Dust Explosions

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PLENUM PRESS • NEW YORK AND LONDON

Library of Congress Cataloging in Publication Data

Cross, Jean, 1947–
Dust explosions.

Bibliography: p.
Includes index.
1. Chemical plants—Safety measures. 2. Dust explosion. I. Farrer, Donald. II. Title.
TP155.5.C7 660.2′804 82-7499
ISBN 0-306-40871-6 AACR2

A Division of Plenum Publishing Corporation
233 Spring Street, New York, N.Y. 10013

Printed in the United States of America

Preface

The interest of the media in dust explosions increased considerably following two major grain-elevator disasters in the United States in 1979. However, these were not isolated incidents and were statistically unusual only in the high loss of life involved.

Any oxidizable material that is dispersed in fine powder form may be explosive, and ignition sources with sufficient energy to ignite a dust cloud are easily produced in normal industrial processing. Dust fires and minor incidents are not uncommon in many industries, but fortunately the combination of events and circumstances that must coincide for a large-scale explosion arise only rarely. Nevertheless, this is often more by luck than by good management and many potentially hazardous situations are common in industry.

An explosive dust cloud and the circumstances in which it can ignite are not as simple to define as the equivalent situation in gases or flammable vapors. A large number of definitions and experimental tests have been devised to characterize the explosibility of dusts and ignition sources. The aim of this book is to provide a guide describing conditions in industry that could lead to dust explosions and the means to avoid them. Ignition sources and the way in which they can arise in powder processing are discussed and illustrated by case histories of reported incidents. The methods by which the potential hazards of a process or product can be evaluated are described, with special attention paid to the interpretation of the results of the different experimental methods. Finally, the commonly quoted ignition characteristics of powders and their relevance to the industrial situation are evaluated.

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Notation

a	radius of a particle
c	mass concentration of dust
d	distance or length
f	vent ratio = vent area/vessel volume
k	cell constant
l	length
m	mass
p	pressure
q	charge
r	distance (polar coordinates)
t	time
v	velocity
x	distance (cartesian coordinates)
A	area
C	capacitance
D	density of material
E	electric field
F	force
I	current
K	chemical reaction rate
K_{st}	dust explosion classification
L	inductance
M, N	constants
P	powder cloud density
Q	charge density
R	electrical resistance
S	surface area
T	temperature
V	voltage (or volume of vessel)
W	spark energy
R	chemical gas constant
ϵ_0	permittivity of free space = 8.8×10^{-12} f/m
ϵ	dielectric constant
ρ	resistivity
σ	conductivity
τ	time constant
γ_c	constant
η	viscosity
κ	reaction rate
ω	frequency

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Introduction

1.1. HOW, WHERE, AND WHY DUST IGNITIONS OCCUR

Any material that will burn in air when it is in a solid form may explode when it is in the form of a finely divided powder. Even materials that oxidize more slowly than would normally be implied by the term "burning" can ignite catastrophically if the particle size is small. Explosions of foods pharmaceuticals, grain products, organic materials, polymers, and metals all occur. Oxidation is an exothermic reaction. Normally in a solid sample the heat formed is easily absorbed into the solid. In a powder, however, the surface area on which oxidation occurs is very large and the volume of the particle is very small so the temperature rises. This increases the rate of oxidation, creating yet more heat, so a runaway situation is rapidly reached.

There is some evidence that solids vaporize before exploding and that the production of sufficient heat to vaporize the surface is a necessary part of the explosion. It is not known whether this is true for all materials, although it certainly plays an important part in the ignition of coal dust, where methane gas is given off, and in the burning of many polymers that partially decompose as ignition begins.

When a powder is settled into a layer or heap, or when the dust cloud is very dense, there may be insufficient oxygen to allow the reaction to proceed rapidly enough for an explosion. For most dusts there is an optimum density of particles in the air for the propagation of a dust explosion: the particles should be close enough together for the heat of one particle to initiate reaction in the next, but far enough apart to allow free access of oxygen. This leads to the concept of a *minimum* and *maximum explosion concentration*.

The maximum explosion concentration is not a well-defined parameter and is seldom measured. From a safety viewpoint it is dangerous to assume that powder above a certain density is safe because dust layers can burn or smoulder slowly and can also self-heat to ignition. Dust layers are also very easily disturbed to create an explosive cloud. It is often difficult to detect the slow burning of settled dust, and this can provide a particularly dangerous ignition source when it is moved to another part of the system or disturbed into a cloud.

The minimum explosive concentration (which, following the terminology of gases and vapors, is sometimes known as the *lower explosive limit* or LEL) is better defined and is one of the parameters by which an explosive dust is characterized.

Dust explosions can occur whenever there is a combination of a dust cloud in the air within the explosive concentration range and an ignition source. Ignition sources are provided by electrical or electrostatic sparks, hot surfaces, overheated powder particles, or any other source of sufficient energy to initiate reaction in a few particles. There are so many ignition sources that can arise under fault conditions or from operator error that it is seldom realistic to base a safety policy entirely on the elimination of ignition sources. If an explosive cloud might occur in an area, it is necessary to ensure either that explosion is prevented by reducing the oxygen level in the area or that the results of an explosion are controlled by venting, suppressing, or containing the pressure rise.

It cannot be over emphasized that, in the majority of major dust explosions, the greatest damage occurs during secondary explosions. The primary explosion is often limited to a small-scale incident in a limited area but this then forms a high-energy ignition source for dust in other areas or for dust clouds raised by the initial explosion.

In designing equipment and plants to eliminate hazards and minimize the damage due to failure, it is necessary to consider not only each section individually but also the plant as a whole: There must be no dust layer to aid propagation of an explosion from one area to another, and a fault in one area must not produce a hazardous condition in the next operation. It is not uncommon for the consequences of a small ignition in one area to initiate an explosion in another area because of bad positioning of vents or lack of foresight concerning the path that would be taken by debris or burning powder.

1.2. IGNITION SOURCES—STATISTICAL DATA

Clear statistics concerning the causes of fires and explosions involving dusts are not readily available for most industries. Data published by organizations in different countries do not agree since the sources do not deal with data on the same basis. Different industries may well have different problems and this reflects on the most common ignition source attributed to each industry. However, it is also possible that once a source has been identified, accidents become wrongly attributed. Thus one particular source becomes "fashionable" in a particular industry with little justification in fact.

The majority of accidents widely reported, and for which a major study is carried out, are incidents where there is considerable damage. In these cases reliable identification of the source of ignition is difficult. Minor fires and explosions, some of which could easily have led to severe accidents in only slightly different circumstances, seldom reach the statistical reports. Often, in the interest of a rapid return to full production, a complete investigation of causes is not carried out.

Although it is possible to gain considerable knowledge of the ignition source from analysis of the results of an explosion—such as the fire damage and the range of debris—this exercise is seldom carried out except where damage is too severe to separate which faults caused the explosion and which were caused by it.

Often, the study reveals two or three possible ignition sources and the accident is reported as an unknown source, or a guess will be made as to the most probable source given the various possibilities.

The result is that it is only possible to use the published statistics and case histories as a general guide to possible ignition sources, plant failures, and situations that should be avoided.

Reports of fires and explosions are published by the *Fire Protection Journal* in the United Kingdom, The National Fire Protection Association in the United States, the Arbeitsschutz in Europe, and also by organizations representing insurance companies and major chemical companies.

Although the published case histories cannot be considered as a good record of the actual causes of fires and explosions in industry, they are an extremely useful stimulation to the imagination when considering all the possible problems that could occur in a particular installation. In particular, they often clearly show up the interactions between different parts of the plant and the reasons that caused a small incident to escalate into a major disaster. For this reason a number of case histories and examples are given throughout this book. They cannot be considered a representative sample of industrial accidents—simply examples of what may occur and illustrations of different types of incidents.

Two accidents occurred in the grain industry in the United States in December 1977. They resulted in a major reawakening of interest in the problems of dust explosions because they were very close together in time and resulted in a large loss of life. The following extracts of reports on the incidents are taken from the *Fire Journal* of September 1978 published by the National Fire Protection Association.

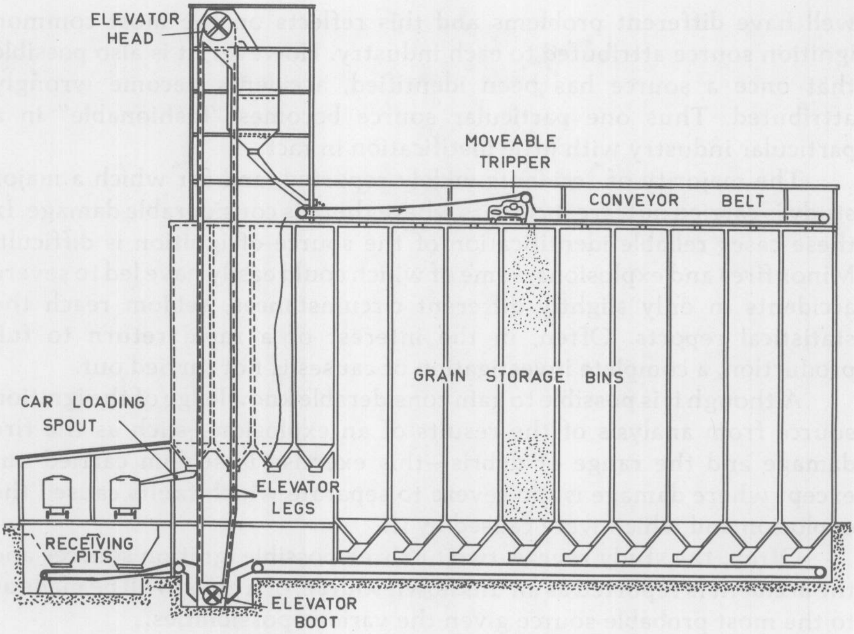

FIGURE 1.1. A typical grain export terminal.

The explosions were similar in several ways: (i) the premises were relatively new; (ii) the construction was reinforced concrete; (iii) both lacked adequate provision for explosion relief; and (iv) the office buildings were located near the head house.

Case Histories—Grain Elevators

CONTINENTAL GRAIN ELEVATOR, WESTWEGO, LOUISIANA: THIRTY-SIX KILLED; ESTIMATED DAMAGE £15 MILLION

The facility consisted of 73 silos; five large metal grain tanks; train-unloading, barge-unloading, and ship-loading facilities; a head house which is a towerlike building containing grain conveyors, scales, and other equipment for moving, cleaning, and sampling grain; and, adjacent to the head house, an office building which, in addition to offices, housed a laboratory, lunch room, and control room.

The silos and head house were constructed of reinforced concrete. The silos were in three groups. They were all 35 m high but of three different diameters—7.6 m, 7.9 m, and 9.4 m. The gallery, basement, and an elevated conveyor structure above the silos had provision for explosion relief. Some of the silos were reported to have interbin venting. The top 23 m of the 76-m high head house was constructed of lightweight metal panels for explosion-relief purposes. Although some explosion-relief venting had been provided, it appeared to be inadequate.

The explosion occurred at about 9:05 am when some 75 people were on the site. It resulted in the top 40 m of the head house collapsing onto the office building and a series of explosions that continued throughout the morning in two of the groups of silos.

When area fire brigades reached the scene they found a mass of concrete, steel, and burning grain where the head house and office building had been. One man was rescued by helicopter from the top of one of the silos. The bodies of 35 fatalities were located in the rubble; 25 of them had been in the office building. One of the injured died several weeks afterwards.

In addition to the destruction of the head house and office building, the explosions and fires destroyed more than half of the silos; these were in the 1959 and 1962 groups. Many were blown out at the top and at the sides near the bottom. Few of the silos in the 1977 group had contained grain, but their conical metal bottoms had imploded and most of the silo tops of this group were also destroyed.

FARMERS EXPORT GRAIN ELEVATOR, GALVESTON, TEXAS: EIGHTEEN KILLED ESTIMATED DAMAGE £12 MILLION

The facility came into service in the summer of 1976. It included (i) 60 reinforced concrete silos each 7.6 m in diameter and 38 m high with 178-mm walls and a 127-mm roof; (ii) two large metal grain tanks; (iii) a reinforced-concrete-built, 70-m high, head house; (iv) a single-storied office building of noncombustible construction; (v) a freight-wagon unloading shed built of metal on a metal framework; and (vi) a reinforced-concrete tunnel housing three conveyors connecting the unloading shed with the head house. (This tunnel ran under the office building.)

No effective explosion-relief venting had been provided for the head house, silos, or conveyor tunnel. Each elevator leg in the head house had an explosion-relief panel measuring 1.68 m × 1.29 m in the head section.

The freight-wagon unloading shed had facilities for bottom unloading three wagons at a time into the three pits provided. One pit could also receive grain by tipping but on the night of the explosion all three pits were using bottom unloading.

Prior to the explosion, the conveyor belt carrying grain to the northernmost row of silos had been stopped for repairs to be made. The motor driving the belt was in the basement of the head house. The employee who carried out the repairs had just radioed the control room to restart the belt when the explosion occurred, but it is not known whether the motor had been started.

The explosion in which the 18 people were killed and 22 injured occurred at 8:31 pm. It destroyed the freight-wagon unloading shed, the tunnel between this shed and the head house, and the central control room. The head house and office building were so badly damaged that they had to be demolished. Grain tank No. 1 collapsed and grain in the second tank caught fire.

A large ditch was created by the destruction of the tunnel, and this cut off the only road giving access to the site for fire fighting and also cut the main water distribution line.

Six of the fatalities were in the unloading-shed area, nine in the head house, two in the control room, and one outside. Fortunately, because of the late hour no one was in the office building.

Consideration of Both Incidents

In neither case was the source of ignition determined. The Galveston explosion is thought to have started in the area of pit No. 2 in the freight-wagon unloading shed and to have traveled through the tunnel into the head house. Possible sources of ignition included a diesel-electric locomotive that was over pit No. 2 at the time. Dust accumulations were reported to be a problem at the Galveston site.

Humidity levels were taken into account but, although low for these humid areas, they were not considered low for many areas where grain is handled.

The inadequate explosion-relief venting allowed the explosions to build up more pressure and cause more damage than would be expected if sufficient venting had been provided.

The incidents are not atypical of the problems that may occur at any time. A combination of the lack of explosion venting or other forms of protection and the layers of dust throughout the plant turned these incidents into major disasters, and the siting of office buildings near to an unvented dust-cloud area added considerably to the death toll.

It is not always realized by other industries that these two incidents

TABLE 1.1. Explosions, Deaths, Injuries, and Fires in Grain-Handling Facilities for 1958–1978

Year	Number of explosions in U.S.	Number of deaths	Number of injuries	Estimated number of fires in elevators[a] (NFPA)
1958	10	2	27	3200
1959	10	3	18	2200
1960	12	4	18	2300
1961	10	0	17	2100
1962	9	3	51	2300
1963	14	3	30	2200
1964	8	3	22	2000
1965	9	2	5	1900
1966	14	2	22	2000
1967	17	1	14	3000
1968	16	12	38	5300
1969	6	4	13	4700
1970	10	1	14	3000
1971	10	4	14	3100
1972	8	7	23	2400
1973	8	2	10	1800
1974	15	13	37	2200
1975	9	4	19	2200
1976	22	22	82	—
1977	21	65	84	—
1978	12	7	47	—
Totals	250	164	605	

[a] Estimated number of fires in elevators unavailable after 1975.

were statistically unusual only in the high loss of life. Dust explosions causing considerable damage have been a problem in the grain industry for many years with 8–15 major incidents occurring in the United States each year (Table 1.1). For this reason the grain industry has been the subject of the most extensive analysis of free-explosion statistics carried out for a single industry. Chiotti and his co-workers at Iowa University (1976) have looked at dust explosions in the American grain industry between 1958 and 1978.

Figures 1.2(a) and (b) summarize some of their results. It can be seen that in nearly 50% of the 162 accidents investigated the ignition source was not identified. The two most common sources found were in accidents associated with welding and faulty equipment that caused friction, such as the rubbing of conveyor belts.

In mills, foreign material in the grinding process was also a major source of fire and explosion. Further statistics on ignition sources published by the United States Department of Agriculture are given in Table 1.2, which lists 66 incidents between 1969 and 1978.

Of course it is dangerous to draw too many general conclusions

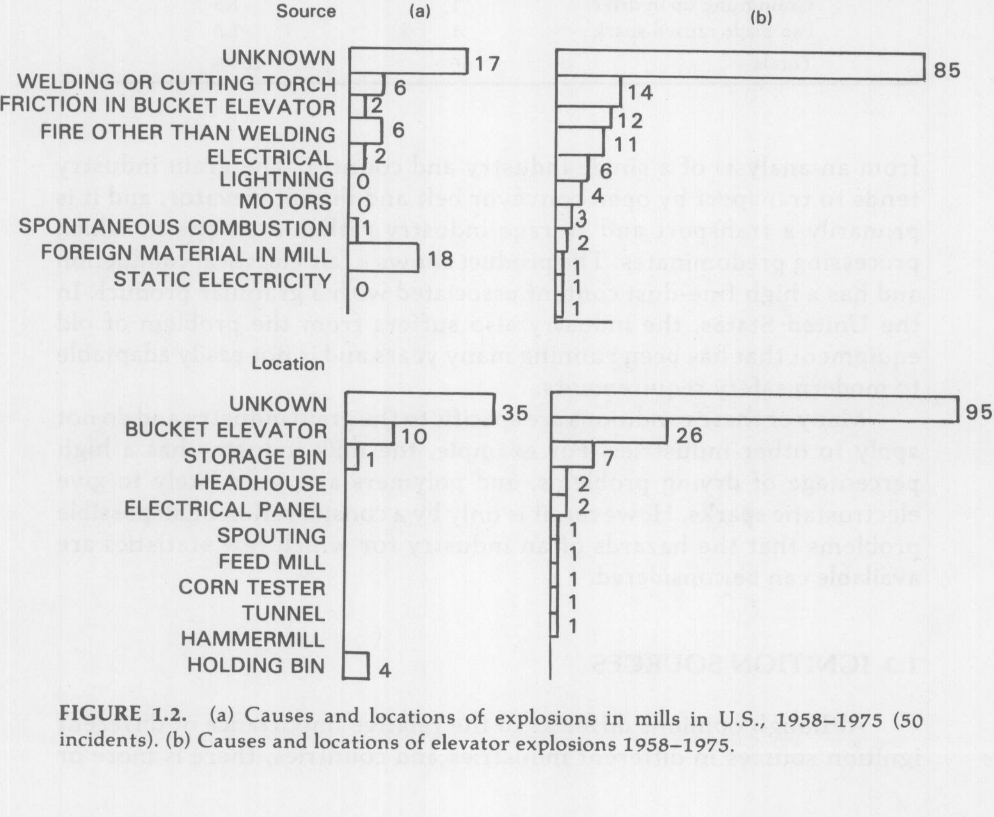

FIGURE 1.2. (a) Causes and locations of explosions in mills in U.S., 1958–1975 (50 incidents). (b) Causes and locations of elevator explosions 1958–1975.

TABLE 1.2. Probable Ignition Sources for 66 Incidents in Elevators

Ignition source	Number of elevators	Percent of elevators
Unknown	17	25.7
Welding/cutting	16	24.3
Hot bearings	7	10.6
Lightning	1	1.5
Static electricity	1	1.5
Electrical	4	6.0
Tramp metal	6	9.1
Blockage in leg	1	1.5
Extraction of oil from corncake	1	1.5
Switch engine on rail dump	1	1.5
Explosive vapor	2	3.1
Heating system	2	3.1
Dust system	2	3.1
Choked leg	1	1.5
Electric cord in leg	1	1.5
Volatile solvent escaped from processing of soybeans	1	1.5
Grain hung up in drier	1	1.5
Fan blade caused spark	1	1.5
Totals	66	100%

from an analysis of a single industry and country. The grain industry tends to transport by open conveyor belt and bucket elevator, and it is primarily a transport and storage industry rather than one in which processing predominates. The product shows a fair electrical conduction and has a high fine-dust content associated with a granular product. In the United States, the industry also suffers from the problem of old equipment that has been running many years and is not easily adaptable to modern safety requirements.

Many of these conditions are specific to the grain industry and do not apply to other industries. For example, the milk industry has a high percentage of drying problems, and polymers are more likely to give electrostatic sparks. However, it is only by a consideration of all possible problems that the hazards of an industry for which few statistics are available can be considered.

1.3 IGNITION SOURCES

Although opinions differ as to the relative importance of different ignition sources in different industries and countries, there is more or less universal agreement that the most common cause of accidents involving dust clouds is the use of welding torches or power tools without proper precautions and proceedures.

Welding torches or flames provide a very high energy that easily ignites any residual dust near the welding area. Even if maintenance is carried out only when no powder is transported, residual dust layers can ignite and smoulder and be swept into a dust cloud when the plant is restarted. A similar problem can be caused by cigarettes smoked by maintenance workers who think the plant must be safe when shut down.

Although high-energy sources of this type still cause the largest number of fires, other less-energetic sources must not be neglected.

For some time it was believed that dusts were much harder to ignite than vapors and that a major ignition source like a welding torch, electrical arc, or gross overheating was required before an explosion could occur. As time progressed and techniques for producing dispersed dust clouds in laboratory test equipment improved, the minimum energy capable of igniting a dust cloud was reduced. Now some 10% of organic materials ($< 75\ \mu m$ in diameter) can be ignited by a spark containing less than 5 mJ of energy, and some materials such as aluminum and sulfur have been ignited with sparks of less than 1 mJ. (Gases and vapors such as propane, methane, and many organic solvents have an ignition energy at their optimum concentrations between 0.15 and 1 mJ). Therefore, it is necessary to pay special attention to the low-energy sources of ignition such as electrostatic sparks and impact sparks from falling objects, if only because these often have not been considered in detail in the past because they were considered to be too low in energy to be of significance.

Electrostatic sparks, in particular, are often poorly understood in industry. A number of incidents occur each year which could easily be prevented if the importance of low-energy ignition sources were realized.

Although the vast majority of accidents continue to be caused by plant failure, human error, and failure to observe specified rules, it is important that low-energy ignition sources should not be neglected in favor of the more obvious high-energy sources.

In this book special attention is given to low-energy sources in general and electrostatic problems in particular. Electrostatics remains a poorly understood subject in industry and static sparks become the scapegoat when no other source of ignition seems likely. The aura of mystery that often seems to surround the question of electrostatics is not justified.

Static levels can be quantified and hazards evaluated, and in Chapters 3 and 4 the means by which this is accomplished are specified. Impact sparks require additional research because laboratory tests have not yet succeeded in igniting an organic dust cloud by an impact spark