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Development and Control of Dust Explosions

John Nagy
Harry C. Verakis

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John Nagy
Retired from
U. S. Department of Labor, Mine Safety and Health Administration
and
U. S. Department of the Interior
Bureau of Mines
Pittsburgh, Pennsylvania

Harry C. Verakis
U. S. Department of Labor, Mine Safety and Health Administration
Triadelphia, West Virginia

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DEDICATION

To our former co-workers at the Bureau of Mines who performed the experimental research; and to Connie, Barbara, and David, who encouraged and supported the preparation of the manuscript.

PREFACE

This book encompasses the development and control of explosions which may result when combustible fuels become mixed with oxidizing atmospheres and are ignited in confined or partially confined spaces. Research findings are given on many factors leading to or inhibiting ignition. Explosion development in closed and vented vessels as well as the flow of the gases through the vent are examined mathematically. The equations developed relate the chemical reactivity of the fuel to the physical environment of the explosion vessel. Disruptive pressure can develop unless the design and fabrication of the enclosure provide for containment of the gas or dust explosion. The resulting explosion can burst the container, produce flame, hot and toxic gases, and wind forces. Where design for containing the explosion is not possible, provision of adequate vents can reduce the resulting forces and limit damage.

Considering present-day advances in science and technology, a mathematical treatment of explosion phenomena can be fairly rigorous. However, even with rigorous treatment, assumptions are generally made which vary from practical situations. For this reason, a simplified approach is used in this text. An attempt is made to show general agreement between theory and experiment. Better agreement could be achieved by considering adiabatic rather than isothermal expansion of gases. However, the improvement is far overshadowed by poorly defined variables occurring in practice such as turbulence, extent and concentration of fuel, and the location and intensity of the igniting source.

Both authors served as staff members of the Bureau of Mines, performing research primarily on dust explosions. In the course of these duties, some work was performed on gas explosions, both to correlate the two types of fuels as well as to simplify the analyses of explosion development. Although gas explosions are generally better understood than dust explosions, emphasis is given to dust explosion phenomena. During the 1960's, considerable effort was made to publish the Bureau's research findings on dust explosions. However, following a disasterous coal mine explosion in 1968, the course of the Bureau's activities was altered to phases dealing directly with mine safety. Consequently, the activities relating to industrial explosions were sharply curtailed. The summation of the studies on industrial dust explosions was not completed. Both authors have received permission from the Director's office to use the data and photographs originally obtained in the studies by the Bureau and, as individuals independent of their employment, to develop the data in book form. Consequently, any statements or conclusions in the book are those of the authors and not of the Government.

The primary purpose of this book is to provide fundamental information on dust explosion phenomena rather than to offer detailed design specifications. The better the understanding of basic principles involved in the ignition and explosion of dusts and effective explosion venting, the greater the degree of control achieved over such hazards. Combustible dusts occur as the product or a by-product in numerous American industries. These industries include those involved in the preparation, manufacture or use of chemicals, dyes, drugs, foods and beverages, grains, feeds, metals, plastics, paints, textiles and wood.

The subject of dust explosions is of interest to a wide range of professionals in a variety of commercial and governmental activities. Information presented in this book has direct benefit to safety engineers, insurance representatives, plant managers and operators, as well as to architects and others responsible for safe building and design. It is appreciably more economical to prevent or control an explosion than to rectify and rebuild should one occur. Data presented in this book will also be useful to fire safety engineers and of course to firefighters who more and more must face the hazards of dust explosions and fires. The mathematical approach used herein to develop basic concepts of explosion venting will aid scholars, those professionals engaged in ignition and explosion research, and the military.

Although the information contained in this book is believed to fairly present the state of the art in this field to the best knowledge of the authors, the book is intended for informational purposes only. Neither the authors nor the publisher make any representations or warranties regarding the accuracy or completeness of the contents of the book nor assume any responsibility whatsoever in connection with any user's interpretations, conclusions, recommendations, designs, installations, operating practices, safety procedures and/or other commercial uses derived from the information in this book. In actual practice, all designs, installations, operating and/or safety procedures should be developed and followed solely in accordance with the requirements and suggested procedures of applicable legislative authorities, pertinent accepted codes and/or other mandated requirements.

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Harry C. Verakis

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Chapter 1

INTRODUCTION

SCOPE

This book presents a comprehensive treatment of the development and control of dust and gas explosions. It was originally intended to address dust explosions alone, but since gas and dust explosion development is similar, some facets of gas explosions are considered. The work is an outgrowth of the research conducted primarily from 1940 through 1970 by the Dust Explosions Section of the U.S. Bureau of Mines. A complete list of the Bureau's studies conducted by the Dust Explosions Section is included in the references to this chapter. These references deal mostly with factors affecting dust explosibility. This book consolidates these research reports and extends the work with particular reference to explosions in closed and vented vessels.

Explosions in Industry

Precise statistical data on the number of explosions and the resulting injuries and fatalities occurring in the United States cannot be given because explosion incidents are not mandated to be reported to any agency. The gas explosion hazard is more prevalent than the dust explosion hazard because of the wide use of a variety of combustible gases in industry, and because natural gas is widely used in homes.

The first well-documented dust explosion incident occurred in an Italian flour mill in 1785. Dust explosions continue to occur in a wide variety of industries. During the period from 1970 to 1980, about 100 reportable industrial dust explosions occurred, causing approximately 25 fatalities. The average yearly property loss was about $20 million. This estimate does not include losses from grain dust explosions. According to U.S. Department of Labor statistics, 250 grain dust explosions occurred during the period from 1958 to 1978 causing 164 fatalities. In 1977, there were 21 grain dust explosions which caused 65 fatalities. The property loss in these explosions exceeded $500 million. The potential explosion hazard of grain dusts does not differ from that of other combustible dusts. Generally, the magnitude of the operations involved in the storage and transfer of agricultural dusts is greater than for other types of dust.

In his recent book on explosion, Bartknecht [44] states that in Europe more than 4000 dust explosions occurred in the past 12 years. This amounts to about one explosion each working day. His data were obtained from insurance records and are more complete and reliable than the preceding estimates made for American industry. It is surmised that the number of explosions in American industry are comparable to those in Europe.

The hazard of a gas or dust explosion encompasses all segments of American industry, no matter what type of combustible gases or dusts are present. The gases or dusts may be the main or intermediate product or by-products. Some of the more common materials presenting a dust explosion hazard are drugs, dyes, feeds, fertilizers, foods, grain, insecticides, meals, metals, paper, plastics, rubber, sulfur, soaps, spices, starches, wood, and of course, those plants using coal or other carbonaceous materials. Explosions have occurred in buildings from dust on the floor, on ledges, and on beams. They have also occurred in ducts, pipes, and in equipment such as bins, blenders, buffers, coating machines, collectors, conveyors, crushers, driers, elevators, furnaces, grinders, machinery, mixers, ovens, packaging, pneumatic transport, pulverizers, screens, silos, spreaders, and storage facilities. A potential dust explosion hazard is intensified by the presence and multiplicity of potential igniting sources.

RESEARCH ON EXPLOSIONS

Industrial Explosions

Research on the explosion hazard of gases and dusts is actively pursued by industrial organizations, universities, private laboratories, insurance groups, and by State and Federal agencies. Much of the research overlaps studies on fires. Efforts paralleling those in the United States are made in most industrialized and coal mining countries. Although the potential explosion hazards of gases were recognized for centuries, general recognition of the hazards from dusts began at about the turn of the 20th Century. Recognition of explosion and fire hazards in an organized manner began formally in the United States with the National Fire Protection Association. The National Fire Protection Association was organized in 1896 to promote the science, improve methods of fire protection and prevention, obtain and circulate information on these subjects, and secure the cooperation of its members in establishing proper safeguards against loss of life and property. In 1922, the NFPA formed a Committee on dust explosion hazards. This Committee has remained active and has coordinated results of research efforts from government, industry, and academia to provide industry with effective codes for minimizing hazards and preventing explosions. Shortly thereafter, the Association began to publish specific codes [45] for the control of gas and dust hazards. This organization has consistently devoted much energy and time to education, publicizing the hazards, and developing codes for safe operations in industry and homes.

Shortly after the turn of the present century, the Department of Agriculture and the Department of the Interior began explosibility studies on industrial and grain dusts. In the mid-1930's, governmental activities became restricted as a result of the depression and these two organizations ceased their experimentation. In 1910, the Bureau of Mines began to study the causes of and to develop means to minimize disasters in coal mines. Much of the research on mine explosions was conducted in the Experimental Coal Mine at Bruceton, Pennsylvania. Associated with the large-scale studies in the mine were laboratory and surface-testing facilities. These facilities were used to a limited extent to study the hazards of gases and dust in industrial and other operations. The Bureau's work on industrial explosions increased in 1936 and during the 1940's supportive research was performed for the military. Following World War II, research by the Bureau of Mines on industrial dusts became broader in scope to include many of the dusts commonly found in American industry and to begin a study of venting. The work by the Bureau of Mines on industrial dusts continued until 1970 when this phase was curtailed following the passage of the Coal Mine Health and Safety Act of 1969. Emphasis was then given primarily to the study of mining hazards, mineral dust explosions, and the promulgation of mine health and safety regulations.

In the development of equipment and test procedures for evaluating dust explosion parameters, those engaged in applied research tend to use physical test arrangements which produce values representing the maximum hazard. Most industrial explosions are less severe than the maximum; however, in some instances, the most violent type of explosion does occur in industry. As such circumstances do exist in industry, the engineer or others responsible for plant safety must, therefore, choose the degree of protection that can be afforded and yet be consistent with the potential hazards present. Gross estimation usually must be made of several of the variables, particularly for vent area calculations.

The engineer designing a vessel or structure in which a gas and/or a dust explosion may occur has a formidable task. In designing for containment, one must consider the vessel size and strength; the type and concentration of fuel; the initial temperature and pressure; turbulence; the intensity and location of the ignition source; uniformity and extent of mixture; and also make judgment as to the factor of safety. For venting, one must consider all these factors, as well as the vessel shape, initial turbulence, potential location of igniting source relative to the vent, and the type of vent closure. A long, narrow container may require several vents, but a single vent may suffice for a spherical or cubical container. The factor of initial turbulence does not materially affect the maximum pressure developed in a closed vessel, but does significantly affect pressure development in a vented vessel. For a vented vessel, the location and intensity of the igniting source may affect the rate of explosion development by a factor as high as 8, and the maximum pressure by a factor of 4, depending on the shape and size of the container. Finally, the engineer must consider the size, shape, and location of the vents, together with the type and bursting strength of the vent closure. For both vented and unvented explosions, the type of fuel (its fundamental reaction rate), the oxygen content of the atmosphere, and the presence of inert material are prime factors. For dusts, the shape and particle size are major concerns.

Mine Explosions

Mine passageways provide a significantly greater degree of confinement to an explosion than do buildings on the surface. Hence, a mine explosion generates highly destructive wind forces from the dynamic pressure which develops. In a mine, these forces cause damage at great distances from the origin of the explosion. Explosions in surface industries are usually considered separately from those in underground mines, partly because of the different environment, and partly because methane gas is usually involved in the mine explosions. An overview of the explosion hazard in mines which summarizes current knowledge was recently published [46]. In surface explosions, the destructive forces are generally confined to the area exposed to the high static pressure generated by the explosion. The destructive forces may result from a primary or from a secondary dust explosion.

Related Explosion Hazards

Although dust, gas, and mist explosions are possible with gases other than oxygen (e.g., chlorine), their occurrence in industry is relatively rare. For this reason, the ensuing treatment considers the oxidation reaction.

No attention in this book is given to the explosion hazard of combustible mists or of the hazards of primary explosives.

REFERENCE MATERIAL

Much work has been performed in the field of gas and dust explosions. Pertinent references are included to support observations or conclusions; however, no attempt is made to provide a complete bibliography in this text. Much of the laboratory data obtained by the Bureau of Mines have been republished in tabular form in the NFPA Fire Protection Handbook [47]. Similar data were published by the Germans [48] for more than 800 dusts. Explosibility data were also published by the British [49] in 1968. A study on the ignition and explosion characteristics of gases was published by the Bureau of Mines in 1965 [50].

The subject of the venting of explosions is being studied universally. H. R. Maisey [51] has provided a bibliography of the work up to 1965. Recent works on dust explosions and venting are those by Bartknecht [44], Bodurtha [52], and Field [53]. In 1973, Palmer [54] published a book on dust explosions emphasizing the hazards of dusts and methods of testing. He also discussed venting as a means for explosion control. Books by Bartknecht, Fields, and Palmer contain numerous references to earlier work. The Bureau of Mines continues its study on the ignition and explosion hazards of mineral dusts and is actively publishing in this field [55].

Considering present advances in science and technology, a mathematical treatment of explosion phenomena can be fairly rigorous. However, even with rigorous treatment, assumptions are generally made which vary from practical situations. For this reason, a simplified approach is used in this text. An attempt is made to show general agreement between theory and practice. Greater accuracy could be achieved by considering adiabatic rather than isothermal expansion of gases. However, the improvement is far overshadowed by poorly defined variables occurring in practice such as turbulence, extent, and concentration of fuel, and the location and intensity of the igniting source.

REFERENCES

1. Hartmann, I., Nagy, J., and Brown, H. R. Inflammability and Explosibility of Metal Powders, Bureau of Mines RI 3722, 1946.
2. Hartmann, I., Nagy, J., and Brown, H. R. Explosibility of Metal Powders: Metal Progress 45:886, 1944.
3. Hartmann, I. and Nagy, J. Inflammability and Explosibility of Powders Used in the Plastics Industry, Bureau of Mines RI 3751, 1944.
4. Hartmann, I. and Greenwald, H. P. The Explosibility of Metal Powder Dust Clouds: Mining and Metallurgy, 26:331-335, 1945.

5. Hartmann, I. and Nagy, J. Effect of Relief Vents on Reduction of Pressure Developed by Dust Explosions, Bureau of Mines RI 3924, 1946.
6. Hartmann, I. Pressure Release for Dust Explosions, Nat. Fire Protection Assoc. Quarterly, 40:47-53, 1946.
7. Explosion Venting Meeting and Demonstration, Nat. Fire Protection Assoc. Quarterly, 41:149-152, 1948.
8. Hartmann, I. Recent Research on Explosibility of Dust Dispersions, Industrial and Engineering Chemistry, 40-4:752-758, 1948.
9. Hartmann, I. The Explosion Hazard of Metal Powders and Preventive Measures, Metals Handbook, Am. Soc. of Metals, pp. 52-54, 1948.
10. Hartmann, I. Explosion and Fire Hazards of Combustible Dusts, Industrial Hygiene and Toxicology, 1:439-454, 1948.
11. Cassel, H. M., DasGupta, A. K., and Guruswamy, S. Factors Affecting Flame Propagation through Dust Clouds, The Third Symposium on Combustion and Flame and Explosion Phenomena, Baltimore: The Williams and Wilkens Co., 185-190, 1949.
12. Hartmann, I. and Nagy, J. The Explosibility of Starch Dust, Chemical and Engineering News, 27:2071, 1949.
13. Nagy, J., Zeilinger, J. E., and Hartmann, I. Pressure-Relieving Capacities of Diaphragms and Other Devices for Venting Explosions, Bureau of Mines RI 4636, 1950.
14. Hartmann, I. Dust Explosions, Marks' Mechanical Engineers Handbook, New York: McGraw-Hill, rev. 5th ed., pp. 795-800, 1951.
15. Hartmann, I., Cooper, A. R., and Jacobson, M. Recent Studies on the Explosibility of Cornstarch, Bureau of Mines RI 4725, 1950.
16. Hartmann, I. The Explosibility of Titanium, Zirconium, Thorium, Uranium and Their Hydrides, U.S. Atomic Energy Commission Dept. NYO-1562, June 1951.
17. Hartmann, I., Nagy, J., and Jacobson, M. The Explosive Characteristics of Titanium, Zirconium, Thorium, Uranium, and Their Hydrides, Bureau of Mines RI 4835, 1951.
18. Hartmann, I., Jacobson, M., and Williams, R. P. Laboratory Explosibility Study of American Coals, Bureau of Mines RI 5052, 1954.
19. Hartmann, I. Dust Explosions in Coal Mines and Industry, The Scientific Monthly, 79-2:97-108, 1954.
20. Brown, H. R., Dalzell, C. J., Hartmann, I., Toothman, G. J. R., and Schwartz, C. H. Fire and Explosion Hazards in Thermal Coal-Drying Plants, Bureau of Mines RI 5198, 1956.
21. Hartmann, I. Explosion and Fire Hazards of Combustible Dusts, Industrial Hygiene and Toxicology (Patty), rev. 2nd ed., New York: Interscience Publishers, Inc., pp. 549-578, 1958.
22. Hartmann, I. Dust Explosions, Marks Mechanical Engineers Handbook, rev. 6th ed., New York: McGraw-Hill, pp. 41-48, 1958.

23. Cassel, H. M., Liebman, I., and Mock, W. K. Radiative Transfer in Dust Flames, The Sixth Symposium (International) on Combustion, New York: Reinhold Publishing Co., pp. 602-605, 1957.
24. Hartmann, I. Recent Findings on Dust Explosions, Chemical Engineering Progress, 53-3:107-111M, 1957.
25. Hartmann, I. and Nagy, J. Recent Studies on Venting of Dust Explosions, Industrial and Engineering Chemistry, 49:1734-1740, 1957.
26. Dorsett, H. G., Jr., Jacobson, M., Nagy, J., and Williams, R. P. Laboratory Equipment and Test Procedures for Evaluating Explosibility of Dusts, Bureau of Mines RI 5624, 1960.
27. Jacobson, M., Nagy, J., Cooper, A. R., and Ball, F. J. Explosibility of Agricultural Dusts, Bureau of Mines RI 5753, 1961.
28. Jacobson, M., Nagy, J., and Cooper, A. R. Explosibility of Dusts Used in the Plastics Industry, Bureau of Mines RI 5971, 1962.
29. Jacobson, M. and Nagy, J. Recent Research on the Explosiveness of Agricultural Products, Food Technology, 16-2:32-34, 1962.
30. Nagy, J. and Mitchell, D. W. Gas Explosion Phenomena, Mechanization, 39-42, 1963.
31. Jacobson, M., Cooper, A. R., and Nagy, J. Explosibility of Metal Powders, Bureau of Mines RI 6851, 1965.
32. Nagy, J., Cooper, A. R., and Stupar, J. M. Pressure Development in Laboratory Dust Explosions, Bureau of Mines RI 6561, 1964.
33. Nagy, J., Dorsett, H. G., Jr., and Jacobson, M. Preventing Ignition of Dust Dispersions by Inerting, Bureau of Mines RI 6543, 1964.
34. Nagy, J. Dust Explosion Hazards in Plastic Processing, Storage and Air Conveying, Nat. Safety Congress Trans., 5:5-8, 1965.
35. Dorsett, H. G., Jr. Dust Explosions in Buildings, Marks Mechanical Engineers Handbook, 7th ed., 38-45, 1967.
36. Nagy, J. and Surincik, D. J. Thermal Phenomena During Ignition of a Heated Dust Dispersion, Bureau of Mines RI 6811, 1966.
37. Mitchell, D. W., Holtz, J. C., Nagy, J., and Jacobson, M. Dust Explosion Hazards in Manufacture of Plastics, Polymer Conference Series, Wayne State University, Detroit, Michigan, May 9, 1966.
38. Dorsett, H. G., Jr. and Nagy, J. Dust Explosibility of Chemicals, Drugs, Dyes, and Pesticides, Bureau of Mines RI 7132, 1968.
39. Nagy, J., Cooper, A. R., and Dorsett, H. G., Jr. Explosibility of Miscellaneous Industrial Dusts, Bureau of Mines 7208, 1968.
40. Nagy, J., Conn, J. W., and Verakis, H. C. Explosion Development in a Spherical Vessel, Bureau of Mines RI 7279, 1969.
41. Nagy, J., Seiler, E. C., Conn, J. W., and Verakis, H. C. Explosion Development in Closed Vessels, Bureau of Mines RI 7507, 1971.