the measured and calculated suppressed explosion pressures for the three suppression systems used against an St2 maize dust explosion in the 25-m³ vessel. A similar analysis for the results of Fig. 9 is presented in Table 4. Note that there is a reasonable correspondence between the measured and calculated values of P_{RED} and that the failed suppression observed corresponds with a prediction of "failed suppression." Figure 13 compares the calculated and measured values of P_{RED} for all suppressed maize dust explosion tests undertaken in the 25-m³ vessel. The correspondence is scattered, but the measured suppressed explosion pressures are generally lower than that calculated, thus demonstrating that the calculation errs on the side of safety and that such analysis can provide a more meaningful design guide for a given application than can, perhaps, interpolation from test results in another volume with a different suppressor configuration.

Conclusions

This research has shown that the effectiveness of suppression measures against maize dust explosion hazards is more dependent on choice of suppressant and speed of deployment of the suppressant than on absolute suppressant concentration.

TABLE 3—*Comparison of measured with calculated* P_{RED}—*various suppressors (suppressant: MAP).*[a]

Maize Dust Explosion Class	Suppression System	Measured P_{RED}, bar	Calculated P_{RED}, bar
St2	5 × 20 L HRDs/76 mm Ø	0.75	0.77
St2	3 × 45 L HRDs/76 mm Ø	1.66	fail
St2	2 × 45 L HRDs/127 mm Ø	0.41	0.64

[a] 1 bar = 100 kPa.

TABLE 4—*Comparison of measured with calculated* P_{RED}*—various suppressants*[a]

Maize Dust Explosion Class	Suppression System	Measured P_{RED}, bar	Calculated P_{RED}, bar
St1	4 HRDs—64-kg MAP	0.56	0.54
St1	4 HRDs—48-kg water	0.39	0.32
St1	5 HRDs—100-kg halon	0.24	0.58
St2	5 HRDs—80-kg MAP	0.75	1.01
St2	5 HRDs—60-kg water	0.54	0.62
St2	5 HRDs—100-kg halon	11.20	fail

[a] 1 bar = 100 kPa.

Increasing the size of the suppressors by a factor greater than two does not result in a corresponding halving of the number of suppressors required unless this size increase corresponds with an increase in suppressor outlet area.

Mono-ammonium phosphate and water suppressants have been demonstrated effective against maize dust explosion hazards, but for both Halon 1011 and Halon 1011/MAP hybrid, the border between an effective suppression and catastrophic failure is very marginal.

Acknowledgment

The experimental tests were undertaken at Graviner Ltd. and at Ciba Geigy Central Safety Division. I thank Dr. W. Bartknecht for his guidance and helpful interpretation of the results, and the experimental workers for their dedication during an arduous program of tests.

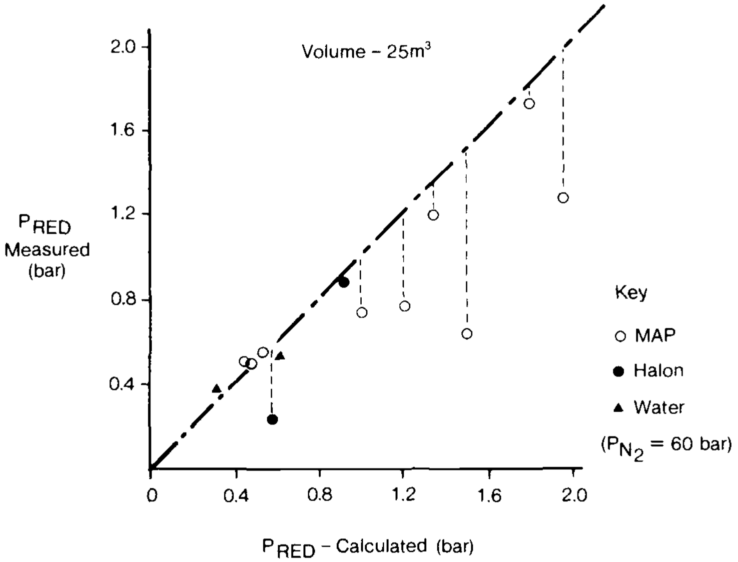


FIG. 13—*Comparison of theoretical and experimental reduced explosion pressures.*

References

[1] Moore, P. E. and Bartknecht, W., paper presented at 5th International Symposium—Loss Prevention & Safety Promotion in Process Industries, 18 Sept. 1986, Cannes France.

[2] Larsen, E. R., *Journal of Fire Flammability*, Vol. 2, No. 5, 1975.

[3] Moore, P. E., in *Proceedings of the International Colloquium, Explosibility of Industrial Dusts*, Polish Academy of Sciences, Warsaw, Nov. 1984.

[4] Perlee, H. E. et al., "Flammability Characteristics of Selected Halogenated Hydrocarbons," U.S. Bureau of Mines RI 6748, 1966.

[5] Moore P. E., PhD thesis, "Propagation and Suppression of Gas and Dust Explosions," University of Surrey, Guildford, U.K., 1981.

Narayanan Rajendran[1]

Grain Dust Probes—Calibration and Measurement

REFERENCE: Rajendran, N., "**Grain Dust Probes—Calibration and Measurement,**" *Industrial Dust Explosions, ASTM STP 958,* Kenneth L. Cashdollar and Martin Hertzberg, Eds., American Society for Testing and Materials, Philadelphia, 1987, pp. 294–309.

ABSTRACT: In situ light attenuation and backscattering probes were designed, fabricated, and calibrated for monitoring the dust levels in grain elevators. The calibration was performed both in a dust cloud chamber using mixed grain dust and in an elevator facility with various types of grain. The true dust concentration was determined with an isokinetic sampling probe.

KEY WORDS: dust probes, grain dust monitoring, attenuation probe, backscattering sensor, dust probe calibration

The elevator leg has been identified as the most dangerous location in grain handling facilities with respect to the initial or primary source of dust explosions [*1*]. The leg has all the basic elements necessary for the occurrence of a dust explosion: ignition sources, fuel (grain dust), oxygen (air), and a confined volume [*2*]. Airborne dust concentrations in operating elevator legs may be frequently above the lower explosive limit (LEL). At present, no reliable technique exists to measure accurately grain dust levels in the legs of bucket elevators. Current methods lack acceptable calibration, give poor reproducibility, and are unable to deal with high concentrations of grain dust.

In a recent study [*3*], five grain dust measurement techniques were evaluated in a dust cloud chamber using mixed grain dust. In situ light attenuation and backscattering probes were determined to be the most promising techniques for use as dust monitors in elevator legs. This paper presents the dust concentration levels in grain elevator legs measured with the light attenuation and backscattering probes. The probes were evaluated and calibrated in a research elevator. The calibrated probes are currently being used to measure dust levels in active grain elevators as part of an ongoing study.

Probes and Samplers

Backscattering Aerosol Monitor (ORNL)

The backscattering aerosol sensors used in this study were fabricated based on the design of Oak Ridge National Laboratory (ORNL). The circuit diagram for the monitor is shown in Fig. 1. A complete description of the ORNL sensor and its operation and calibration can be found in Ref *4*.

The ORNL aerosol monitor system consists of a light scattering sensor and an electronic readout module (see Fig. 2). The sensor is a commercially available assembly (Optron OPM-710) consisting of a light emitting gallium arsenide diode mounted directly beside a high gain phototransistor. The

---

[1] Research engineer, IIT Research Institute, 10 W. 35th St., Chicago, IL 60616.

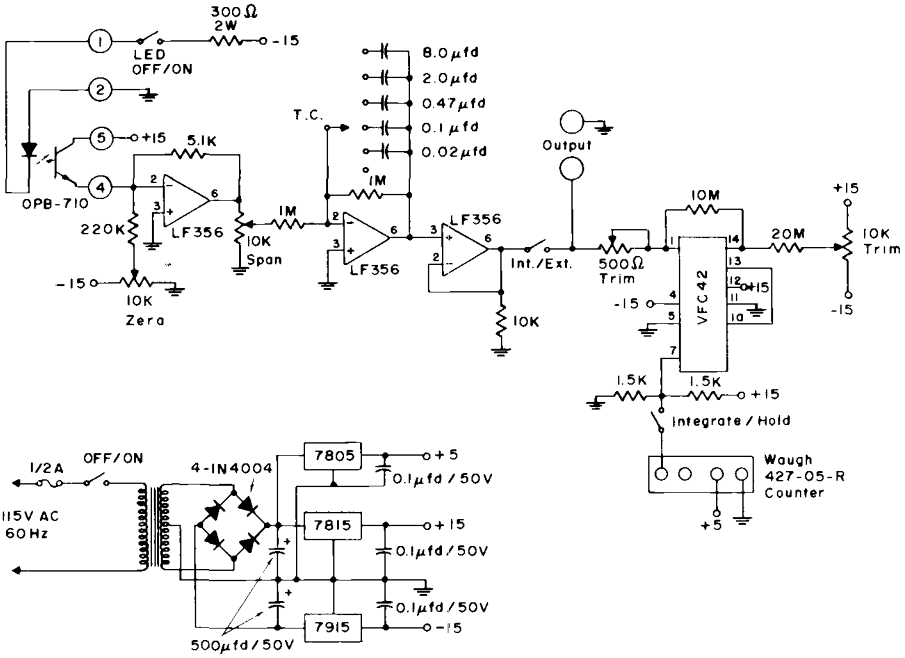


FIG. 1—*Circuit diagram of ORNL backscattering probe.*

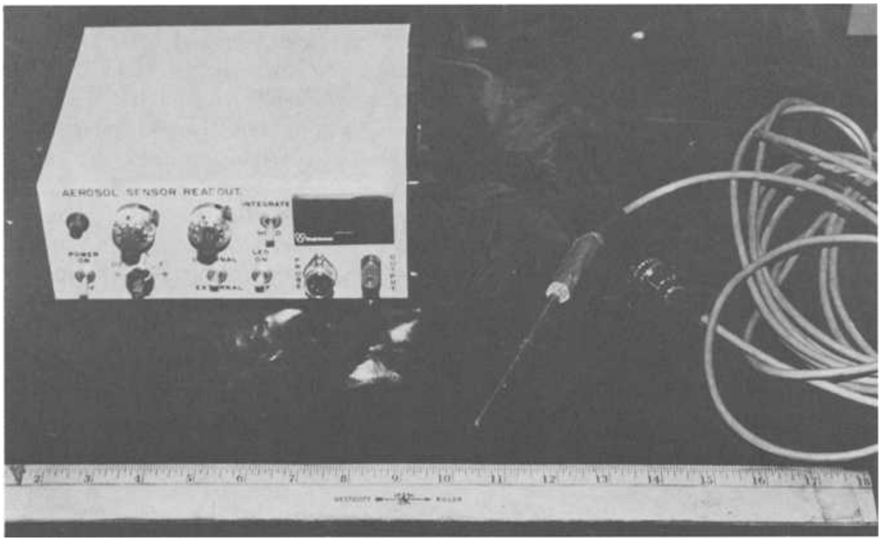


FIG. 2—*ORNL backscattering aerosol sensor and module.*

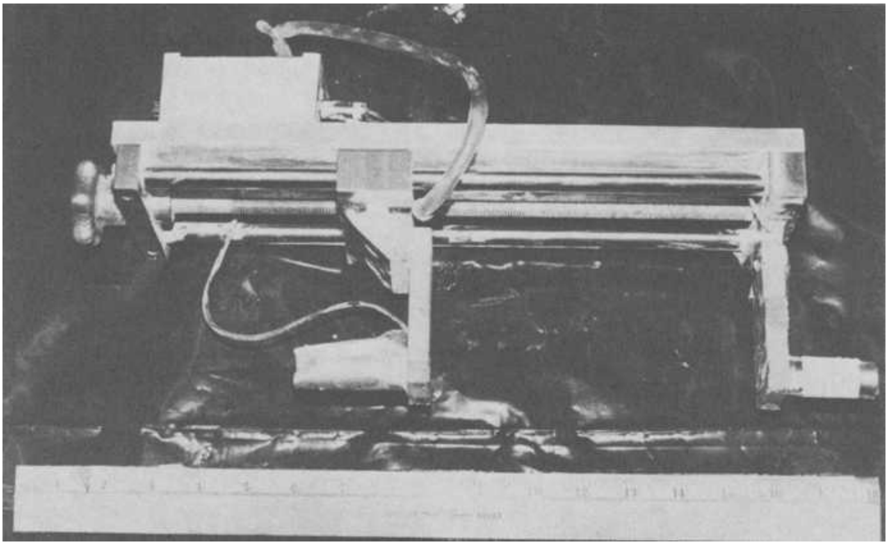


FIG. 3—*Modified USBM light attenuation probe.*

LED and the phototransistor are mounted in the end of a ¼-in. (0.6-cm) outside diameter (OD) probe. The LED emits light in the near-infrared region (~900 nm). The emitted light is scattered by dust particles in the vicinity, and the backscattered light is detected by the phototransistor.

The readout module contains the circuitry to power the LED and to condition, amplify, and display the signal from the phototransistor. The signal is routed in analog form to a chart recorder. An integrating system with a digital display sums the signals.

Light-Attenuation Monitor (USBM)

The light-attenuation monitor (Fig. 3) used in this study was similar to the U.S. Bureau of Mines (USBM) probe except for a few modifications. A complete description of the USBM probe is given in Ref *5* and *6*. The USBM probe had a fixed path length, while the modified probe was designed to function at variable path lengths. The path lengths can be changed continuously from a minimum of 2 in. (5 cm) to a maximum of 9³⁄₁₆ in. (23 cm). A signal conditioning circuit with two-stage signal amplifications and electronic noise suppression was also added to the probe (see Fig. 4).

The basic components of the USBM optical probe are the prong sections, with a path length for light transmission across the open end. Incorporated into the section are an LED source and a photodetector. The LED emits light in the near-infrared region with a central wavelength of 0.95 μm and a bandwidth of about 0.05 μm. The photodiode is silicon with a response time of 200 μs. Output from the photodetector is fed directly into an operational amplifier. The final voltage output of the amplifier is directly proportional to the input light to the photodiode. The output is recorded on a strip chart recorder.

The LED and photodetector of the dust probe are recessed from the legs, and the lenses are flush with the inner surface of the legs. Pressurized air is fed through internal passageways in the probe to a channeled cover plate; the air then exits from the channel through a 0.5- by 5-mm slit opening to sweep across each window. This flow rate is sufficient to keep the windows of the probe almost dust-free. The air jets have minimal effect on the surrounding dust cloud being measured.

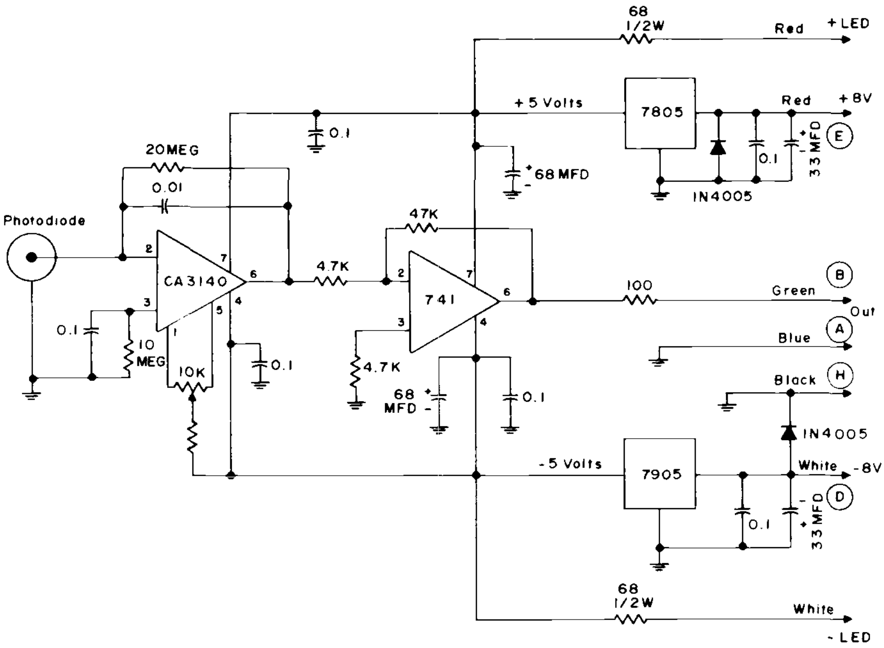


FIG. 4—*Signal conditioning circuit for USBM probe.*

Isokinetic Extractive Sampler

An isokinetic extractive sampler was constructed using the vacuum pump, cyclone separator, and filter of the Aerotherm High-Volume Stack Sampler (Accurex Corp., Mountain View, California). A stainless steel, ½-in. (1.3-cm) diameter probe was used to extract the sample from the elevator leg isokinetically at suitable flow rates. The assembled unit is shown in Fig. 5.

Cumulative gas flow was measured with a Rockwell Model 415 dry gas meter with a digital counter and pointer display having a resolution of 0.005 ft^3(0.000 14 m^3). Gas flow rate was checked with a rotometer (Matheson Gas Products, Tube No. 605) before and after dust sampling.

The vacuum pump is a leak-free, vane-type, Gast Model 1022. The pump has a ¾ horsepower (hp) motor and flow rated at 10 ft^3/min (4.7 km^3/s) at 0 in. Hg. Flow is controlled by both coarse and fine adjustment valves. The leak rate of the pump was measured and found to be within the manufacturer's limit of 0.02 ft^3/min (0.094 km^3/s).

The cyclone and filter assembly were used to catch the sampled dust. The cyclone captures particles of approximately 5 μm and larger in size at 4 ft^3/min (19 km^3/s). Gelman, Type A-E, 142-mm diameter, glass fiber filters were used to collect the smaller particles.

A sampling probe was made from ½-in. (1.3-cm) diameter stainless steel tubing. The interior wall of the probe tip was machined to a sharp edge to serve as the sampling nozzle. The probe was prone to plugging with corn kernels but not with wheat. The corn kernels were caught in the probe, restricting the flow and eventually plugging the probe. To alleviate the plugging problem, two concepts were considered to modify the probe. The first was a wire basket that fit around the probe nozzle; the second was thin wire strands across the nozzle inlet. Tests were also run with a nozzle having three strands. However, these concepts proved to be unacceptable due to sampling bias.

The problem was solved using an open probe and a dry gas meter. During sampling, the flow

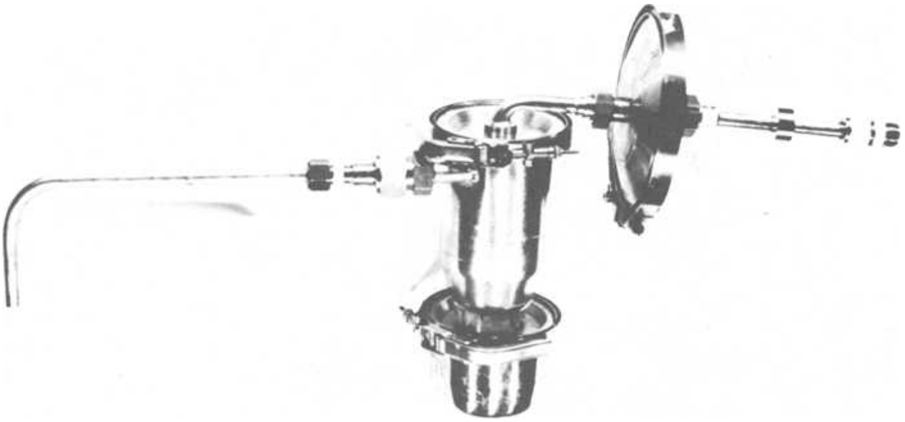


FIG. 5—*Aerothermisokinetic sampler probe.*

was monitored with the dry gas meter and the sampling was stopped when a reduction in the rotational speed of the needle was noticed.

After the sample was taken, the dust collected in the probe and cyclone was removed and sieved using a U.S. Standard size 35 mesh (500-μm opening) screen. The fraction passing through the sieve was considered to be the grain dust and was weighed on an analytical balance. The filter was carefully removed from the filter holder and either weighed on a Metler H31AR analytical balance fitted with an attachment for weighing large size filters, or the filtered dust was brushed from the filter and added to the cyclone catch. Compared to the cyclone catch, the filter catch was insignificant; thus, no error was introduced in the results by brushing the dust from the filter. The dust concentration was calculated by dividing the total mass of dust collected by the cumulative gas flow as determined by the initial and final readings on the dry gas meter. The isokinetic sampler was used as the reference method to calibrate the optical probes.

Probe Calibration and Evaluation

Interference Evaluation

Preliminary testing was undertaken to determine the response characteristics, survivability, and operational problems of the optical probes in an elevator environment.

We anticipated that flying grain kernels in the optical path length might damage the probes and induce artifacts in measurements. Also, the buckets might scatter light into the probes, making the measurements erroneous. These potential problems would have to be resolved.

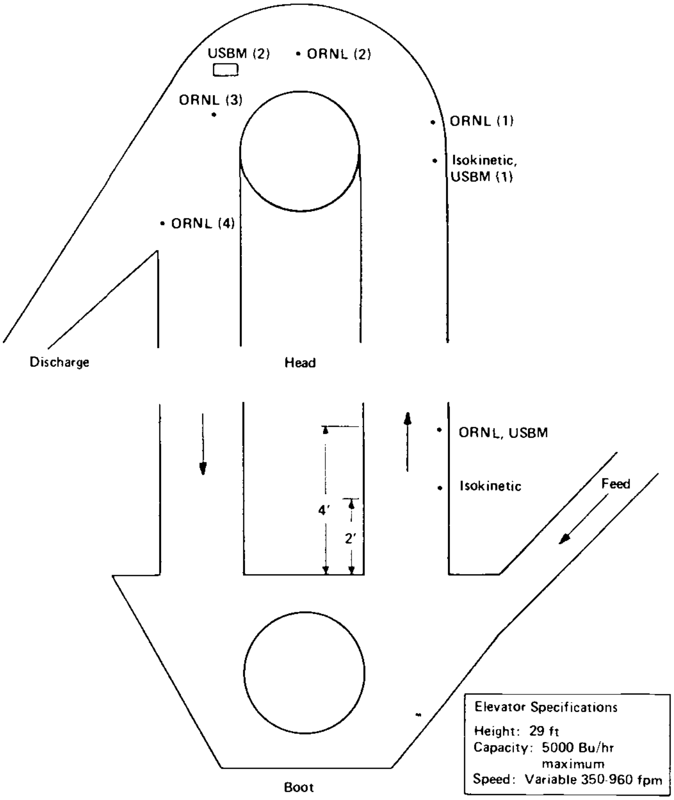


FIG. 6—*Probe locations in research elevator (not to scale).*

The operating variables that might contribute to these potential problems are size of grain, belt speed, grain dustiness, and bucket composition. In commercial elevators, these variables are basically set at one level and cannot be changed easily. Hence, the tests were performed on the research leg and Elevator 7 at the Grain Research Laboratory, Cargill, Inc., Minneapolis, Minnesota.

The sampling locations in the head and boot sections of the research leg are shown in Fig. 6.

In the head of the research elevator, the prime sampling location was on the upside of the leg, position 1. Three alternate locations were provided for the scattering probe and one for the attenuation probe. After setting the belt speed at the desired rate, a velocity traverse was made across the space between the bucket facing and the casing wall. The measurements were made with the Kurz Model 441 air velocity meter.

The velocity in the elevator fluctuated widely. The velocity tended to be high at the edge of the casing and low near the middle. The average air velocity was less than the belt speed.

Probe Calibration

Both probes were calibrated at the dust cloud chamber (Fig. 7) located at IIT Research Institute (IITRI), Chicago, Illinois, using grain dust. The reference dust concentration in the chamber was determined using the Aerotherm sampler and also from the cyclone/fabric filter catch of the dust

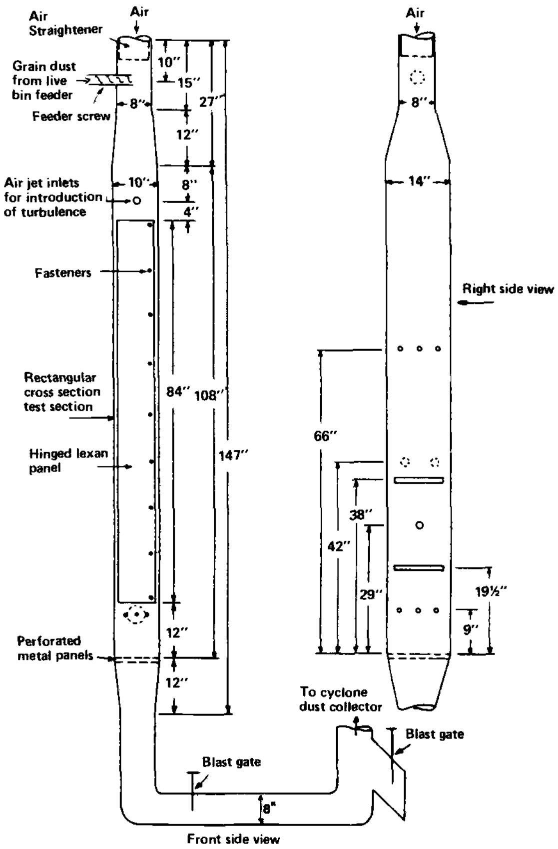


FIG. 7—*Laboratory dust cloud test chamber.*

collector. The dust cloud chamber was employed to establish known dust concentrations at various air velocities to simulate the movement of air and grain dust in a bucket elevator. The test chamber (Fig. 7) was 14 by 10 in. (35.5 by 25.4 cm) in cross section and 108 in. (274 cm) in height. The overall height of the chamber, including the 8-in. (20-cm) diameter inlet and outlet sections and the two transition sections, was 147 in. (373 cm). The chamber was constructed of sheet metal with the two 10-in. (25.4-cm) width sides, front and rear, having 84 by 8-in. (213- by 20-cm) clear Lexan® plastic panels. The front panel was hinged for easy ingress into the test chamber for installation of equipment and monitoring devices. The hinged panel was secured to the chamber with nine screw fasteners. The clear plastic panels were intended to permit visual observation of the dust cloud during the experiments, but the electrostatically charged dust deposited on the panels during testing prevented clear visibility. Application of an antistatic spray did not decrease the dust accumulation noticeably.

Uniform air flow in the duct was accomplished by an air straightener tube bundle placed in the circular inlet of the chamber and a series of two perforated flat metal plates at the bottom of the rectangular cross-sectional portion of the chamber. The tube bundle contained 7-¾-in. (20-cm) long soda straws.

Air flow in the test chamber was controlled by adjusting two blast gates in the 8-in. (20-cm) circular duct connecting the test chamber to the cyclone dust collector. Turbulence equal to that measured in active bucket elevators was achieved by jetting air through two inlets located 35 in. (89 cm) below the top of the chamber.

The grain dust from the Vibra-screw feeder entered at the center line of the chamber 10 in. (25.4 cm) below the inlet. Turbulence distributed the dust throughout the cross-sectional area of the chamber.

Holes and slots were drilled through the chamber walls at various elevations to accommodate samplers, monitors, and probes. Their locations are shown in Fig. 7.

To account for the effects of grain kernels and moving buckets, the ORNL probe and USBM monitor were calibrated in the Cargill research elevator leg in Minneapolis. The reference dust concentration in the leg was measured with the Aerotherm sampler.

The leg was operated at 815 ft/min (4.14 m/s) for all the tests. However, during the interference evaluation phase the belt speed was changed and did not interfere with the probe response. Corn and corn screenings were elevated. Various dust concentration levels were obtained by feeding grain and screenings at different percentages of the rated leg capacity.

Calibration and Evaluation Results

Interference Evaluation

The probes survived the elevator environment and performed satisfactorily. The response of the probes was unchanged by the bucket type and color and belt speed. The isokinetic sampler tended to plug with corn but not with wheat. The plugging problem was solved using a dry gas meter to monitor the sampling flow rate. The sampling was terminated when a reduction in the rotational speed of the meter needle was noticed.

Calibration

A total of 16 tests were performed in the laboratory dust cloud chamber; the results are listed in Table 1. The reference concentration as measured by the Aerotherm isokinetic sampler agreed very well with the concentration measured from the cyclone and filter at the exit of the test chamber (see Columns 3 and 4 of Table 1). The isokinetic dust concentration was correlated to the probe response. Using the transmission data from Column 5 of Table 1, the attenuation probe regression equation was

$$ln(T) = -0.000\,81 \cdot L \cdot C$$
$$r^2 = 0.99;\ \text{significance level} > 0.99$$

where

T = fractional transmission,
L = path length in inches, and
C = dust concentration in grams per cubic metre.

Using the data from Column 6 of Table 1, the regression equation for the backscatter probe was

$$\text{Response (mV)} = -1.5 + 0.98C$$
$$r^2 = 0.99;\ \text{significance level} > 0.99$$

where C = dust concentration in grams per cubic metre.

The laboratory calibrations, however, do not account for the interference from grain movement.

Figures 8 and 9 present the calibration curves obtained in the research elevator and the laboratory calibration data. For the attenuation probe, the regression equation was

$$ln(T) = -0.000\,86 \cdot L \cdot C$$
$$r^2 = 0.92;\ \text{significance level} > 0.99$$

TABLE 1—*Calibration data from the laboratory cloud chamber.*

		Measured Reference Concentration, g/m³		Optical Probe Response[b]	
Test	Flow Velocity, m/s	Aerotherm Isokinetic Sampler	Cyclone Plus Filter Catch[a]	USBM Transmission, %	ORNL Scattering Response, mV
1	1.3716	11.6	11.9	91.7	13
2	1.3716	35.6	37.2	77.0	36
3	1.3716	48.4	48.2	70.8	46
4	2.794	28.7	29.1	82.0	29
5	2.794	60.8	58.2	62.0	57
6	2.794	94.0	98.0	46.0	92
7	2.794	54.5	56.6	67.0	58
8	2.794	17.1	18.0	88.0	17
9	2.8446	78.6	81.2	54.0	83
10	2.8446	26.1	27.0	83.5	29
11	2.8446	23.6	24.6	83.0	25
12	2.9464	100.1	99.2	49.5	101
13	2.9464	156.8	149.4	33.0	151
14	5.0292	9.8	10.0	90.0	10.2
15	5.0292	16.2	16.8	87.5	16
16	5.0292	110.8	109.0	42.5	112

[a] Collected by the dust collection system at the exit of the cloud chamber.

[b] Span for ORNL: 230; USBM path length: 9 in. (23 cm). This is apparently true for all tests, not just No. 1.

where

T = fractional transmission,
L = path length in inches, and
C = dust concentration in grams per cubic metre.

For the scattering probe, the regression equation was

$$\text{Response (mV)} = 6.8 + 0.95C$$
$$r^2 = 0.93;\ \text{significance level} > 0.99$$

where C = dust concentration in grams per cubic metre.

Figures 8 and 9 show that the laboratory and field calibrations agree to within measurement error.

Dust concentrations below 15 g/m³ were not attainable in the research elevator, and no data were obtained for concentrations below 15 g/m³. Hence, the regression equations are considered valid only for concentrations greater than 15 g/m³. For concentrations lower than 15 g/m³, the laboratory calibration curves were used.

Field Tests

The probes were tested in an active bucket elevator to establish their operation in a typical commercial elevator environment. The elevator facility had an air aspiration dust collection system. Tests were designed to determine the following:

- The effect of grain handling operations such as start of grain flow, shut off, and feed rate on the dust level in the leg
- The variation in the dust level in the elevator, with the aspiration system on, at the designed

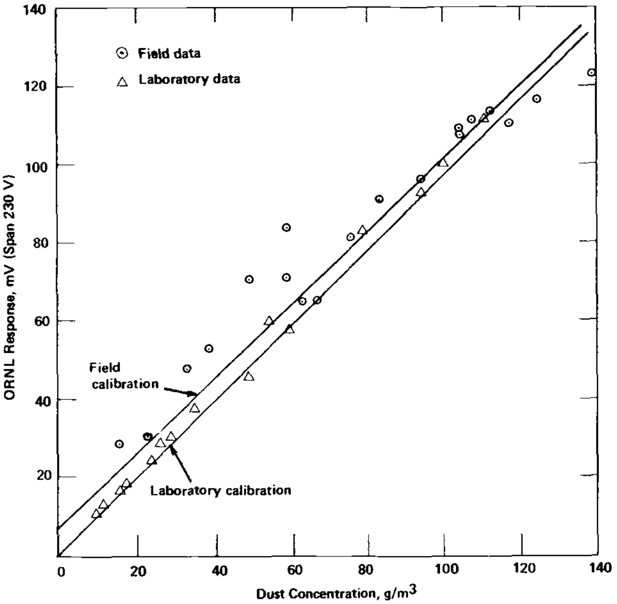


FIG. 8—*Correlation between ORNL backscattering probe and dust concentration.*

flow rate and fractions of designed flow rate. A velocimeter was used to monitor the aspiration velocities.

- The dust level in the elevator legs at various locations.

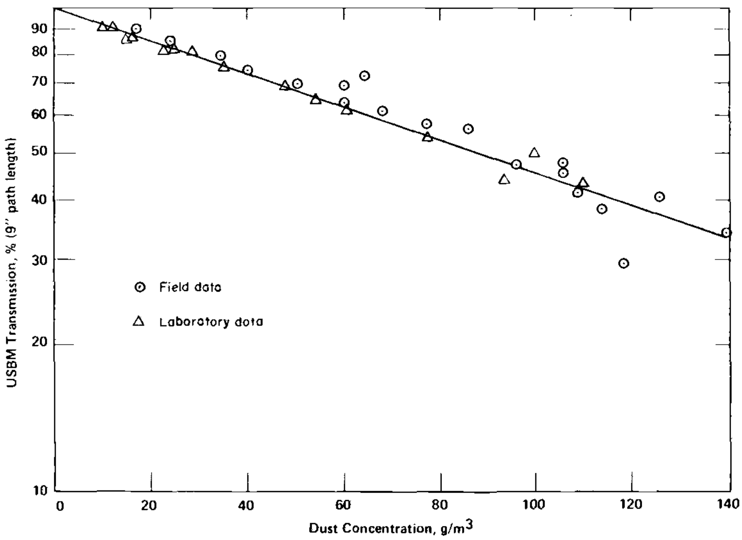


FIG. 9—*Correlation between USBM light attenuation probe and dust concentration.*

Elevator Specifications

Capacity:	5500 Bu/h (194 m^3/h)
Height:	183 ft (56 m)
Head pulley diameter:	60 in. (152 cm)
Head pulley rpm:	41
Belt type:	rubber
Belt speed:	660 ft/min (0.3048 m/s)
Bucket type:	metal and plastic
Bucket size:	12 by 7 in. (30 by 18 cm)
Feed location:	upside, spout type
Aspiration location:	boot: 4 ft (1.2 m) above on both sides of casing head: discharge chute
Aspiration flow rate:	1850 ft^3/min (0.873 m^3/s) at boot and 250 ft^3/min (0.1180 m^3/s) at head
Casing dimension:	12- by 18-in. (30- by 46-cm) upleg; 12 by 18 in. (30- by 46-cm) downleg
Bucket clearance:	¾ in. (2 cm)

Figures 10 and 11 show the head and boot sections of the elevator with probe locations. Because there was very little bucket clearance, the USBM attenuation probe could not be installed and hence no USBM probe data were obtained. Table 2 shows the results obtained for the elevator.

Grain grade influenced the dust level in the boot. The dust concentration in the boot varied from 37 g/m^3 with No. 2 corn to 61 g/m^3 for No. 4 corn. For No. 3 corn, with the aspiration system on, the dust levels in the boot, below and above the pickup point, were 52 and 22 g/m^3 respectively. With the aspiration system off, the levels were 62 and 59 g/m^3, respectively. Dust levels in the head were generally lower than the boot levels. However, ORNL 2 (head), located at the start of grain discharge, showed high dust levels. With full feed and aspiration off, ORNL 2 sensed a dust level of 78 g/m^3 compared to the 11.8 g/m^3 sensed by ORNL 1, located in the head upleg section. Aspiration had only a minor effect on dust levels in the head upleg section, but reduced the dust levels noticeably in the head discharge section.

In a second set of experiments at the elevator, we monitored the effect of grain operations such as grain flow, feed rate, and grain shutoff on dust concentration, as well as the effect of aspiration flow rate on the dust concentration. Dust concentrations in the head and boot were monitored simultaneously.

Figures 12 and 13 are strip chart recordings of the probe response versus dust concentration. Table 3 presents a summary of the results. At the boot, concentration above the aspiration point was strongly affected by the operation of the dust collection system. Variables affecting the generation of dust, such as feed rate and grain cleanliness, also produced noticeable changes in dust levels. Operational changes such as start of grain feed, reduction in aspiration flow rate, and grade of grain resulted in changes in dust level. However, for No. 2 corn there was no difference in dust levels between full and half feed. Steady-state values were reached within a minute of any change.

Conclusions

Two concentration monitors and one sampling method were evaluated to determine their ability to measure reliably the dust levels in grain elevator legs. We investigated

- Aerotherm—an extractive sampling method that used isokinetic sampling and gravimetric determination of the dust collected in a cyclone and filter. This probe requires a casing clearance of 1 to 1½ in. (2.54 to 3.8 cm).

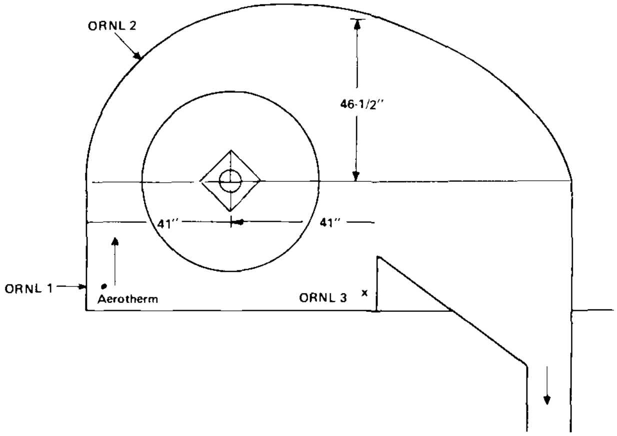


FIG. 10—*Head section of grain elevator with probe location.*

- ORNL—electro-optical probes that were positioned at fixed locations in the elevator leg and measured the light backscattered by the grain dust. The required clearance is 0.5 in (1.3 cm).
- USBM—an electro-optical probe that was positioned in the leg and measured the reduction in light transmission caused by the grain dust across a preset path length. The clearance required is 1 in. (2.54 cm).

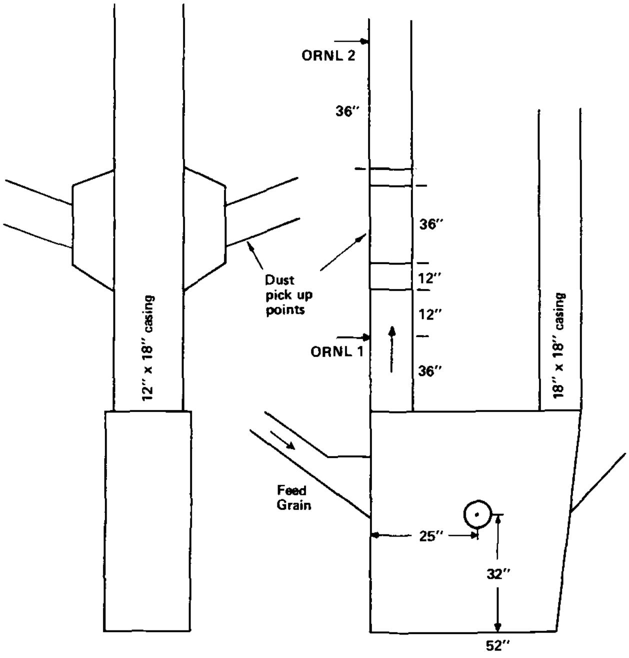


FIG. 11—*Boot section of grain elevator with probe locations.*

TABLE 2—*Elevator test results (grain, No. 3 corn; weather, rainy, cloudy; temperature, 50 to 60°F [10 to 15.5°C]).*

Test Conditions			Dust Concentration, g/m^3[a]				
Location	Feed	Aspiration	ORNL 1	ORNL 2	ORNL 3	USBM	Aerotherm
Head	full	on	9.8	51	9.8	. . .[b]	10[c]
	full	off	11.8	78	10.8	. . .	16
	half	on	5.9	26.5	12.7	. . .	8
	half	off	7.8	44.1	15.7	. . .	13
Boot	full	on	52	21.6	. . .	. . .[b]	. . .
	full	off	61.8	59	. . .	. . .	. . .
	half	on	27.5	9.8	. . .	. . .	. . .
	half	off	50	53	. . .	. . .	. . .

[a] Measurements obtained simultaneously.

[b] Probes could not be placed due to tight clearance.

[c] Aerotherm sample obtained from the side.

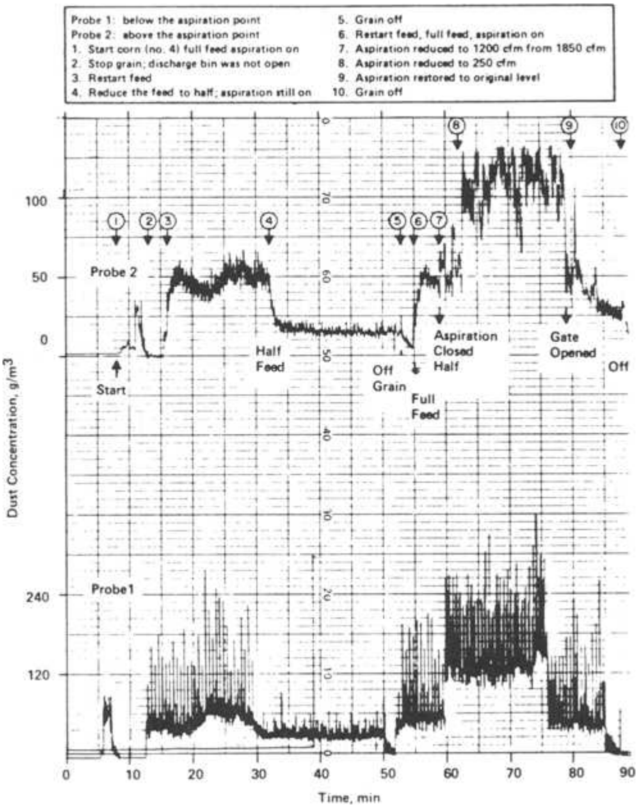


FIG. 12—*ORNL probe response in boot, No. 4 corn.*

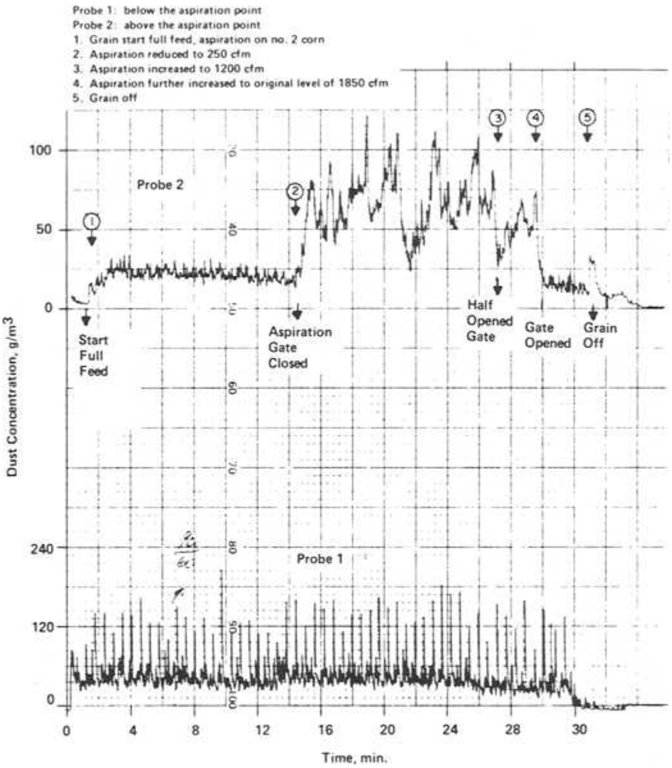


FIG. 13—*ORNL probe response in boot, No. 2 corn.*

TABLE 3—*Dust concentration in elevator (ORNL probe).*

Conditions			Dust Concentration, g/m³		
			Boot		
Grain	Feed	Aspiration Flow Rate, ft³/min[a]	Below Aspir. Probe 1	Above Aspir. Probe 2	Head Probe 3
No. 4 corn	full	1830	61	49	103
	half	1830	29	15	10
	full	1200	61	55	147
	full	250	137	106	147
No. 2 corn	full	1830	37	20	. . .
	half	1830	36	19	. . .
	full	1200	49[b]	49	. . .
	full	250	67[b]	68	. . .

[a] 1 ft³/min = 0.000 471 9 m³/s.

[b] Initial reading of the probe was −7 mV.

One USBM probe was fabricated with the following modifications:

- The path length could be varied from 2 to 9 in. (5 to 23 cm).
- A signal conditioning circuit was added to eliminate background interference and to smooth out the fluctuation.
- Collimating lenses were added to the optics.

Three ORNL probes were fabricated as per the design provided by Oak Ridge National Laboratory. No major modifications were made.

The probes were first evaluated and calibrated in a laboratory chamber and in the research elevator at Cargill Grain Research Laboratory, Minneapolis, Minnesota. The elevator tests were run at various grain feed rates and belt speeds. Two types of buckets were installed to check out the possible interference from the bucket. Three types of grain were tested: corn, corn screenings, and wheat. Aerotherm results were used as the reference method to determine the true concentration of dust inside the elevator legs. The responses of the other techniques were translated into dust concentrations with Aerotherm results. The results of the initial evaluation are given below.

- *Aerotherm* performed satisfactorily for wheat and corn screenings. For corn, however, probe plugging was a major problem. Probes with wire strands at the inlet were used to alleviate the plugging problem. The plugging was eliminated, but sampling bias was introduced. The problem was circumvented with the use of an open probe and a dry gas meter to monitor the flow rate. When a reduction in flow rate was noticed, the sampling was stopped.
- *ORNL* probes operated satisfactorily: they survived the elevator environment and there was no interference due to grain kernels and various types of buckets. At colder temperatures, below 32°F (0°C), the probe had to be cleaned often to remove dust deposits on the probe head, but this was not a major problem to clean. The probe is small, easy to manipulate, portable, and provided both instantaneous and time-integrated response. It responded to dust concentrations very well with adequate sensitivity and resolution.
- *USBM* operated satisfactorily for all the conditions. The probe survived the harsh environment inside the legs. There was no interference as a result of grain kernels and the bucket movement for both plastic (white) and metal buckets. The probe operated satisfactorily even at temperatures of −5°F (20.5°C). However, the sheath air system required water and oil filters to prevent condensation on the lens.

The ORNL sensors were used to measure dust concentration levels in one operating commercial elevator. The elevator had an aspiration-type dust collection system. The dust concentration was monitored in the head and boot. Tests were run to determine the effect of aspiration, grade of grain, feed rate, and location in the leg.

We drew the following conclusions from the field tests:

- It was possible to place ORNL and USBM probes in the elevator; the elevator had less than a ¾-in. (2-cm) bucket clearance.
- All the probes survived the elevator environment.
- The probes were sensitive and able to follow the changes in dust level in real time.
- Some of the measured dust concentrations in the elevators may have been above the lower explosive limit, which is of the order of 50 g/m^3 for fine wheat and corn dust [7].
- The dust aspiration system reduced the dust level downstream. However, there were several locations upstream of the dust pickup point that had dust levels greater than 40 g/m^3.
- Dust concentration generally decreased as a function of location height.
- Grain feed rate had a strong effect on dust level; a reduction in feed rate reduced the dust level significantly. Grain cleanliness also had a noticeable effect on dust concentration.
- The dust concentration in the head was lower than in the boot section. Also, the aspiration system had only a minor effect on the dust level in the head.

- Tests with varied aspiration flow rates showed that the dust level increased with a decrease in flow rate. An optimal aspiration system should capture the maximum amount of dust generated without the suction of grain.

Acknowledgments

This study was sponsored by the National Grain and Feed Association.

The author gratefully acknowledges the technical direction, advice, and support of the National Grain and Feed Association and the suggestions of its Dust Explosion Committee.

The Grain Research Laboratory, Cargill, Inc., Minneapolis, Minnesota, provided the research elevator facility for interference evaluation and probe calibration. The contribution of Bruce Moechnig of the Grain Research Laboratory is acknowledged.

In addition, Dr. Kenneth Cashdollar of the U.S. Bureau of Mines provided valuable assistance in fabricating the light attenuation probe. Dr. Tom Gayle of Oak Ridge National Laboratory assisted in the fabrication of the backscattering probe.

References

[1] Verkade, M. and Chiotti, P., "Literature Survey of Dust Explosions in Grain Handling Facilities: Causes and Prevention," Energy and Minerals Resources Institute, Iowa State University, Ames, IA, 1976.

[2] Manness, J., "Industry Views on the Problems of Grain Elevator Explosions" International Symposium on Grain Elevator Explosions, National Academy of Sciences, Washington, DC, 1978.

[3] Stockham, J. and Rajendran, N., "Establishing a Reliable Grain Dust Measurement Technique for the Bucket Elevator," DCE-84-080, Report to National Grain and Feed Association, July 1984.

[4] Moneyhum, J. H., Gayle, T. M., and Homberg, R. W., "ORNL Aerosol Particle Sensor—Description, Operation, and Calibration," Oak Ridge National Laboratory, Oak Ridge, TN, 1982.

[5] Liebman, I., Conti, R. S., and Cashdollar, K. L., "Dust Cloud Concentration Probe," *Review of Scientific Instruments,* Vol. 48, No. 10, Oct. 1977, pp. 1314–1316.

[6] Cashdollar, K. L., Liebman, I., and Conti, R. S., "Three Bureau of Mines Optical Dust Probes," Report of Investigation 8542, U.S. Bureau of Mines, Washington, DC, 1981.

[7] Jacobson, M., Nagy, J., Cooper, A. R., and Ball, F. J., "Explosibility of Agricultural Dusts," Report of Investigation 5753, U.S. Bureau of Mines, Washington, DC, 1961.

Douglas H. Napier[1] *and Denver R. Roopchand*[1]

Ignition Probability of Hybrid Mixtures

REFERENCE: Napier, D. H. and Roopchant, D. R., "**Ignition Probability of Hybrid Mixtures,**" *Industrial Dust Explosions, ASTM STP 958,* Kenneth L. Cashdollar and Martin Hertzberg, Eds., American Society for Testing and Materials, Philadelphia, 1987, pp. 310–323.

ABSTRACT: The behavior of hybrid mixtures (combustible dusts and flammable gas in air) has been studied at concentrations near to the lower limit. The mixtues were comprised of polyethylene particles (5 to 50 μm and 30 to 44 μm) and either ethylene or methane. Experiments were undertaken in a modified Hartmann vertical tube apparatus with a resistive/capacitive spark discharge circuit. The measured variables in the system were: dust concentration, addition of flammable gas, total ignition energy, and rate of its delivery to the spark channel. Thereby, minimum ignition energies (MIE) given in terms of series resistances and lower flammable limits (LFL) were obtained. The results obtained were compared with values in the literature. This led to consideration and reporting of the significance and confidence of experimentally determined values of MIE and LFL. Extensive measurements on the ignition of hybrid mixtures demonstrated that simple additivity does not apply. Probability of ignition was increased by addition of flammable gases, the type of which proved to be of major importance.

KEY WORDS: ignition probability, dusts, flammable mixtures, hybrid mixtures, ignition energy

Mixtures of flammable gas and combustible dusts (that is, hybrid mixtures) have been reported to exhibit anomalous behavior when combusted at near limit concentrations. The behavior of each component of the fuel mixture has been subjected to considerable investigation, and as a result, considerable understanding of the processes involved has been acquired. However, the present understanding of hybrid mixtures is incomplete as it cannot account for their flammability characteristics in low fuel concentration regimes.

Experimental investigation of hybrid mixtures has centered around the coal dust-methane-air system [*1–6*] primarily as a result of the high probability of occurrence of such mixtures in coal mining operations. Hybrid mixtures can also occur in other industrial operations, for example, those in which flammable solvents are removed from powdered dyestuffs, the production and subsequent machining and grinding of polymeric materials where the highly volatile or gaseous monomer may be present, and the storage of powdered footstuffs where methane production may occur. Hybrid mixtures may also be produced during attempts to ignite suspensions of reluctantly combustible dusts. Research has also been conducted with polymeric materials [*7–10*]. The results of these investigations were far from conclusive and primarily served to demonstrate the complex behavior of hybrid mixtures. There is experimental evidence to support an additive interaction between the two fuel phases, which may be anticipated; fundamental to the present understanding of the combustion of dusts is the concept of finite particle burning time [*11*] and a delayed release of volatile fuel matter which is clearly not the case for flammable gas mixtures. Based on present understanding, hybrid mixtures should not exhibit additivity particularly at concentrations below the lower flammable limit (LFL) and the minimum explosible concentration (MEC) as the volatiles from the solid are not immediately available. Experimental results have been adduced of the

[1] Professor of industrial hazard control and research student, respectively, Department of Chemical Engineering and Applied Chemistry, University of Toronto, 200 College St., Toronto, Ontario, Canada M5S 1A4.

possibility of synergistic behavior, wherein hybrid mixtures were found to combust at a total fuel concentration below that predicted using a Le Chatelier-type mixing rule (for example, Refs *5* and *7*).

The minimum ignition energy (MIE) for hybrid mixtures was found to be higher than that for a flammable gas, but significantly lower than that for a combustible dust. As such, hybrid mixtures pose an insidious hazard to industry; the design parameters of LFL, MEC, and MIE may not provide adequate protection against the development of combustion and explosion phenomena of such mixtures.

The aim of the experimental study reported below was to investigate the possibility of synergism, and to establish the values of MIE and minimum fuel limits at conditions where both energy and fuel are limiting.

Review of Pertinent Work

Flammability Limits for Gaseous Mixtures

An investigation of the ignition of hybrid mixtures of necessity must include an examination of the ignition related parameters of flammability limits and minimum ignition energy.

Originally it was thought that "flammability limits (FL) were a specific property of gaseous mixtures under definite conditions of temperature and pressure and independent of the vessel or nature of the ignition source" [*12*]. After many years of extensive research, FLs have yet to be established as such. Research on FLs has been reported by many authors; the topic has also been reviewed extensively (for example, Ref *13*). Hertzberg [*14,15*] has recently reexamined the concept of FLs in terms of limiting burning velocities. He considered a combustion wave in which the heat generated by reaction is dissipated by competitive processes, thereby quenching propagation of the flame. Four competing processes and one complication were identified. These processes would occur in various combinations and to various extents depending on the fuel and its environment. They are: (a) free buoyant convection; (b) convective-conductive wall losses; (c) radiation, and the complication, selective diffusional demixing; and (d) flow gradient effects (flame stretch). From these considerations a list of parameters may be identified that bear on the FLs of gases. This includes the range of data relating to reaction kinetics and thermochemistry and the physical and physiochemical parameters of the system such as the geometry and design of the system, the state of the gas mixture, and the physical properties of the components of the system.

Minimum Ignitable Concentration and Probabilistic Considerations

The parameters referred to in the last section must be carried forward for consideration in the more complex system of dust suspensions in air for which minimum ignitable concentrations (MIC) are determined. Among the features of this system and that of hybrid mixtures is the difficulty of producing a homogeneous dust suspension with minimal flow gradients and turbulence. In some situations, determination of dust concentration is not without difficulties.

In this connection, consideration of the context of a typical spark channel (about 5 mm^3) illustrated the clear difference between gas mixtures and dust suspensions. In a 5% mixture of methane in air this volume would contain 6.7×10^{15} molecules of methane, while in a polyethylene (particle density, 950 $kg.m^{-3}$)/air suspension (30 mg/L) it would contain 38 particles (diameter 20 μm). This number of particles may be altered by gravitational settling, drifting, or by interaction with an electrical discharge. The particle population at the point of discharge will affect the likelihood of ignition. The situation in gas mixtures is basically different as a result of the state of subdivision of matter and to the movement of molecules.

This situation has been illustrated in plots of probability of ignition versus fuel concentration [*16*]. For flammable gas mixtures the transition of probability from 0 to 1 is very sharp, whereas for dusts the transition is gradual and dependent on the magnitude of the ignition energy supplied.

Hence, the specification of the MIC for a combustible dust must be expressed in terms of an ignition probability (IP) coupled to a specific input of ignition energy.

Various types of test apparatus have been and are being used; a large amount of the testing has been undertaken in the Hartmann series of apparatus [*17*]. Sources of ignition both in terms of magnitude [*18*] and rate of release of energy [*19*] present problems in the context of definition of a test.

The probabilistic nature of ignition poses a serious problem, in that a test criterion must be chosen. For example, typically a dust is considered to be nonignitable if perhaps 4 [*20*], 10, or 100 [*21*] trials do not yield ignition.

The criteria for ignition of dusts are not as rigorous as that for gases (propagation through length of a Coward and Jones tube [*22*]). Thus, in the United Kingdom it is any flame propagation away from the ignition source. Other criteria include propagation through the length of the tube [*19*] and the bursting of a paper diaphragm at the top of the tube; the flip-top apparatus has also been used. The statistical significance of these trials is fairly low.

Consider the case where ten ignition trials were performed and no ignitions were observed based on whatever ignition criteria were chosen. Each trial can be considered as a Bernoulli trial with a positive or negative (ignition or no ignition) outcome much like tossing a coin. Let n be the number of trials undertaken, in this case ten; let r be the number of successes in n trials. Let p be the probability of successes or the success rate given by r/n. Let P be the true probability that would be obtained if it were possible to do an infinite number of trials. P, the true probability, will range between a value less than p and one greater than p, p being the best estimate based on the n trials. The width of this range will be determined by:

(1) the sample size n,
(2) the number of successes r, and
(3) the value of statistical confidence being sought.

Using standard statistical tables [*23*] and diagrams (see Fig. 1), the upper and lower bounds of P can be calculated for the given values of n, and r listed above, at various degrees of statistical confidence. The bounds of P are 0 to 0.222, 0.267, and 0.376 for 90, 95, and 99% statistical confidence. If n were increased to 30 ($r = 0$), the limits of P would be 0 to 0.11, 0.13 (from Fig. 1), and 0.17 for 90, 95, and 99% statistical confidence. These mixtures would be classified as being unignitable despite the fact that the true value of P may be as high as 0.222 ($n - 10$, 90%). The ignitability criterion used in obtaining FLs is statistically weak, and may explain some of the variations of experimentally determined FLs quoted in the literature.

In comparing flammable gas and explosible dust mixtures, the processes that take place vary considerably. The solid dust particles are virtually nonvolatile until heated substantially by the ignition source or the flame. As the particle temperature rises, volatile matter is produced. These processes give rise to a characteristic ignition lag in dust-air mixtures, which may be of the order of a few milliseconds to several hundred milliseconds.

The role of radiative heat transfer is also greater for "dusty" gases than for pure gases, as the hot particles are better radiators than gases. In the case of droplets and spray combustion, this heat ahead of the reaction zone can cause vaporization. In the case of dusts, it may lead to pyrolysis, heterogeneous reactions such as oxidative decomposition, and the evolution of volatile fuel components. The principal difference between fuel droplets and polymeric dusts is that the former undergoes evaporation, whereas the latter requires chain processes such as depolymerization and oxidative decomposition to produce gaseous fuel.

Minimum Ignition Energy

The minimum ignition energy for a flammable gas is the least amount of energy required to cause ignition and it is strongly dependent on electrode spacing. As the electrodes are separated,

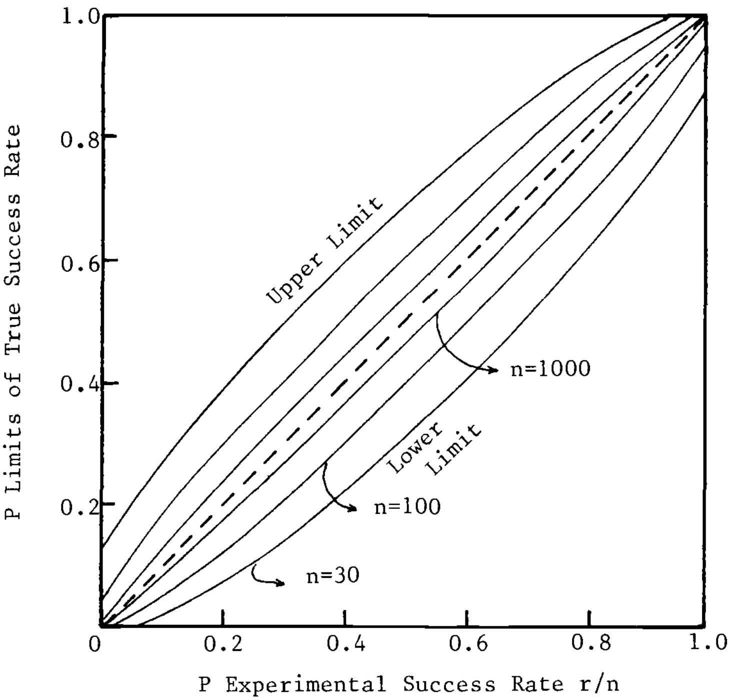


FIG. 1—*Upper and lower 95% confidence limits of* P *based on* p *(obtained experimentally).*

the ignition energy decreases as the heat sink effect of the electrodes decreases. At some separation distance, the ignition energy becomes independent of the amount of separation; this is the electrode quenching distance and the energy is the MIE [*24*]. The MIE is strongly dependent on fuel concentration and is usually obtained for stoichiometric mixtures as these often yield the lowest values of MIE. For hydrocarbons it is typically 0.3 mJ.

The MIEs for dusts have been a source of controversy in that they were originally quoted as being 0.5 CV^2 (C-capacitance, V-voltage) for a capacitive discharge; it was later discovered that much of the capacitor energy was not discharged and the MIE ranged from 5 to 10% of the 0.5 CV^2 [*19,25*]. The addition of a series resistance to the discharge circuit caused a further reduction in the MIE. The actual effects of series resistance are not entirely known. It has been suggested that the resistance caused a prolongation of the spark discharge which reduced the rate of heat loss from the spark channel, also when the resistance is low the spark is bright and sharp and it appears to push the dust out of the spark channel, whereas large series resistance sparks are less bright and do not affect the dust concentration significantly [*25*]. The concentrations used to evaluate the MIE for dusts are often not universally specified and often depend on the test apparatus. Again, a probabilistic estimation must be made as to how many unsuccessful trials constitute an energy level that is just below the MIE.

Experimental Procedure

The polyethylene/ethylene and polyethylene/methane systems were investigated. Attention was focused on dust concentrations ranging from the MIC upwards to about ten times the MIC, with trace addition of flammable gases. The polyethylene was of two types, one with a size range from 5 to 50 μm, and the other was from 30 to 44 μm; both were supplied by Dow Chemical Canada of Sarnia, Ontario and were referred to as TRII powder with a density of 0.905 g/mL. The gases used were commercial grade cylinder gas.

The test apparatus consisted of a modified Hartmann open tube (vertical aluminum column, 38 cm long, 7-cm square internal cross section, volume 1.86 L) with an additional entry provided in the compressed air reservoir for the injection of the flammable gas (this was the only point of addition). The ignition energy was provided by a capacitive discharge circuit with variable series resistance. The apparatus is described in detail elsewhere [*9*]. Measurements of the voltage and current (as a function of time during the discharge) across the spark gap were taken from oscillographs. The oscillographs were interpreted with a Compaq computer via a Houston Instruments Digitizer pad which facilitated the calculation of the total energy delivered, the instantaneous rate of energy delivery, the gap resistance as a function of time, and the average rate of energy delivery.

Several problems have been associated with the Hartmann open tube [*26*]. The primary problems involve the concentration in the spark gap at the time of ignition; there, instantaneous concentrations may be four times the nominal concentration. The concentration depends on the evenness of distribution of dust in the dispersal cup, the turbulent flows to suspend the dust, the time of gap breakdown which in turn depends on the material in the gap, the extent of agglomeration in the dust, and the spark energy. It is assumed that any problems with the open tube will be systematic throughout the duration of the trials or will be statistically smoothed with repeated trials. The experimental goal was to examine the change in ignition frequency with changes in energy, and with the addition of varying quantities of flammable gas to varying quantities of dust.

The procedure consisted of selecting a capacitance typically 2300 pF and a voltage typically 6000 V, the dust concentration (0.03 to 0.3 g/L), the series resistance (12.38 to 50.37 kΩ) and the amount of methane or ethylene (0.1 to 0.4%) were systematically varied. For each set of conditions, 30 attempts at ignition were made. The ignition criterion used was flame propagation away from the spark gap judged over 30 events by a trained observer through a glass plate forming 1 wall of the column. The dust concentration is a nominal concentration based on the quotient of the weight added to the dispersion cup and the volume of the cloud as observed visually in the tube over several hundred trials. Information on the discharge characteristics of the system, that is, effects of series resistance on total energy delivered, spark duration, average rate of energy release, and percentage of total energy discharged in 20% intervals of total spark duration are provided in Fig. 2 and Table 1. These results were obtained from oscillographs, with air alone in the spark gap, that is, no fuel. This would ensure similar turbulence effects. The total energy delivered was high at high series resistance and low at low series resistance, but the decreasing trend is not constant over the range of series resistance chosen.

Spark duration was of the order of 1 ms and decreased with decreasing resistance (for example, 19% decrease for a decrease in series resistance of 75%).

No simple trend appeared in the variation of average rate of energy release with series resistance. On Fig. 2 it appears that as series resistance decreases the energy delivered tends to be more evenly distributed throughout the spark duration. In the 0 to 20% time interval the amount of energy delivered increases with increasing resistance. This may be of significance as the greater energy deposition rate could affect the dust concentration in the gap and the rate of energy losses from the gap.

Results and Discussion

The results of 7800 ignition trials are plotted in Figs. 3 through 10. On Fig. 3, ignition probability is plotted against dust concentration for various values of series resistance. The general trends on Fig. 3 are as follows: increasing dust concentration and higher series resistance give rise to higher ignition probabilities. The addition of 0.13% methane (see Fig. 4) caused an increase in

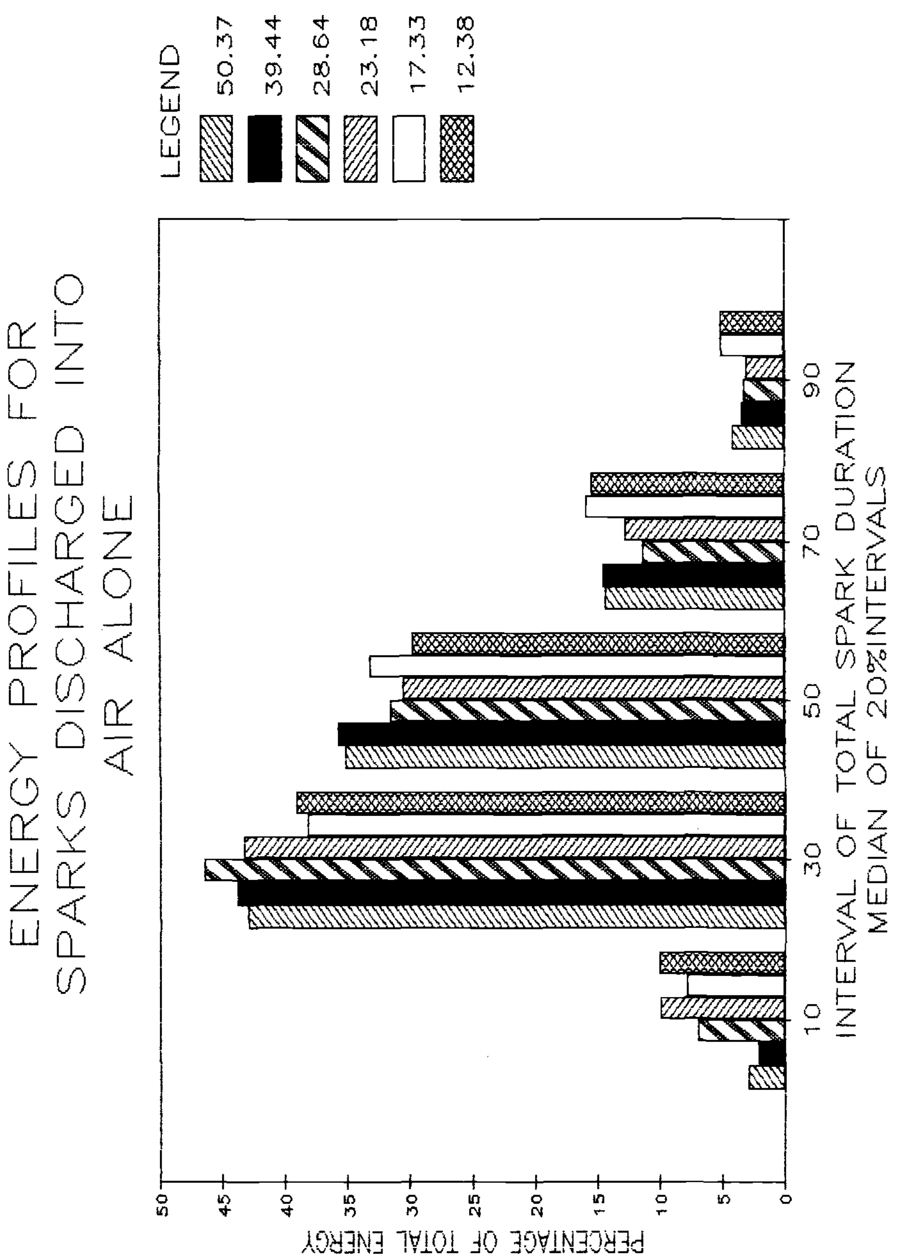


FIG. 2—*Energy profiles for sparks discharged into air alone.*

TABLE 1—*Energy characteristics for sparks discharged into air alone.*

Resistance, kOhms	Total Energy, mJ	Spark Duration, ms	Average Rate of Release, J/s	Percentage of Total Energy Delivered Time Intervals in %				
				0–20	20–40	40–60	60–80	80–100
50.37	4.28	1.08	3.96	3.02	42.99	35.22	14.45	4.29
39.44	3.35	1.04	3.22	2.21	43.9	35.76	14.57	3.54
28.64	3.51	1.04	3.38	7.04	46.5	31.62	11.4	3.36
23.18	3.86	0.99	3.90	9.98	43.32	30.65	12.83	3.19
17.33	3.37	0.85	3.96	7.96	38.27	33.3	16.00	5.18
12.38	2.94	0.87	3.38	10.08	39.23	29.92	15.52	5.21

IP at low dust concentrations and a decrease in IP at high dust concentrations. Further addition of methane (0.26%, see Fig. 5) caused further increases in IP. These increases were, however, dependent on dust concentration and series resistance as there were some combinations of the latter where decreases were observed. At 0.39% methane, IP was generally higher (see Fig. 6). Throughout these figures there are irregular occurrences of local maxima at 0.15 g/L (dust concentration) and to a lesser extent at 0.05 g/L.

The addition of 0.13% ethylene as compared to 0.13% methane produced lower IP; this effect was greatest at low series resistance, where the addition of ethylene inhibited ignition such that the resulting IP was below those for dust without addition of flammable gas (see Fig. 7). At higher concentrations of ethylene (0.26%, see Fig. 8), the IP increased with increases at low series resistance. In comparison with equivalent amounts of methane the ethylene curves were, in general, lower at 0.10 g/L., 0.20 g/L, higher at 0.15 g/L, and at other concentrations the ratio of ignition probabilities of the two gases appeared to be dependent on the series resistance. With further addition of ethylene (0.39%, see Fig. 9), the ratio of ignition probability of the two gases is strongly dependent on the dust concentration and series resistance. There were also irregular

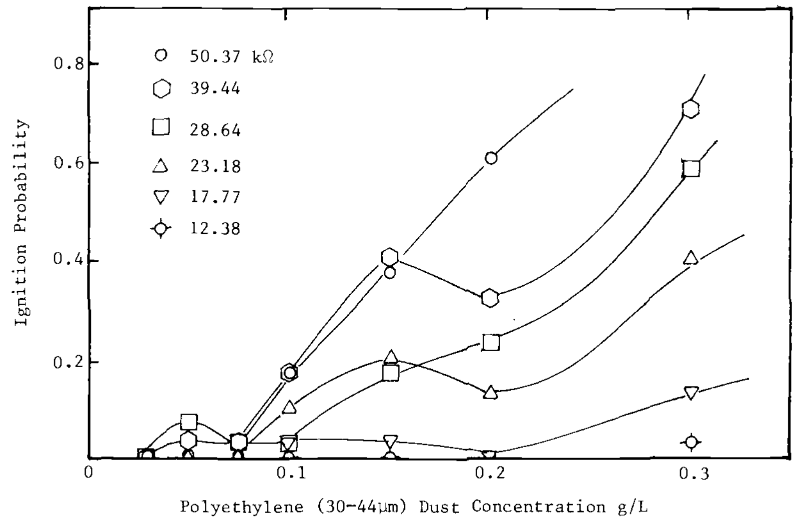


FIG. 3—*Ignition probability versus dust concentration for various series resistances.*

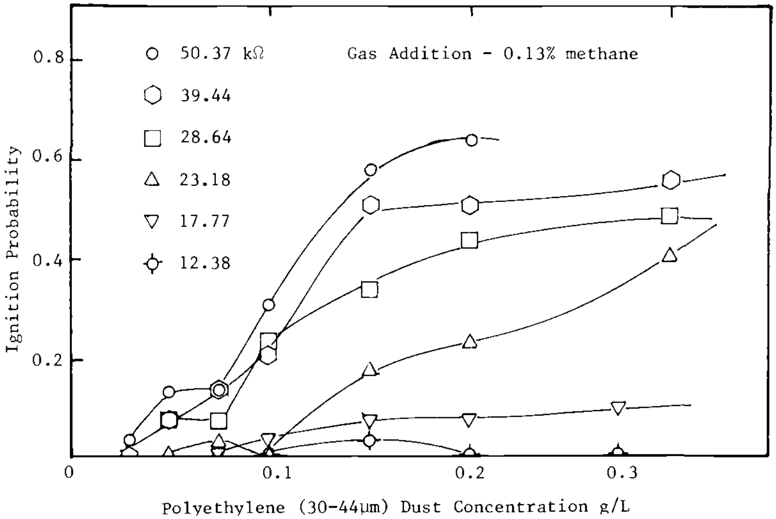


FIG. 4—*Ignition probability versus dust concentration for various series resistances—gas addition 0.13% methane.*

occurrences of maxima (at the same dust concentrations as before) with hybrid mixtures containing ethylene.

Test results obtained with fuel-rich mixtures of finer polyethylene dust particles are shown in Fig. 10. IP increased with increasing series resistance; the dependence of IP on percent methane addition is not linear which is expected for already fuel-rich mixtures. Much lower values of series resistance were required to get an IP of zero. Therefore MIE appears to be strongly affected by particle size. Experiments with this dust were limited as a result of a limited supply.

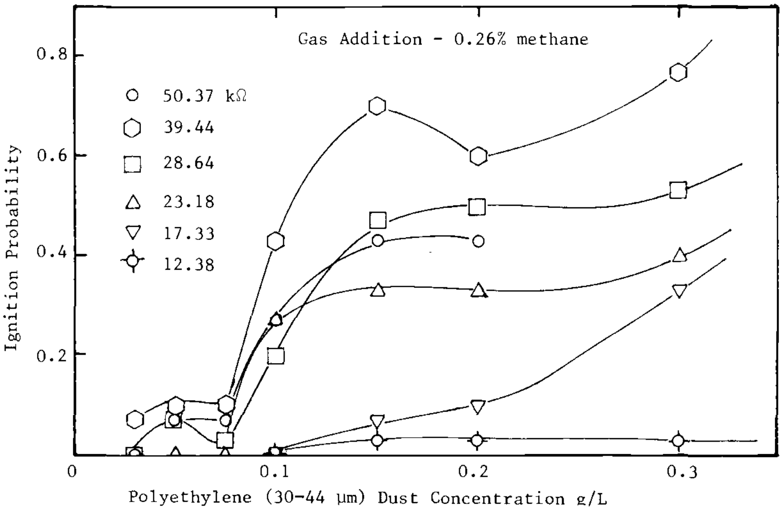


FIG. 5—*Ignition probability versus dust concentration for various series resistances—gas addition 0.26% methane.*

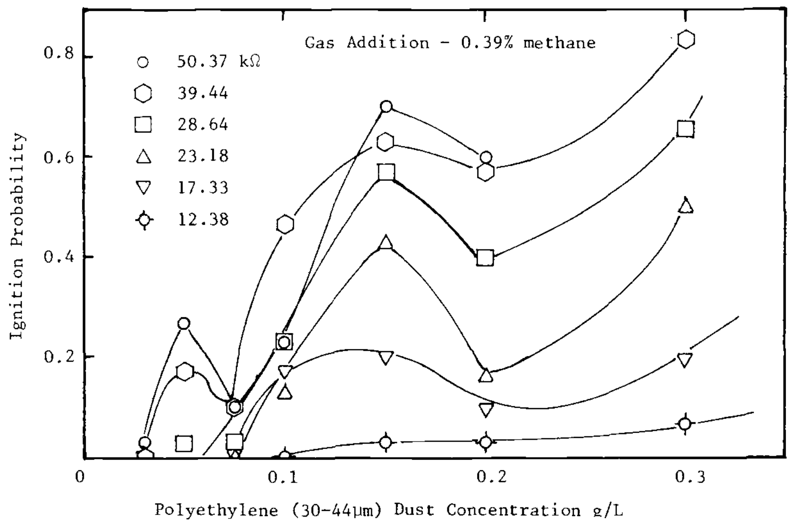


FIG. 6—*Ignition probability versus dust concentration for various series resistances—gas addition 0.39% methane.*

The results obtained indicate that the role of the flammable gas is complex and not a case of simple additivity. If additivity of fuel was the primary effect, then curves similar in shape would be expected for all values of series resistance with increasing IP as the flammable gas concentration increased. Similarly the addition of ethylene should produce higher IPs as 0.13, 0.26, and 0.39% represent a larger percentage of the LFL for ethylene (2.75%) as compared to the same percentages

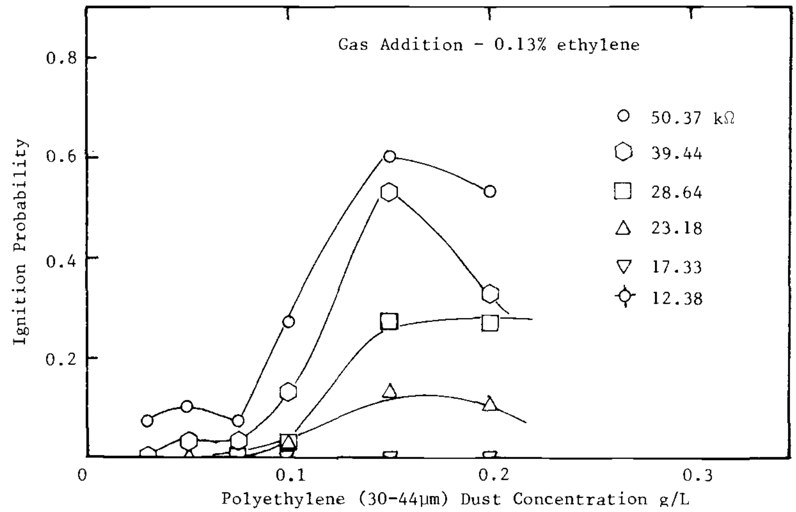


FIG. 7—*Ignition probability versus dust concentration for various series resistances—gas addition 0.13% ethylene.*

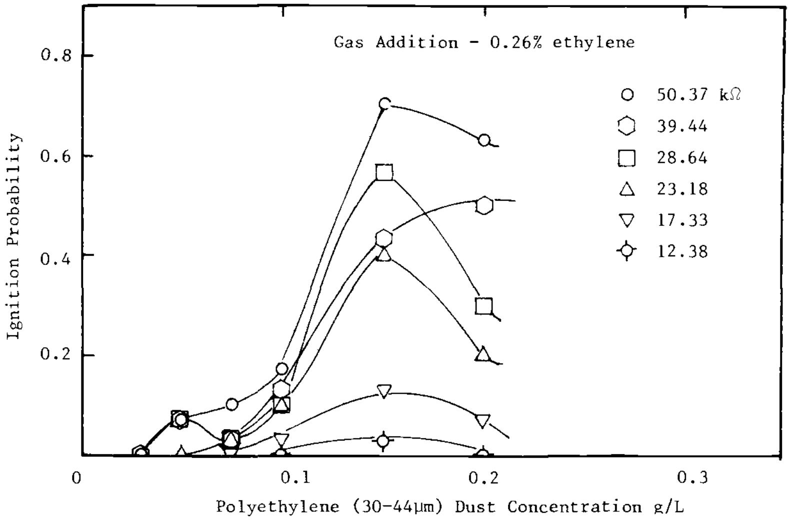


FIG. 8—*Ignition probability versus dust concentration for various series resistances—gas addition 0.26% ethylene.*

for methane (5.0%). In this context, the following comparisons are of interest:

	Ethylene	Methane	Polyethylene [27]
Minimum ignition energy, mJ	0.12	0.29	30–70
Gross heat of combustion, kJ/mol^{-1}	1410	890	. . .
Auto-ignition temperature, °C	490	600 [*28*]	395

Clearly, ethylene is the more reactive gas, and yet there are only limited combinations of dust concentration and series resistance in which it is more effective in promoting ignition than methane.

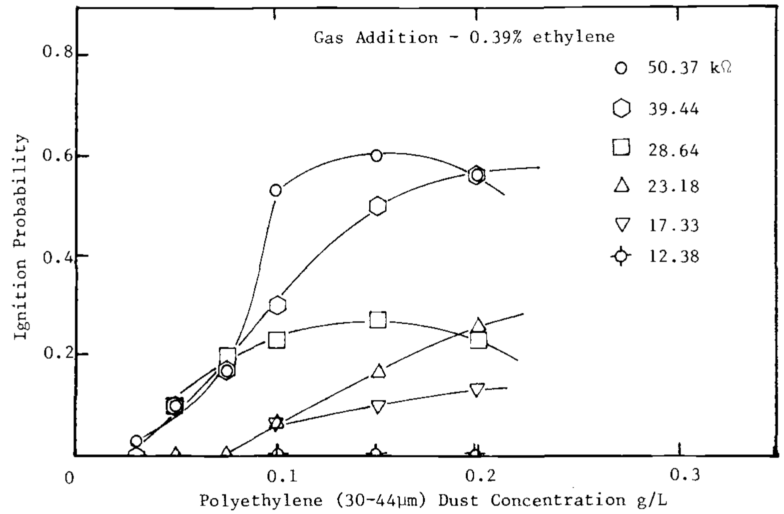


FIG. 9—*Ignition probability versus dust concentration for various series resistances—gas addition 0.39% ethylene.*

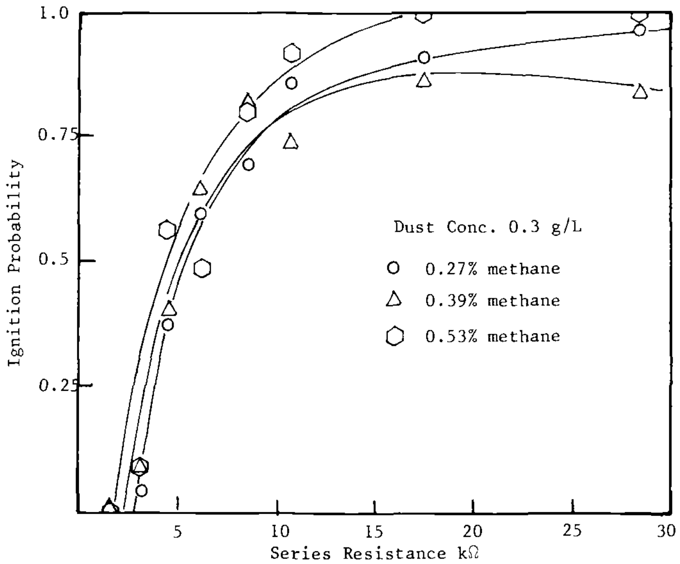


FIG. 10—*Ignition probability versus series resistance for 0.3-g/L polyethylene dust (5 to 50 μm).*

Methane has a higher diffusivity than ethylene, and a lower flame temperature. Based on previous experimental work cited earlier in this paper, these two properties may play a crucial role in the combustion phenomena and partially account for the results observed.

The possibility of synergism is examined using a Le Chatelier-type mixing rule as described by Cardillo [7]. The fuel contributions of gas and dust can be treated as a binary mixture, such that:

$$n_1 = N_1 - \frac{N_1}{N_2} \cdot n_2$$

where n is the volume percentage fuel gas of a component in a limit composition and N is the percentage limit composition of the fuel component itself. Subscripts 1, 2 relate to the components.

Concentrations (in kg/m^3) can also be introduced for percentages of gas and dust. The resulting equation, if Le Chatelier's Rule holds, can be visualized as a linear relation of dust concentration with gas concentration with intercepts at the lower flammable limit of the single components. If experimental points fall below the line produced, that is, are flammable, then synergism has occurred, whereas points falling above the line are considered as evidence of inhibition.

In this experiment, several values of ignition energy were used, and the MIC for polyethylene dust was found to be dependent on these values. At 50.37 kΩ, the MIC for the dust was 0.075 kg/m^3. The LFLs for methane and ethylene from the literature are 0.038 and 0.035 kg/m^3, respectively. Using Le Chatelier's Rule the following equations emerge:

$$D = 0.075 - 2.14\,E \qquad D = 0.075 - 1.97\,M$$

where D, M, and E are dust, methane, and ethylene concentrations in kg/m^3 for limit compositions.

If a dust concentration of 0.05 g/L were used, assuming Le Chatelier's Rule, then the amount of methane required for creation of a limit mixture would be 0.013 kg/m^3 or 1.71%. From the experiments performed, the methane addition required for ignition at the *same series resistance* was found to be 0.13%, a reduction factor in the amount predicted based on an additivity rule of 13. This is evidence for synergistic behavior. Synergistic behavior is also found for ethylene addition. This is contrary to the results obtained by Cardillo, who found perfect additivity for the polyethylene/ethylene system. In this experiment the gas additions were made in increments of 0.13%, which correspond to a concentration change of 0.001 kg/m^3 for methane and 0.0017 kg/m^3 for ethylene. Therefore, with respect to the previous calculations, it can be said that the addition of 0.001 and 0.0017 kg/m^3 of methane and ethylene, respectively, were equivalent to reductions in dust concentration of 0.025 kg/m^3. The situation is further aggravated when the results at 0.03 g/L are considered. Here the same addition of methane and ethylene are equivalent to a reduction of 0.04 kg/m^3 (from 0.075 to 0.03 kg/m^3) in dust concentration which represents a 53% reduction in the MIC at a series resistance of 50.37 kΩ. In practical terms, if a 50% safety margin was used in operating below the MIC, the addition of 0.1% methane could produce an ignitable mixture. The synergistic properties of hybrid mixtures as stated before cannot be explained in terms of conventional flammability theory. Preliminary hypotheses based on this experimental work include the possibility of local regions of combustion in the vicinity of individual particles. This gives rise to local volumes of high temperatures as opposed to the large volumes of high temperature in flammable gas explosions. If the volume that must be heated to the AIT is substantially reduced, then based on previous flammability theory, the quantity of fuel required will also be substantially reduced. This hypothesis requires that particle burning time be short. This may occur, as the surface of the particles may provide sites for reaction of the flammable gas with adsorbed oxygen. The catalyzed oxidation processes would provide additional energy and more efficient heat transfer to the particle to affect a higher rate of heating and hence a shorter particle burning time.

Despite the relatively small changes in spark characteristics with series resistance as discussed earlier, the effects of the latter on ignition probability are very pronounced. A pronounced effect should be apparent in Table 1 and Fig. 2; no such effect is observed. Based on these results it appears that spark duration and temporal rate of energy delivery (0 to 20% interval) are the factors of major importance. This discussion is based on discharges in fuel-free gaps. The presence of fuel may well modify the nature of the discharges, however, it is anticipated that the general trends would remain unchanged.

The minimum ignition energies given in terms of series resistance for mixtures of dust and gas are tabulated in Table 2. For the case of dust alone, the MIE (series resistance) are lowest for 0.10 and 0.15 g/L. With the addition of flammable gas, the series resistance required tended to decrease; there are however, specific examples where increases were noted. These were primarily with the addition of ethylene. The addition of methane in most cases caused a reduction in the series resistance required for ignition.

TABLE 2—*Lowest series resistance required for ignition of mixtures of polyethylene (minus 325 mesh) and methane or ethylene.*

Dust Concentration, g/L	Percentage Flammable Gas Methane/Ethylene			
	0	0.13	0.26	0.39
0.30	nd[a]	12.38/nd	9.37/nd	9.37/nd
0.20	17.33	12.38/17.33	9.37/12.38	9.37/12.38
0.15	12.38	9.37/17.33	9.37/9.37	9.37/12.38
0.10	12.38	12.38/17.33	17.33/12.38	12.38/12.38
0.075	23.18	17.33/28.64	23.18/17.33	23.18/23.18
0.05	23.18	23.18/28.64	23.18/23.18	23.18/23.18
0.03	50.37	39.44/39.44	28.64/39.44	39.44/39.44

[a] nd—not determined.

Conclusions

Based on the experiments performed, the following are concluded:

1. The combustion processes and flammability phenomena of polyethylene dust mixtures are altered with the presence of a flammable gas.
2. The addition of flammable gas does not result in a simple addition of fuel to the system and may produce synergistic behavior.
3. The type of flammable gas is of importance in determining the ignition probability of the mixture. Under most conditions, methane was a better promoter of ignition than ethylene.
4. The examination of the effects of series resistance on properties for discharges into air alone did not produce significant trends to explain the dependence of ignition probability on series resistance other than those of decreasing spark duration and increasing rate of energy delivery early in the spark duration with decreasing series resistance.
5. In general, the addition of flammable gas reduced the MIE of dust mixtures.

References

[*1*] Cybulski, W. B., "Investigations on the Ignition of Methane-Coal Dust Mixtures by Explosives" Paper 11, presented at the 10th International Conference of Directors of Safety in Mines Research, Pittsburgh, PA, Sept. 1959.

[*2*] Singer, J. M., "Ignition of Mixtures of Coal Dust, Methane, and Air by Hot Laminar Gas Jets," presented at the Ninth International Symposium on Combustion, Ithaca, NY, 1963.

[*3*] Singer, J. M., "Ignition of Coal Dust-Methane-Air Mixtures by Hot Turbulent-Gas Jets," U.S.B.M. Report of Investigations 6369, 1964.

[*4*] Singer, J. M., Bruszak, A. E., and Grumer, J., "Equivalences of Coal Dust and Methane at Lower Quenching Limits of Flames and their Mixtures," U.S.B.M. Report of Investigations 6761, 1966.

[*5*] Singer, J. M., Cook, E. B., and Grumer J., "Equivalences and Lower Ignition Limits of Coal Dust and Methane Mixtures," U.S.B.M. Report on Investigations 6931, 1966.

[*6*] Nagy, J. and Portman, W. M., "Explosibility of Coal Dust in an Atmosphere Containing a Low Percentage of Methane," U.S.B.M. Report of Investigations 5815, 1961.

[*7*] Cardillo, P. and Anthony, E. J., "The Flammability Limits of Hybrid Gas and Dust Systems," *La Rivista Dei Combustubili,* Vol. 32, 11–12 Nov–Dec. 1978.

[*8*] Anthony, E. J., "The Determination of the Minimum Explosible Concentration of Polyvinyl Chloride in the Presence of Methane and Air," Fire Research Note 1072, Fire Research Station, Borehamwood, England, Aug. 1977.

[*9*] Sinukoff, R. J., "Ignition Energy of Dust Clouds and Hybrid Mixtures," M.A.Sc. thesis, University of Toronto, 1984.

[*10*] Pellmont, G., "Minimum Ignition Energy of Combustible Dusts and Explosion Behaviour of Hybrid Mixtures," presented at the 3rd International Symposium on Loss Prevention and Safety Promotion in the Process Industries, Basle, Switzerland, 1983.

[*11*] Beer, J. M. and Essenhigh, R. H., *Nature,* Vol. 187, 24 Sept. 1960.

[*12*] Burgess, M. J. and Wheeler, R. V., *Journal of Chemical Society,* Vol. 105, 1914, p. 2591.

[*13*] Lovachev, L. A., Babkin, V. S., Bunev, V. A., V'Yun, A. V., Krivuli, V. N., et al., *Combustion and Flame,* Vol. 20, 1973, pp. 259–289.

[*14*] Hertzberg, M., "The Theory of Flammability Limits: Natural Convection," U.S.B.M. Report of Investigations 8127, 1976.

[*15*] Hertzberg, M., "The Theory of Flammability Limits: Conductive-Convective Wall Losses and Thermal Quenching," U.S.B.M. Report of Investigations 8469, 1980.

[*16*] Rose, H. E., *British Chemical Engineering,* Vol . 15, 3 March 1970, p. 371.

[*17*] Hartmann, I., *Industrial and Engineering Chemistry,* Vol. 40, No. 4, 1948, p. 752.

[*18*] Gibson, N., Maddison, N., Rounsley, J. S., and Stokes, P. S. N., "Assessment of Dust Explosion Hazards; Effect of Changes in Test Methods and Criteria," in *Hazards IX, Institution of Chemical Engineers Symposium Series 97,* 1986, p. 62 and discussion by A. Mitcheson, A. D. Craven, and K. N. Palmer.

[*19*] Hay, D. M. and Napier, D. H., "Minimum Ignition Energy of Dust Suspensions," in *Chemical Process Hazards in Plant Design VI, Institution of Chemical Engineers Symposium Series 49*, 1977, pp. 73–78.
[*20*] Bardon, M. F. and Fletcher, D. E. in *Combustion Institution, Proceedings from Spring Technical Meeting,* Banff, Alberta, May 1982.
[*21*] Eckhoff, R. K., "The Energy Required for the Initiation of Explosions in Dust Clouds by Electric Sparks," M.Phil thesis, University of London, 1970.
[*22*] Coward, H. F. and Jones, G. W., "Limits of Flammability of Gases and Vapors," U.S.B.M. Bulletin 503, 1952.
[*23*] Crow, E. L., Davis, F. A., and Maxfield, M. W., *Statistics,* Coles Publishing Company, Toronto, Canada, 1978.
[*24*] Fells, I. and Lowes, T., *Combustion and Flame,* Vol. 11, 1967, p. 430.
[*25*] Eckhoff, R. K., *Combustion and Flame,* Vol. 24, 1975, p. 53.
[*26*] Hertzberg, M., Cashdollar, K. L., and Opferman, J. J., "The Flammability of Coal Dust-Air Mixtures," U.S.B.M. Report of Investigations 8360, 1979.
[*27*] Hertzberg, M., Conti, R. S., and Cashdollar, K. L., "Spark Ignition Energies for Dust Air Mixtures: Temperature and Concentration Dependences," presented at the 20th International Symposium on Combustion, Michigan, 1984.
[*28*] Robinson, C. and Smith, D., *Journal of Hazardous Materials,* Vol. 8, 1984, p. 199.

C. James Dahn[1] *and Bernadette N. Reyes*[1]

Determination of Metal Sparking Characteristics and the Effects on Explosive Dust Clouds

---

REFERENCE: Dahn, C. J. and Reyes, B. N., **"Determination of Metal Sparking Characteristics and the Effects on Explosive Dust Clouds,"** *Industrial Dust Explosions, ASTM STP 958,* Kenneth L. Cashdollar, and Martin Hertzberg, Eds., American Society for Testing and Materials, Philadelphia, 1987, pp. 324–332.

ABSTRACT: Of major concern in industry are hazards posed by metal-to-metal sparking in environments where potentially explosive dusts are present. The probability of ignition of a dust cloud by metal sparking is dependent on many factors including the type of metal, the contact speed of the metal surfaces, the contact time of the metal surfaces, the pressure on the contact surface, and the type and concentration of the dust cloud present (per Bowden, F. P. and Thomas, P. H., "The Surface Temperature of Slidings Solids," *Proceedings of the Royal Society of London,* Series A, Vol. 223, May 1954, pp. 29–40).

The purpose of the test program was to determine the sparking characteristics of a series of metals and the effects of the sparks produced on several types of hazardous dust clouds. Propellant and black powder dust layers and clouds would be considered as hazardous materials. The test program showed metal sparking could ignite hazardous materials in dust cloud form.

KEY WORDS: dust clouds, metal-to-metal sparking, hazardous materials, explosiveness

A literature survey was conducted to determine state of the art for metal sparking initiations of dust clouds. Of all the literature reviewed, none had addressed the gun propellants and black powder dust cloud ignition potentials. Thus, a gap in technology regarding the ignition thresholds of gun propellants and black powder dust to metal sparks exists.

Mechanisms involved in the metal-to-metal impact initiations were analyzed and test methods to evaluate potential hazards were recommended.

Initiation thresholds in the past were tested to determine the level of metal sparking required to initiate dust cloud. Of the various test methods utilized, the rotating wheel-stationary slug concept produced the greatest potential of initiations for vapor/air mixtures [*1*], and thus was chosen as the best metal sparking source to determine initiation thresholds of the dust clouds.

As a result of this study, the rotating wheel type of tests was recommended. The test involved placement of a rotating wheel into a closed chamber and a load concentrator to apply uniform pressure on the sample material as it is forced into the rotating wheel. Rotating wheel speed would be varied to determine the effect of initiation on the dust cloud.

Six different types of metal rods were chosen for this study to determine the sparking characteristics against seven dust samples. The seven dust samples consisted of five propellant dusts, M6 (87% nitrocellulose, 13% nitrogen, 10% dinitrotoluene), M30 (28% nitrocellulose, 12.6% nitrogen, 22.5% nitroglycerin, 47% nitroguanidine), M31 (20% nitrocellulose, 12.6%

---

[1] President and project engineer, respectively, Safety Consulting Engineers, Inc., 5240 Pearl St., Rosemont, IL 60018.

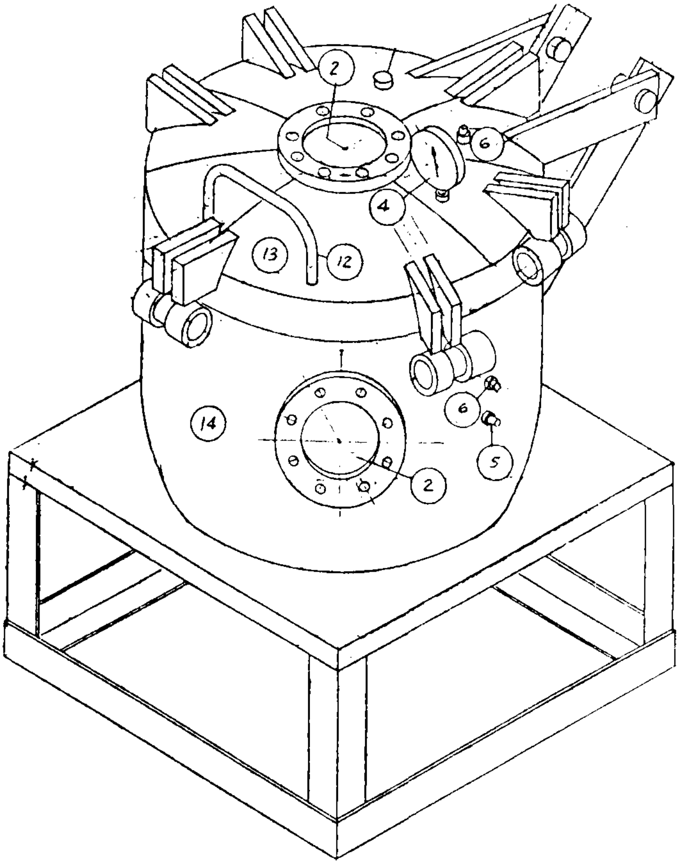


FIG. 1—*Safety Consulting Engineers, Inc. 20-L chamber (Bureau of Mines design).*

nitrogen, 19% nitroglycerin, 54% nitroguanidine), CBI (ignitor material) [*2*], and black powder (saltpeter, charcoal, sulfur) [*3*]; a coal dust; and a grain product dust.

Procedure

A Bureau of Mines design 20-L chamber [*4,5*] (Fig. 1) used for explosibility tests was modified to contain the mechanical sparking system (Fig. 2).

The near spherical shape of the 20-L chamber helps provide a uniform dust suspension. A 3-in. (7.6-cm) diameter by 0.25-in. (0.6-cm) thick 304L stainless steel contact wheel mounted on a shaft, which protrudes through the side wall of the chamber, is driven by an electric motor located outside the chamber. A 0.25-in. (0.6-cm) diameter by 2-in. (5-cm) long rod is held by a support bar against the circumference of the metal wheel. A dead weight of 3 lbs (1362 g) is located at the outside portion of the support bar. A viewing window and mirror allowed remote observations of the tester.

Six types of metals were tested for sparking against seven dust samples. The dust samples were previously tested for minimum ignition concentration [*6*]. Each dust sample was tested at its most ignitable concentration, ten times its minimum ignition concentration.

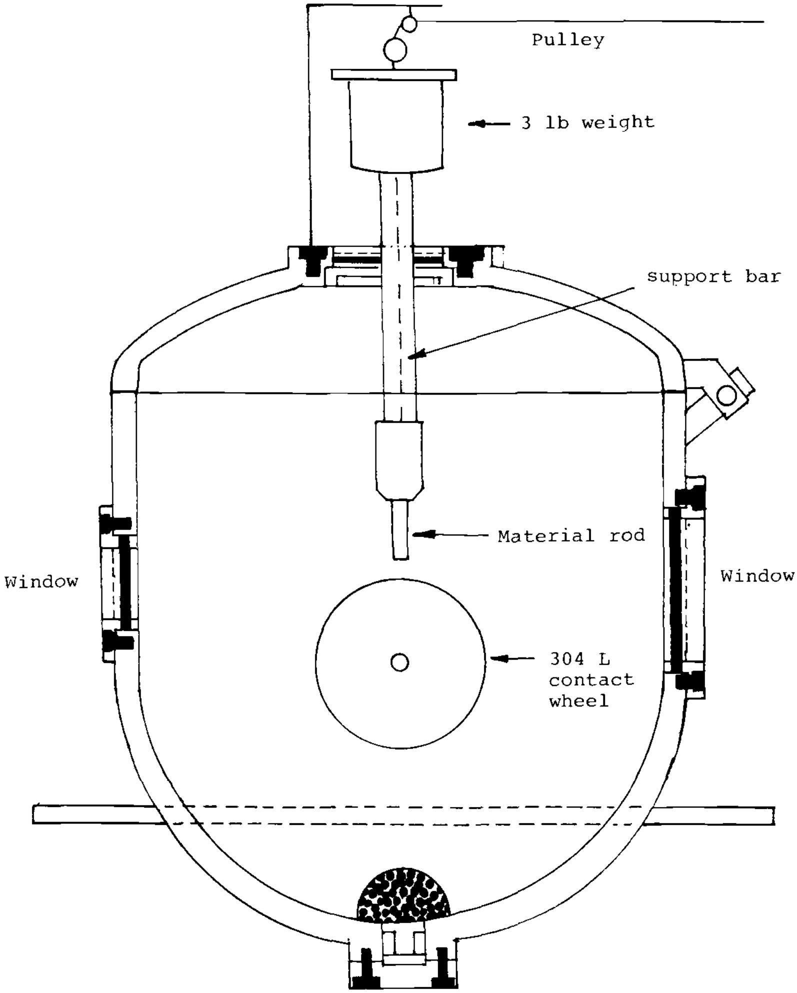


FIG. 2—*Modified 20-L chamber.*

Each metal rod/dust combination test was performed as follows. The preweighed dust sample was first placed in the bottom of the chamber. The rod material was raised using a pulley mechanism before the test chamber was closed. The electric motor was turned on to start the contact wheel. Pressurized air from the test chamber nozzle dispersed the sample dust uniformly while the metal rod was dropped to make contact with the rotating wheel. The contact time was controlled manually by the operator. Ignition of the dust cloud was observed through the view mirror. The setup is illustrated in Fig. 3.

Test Results

The first series of tests consisted of testing the six metal rods to determine the minimum contact wheel speed that would produce sparking for each rod. The following metal rods were tested: 1018 mild steel, 316 stainless steel, 304 stainless steel, 304L stainless steel, 3003-H14 aluminum,

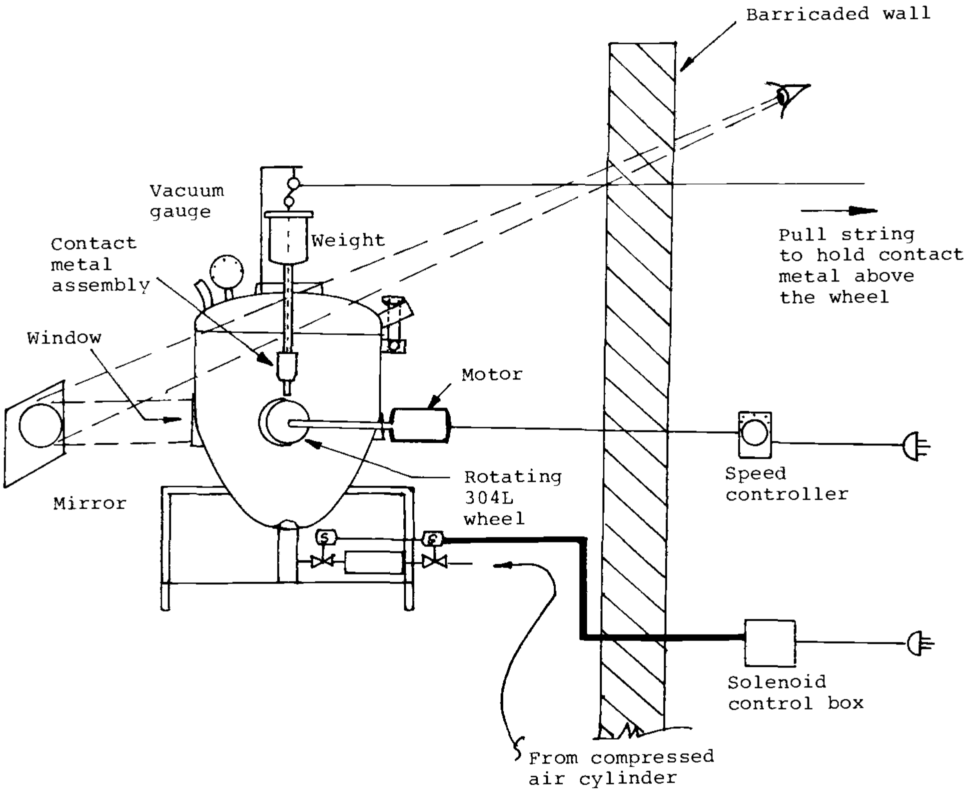


FIG. 3—*Metal sparking test setup.*

and 6061-T6 aluminum. By determining the minimum wheel rotation speed that produced sparking for each one of the metal rods tested, the types of metals more likely to produce sparking were identified. Table 1 contains results of these tests and shows that 304 stainless steel rod produced sparking at the lowest wheel speed. Neither aluminum rod produced sparking at the maximum wheel speed available.

TABLE 1—*Minimum contact wheel speed that would produce sparking for each rod.*[a]

	Minimum Contact Wheel Speed		
Material rod	m/s	rpm	ft/s
1018 mild steel	9.2	2300	30.1
304L stainless steel	8.4	2100	27.5
304 stainless steel	7.2	1800	23.6
316 stainless steel	8.4	2100	27.5
3003-H14 aluminum		no visible spark at maximum speed of	
	19.9	5000	65.4
6061-T6 aluminum		no visible spark at maximum speed of	
	19.9	5000	65.4

[a] Contact force: 13.2 N (3 lbf).

TABLE 2—*Minimum sparking speed for each material rod that would ignite the sample.*

Sample Dust Test	Dust Particle Size, μm	Sample Dust Concentration, g/L	Rod Material					
			1018 Mild Steel	304L Stainless Steel	304 Stainless Steel	316 Stainless Steel	3003-H14 Aluminum	6061-T6 Aluminum
			Minimum Speed to Cause Ignition, m/s (ft/s)					
M6	<75	0.25	12.4 (40.6)	14.0 (45.8)	14.0 (45.8)	13.5 (44.5)	NI[a]	NI
M30Al	<75	0.41	11.2 (36.6)	13.2 (43.2)	13.2 (43.2)	13.5 (44.5)	NI	NI
M31Al	<150	0.32	10.4 (34.0)	14.0 (45.8)	14.0 (45.8)	14.0 (45.8)	NI	NI
CBI	<150	0.41	8.8 (28.8)	14.0 (45.8)	14.0 (45.8)	14.0 (45.8)	NI	NI
Black powder	<75	0.25	11.6 (37.9)	13.2 (43.2)	>19.9 (>65.4)	14.0 (45.8)	NI	NI
Pittsburgh coal dust	<75	0.35	10.0 (32.7)	>19.9 (>65.4)	>19.9 (>65.4)	>19.9 (>65.4)	NI	NI
Cornstarch	<75	0.35	8.0 (26.2)	14.0 (45.8)	14.0 (45.8)	14.0 (45.8)	NI	NI

[a] NI: showed no ignition up to a maximum speed of 19.9 m/s (65.4 ft/s).

After the minimum sparking speeds were found, five different propellant dusts, M6, M30A1, M31A1, CBI, black powder, and two carbonaceous dusts, Pittsburgh bituminous coal dust and a commercial cornstarch, were tested to determine the minimum sparking speed (Table 2) for each rod type that would ignite each sample dust. The sample materials tested were ground and sieved through 200 or 100 mesh U.S. sieve screens. Each dust sample was dispersed and remained airborne for more than 1 s while the rod material was dropped to make contact ($\leq$ 1 s) with the rotating wheel. Table 2 lists the minimum sparking speed for each rod tested that would ignite each sample dust. Results of testing indicated that 1018 mild steel was the material most likely to produce ignition of the sample dusts. As the aluminum rods failed to produce sparking, these materials did not ignite the sample dusts.

The third test series (Table 3) was conducted at a peripheral wheel speed of 14.0 m/s (45.8 ft/s) for all rod material-sample dust combinations. This test series allowed a ranking of the sample dusts based on ignition sensitivity. The most sensitive dust was M6 propellant and the least sensitive was the coal dust, with the order of the intermediate dusts dependent on the rod material. The test rod material most likely to produce ignition was the 1018 mild steel, and the materials least likely were 3003-H-14 aluminum and 6061-T6 aluminum. Other test rod materials varied dependent on dust samples.

The fourth series of tests (Table 4) consisted of testing all rod material sample/dust combinations that produced ignition in the third series of tests at a peripheral wheel speed of 14.0 m/s, but for this series the contact time of the rod material and wheel was limited to 0.5 s. Again this test series allowed a ranking of the sample dusts based on ignition sensitivity during a relatively short exposure to sparking. Table 4 shows that all sample dusts, except for the coal tested, ignited when 1018 mild steel was used. Cornstarch, CBI, M6, and black powder ignited when tested with 316 stainless steel rod. Only the cornstarch ignited with the 304 stainless steel.

Conclusions

Metal sparking tests on various metals in several dust cloud environments showed a distinction between metals that are relatively safer to use in an explosive dust cloud atmosphere and those that may be unsafe. Metals found to present a lower sparking hazard include both 3003-H14 and 6061-T6 aluminum. Metals tested that are not well suited to an explosive dust cloud atmosphere include 1018 mild steel, 304L stainless steel, 304 stainless steel, and 316 stainless steel because of their greater tendency to produce ignition.

The potential for explosive dust initiation appears to be greater when contact speed with metals exceeds 9.2 m/s (30.1 ft/s) for 1018 mild steel, 8.4 m/s (27.5 ft/s) for 304L stainless steel, 7.2 m/s (23.6 ft/s) for 304 stainless steel, and 8.4 m/s (27.5 ft/s) for 316 stainless steel.

At a longer metal contact times (with speed greater than the minimum contact speed which would produce sparking for each metal), a greater potential hazard of ignition may also be possible.

References

[1] Bernstein, H., "Sparking Characteristics and Safety Hazards of Metallic Materials," U.S. Dept. of Commerce, Pb 131131, April 1957.

[2] Dahn, C. J., "Bulk Propellant Delivery System Preliminary Hazards Analysis," Report 8209, for ICI Americas, Inc., Charlestown, IN, 12 March 1982.

[3] Fedoroff, B. T. and Sheffield, O. E., *Encyclopedia of Explosives and Related Items,* Part 2700, Vol. 2, Picatinny Arsenal, Dover, NJ, 1962.

[4] Cashdollar, K. L. and Hertzberg, M., "20-L Explosibility Test Chamber for Dusts and Gases," *Review of Scientific Instruments,* Vol. 56, 1985, pp. 596–602.

[5] Cashdollar, K. L., Sapko, J. J., Weiss, E. S., and Hertzberg, M., "Laboratory and Mine Dust Explosion Research at the Bureau of Mines," in this volume, pp. 107–123.

TABLE 3—*Metal sparking test results at metal wheel speed of 14.0 m/s (45.8 ft/s) with rod material contact time of 1 s.*

				Rod Material (Number of Ignitions in 20 Runs)				
Sample Dust Tested	Dust Particle Size, μm	Sample Dust Concentration, g/L	1018 Mild Steel	304L Stainless Steel	304 Stainless Steel	316 Stainless Steel	3003-H14 Aluminum	6061-T6 Aluminum
M6	<75	0.25	20	19	18	18	. . .[b]	. . .
CBI	<150	0.41	19	17	18	18	. . .	. . .
Cornstarch	<75	0.35	20	9	7	16	. . .	. . .
M30Al	<75	0.41	19	18	15	15	. . .	. . .
M31Al	<150	0.32	14	13	11	9	. . .	. . .
Black powder	<75	0.25	17	8	6	8	. . .	. . .
Pittsburgh coal dust	<75	0.35	5	NI[a]	NI	NI	. . .	. . .

[a] NI: showed no ignition up to a maximum speed of 19.9 m/s (65.4 ft/s).

[b] Not tested.

TABLE 4—*Metal sparking test results at metal wheel speed of 14.0 m/s (45.8 ft/s) with rod material contact time of 0.5 s.*

				Rod Material (Number of Ignitions in 20 Runs)				
Sample Dust Tested	Dust Particle Size, µm	Sample Dust Concentration, g/L	1018 Mild Steel	316 Stainless Steel	304 Stainless Steel	304L Stainless Steel	3003-H14 Aluminum	6061-T6 Aluminum
Cornstarch	<75	0.35	15	10	3	NI	. . .	. . .
M6	<75	0.25	12	2	NI	NI	. . .	. . .
CBI	<150	0.41	10	5	NI	NI	. . .	. . .
Black powder	<75	0.25	10	2	NI	NI	. . .	. . .
M31Al	<150	0.32	9	NI	NI	NI	. . .	. . .
M30Al	<75	0.41	8	NI	NI	NI	. . .	. . .
Pittsburgh coal dust	<75	0.35	NI[a]	. . .[b]	NI	. . .	. . .	. . .

[a] NI: showed no ignition up to a maximum speed of 19.9 m/s (65.4 ft/s).

[b] Not tested.

[6] Dahn, C. J., "Dust Explosibility Tests on Black Powder and CBI," Report 8353, for ICI Americas, Inc., Charlestown, IN, 3 Oct. 1983 and "Dust Explosibility Tests on M6, M30A1 and M31A1," for ICI Americas, Inc., Charlestown, IN.

Ronald C. Vaickauski[1]

Testing of Electrical Equipment for Use in Class II Hazardous Locations

REFERENCE: Vaickauski, R. C., "**Testing of Electrical Equipment for Use of Class II Hazardous Locations,**" *Industrial Dust Explosions, ASTM STP 958,* Kenneth L. Cashdollar and Martin Hertzberg, Eds., American Society for Testing and Materials, Philadelphia, 1987, pp. 333–341.

ABSTRACT: To prevent dust explosions, electrical equipment in Class II hazardous locations must have special construction features that meet rigid performance criteria. Dust-ignition-proof, dust-tight, and intrinsically safe are types of constructions used.

Underwriters Laboratories (UL) has developed construction and performance standards for these types of equipment. UL's hazardous location equipment test lab is a specially designed facility that provides separation of dust and explosion testing areas from laboratory personnel working areas. The lab has two dust test chambers for conducting dust penetration and dust blanket temperature tests. After each test setup is completed, testing is controlled remotely to protect lab personnel in case of a dust explosion. Testing is conducted using either grain or magnesium dust. Intrinsically safe equipment undergoes spark ignition tests with a specially constructed switching mechanism.

This paper describes Class II hazardous locations, types of protection used for equipment, and how electrical equipment tests are performed.

KEY WORDS: dust, dust-ignition-proof, dust-tight, electrical equipment, hazardous locations, intrinsically safe

To reduce the risk of dust explosions, electrical equipment used in Class II hazardous locations must have specially designed enclosures that prevent dust from coming into contact with sources of ignition. Depending upon the specific Class II location, enclosures that are dust-ignition-proof or dust-tight or that minimize the entrance of dust can be used. Alternatively, intrinsically safe circuits may be employed. Underwriters Laboratories (UL) has developed construction and performance standards for these types of equipment.

Class II Classified Areas

National Fire Protection Association Standard 70–1984, also known as the National Electrical Code (NEC), recognizes two groups in Class II hazardous locations based on the type of dust present.

Group E: Atmospheres containing combustible metal dust regardless of resistivity, or other combustible dust of similarly hazardous characteristics having resistivities of less than 10^{+5} ohm-cm.

Group G: Atmospheres containing combustible dust having resistivity of 10^{+5} ohm-cm or greater.

Furthermore, Class II hazardous locations are grouped into two divisions, based on whether dust is present under normal conditions or only under abnormal conditions.

Division 1: A Class II, Division 1 location is a location: (1) in which combustible dust is in the air under normal operating conditions in quantities sufficient to produce explosive or ignitable mixtures; or (2)

---

[1] Assistant managing engineer, Underwriters Laboratories Inc., 333 Pfingsten Rd., Northbrook, IL 60062.

> where mechanical failure or abnormal operation of machinery or equipment might cause such explosive or ignitable mixtures to be produced, and might also provide a source of ignition through simultaneous failure of electric equipment, operation of protection devices, or from other causes; or (3) in which combustible dust of an electrically conductive nature might be present in hazardous quantities.
>
> *Division 2:* A Class II, Division 2 location is a location where combustible dust is not normally in the area in quantities sufficient to produce explosive or ignitable mixtures, and dust accumulations are normally insufficient to interfere with the normal operation of electrical equipment and other apparatus, but combustible dust may be in suspension in the air as a result of infrequent malfunctioning of handling or processing equipment and where combustible dust accumulations on, in or in the vicinity of electrical equipment may be sufficient to interfere with the safe dissipation of heat from electrical equipment or may be ignitable by abnormal operation or failure of electrical equipment.

Where Class II, Group E dust having a resistivity less than $10^{+}5$ ohm-cm is present, there are only Division 1 locations.

National Fire Protection Association No. 497M-1983, ''Manual for Classification of Gases, Vapors and Dusts for Electrical Equipment in Hazardous (Classified) Locations'' provides additional information on the classification of Class II locations.

Formerly, the NEC recognized three groups in Class II, defined in the 1981 NEC as follows:

> *Group E:* Atmospheres containing metal dust, including aluminum, magnesium and their commercial alloys, and other metals of similarly hazardous characteristics having resistivity of 10^{+2} ohm-cm or less.
>
> *Group F:* Atmospheres containing carbon black, charcoal, coal or coke dust which have more than 8% total volatile material (carbon black per ASTM D1620, charcoal, coal and coke dust per ASTM D271) or atmospheres containing these dusts sensitized by other materials so that they present an explosion hazard, and having resistivity greater than 10^{+2} ohm-cm but equal to or less than 10^{+8} ohm-cm.
>
> *Group G:* Atmospheres containing, flour, starch, grain, or combustible plastics or chemical dust having resistivity greater than 10^{+8} ohm-cm.

The elimination of Group F resulted in Group F materials being placed into either Group E or Group G depending on the conductivity involved. The impetus behind this change related to the degree of enclosure protection required for electrical circuits. However, this action created problems for heat producing equipment and equipment with rotating shaft openings. For example, two problems that arose from the elimination of Group F are:

1. Heat producing equipment for use with materials previously in Group F must now be designed to meet Group G requirements. Group G equipment is more complex to construct than Group F equipment because it must operate at lower temperatures.
2. Equipment with shaft openings for use with materials previously placed in Group F, and now in Group E, must use more-difficult-to-fabricate designs needed to prevent metal dust from entering the enclosure through the shaft opening.

Because of the technical and economic complexities generated by the deletion of Group F, Group F was reinstated in the 1987 National Electrical Code.

Electrical Equipment for Class II Locations

Electrical equipment used in Class II locations must have enclosures which prevent dust from coming into contact with possible sources of ignition such as arcing or sparking parts or components operating at high temperatures. Such enclosures cannot have ventilating openings and must employ precision fits or gaskets where enclosure parts are joined.

Typically, enclosures for Class II locations are made of cast iron or aluminum. However, the use of plastic enclosure materials is becoming more popular; these plastic materials bring about the additional concerns with grounding continuity and electrostatic charge accumulation. Special designs must be used to deal with these problems.

TABLE 1—*Maximum surface temperature in °C.*[a]

Class II Group	Equipment Not Subject to Overloading	Equipment That May Be Overloaded[b]	
		Normal Operation	Abnormal Operation
E	200 (392)	200 (392)	200 (392)
F	200 (392)	150 (302)	200 (392)
G	165 (329)	120 (248)	165 (329)

[a] °F given in parentheses.
[b] For example, motors or power transformers.

For lighting fixtures, motors, heaters, and other heat producing equipment, external surface temperatures must be kept below the ignition temperature of the surrounding dust. The NEC additionally establishes limits based on the Class II group and whether or not the equipment is subject to overloading. These limits are shown in Table 1.

Types of Protection

The level of protection an enclosure must provide against the entrance of dust depends on the Class II division in which it is intended to be used.

Dust-Ignition-Proof Enclosures

The highest level of protection is required for Division 1 locations, because it is assumed that dust could always be present in ignitable quantities. Enclosures for Division 1 locations must have enclosure joints and shaft openings that meet certain minimal width and maximum clearance criteria and, additionally, pass a rigorous dust penetration test. Underwriters Laboratories Inc. Standard UL 674, "Standard for Electric Motors and Generators for Use in Hazardous Locations," requires flat joints to be a minimum of 4.8 mm wide with a maximum clearance of 0.05 mm at that width. Gasketed joints are required to be a minimum of 4.8 mm wide. Shaft openings must be at least 12.7 mm long with a maximum diametrical clearance of 0.25 mm.

Preventing the entrance of metal dust found in Group E is even more difficult than preventing the entrance of grain or carbonaceous dust. Also, metal dust can be more detrimental to bearings. Typically, revolving seals known as "slingers" must be used on rotating shafts of equipment for Class II, Group E locations to prevent entry of metal dust into bearing chambers.

Dust-Tight Enclosures

Enclosures for Class II, Division 2 locations do not need to meet as stringent requirements as enclosures for Division 1 because in a Division 2 location dust is assumed to be present infrequently due to some abnormal circumstance. It is not expected that Division 2 equipment will be exposed to a cloud of dust over an extended period of time as is the case with Division 1 equipment.

Within Division 2, requirements applied to enclosures depend on the types of equipment contained within the enclosure. According to the NEC, enclosures housing parts such as normally arcing contacts, high temperature components, or other parts which present an imminent possibility of igniting dust are required to be dust-tight. Enclosures containing other types of parts and circuits less likely to be a source of ignition are required only to minimize the entrance of dust.

Dust-tight enclosures must demonstrate the ability to exclude dust when tested by one of three methods:

(a) Dust penetration test,
(b) Atomized water test, or
(c) Dust blast test.

Enclosures that Minimize the Entrance of Dust

Enclosures intended to minimize the entrance of dust can be used to house parts and circuits less likely to cause ignition of dust. These enclosures must have telescoping or close-fitting covers and shall have no openings, such as holes for mounting screws.

Intrinsically Safe Circuits

Intrinsically safe circuits are incapable of releasing sufficient energy to ignite a Class II atmosphere under normal operating conditions and certain fault conditions. The circuits that establish the intrinsically safe circuit are located outside the Class II area or within the Class II area if in a dust-ignition-proof enclosure.

UL 913, "The Standard for Intrinsically Safe Apparatus and Associated Apparatus for Use in Class I, II and III Division 1 Hazardous Locations," requires intrinsically safe circuits to undergo spark ignition testing with safety factors and certain faults introduced depending on the types and reliability of the circuits and components used. (Class I deals with gases and vapors and Class III deals with fibers and flyings.)

Test Facilities and Methods

Facilities

UL has built a special laboratory at its Northbrook, IL office for testing hazardous location equipment. The laboratory is a reinforced concrete structure partitioned into two main areas. One area is for testing with flammable gases, vapors, and dust. These tests are remotely controlled from the other area, where laboratory personnel normally work. The area for testing is provided with blowout panels which are intended to relieve pressure in case of a mishap involving an explosion. In the dust testing area there are two dust testing chambers used for dust penetration and dust blanket temperature tests. A third chamber is under construction.

UL's small dust test chamber shown in Fig. 1 is typical of the construction used for all three UL chambers. Below each chamber is a V shaped hopper and an auger. Dust in the chamber falls out of suspension in air into the hopper. The auger at the bottom of the hopper collects the dust and carries it to one end, where it is mixed with air and reinjected into the chamber by a centrifugal blower, plenum, and injection tube system.

Equipment auxiliary to the dust test chambers includes ambient temperature control systems, power supplies, electrical loads, dynamometers, and fire suppression and temperature recording systems. The control panel for UL's small dust test chamber is shown in Fig. 2.

Dust Blanket Temperature Test

Equipment for Class II hazardous locations is temperature tested with a dust blanket to take into account the increased operating temperatures obtained as a result of the insulating effects of dust which can collect on exposed surfaces. Equipment for Group E is tested with magnesium dust.

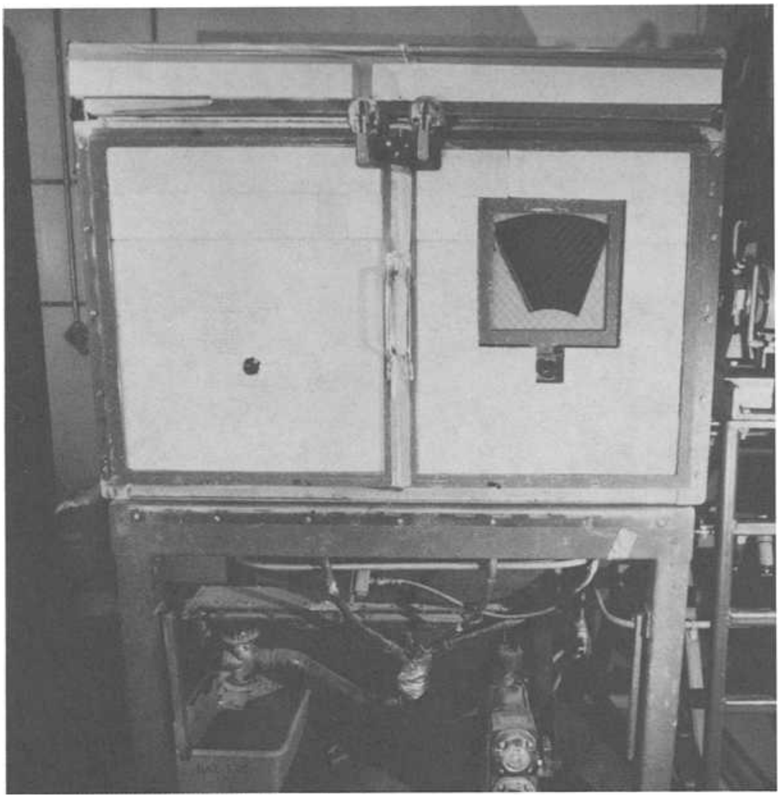


FIG. 1—*Small dust test chamber.*

FIG. 2—*Control panel for dust test chamber.*

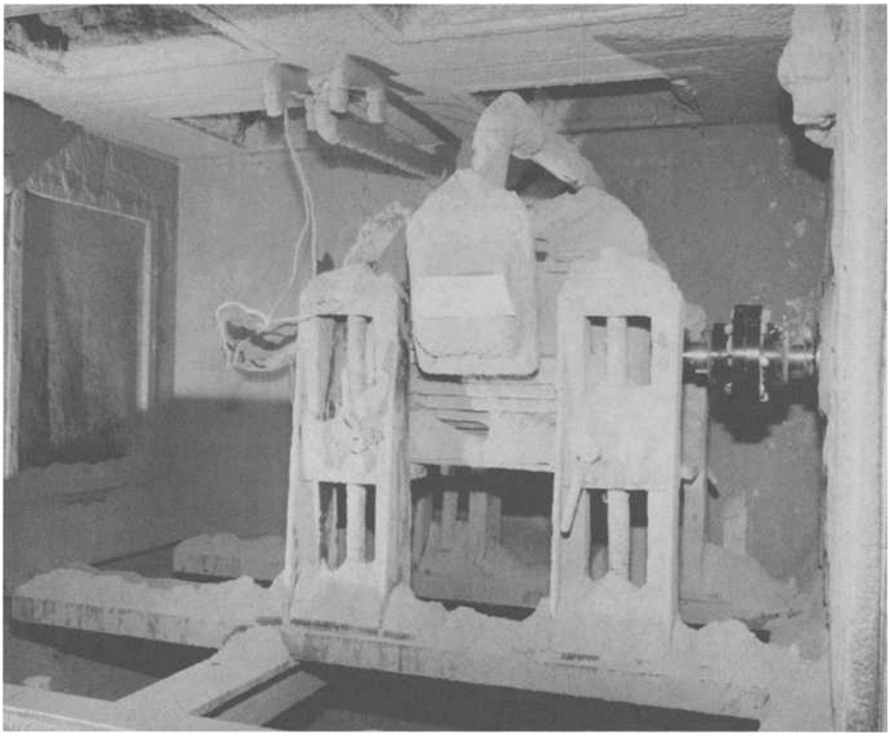


FIG. 3—*Motor with dry dust blanket.*

Equipment for Group F or Group G is tested with grain dust. Maximum permissible surface temperatures are noted in Table 1.

The dust blanket temperature test is conducted by placing thermocouples on exterior surfaces of the equipment under test and mounting the equipment in the dust test chamber. A power source is connected to the equipment. Motors are loaded by means of a dynamometer. The equipment under test is operated in the chamber while dust in suspension with air is circulated around it. Dust circulation is continued until a maximum build up of dust is obtained, at which time the dust circulation is stopped. The equipment being tested is then operated until stable temperatures are obtained. Figure 3 shows a motor blanketed with dry grain dust.

In addition to normal operating conditions, equipment subject to overload is tested under overload conditions. For example, while blanketed with dust, a motor is tested under running overload, single phasing, and locked rotor conditions, in addition to being tested under normal full load or service factor load. Motors for Group G are packed with moist grain dust to simulate the gradual build up of dust on a motor in a moist environment and subjected to overload testing. Moist dust blankets are considered to be a more severe test condition than dry grain dust blankets because the moist dust blanket causes the motor to operate at higher temperatures.

Equipment for Group E only is tested with a dry magnesium dust blanket.

Dust Penetration Test

Dust-ignition-proof and dust-tight enclosure designs must prevent the entrance of dust into the enclosure. The ability of the enclosure to do so is investigated by mounting the test sample in the dust test chamber, where it is exposed to an atmosphere of dust in suspension in air, and operating it through heating and cooling cycles. For example, a heating and cooling cycle for a motor is obtained by operating the motor at rated load until reaching normal operating temperature followed by de-energization of the motor until ambient temperature is reached. The heating and cooling cycles are used to duplicate the "breathing" of the enclosure which occurs during normal use and tends to draw dust into the enclosure. For Division 1 equipment, the test is conducted for six heating and cooling cycles for a minimum of 30 h in the chamber. Also, dust is directed at the enclosure joints by nozzles. For Division 2 equipment, the test is conducted for only two heating and cooling cycles for a minimum of 10 h, and nozzles are not directed at enclosure joints. After the test, the enclosure is examined for the entrance of dust. Figure 4 shows a lighting fixture after the dust penetration test.

Atomized Water Test

An alternative test for Division 2 dust-tight enclosures is the atomized water test. As shown in Fig. 5, the test sample is sprayed with atomized water by using a nozzle that produces a round pattern 76 to 102 mm in diameter, 305 mm from the nozzle. Not less than 485 mL per metre of test length of the enclosure under test is applied at a rate of 11 L per hour. The nozzle is held 305 to 381 mm from the enclosure, and the spray of water is directed at all points of potential dust entry, such as seams, joints, and external operating mechanisms. Afterwards, the enclosure is examined for the entrance of water.

Dust Blast Test

As an alternative to the atomized water test, Division 2 dust-tight enclosures may be tested using the dust blast method. The enclosure is subjected to a blast of compressed air mixed with

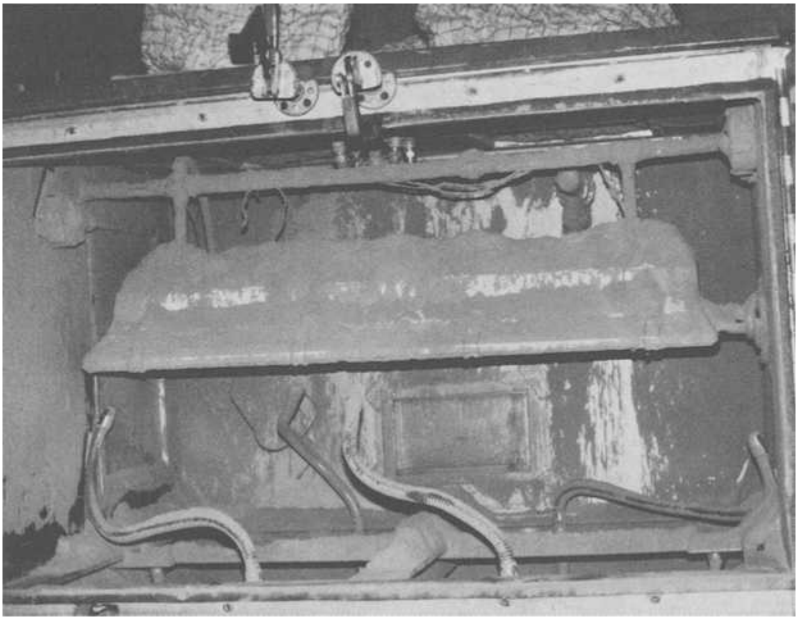


FIG. 4—*Lighting fixture after dust penetration test.*

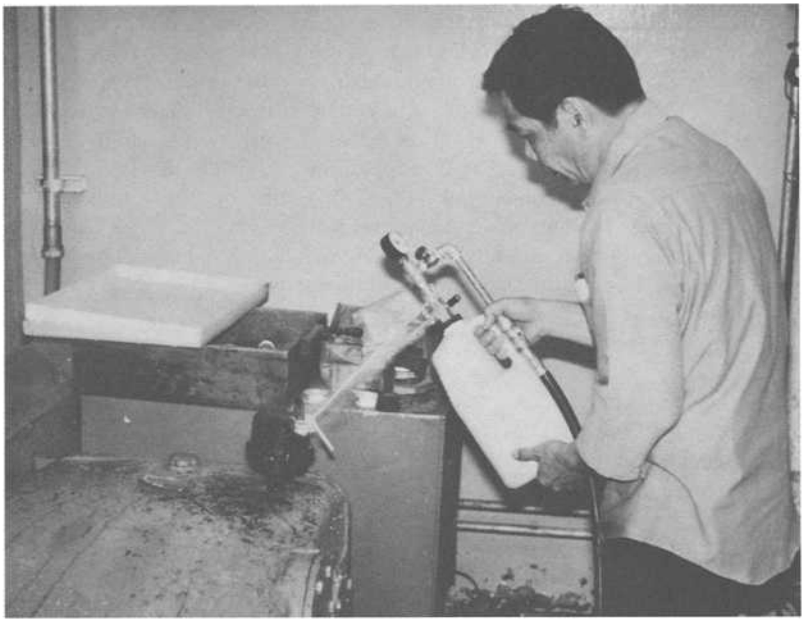


FIG. 5—*Atomized water test.*

dry, Type 1 general purpose Portland cement by using a suction-type sandblast gun equipped with a 4.8-mm-diameter air jet and a 9.5-mm-diameter nozzle. Not less than 6 kg of cement per metre of test length of the enclosure under test is applied at a rate of 2.3 kg per minute. The nozzle is located 305 to 381 mm away from the enclosure, and the blast of air and cement is directed at all points of potential dust entry, such as seams, joints, and external operating mechanisms. The enclosure is then examined for the entrance of dust.

Spark Ignition Test

Intrinsically safe circuits are required to undergo spark ignition testing to demonstrate that they are incapable of causing ignition of a specified flammable atmosphere under certain fault conditions and with the introduction of safety factors.

A typical spark ignition test setup is shown in Fig. 6. The spark ignition apparatus consists of an explosion chamber of about 250 cm^3 volume, in which circuit making and breaking sparks can be produced in the presence of a prescribed test gas.

The switching mechanism consists of a cadmium disk with two slots and four tungsten wires of 0.2 mm diameter, which slide over the disk. The drive spindle to which the tungsten wires are attached makes 80 revolutions per minute. The spindle on which the cadmium disk is mounted revolves in the opposite direction. The ratio of the speed of the driving spindle to the speed of the disk spindle is 50 to 12. The spindles are insulated from one another and from the housing. When cadmium, zinc, or magnesium will not be present in the application, the cadmium disk may be replaced by a tin disk.

Spark ignition tests with dust in suspension with air can be difficult and time-consuming. As a practical expedient, spark ignition testing for Class II hazardous locations is done with flammable gases.

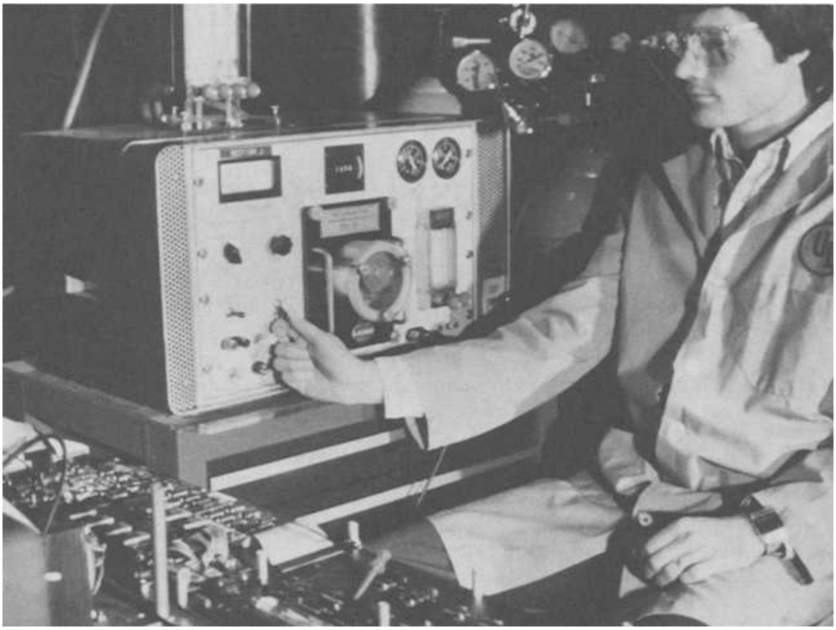


FIG. 6—*Spark ignition test.*

For Class II, Group F or Group G, Division 1, the test mixture is 5.25 ± 0.25% propane in air.

For Class II, Group E, Division 1, the test mixture is 7.8 ± 0.5% ethylene in air.

The sensitivity of the spark test apparatus is verified before and after each test series. After verification, the spark test apparatus is connected to the circuit requiring test, and testing is carried out for the following number of revolutions of the tungsten wire holder in the spark test apparatus:

(a) For DC circuits, not less than 400 revolutions (5 min), 200 revolutions at each polarity;
(b) For AC circuits, not less than 1000 revolutions (12.5 min).

Summary

Equipment for use in Class II hazardous locations must operate with external temperatures below the ignition temperature of the dust present. Measurement of these temperatures must be carried out under conditions that take into account the additional temperature rise that can occur as a result of buildup of a layer of dust on the equipment. Unless demonstrated as being intrinsically safe, electrical circuits must be enclosed to prevent dust from coming into contact with sources of ignition for the dust. UL standards for hazardous location equipment contain requirements for Class II applications.

Harry C. Verakis[1] *and John Nagy*[2]

A Brief History of Dust Explosions

REFERENCE: Verakis, H. C. and Nagy, J., "**A Brief History of Dust Explosions,**" *Industrial Dust Explosions, ASTM STP 958,* Kenneth L Cashdollar and Martin Hertzberg, Eds., American Society for Testing and Materials, Philadelphia, 1987, pp. 342–350.

ABSTRACT: This paper summarizes the history and early experimental studies of coal and other dust explosions.

In the 1600s, the explosibility of methane, hydrogen, and other combustible gases was recognized by the scientific and industrial community, but few scholars considered the possibility of a dust explosion. (Although a dust explosion could have occurred several centuries earlier, for example in a boat transporting grain from Egypt to Greece, the first recorded dust explosion occurred in an Italian flour mill in 1785.) In Europe, coal mining became an important industry and the dangers from explosions of fire damp (methane) were quickly recognized. However, most miners and many scientists did not accept the explosibility of coal dust.

It was noted in 1803 that coal dust in passageways had burned and contributed to the flame and violence of a mine explosion in England. In the 1800s, more evidence that coal dust in the absence of fire damp was explosive was obtained by investigators of mine accidents and experimental studies.

The pioneering work during the early 1900s of Taffanel in France and Rice in the United States convinced the mining industry of the danger of coal dust. Full-scale experimental studies of mine explosions began in 1911 in the Bureau of Mines Experimental Mine in Bruceton, PA.

Studies on the explosibility of other industrial dusts followed the recognition of the hazard of coal dust. During the late 1800s, investigations were made to evaluate the explosibility of combustible dusts and the causes of serious dust explosions in U.S. flour mills. Formation of the National Fire Protection Association in 1896 gave impetus to the recognition of the explosion hazard of industrial dusts.

Laboratory experiments on coal and other dusts continue to be made by the U.S. Bureau of Mines, universities, industry, and other research organizations.

KEY WORDS: dust explosions, literature review, dust explosion history, research, explosion hazard, explosion safety

This paper summarizes the history and early experimental studies on the explosion hazard of coal dust and other industrial dusts. The early pioneers who studied and contributed significantly to the knowledge of dust explosion hazards are also discussed.

The first recorded dust explosion occurred in an Italian flour mill in 1785 [*1*]. However, dust explosion incidents causing injuries and fatalities most likely occurred much earlier. Today, as in the past, grains and other agricultural products are most common fuels for creating dust explosions. Very common igniting sources are open flames, sparks, and hot surfaces. Thus, one can easily envision a dust explosion occurring centuries ago in the hold of a boat carrying grain. Dust created from the spillage of grain in the presence of the flame of a lighted candle or lantern could readily cause an explosion in the boat. In addition to these common sources of ignition, industry in modern times must also contend with ever present electrical igniting sources.

---

[1] Supervisory physical scientist, Materials and Explosion Testing Branch, U.S. Department of Labor, Mine Safety and Health Administration, Industrial Park Rd., RR1, Box 251, Triadelphia, WV 26059.

[2] Retired, formerly, technical adviser with the U.S. Department of Labor, Mine Safety and Health Administration and the U.S. Department of the Interior, Bureau of Mines, Bruceton, PA.

Early Studies with Gases

In the seventeenth century, the explosibility of methane, hydrogen, and other combustible gases was recognized by the scientific and industrial community. At that time few, if any, scholars considered the possibility and hazard of a dust explosion. Coal had become a chief source of energy during that time. In England and Europe, underground coal mining became an important industry and the dangers from explosion of fire damp (methane) were quickly recognized. It was strongly believed that when a mine explosion occurred a flammable atmosphere of fire damp had to be present. The first mine accident on record caused by an explosion of fire damp and resulting in the death of a miner happened in 1621 in Gateshead, England. Explosions attributed to fire damp occurred more frequently and with more disastrous results over the next several hundred years. The first major disaster caused by an explosion of fire damp also happened at Gateshead in 1705 and resulted in the loss of over 30 lives. Even though the explosion hazard of fire damp was accepted, the mining industry was slow to recognize the serious explosion hazard of coal dust. As early as 1803, John Buddle, who represented the Newcastle coal miners, pointed out that in an explosion in an English colliery the dust in the passageways had burned and contributed to the flame and violence of the disaster. Other investigators concluded from the evidence obtained in subsequent explosions that coal dust was an important factor. Faraday stated in his report on the 1844 Haswell disaster which resulted in 95 fatalities [*2*, p. 11],

> In considering the extent of the fire from the moment of the explosion it is not to be supposed that fire damp was its only fuel; the coal dust swept by the rush of wind and flame from the floor, roof, and walls of the works would instantly take fire and burn if there were oxygen enough present in the air to support its combustion; and we found the dust adhering to the faces of the pillars, props, and walls in the direction of and on the side toward the explosion, increasing gradually to a certain distance as we neared the place of the ignition. . . .

The remarkable evidence presented by Faraday on the importance of coal dust in an explosion was overlooked for many years.

Early Studies of Coal Dust Explosions

Notable among the earliest people who studied or investigated and reported on mine explosion accidents were Hodgson (1820), Bald (1828), Faraday (1844), Galloway (1870), Hall (1876), W. N. and J. B. Atkinson (1886), and the Royal Commission (1894) in England; DuSouich (1855), Mallard and LeChatelier (1882) in France; the Prussian Fire-Damp Commission (1884) in Germany; the Commission on Explosions in Mines (1891) in Austria; and McNeill (1887) in the United States. Some of these were eminent scientists of their day.

Early experimental work with coal dust began in several different countries. The experiments were performed primarily to investigate the explosive dangers of coal dust in the absence of flammable gas. Some of the early scientists who experimented in this field were Galloway (1875), Hall (1876), Marreco, Cochrane, and Morison (1878), and Abel (1881) in England; Verpilleaux (1867) and Vital (1875) in France; Von Meyer (1872) in Germany; and Peck and Peckham (1878) in the United States.

In 1882, the respected scientists Mallard and LeChatelier, who were members of the French Fire-Damp Commission, reported that they "rejected the theory that coal dust was any serious danger, and maintained that no colliery explosion of any importance could be attributed with any probability to the action of coal dust" [*2*, p. 12]. This conclusion caused a delay in recognizing the explosive danger of coal dust in France for many years. It was not until the great Courrieres disaster of 1906 that the explosion hazard of coal dust received general acceptance in France.

The views of several early investigators on the role of coal dust in producing explosions were quite unpopular. Faraday had drawn attention to the role of coal dust in extending the flame of an explosion. Galloway, an English inspector, experimented with coal dust and investigated several great mine explosions during the 1870s. He drew the conclusion it was coal dust which carried the flame along mine passageways with such disastrous consequences and fire damp was not needed for coal dust to propagate flame with explosive effect.

There were some who conceded to the participation of coal dust in an explosion, but the prevailing belief remained that fire damp must be present in the atmosphere for an explosion to occur. Skepticism continued to prevail even though in 1876, Hall, also an English inspector, demonstrated by the first full-scale experiments that flame propagation and violent explosions could be readily obtained by coal dust alone. Hall's experiments were made in a 135-ft (41.2-m) long adit.

In 1880, a disastrous explosion causing 164 deaths occurred at the Seaham mine in England. This explosion attracted broader attention to the dangerous explosive nature of coal dust. Abel received the task of performing moderate-scale tests with coal dust. He concluded at the Seaham inquiry that "if coal dust alone would have exploded, every colliery would have been wrecked long ago" [*2*, p. 14].

Skepticism continued as the British Accident-in-Mines Commission in its preliminary report of 1881 considered the explosibility of coal dust by itself to be improbable. However, by 1886, this Commission had further reviewed evidence from England and other countries and reported that the occurrence of a blown out shot from blasting where coal dust existed in great abundance may, even in the total absence of fire damp, possibly give rise to violent explosions [*2*, p. 17].

Experiments to resolve the coal dust explosibility issue continued into the 1890s and early 1900s in England and Europe. The English had developed a new 900-ft (274.3-m) long tunnel, known as the Altofts gallery, for their experiments. Through the early 1890s Hall continued his experiments on a larger experimental scale and in mine shafts, hoping to convince the mining industry that coal dust alone was explosive. During this time, a new English Royal Commission was formed. Its members reviewed the evidence obtained by Hall. In its report of 1894, the Royal Commission stated conclusively that coal dust without the presence of fire damp may cause a dangerous explosion. Thus, the definite determination of the explosion hazard of coal dust has been credited to England.

As a result of these earlier studies, the explosive danger of coal dust was gaining wider acceptance. A major impetus to more thorough investigations of coal dust explosions and means for combatting them was the 1906 Courriers mine disaster in France. The 1099 fatalities caused by this disaster shocked the world and brought the issue of coal dust explosibility to the forefront of public attention. This disaster prompted many countries to carry out extensive experimental investigations of coal dust explosions. In 1907, Taffanel began conducting comprehensive experiments in a small surface gallery at Lievin, France. A year later, his experiments were made in a full-size gallery. Taffanel devoted much attention to the chemistry of dust explosions, including the effect of volatile matter on coal dust explosibility. His pioneering work was a major contribution to the progress of mine safety.

The extensive investigations and experimental work in England and Europe has shown coal dust was explosive with or without fire damp. Further studies were concentrated on the best means to prevent or arrest explosions. Nevertheless, some mining people continued to believe into the early 1900s that coal dust would not explode under mining conditions.

Dust Explosion Studies in the United States

The early history of dust explosions in the United States was quite similar to English and European experiences. The first commercial mining of coal in the United States began in Virginia in 1702. The first mine explosion occurred in 1810, in Heath's pits, Virginia [*3*].

The explosion hazard of coal dust did not create widespread interest in the U.S. mining industry until a succession of disasters occurred in 1907. Considering the work and facts known in England and other European countries during the latter half of the 1800s, it is surprising how slow the United States was in accepting the explosibility of coal dust.

The 1907 coal mine disasters, especially the Monongah explosion in West Virginia and the Darr explosion in Pennsylvania which caused a combined total of 601 deaths, led the U.S. Congress to appropriate funds for an investigation of mine explosions. Research on the explosibility of coal dust began in the Federal Geological Survey during the latter part of 1908. Preliminary tests were made in a 6.3-ft (1.9-m) diameter, 100-ft (30.5-m) long steel gallery erected in Pittsburgh. In 1910 the work was transferred to the newly created Bureau of Mines in the U.S. Department of the Interior. The late Dr. Joseph Holmes, who was a crusader for mine safety, became the first Director of the Bureau of Mines. Because of the continued reluctance of the mining industry to acknowledge the explosive dangers of coal dust, Holmes concluded experimental testing must be performed in a real mine so conclusions from the tests would be valid and accepted as decisive [*4*].

A plan for an experimental mine was developed and a site near Bruceton, PA was selected. Underground entries were started and the first series of large-scale experimental explosions were conducted during the fall of 1911 and winter of 1912 [*5*, pp. 39–48]. The mine consisted of two parallel entries about 700 ft (213.4 m) long, 9 ft (2.7 m) wide, and 6 to 7 ft (1.8 to 2.1 m) high. The entries were driven into the Pittsburgh coal seam.

The first test demonstration at the Bruceton Experimental Mine convinced the mining industry of the explosive dangers of coal dust. There were about 1500 representatives from the mining industry present for this test demonstration on 30 Oct. 1911. The explosion resulted in a huge volume of flame extending about 500 ft (152 m) outside the main opening and created an explosion pressure of about 26 psi (179.270 kPa) [*5*, pp. 69–72]. One of the coal dust explosion tests made in the Bruceton Experimental Mine is shown in Fig. 1. This test vividly shows the tremendous forces and flame resulting from a coal mine explosion. The test demonstration of 30 Oct. 1911, was several times more intense.

The investigations and full-scale experimental studies on gas and dust explosion hazards pioneered by George Rice from 1908 through the 1930s have been continued by others to the present day. Over 4200 explosion tests have been made in the Bruceton Experimental Mine to date. Many aspects of the physical and chemical nature of explosions and their prevention have been studied in the Bruceton Experimental Mine [*6*].

Experimental studies on mine explosions have also continued in other countries. Presently, there are seven active full-scale experimental mines and surface test galleries in the world. Two facilities are located in the United States, one in Great Britain, one in West Germany, one in Poland, one in China, and one in the Soviet Union.

Industrial Dusts

Most of the research and study on the explosibility of other industrial dusts followed the recognition of the explosion hazard of coal dust. In 1873, Fontaine published notes on the explosibility of asphaltum (grahmite) dust being mined in West Virginia. Peck and Peckham, in 1878, discussed the explosibility of combustible dusts and the cause of serious dust explosions in flour mills in Minneapolis. In 1882, Abel in England wrote about the dangerous properties of dusts and mentioned several explosions in flour mills.

Formation of the National Fire Protection Association in 1896 gave impetus to the recognition of the explosion hazard of industrial dusts. A committee on dust explosion hazards was formed by the NFPA in 1922. The NFPA's work has resulted in a vast body of knowledge which includes codes and practices for the prevention and control of dust explosion hazards in industrial plants and operations.

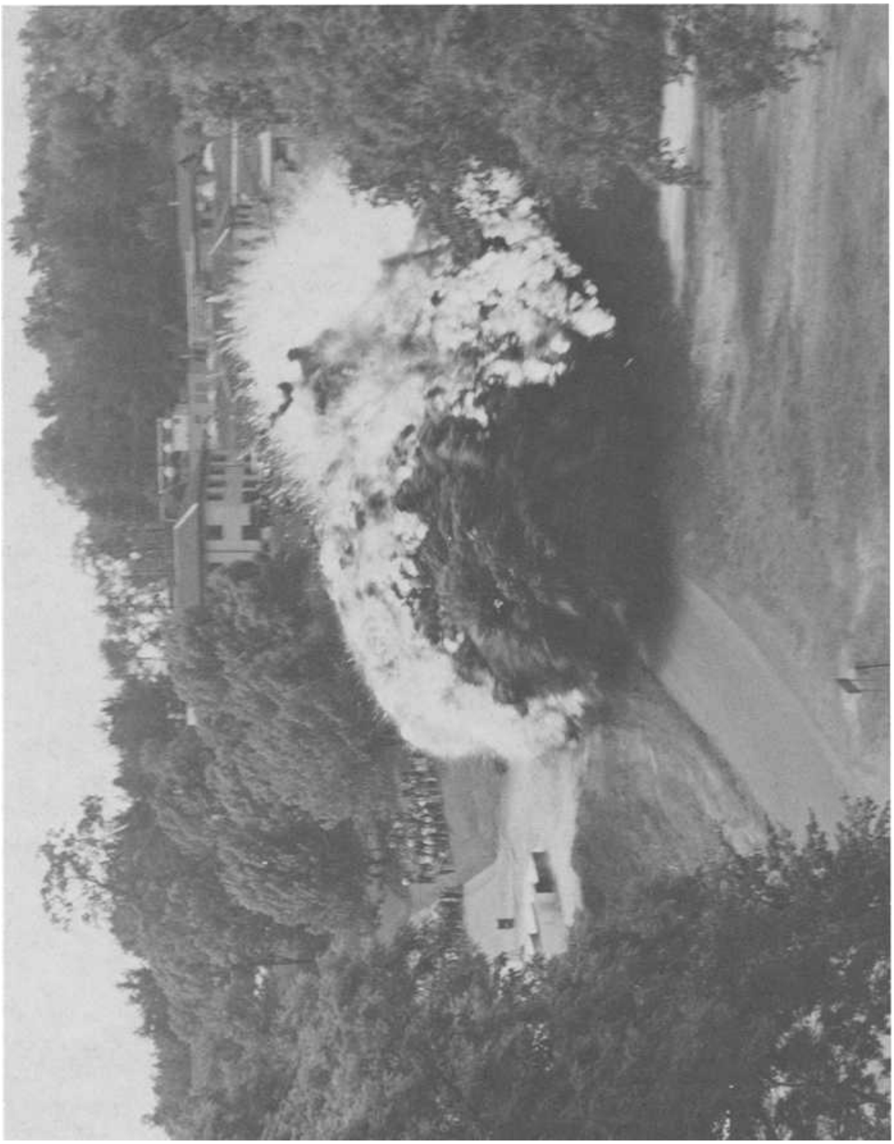


FIG. 1—*A coal dust explosion demonstration in the Bruceton, PA, experimental mine.*

The Bruceton Experimental Mine work was also paralleled by laboratory explosibility tests. Small-scale laboratory experiments on coal and other dusts were subsequently made by the Bureau of Mines, universities, industry, and other research organizations. Data from the laboratory tests could be obtained in less time and with much less expense than full-scale tests. Some of the early laboratory tests were forerunners of present test methods used for evaluating the explosibility of dusts.

Cooperative studies with the Bureau of Mines on the explosibility of grain dusts started about 1914. The studies began as a result of a 1913 explosion which killed 33 people and injured 70 more in a feed grinding plant in New York [*7*]. Subsequently, the testing of agricultural dusts was transferred in 1917 to the Department of Agriculture until about 1936 when the Bureau of Mines resumed work on industrial dust explosions. During the 1940s, supportive dust explosibility research was performed for the military. After World War II, Bureau of Mines research on industrial dusts became broader in scope and included the development of the Hartmann test apparatus and the laboratory explosibility testing of over 3000 dusts [*8*]. Testing and investigation continued on industrial dusts until 1970 when the work was interrupted following passage of the Coal Mine Health and Safety Act of 1969. Primary emphasis was then directed to the study of mine and mineral dust explosion hazards and the promulgation of mine safety regulations.

Conclusion

It is not often realized that less than 100 years ago the mining industry, scientific investigators, and concerned public struggled with the question of coal dust explosibility. Almost half a century of intensive studies, tests, and investigations were necessary for the scientific world and the mining and industrial community to accept the explosive hazards of coal and many industrial dusts. However, it is surprising that, as recently as 1926, a written account by a respected state mine inspector disclaimed the explosion hazard of coal dust in mines. He believed the Bureau of Mines experiments were misrepresented to mislead the public [*9*]. His account expressing this view is still available at the Carnegie Library in Pittsburgh.

The contributions of the pioneers who studied dust explosion hazards and the crusaders who fought for needed safety measures led to a significant reduction of deaths, injuries, and dust explosion disasters. We have them to thank for leading the way to overall improvement in mine and industrial safety.

Some of the early investigators who studied coal and other dust explosion hazards are listed in the Selected Bibliography. A more extensive bibliography is presented in Bulletins 20 and 167 published by the Bureau of Mines.

References

[*1*] Morozzo, Count, "Account of a Violent Explosion which Happened in a Flour Warehouse at Turin," *The Repertory of Arts and Manufactures*, Vol. 2, 1795, pp. 416–432.

[*2*] Rice, G. S., "The Explosibility of Coal Dust," Bulletin 20, U.S. Bureau of Mines, Washington, DC, 1911, p. 11.

[*3*] Humphrey, H. B., "Historical Summary of Coal-Mine Explosions in the United States, 1810–1958," Bulletin 586, U.S. Bureau of Mines, Washington, DC, 1960, p. 5.

[*4*] Rice, G. S., Jones, L. M., Egy, W. L., and Greenwald, H. P., "Coal Dust Explosion Tests in the Experimental Mine 1913 to 1918, Inclusive," Bulletin 167, U.S. Bureau of Mines, Washington, DC, 1922, p. 2.

[*5*] Rice, G. S., Jones, L. M., Clement, J. K., and Egy, W. L., "First Series of Coal Dust Explosion Tests in the Experimental Mine," Bulletin 56, U.S. Bureau of Mines, Washington, DC, 1913, pp. 39–48.

[*6*] Rice, G. S., Greenwald, H. P., and Howarth, H. C., "The Experimental Mine of the United States Bureau of Mines," Information Circular 6755, U.S. Bureau of Mines, Washington, DC, 1933, pp. 4–10.

[7] Greenwald, H. P., "Laboratory Testing of the Inflammability of Coal and Other Dusts Conducted by the Bureau of Mines," Bulletin 365, U.S. Bureau of Mines, Washington, DC, 1932, p. 17.
[8] Nagy, J. and Verakis, H. C., *Development and Control of Dust Explosions*, Marcel Dekker, New York, 1983, pp. 3, 12–14.
[9] Phythyon, H., "The Rock Dust Remedy for Coal Mine Explosions, An Open Letter to the Operators in the 27th Bituminous District of Pa.," Belle Vernon Agency, Belle Vernon, PA, 1926.

Selected Bibliography

1800–1870

Bald, J., "On the Fires That Take Place in Colleries," *Edinburgh New Philosophical Journal*, Vol. 5, 1828, pp. 101–121.
Buddle, J., "Account of an Explosion Which Took Place in Jarrow Colliery on the 3rd of August, 1830," *Transactions of the Northumberland Natural History Society*, Vol. 1, 1831, pp. 184–205.
DuSouich, M., "Report on Explosion at the Charles Pit," Firminy, Loire, France, Aug. 29, 1855.
Faraday, M. and Lyell, C., "Report on the Explosion at the Haswell Colleries," *Philosophical Magazine*, Ser. 3, Vol. 26, 1845, pp. 16–35.
Hodgson, J., *Fossil Fuel, Collieries, and the Coal Trade*, Great Britain, 1820.
Verpilleaux, *Annales des Mines*, Ser. 6, Vol. 12, 1867, pp. 561–566.

1871–1880

"A great flour-mill explosion, May 18, 1878," *Scientific American*, Vol. 38, p. 315.
Fontaine, W. M., "Notes on the West Virginia Asphaltum Deposits," *American Journal of Science*, Ser. 3, Vol. 6, 1873, p. 409.
Galloway, W., "On the Influence of Coal Dust in Colliery Explosions (I)," *Proceedings of the Royal Society of London*, Vol. 24, 1876, pp. 354–372.
Galloway, W., "On the Influence of Coal Dust in Colliery Explosions (II)," *Proceedings of the Royal Society of London*, Vol. 28, 1878, pp. 410–421.
Hall, H. and Clark, G., "Mechanical Effects of Blown-out Shots on Ventilation," *Transactions of the North of England Institute of Mining and Mechanical Engineers*, Vol. 25, 1876, pp. 239–248.
Marreco, A. Freire- and Morison, D. P., "Results of Some Experiments on the Effect of Coal Dust in Colliery Explosions," *Transactions of the Chesterfield and Derbyshire Institute of Mining, Civil and Mechanical Engineering*, Vol. 5, 1878, pp. 267–277.
Peck, L. W., "Explosions from Combustible Dust, *Popular Science Monthly*, Vol. 14, 1878–79, pp. 159–166.
Peckham, S. F., "On the Explosion of the Flouring Mills at Minneapolis, Minn., May 2, 1878, and the Causes of the Same," *American Journal of Science and Arts*, Ser. 3, Vol. 16, 1878, pp. 301–306.
Vital, M., "Recherches sur l'inflammabilite des poussieres de charbon," *Annales des Mines*, Ser. 7, Vol. 7, 1875, pp. 180–197.
Von Meyer, E., "Gases inclosed in coal," *Journal of the Chemical Society*, Vol. 25, 1872, pp. 798–801.

1881–1890

Abel, F. A., "Some of the Dangerous Properties of Dust," *Proceedings of the Royal Institute of Great Britain*, Vol. 10, Pt. 1, 1882, pp. 88–113.
American Institute of Mining Engineers, "The Pocahontas Mine Explosion," *Transactions of the American Institute of Mining Engineers*, Vol. 13, 1884, pp. 237–249.
Atkinson, W. N. and Atkinson, J. B., *Explosions in Coal Mines*, London, 1886.
Chesterfield and Derbyshire Institute of Engineers, "Report of Committee on Dust," *Transactions*, Vol. 10, 1882, pp. 1–44.
"Explosiveness of Coal Dust," *Colliery Engineer*, Vol. 4, Nov. 29, 1884, p. 605.
Galloway, W., "On the Influence of Coal Dust in Colliery Explosions (III)," *Proceedings of the Royal Society of London*, Vol. 33, 1882, pp. 490–495.
Galloway, W., "On the Influence of Coal Dust in Colliery Explosions (IV)," *Proceedings of the Royal Society of London*, Vol. 33, 1882, pp. 437–445.
Galloway, W., "On the Influence of Coal Dust in Colliery Explosions (V)," *Proceedings of the Royal Society of London*, Vol. 37, 1884, p. 42.
Hutchinson, E. S., "Notes on Coal Dust in Colliery Explosions," *Transactions of the American Institute of Mining Engineers*, Vol. 13, 1885, pp. 253–279.
Jones, C. E., "The Explosive Properties of Coal Dust, Coal Gas, and Atmospheric Air, with Special Reference to Mines," *Journal of Gas Lighting*, London, Vol. 13, 1883, p. 358.

Mallard, F. E. and Le Chatelier, H., "Du role des pouisseres de houille dans les accidents de mines," *Annales des Mines*, Ser. 8, Vol. 1, 1882, pp. 5–98.

McNeill, J. "Explosions, Report of State Inspector of Coal Mines of Colorado, 1887–1888," pp. 24–51.

"The Prussian Experiments on Coal Dust in Colliery Explosions," *Engineering and Mining Journal*, Vol. 39, 1885, pp. 221–223.

Prussian Fire Damp Commission, "Zeitschrift fur Berg-, Hutten-, and Salinenwesen im preuss," *Staate*, Vol. 32, Pt. 5, 1884, p. 575.

Royal Commission on Accidents in Mines, "Final Report," London, 1886.

1891–1910

Ashworth, J., "The Courrieres Disaster," *Engineer*, Nov. 1906, pp. 470–471.

Atkinson, W. N., "Report on the Austrian Fire-Damp Commission," *Transactions of the Federal Institute of Mining Engineers*, Vol. 3, 1892, pp. 531–550.

Beard, J. T., *Mine Gases and Explosions*, New York, 1908.

Brown, B. "Coal-Dust Explosions in Mines, Report of Kansas State Inspector of Mines," 1895, pp. 171–195.

Hall, H., "Coal Dust in Mines," *Colliery Engineer*, Vol. 14, 1893, p. 241.

Hall, H., "The Coal-Dust Question in Great Britain," *Engineering and Mining Journal*, Vol. 87, May 22, 1909, pp. 1084–1089.

Rice, G. S., "Dust Explosions in Coal Mines," *Bulletin of the American Institute of Mining Engineers*, March, 1910, pp. 215–219.

Royal Commission on Explosions from Coal Dust in Mines, "2nd Report," London, 1894.

Taffanel, J., "French Coal-Dust Experiments," *Colliery Guardian*, Vol. 98, Aug. 13, 1909, pp. 315–318.

1910–1940

Clement, J. K. and Lawrence, J. N., "Laboratory Determination of the Inflammation of Coal Dust and Air Mixtures," Technical Paper 141, U.S. Bureau of Mines, Washington, DC, 1917.

Dixon, H. B., "Explosion in Mines," *Colliery Guardian* Vol. 107, 1914, p. 349.

Garforth W. E., "British Coal-Dust Experiments," *Transactions of the Institute of Mining Engineers*, Vol. 42, 1911–1912, pp. 220–245.

Godbert, A. L. and Greenwald, H. P., "Laboratory Studies of the Inflammability of Coal Dusts," Bulletin 389, U.S. Bureau of Mines, Washington, DC, 1935.

Greenwald, H. P., "Laboratory Testing of the Inflammability of Coal and Other Dusts Conducted by the Bureau of Mines," Bulletin 365, U.S. Bureau of Mines, Washington, DC, 1932.

Rice, G. S., "The Explosibility of Coal Dust," Bulletin 20, U.S. Bureau of Mines, Washington, DC, 1911.

Rice, G. S. and Greenwald, H. P., "Coal-Dust Explosibility Factors Indicated by Experimental Mine Investigations, 1911 to 1929," Technical Paper 464, U.S. Bureau of Mines, Washington, DC, 1929.

Rice, G. S., Greenwald, H. P., and Howarth, H. C., "Some Experiments on the Initiation of Coal-Dust Explosions by Gas Explosions, Report of Investigation 3028, U.S. Bureau of Mines, Washington, DC, 1930.

Rice, G. S., Greenwald, H. P., and Howarth, H. C., "Explosion Tests of Pittsburgh Coal Dust in the Experimental Mine, 1925 to 1932, Inclusive," Bulletin 369, U.S. Bureau of Mines, Washington, DC, 1933.

Rice, G. S., Jones, L. M., Clement, J. K., and Egy, W. L., "First Series of Coal Dust Explosion Tests in the Experimental Mine," Bulletin 56, U.S. Bureau of Mines, Washington, DC, 1913.

Rice, G. S., Jones, L. M., Egy, W. L., and Greenwald, H. P., "Coal-Dust Explosion Tests in the Experimental Mine, 1913–1918, Inclusive," Bulletin 167, U.S. Bureau of Mines, 1922.

Rice, G. S., Paul, J. W., and Greenwald, H. P., "Coal-Dust Explosion Tests in the Experimental Mine, 1919–24, Inclusive," Bulletin 268, U.S. Bureau of Mines, Washington, DC, 1927.

Wheeler, R. V., "Explosive Dusts Classified," *Coal Age*, Vol. 4, 1913, p. 618.

1940 and Later

Bartknecht, W., *Explosions, Course–Prevention–Protection*, Springer-Verlag, New York, 1981.

Bodurtha, F. T., *Industrial Explosion Prevention and Protection*, McGraw-Hill, New York, 1980.

Brown, K. C., and James, G. J., "Dust Explosions in Factories: A Review of the Literature," Research Report No. 201, Safety in Mines Research Establishment, Great Britain, 1962.

Cybulski, W., "Coal Dust Explosions and Their Suppression," TT73-54001, National Technical Information Service, U.S. Dept. of Commerce, Springfield, VA, 1975.

Dawes, J. G. and Wynn, A. H. A., "The Dispersion of Dust by Blast," Research Report 46, Safety in Mines Research Establishment, Great Britain, 1952.

Dorsett, H. G., Jr., Jacobson, M., Nagy, J., and Williams, R. P., "Laboratory Equipment and Test Procedures for Evaluating Explosibility of Dusts," Report of Investigation 5624, U.S. Bureau of Mines, Washington, DC, 1960.

Eisner, H. S., Davies, J. K. W., and Brooks, F. R., "Mine Explosions: The Current Hazard," Symposium Paper No. 8, presented at a Symposium on Health, Safety and Progress, Harrogate, England, Oct. 27–29, 1976.

Field, P., *Dust Explosions*, Elsevier Scientific, New York, 1982.

Greenwald, H. P., "Proceedings: Fifth International Conference of Directors of Mine Safety Research," Bulletin 489, U.S. Bureau of Mines, Washington, DC, 1950.

Hartmann, I. J., Jacobson, M., and Williams, R. P., "Laboratory Explosibility Study of American Coals," Report of Investigation 5052, U.S. Bureau of Mines, Washington, DC, 1954.

Hartmann, I. J., Nagy, J., Rauschenberger, J. K., and Mitchell, D. W., "Coal-Mine-Explosion Research by the Bureau of Mines, 1954–1955," Report of Investigation 5264, U.S. Bureau of Mines, Washington, DC, 1956.

Humphrey, H. B., "Historical Summary of Coal Mine Explosions in the United States, 1810–1958," Bulletin 586, U.S. Bureau of Mines, Washington, DC, 1960.

Kawenski, E. M. and Bercik, G., "Research on Gas Explosions in the Bureau of Mines Experimental Coal Mine," presented at the 81st Annual Meeting, Coal Mining Institute of America, Pittsburgh, PA, 1967.

Mattes, R. H., Bacho, A., and Wade, L., "Lake Lynn Laboratory: Construction, Physical Description and Capability," Information Circular 8911, U.S. Bureau of Mines, Washington, DC, 1983.

Nagy, J., "The Explosion Hazard in Mining," Informational Report 1119, U.S. Dept. of Labor, Mine Safety and Health Administration, Washington, DC, 1981.

Nagy, J. and Mitchell, D. W., "Experimental Coal-Dust and Gas Explosions," Report of Investigation 6344, U.S. Bureau of Mines, Washington, DC, 1963.

Nagy, J. and Verakis, H. C., *The Development and Control of Dust Explosions*, Marcel Dekker, New York, 1983.

National Coal Board, "Final Report of the Working Party on Coal-Dust Explosions," London, July 1967.

National Fire Protection Association, "A Record of Dust Explosions in the United States and Canada Since 1860," Quincy, MA, 1957.

National Fire Protection Association, *Fire Protection Handbook*, 15th ed., Quincy, MA, 1981.

Palmer, K. N., *Dust Explosions and Fires*, Chapman and Hall, Ltd., London, 1973.

Rae, D., "Initiation of Weak Coal-Dust Explosions in Long Galleries and the Importance of the Time Dependence of the Explosion Pressure," *14th Symposium on Combustion*, The Combustion Institute, University Park, PA, 1972.

Richmond, J. K. and Liebman, I., "A. Physical Description of Coal Mine Explosions," *15th International Symposium on Combustion*, The Combustion Institute, Pittsburgh, PA, 1974, pp. 115–126.

Richmond, J. K., Price, G. C., Sapko, M. J., and Kawenski, E. M., "Historical Summary of Coal Mine Explosions in the United States, 1959–81, Information Circular 8909, U.S. Bureau of Mines, Washington, DC, 1983.

Author Index

Subject Index

ISBN 0-8031-0957-1