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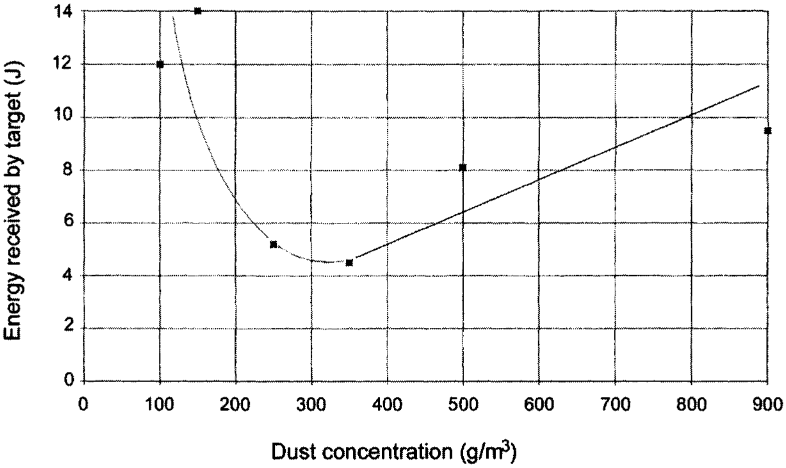

Figure 5–40 Deduced relationship for the minimum energy of a very short laser pulse, hitting a solid inert iron oxide target inside an explosive cloud of starch particles in air, required for igniting the cloud, as a function of the starch concentration in the cloud. From Proust (2002).

are substantially higher than the minimum electric spark ignition energy of 10 mJ found for the actual starch in a standard MIE test.

5.4 Case Histories of Dust Explosions

5.4.1 Motivation for Selection

Most of the case histories given in the following are taken from the book by Eckhoff (2003). Because of his close co-operation with Norwegian industry in investigating accidental dust explosions that have occured there. He has had access to detailed information on several such explosions. It was natural, therefore, to include some of this information even in the present book. However, the case history from China and the very recent one provided by CSB (2003) constitute most valuable additional examples illustrating that the dust explosion hazard continues to threaten a wide range or process industries in many countries.

Some well known dust explosions in other countries, which have been described extensively elsewhere in the open literature, have not been included. This, for example, applies to the catastrophic wheat flour explosion in the Roland Mill in Bremen, Germany, which has been discussed in detail by the Fire and Police Authorities of Bremen (1979). It also applies to many of the major dust explosions in the U.S.A. in the 1970s and 1980s, which have been discussed in detail by Kauffman (1982, 1989) and Kauffman and Hubbard (1984).

5.4.2 Historical Perspective—Wheat Flour Explosion in Turin (1785)

The dust explosion hazard has probably been recognized in Europe for several centuries, but the flour explosion in Turin in 1785 seems to be the first accident of this kind that was investigated extensively. When the Academy of Science of Turin heard about Morozzo's investigations, they asked him to prepare a written account of his findings. Only very rarely are details of Count Morozzo's (1795) fascinating account mentioned in modern literature. It is considered appropriate, therefore, to start this sequence of case histories by quoting some selected sections of the full original account (see Eckhoff, 2003). The wheat flour explosion in Mr. Giacomelli's bakery in Turin was a comparatively minor one, but there is still much to learn from Count Morozzo's analysis. The considerations related to the low moisture content of the flour due to dry weather are still highly relevant. The same applies to the observation of a primary explosion causing a secondary explosion by entrainment of dust deposits.

> On the 14th of December, 1785, about six o'clock in the evening, there took place in the house of Mr. Giacomelli, baker in this city, an explosion which threw down the windows and window-frames of his shop, which looked into the street; the noise was as loud as that of a large cracker, and was heard at a considerable distance. At the moment of the explosion, a very bright flame, which lasted only a few seconds, was seen in the shop; and it was immediately observed, that the inflammation proceeded from the flour warehouse, which was situated over the back shop, and where a boy was employed in stirring some flour by the light of a lamp. The boy had his face and arms scorched by the explosion; his hair was burned, and it was more than a fortnight before his burns were healed. He was not the only victim of this event; another boy, who happened to be upon a scaffold, in a little room on the other side of the warehouse, seeing the flame, which had made its passage that way, and

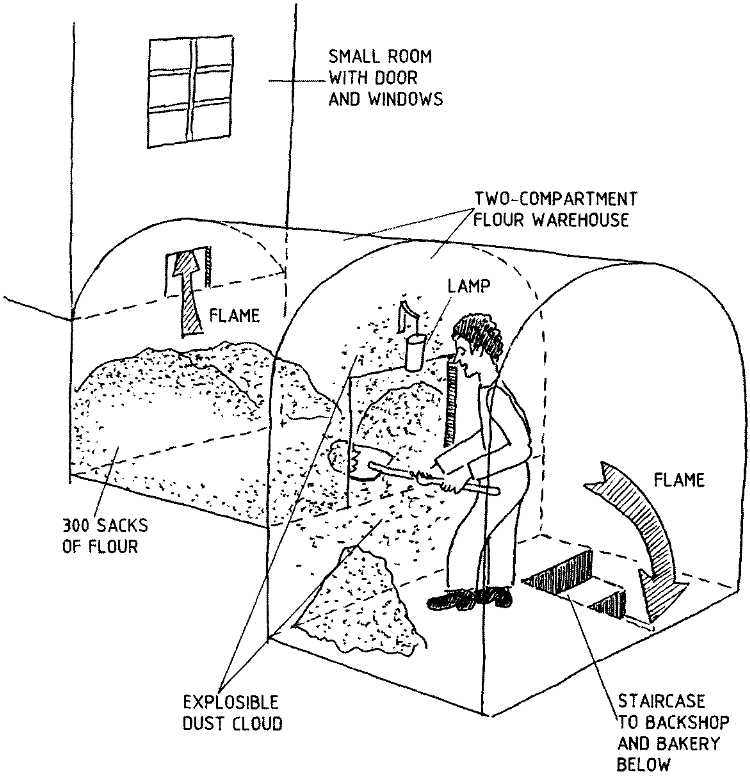

Figure 5–41 Reconstruction of possible scene of wheat flour explosion in Mr. Giacomelli's bakery in Turin, Italy, on 14th December, 1785, as described by Count Morozzo (1795). (From Eckhoff, 2003).

thinking the house was on fire, jumped down from the scaffold, and broke his leg.

The flour warehouse, which is situated above the back shop, is six feet high, six feet wide, and about eight feet long. It is divided into two parts, by a wall; and arched ceiling extends over both, but the pavement of one part is raised about two feet higher than that of the other. In the middle of the wall is an opening of communication, two feet and a half wide, and three feet high; through it the flour is conveyed from the upper chamber into the lower one.

The boy, who was employed in the lower chamber, in collecting flour to supply the bolter below, dug about the sides of the opening, in order to make the flour fall from the upper chamber into that in which he was; and, as he was digging, rather deeply, a sudden fall of a great quantity

> took place, followed by a thick cloud, which immediately caught fire, from the lamp hanging to the wall, and caused the violent explosion here treated of.
>
> The flame pushed itself in two directions; it penetrated, by a little opening, from the upper chamber of the warehouse, into a very small room above it, where, the door and window frames being well closed and very strong, it produced no explosion; here the poor boy, already mentioned, broke his leg. The greatest inflammation, on the contrary, took place in the smaller chamber, and, taking the direction of a small staircase, which leads into the back shop, caused a violent explosion, which threw down the frames of the windows which looked into the street. The baker himself, who happened then to be in his shop, saw the room all on fire some moments before he felt the shock of the explosion.
>
> The baker told me that he had never had flour so dry as in that year (1785), during which the weather had been remarkably dry, there having been no rain in Piedmont for the space of five or six months: indeed, he attributed the accident which had happened in his warehouse to the extraordinary dryness of the corn.
>
> The phenomenon, however, striking at the time it happened, was not entirely new to the baker, who told me that he had, when he was a boy, witnessed a similar inflammation; it took place in a flour warehouse, where they were pouring flour through a long wooden trough, into a bolter, while there was a light on one side; but, in this case, the inflammation was not followed by an explosion.

5.4.3 Three Grain Dust Explosions in Norway (1970-1988)

5.4.3.1 Wheat Grain Dust, Stavanger Port Silo, June 1970

The explosion occurred in Norway's largest and newly built import grain silo in Stavanger on a hot and dry summer day. Fortunately, no persons were killed, but some workers suffered first degree burns. Although the extent of flame propagation was considerable, the material damage was moderate due to the comparatively strong reinforced concrete structure of the buildings and the venting through existing openings.

The entire event lasted for a period of about 25–30 seconds, during which a sequence of six or seven distinct explosions were heard. In the middle of this sequence, there was an interval of 10–12 seconds. The flame propagated a total distance of about 1,500 meters, through a number of bucket-elevators, horizontal conveyors, ducting, filters and rooms in the building. Dust explosions occurred in six of the large, cylindrical storage silos of 2000 m^3 volume each, in one slightly smaller silo, in seven of the slimmer, intermediate silos of capacities 400 or 51000 m^3, in one 150 m^3 silo, and in seven loading-out silos of capacities 50 m^3 each. The six largest silos had no venting, whereas the explosions in the single, slightly smaller silo, and in all the intermediate and loading-out silos, were vented through 0.4 m^2 manholes, which had their covers flung open. It is interesting to note that only one silo was damaged in this incident, namely one of the six unvented, large storage silos, which had its roof blown up, as shown in Figure 5–42. It is thus clear that the maximum explosion pressures in all the other twenty-one silos, vented and unvented, were lower than about 0.2 bar(g), which would be required to blow up the actual type of silo roof.

Almost all the windows, except those in the office department, were blown out, as was a large provisional light wall at the top of the head house. The legs of all of the five bucket elevators of 0.65 m × 0.44 m cross-section were torn open from bottom to top. The dust extraction ducts were also in part torn open.

The ignition source and its location were never fully identified. However, two hypotheses were put forward. The first was self-ignition of dust deposits in the boot of a bucket elevator in which the explosion was supposed to have started. The self-ignition process was initiated by a bucket that had been heated by repeated impacts until it finally loosened and fell into the dust deposit in the elevator boot. The second hypothesis was that the chain of events leading to ignition started with welding on the outside of the grain feeding duct leading to one of the elevator boots. The situation is illustrated in Figure 4–8. Due to efficient heat transfer through the duct wall, self-heating could have been initiated in a possible dust deposit on the inside of the duct wall. Lumps of the smoldering deposit could then have loosened and subsequently become conveyed into the elevator boot, initiating an explosion in the dust cloud there.

Figure 5–42 Damaged silo roof after the wheat grain dust explosion in Stavanger in June 1970. From Eckhoff (2003).

5.4.3.2 Wheat Grain Dust in New Part of Stavanger Port Silo, October 1988

The explosion was described by Olsen (1989). Because of effective explosion mitigation by venting and automatic explosion suppression, the extent of and damage caused by the explosion were minor. There were neither fatalities nor injuries. The incident deserves attention, however, because the chain of events leading to explosion initiation was identified, and because the incident illustrates that properly designed measures for explosion mitigation are effective.

The explosion occurred in a bucket elevator head immediately after termination of transfer of Norwegian wheat grain between two silo cells. At the moment of explosion the transport system was free of grain. In this new part of Stavanger Port Silo, the bucket elevator legs are cylindrical and mounted outdoors, along the wall of the head house. A number of vents are located along the length of the legs. In the explosion incident the vent covers on the elevator leg involved were blown out, which undoubtedly contributed to reducing the extent of the explosion. There was no significant material damage, either by pressure or by heat. Figure 5–43 illustrates the head of the bucket elevator in which the explosion occurred.

Because of a slight offset, the steel cover plate for the felt dust seal for the pulley shaft touched the shaft and became heated by friction during operation of the elevator. The hot steel plate in turn ignited the felt seal, from which one or more glowing fragments dropped into the wheat grain dust deposit on the inclined surface below, initiating smoldering combustion in the deposit. Just after the elevator had stopped, there was presumably still enough dust in the air to be ignitable by the smoldering dust, and to be able to propagate a flame. Alternatively, some of the smoldering dust may have slid down the inclined surface and become dispersed and transformed into an exploding dust cloud. Just after the explosion, some smoldering dust was still left on the inclined plate below the elevator pulley.

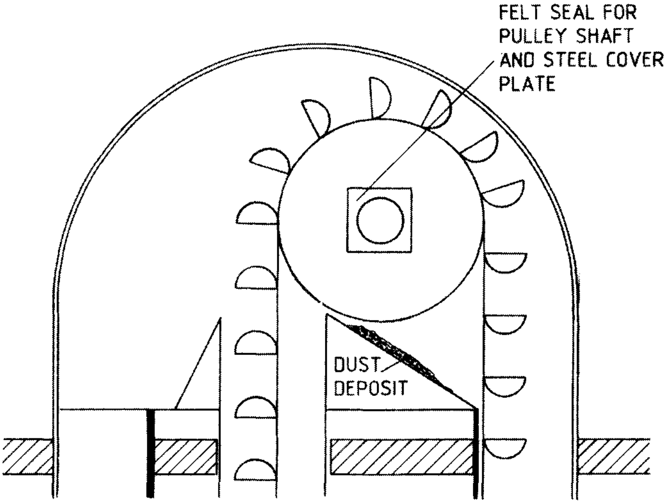

Figure 5–43 Schematic illustration of head of a bucket elevator in the new part of Stavanger Port Silo, where the minor 1988 wheat grain dust explosion was initiated. Courtesy of O. Olsen, Stavanger Port Silo, Norway.

5.4.3.3 Barley/Oats Dust Explosion in Head House of Silo Plant at Kambo, June (1976)

This explosion, described by Storli (1976), caused considerable material damage, but due to fortunate circumstances there were neither fatalities nor significant injuries. The dust involved was from Norwegian barley or oats.

The explosion probably started in a bucket elevator, initiated by burning/ glowing material from an overheated hammer mill. The primary explosion developed into a secondary explosion in the head house itself, which pushed out most of its front wall, as shown in Figure 5–44.

Two of the bucket elevators had bulged out along the entire length and the dust extraction ducting had become torn apart, and this gave rise to the secondary explosion. Because the floors were supported by the wall, and the connections between wall and floors were weak, the entire wall sheet was pushed out at a quite low explosion pressure, leaving the floors unsupported at the front.

After the explosion, the head house was reconstructed. The floors were supported by a rigid framework, and should an explosion occur again, the lightweight wall elements can serve as vent covers, without weakening the support of the floors.

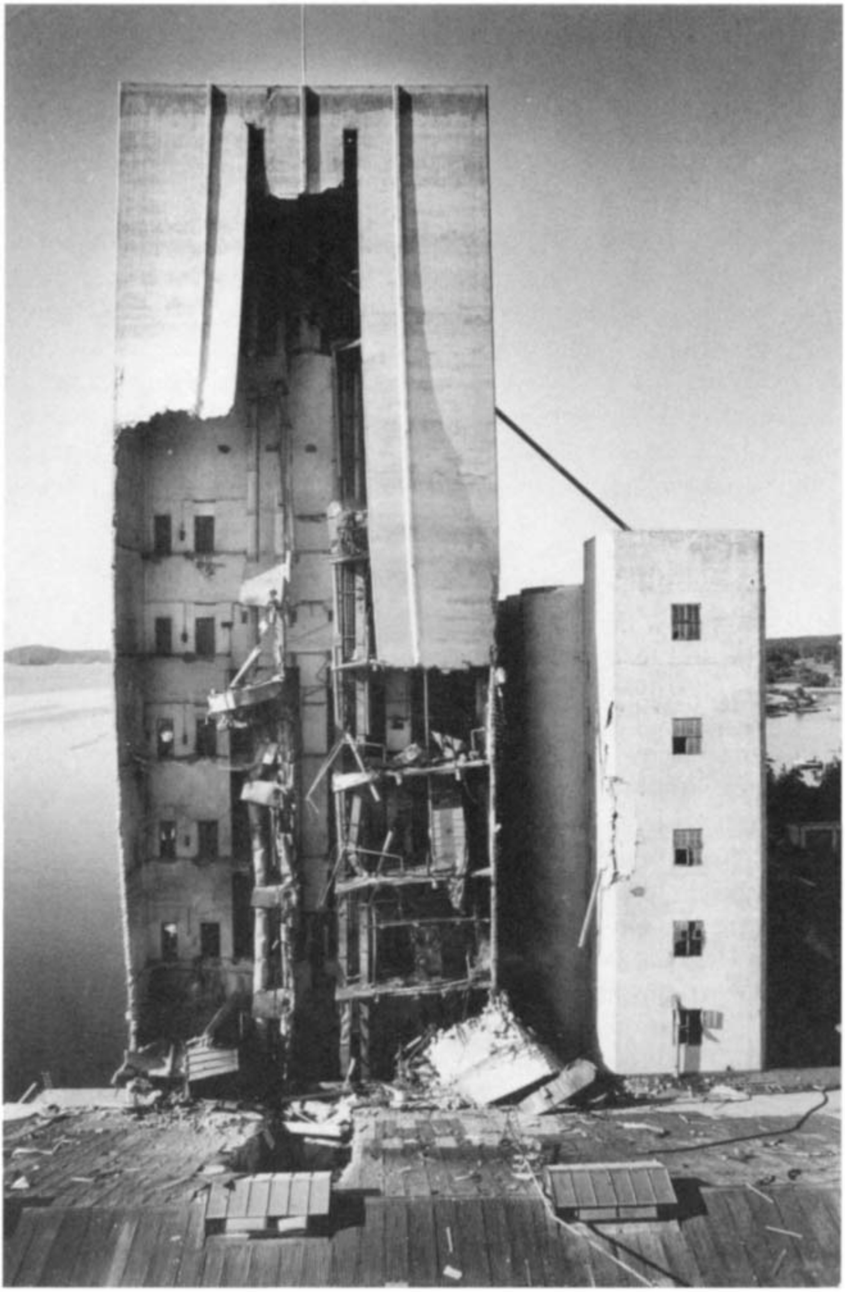

Figure 5–44 Damaged silo head house after a grain dust explosion at Kambo, Norway, in June 1976. Courtesy of Scan Foto, Oslo, Norway.

5.4.4 Major Linen Dust Explosion in Harbin, China (1987)

5.4.4.1 General Outline

In the middle of the night, at 0239 on 15 March, 1987, the spinning section of the large linen textile plant in Harbin, P.R. China, was afflicted with a catastrophic dust explosion. The losses were substantial. Out of the 327 women and men working night shift in the spinning section when the explosion occurred, fifty-eight lost their lives and 177 were injured. 13,000 m^2 of factory area was demolished. The explosion accident has been discussed in detail by Xu Bowen (1988) and Zhu Hailin (1988). Xu Bowen et al. (1988) reconstructed a possible course of the explosion development on the basis of a seismic recording of the explosion by the State Station of Seismology, located only 17 km. from the linen textile plant.

5.4.4.2 Explosion Initiation and Development, Scenario 1

Figure 5–45 illustrates the 13,000 m^2 spinning section through which the explosion swept, and the possible locations and sequence of the nine successive explosions that comprised the event according to Xu Bowen (1988) and Xu Bowen et al. (1988). These workers based their reconstruction of the explosion on three independent elements of evidence. First, they identified the location of the various explosion sites throughout the damaged plant. Secondly, they ranked the relative strengths of the local explosions by studying the extent and nature of the damage. Thirdly, they arranged the various local explosions in time by means of the relative strengths of the nine successive explosions, identified by decoding the seismic recording of the event.

Figure 5–46(a) shows a direct tracing of the amplitude-modulated seismic signal actually recorded 17 km from the explosion site. Figure 5–46(b) shows the sequence of nine energy pulses impacting on the earth at the location of Harbin Linen Textile Plant, deduced from the signal in (a). Finally, Figure 5–46(c) shows the theoretical prediction of the seismic signal to be expected from the sequence of explosions in Figure 5–46(b). The agreement between the (a) and (c) signals is striking, which supports the validity of the postulated energy impact pulse train (b).

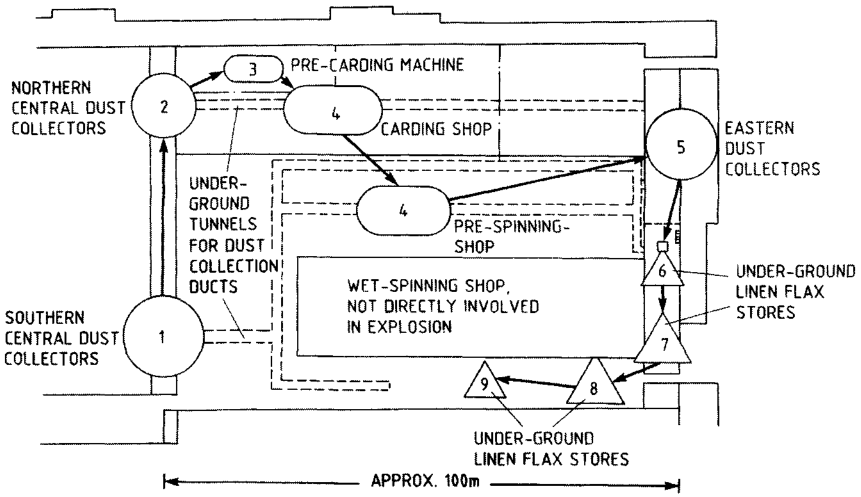

Figure 5–45 Schematic illustration of the 13, 000 m^2 spinning section of the Harbin Linen Textile Plant, P.R. China, that was afflicted with a catastrophic dust explosion on 15 March 1987. Numbered circles, ovals and triangles indicate location and sequence of a postulated series of nine successive explosions. From Eckhoff (2002).

According to Xu Bowen et al. (1988), the explosion was initiated in one of the nine units in the central dust collector system. All nine units were connected by ducting. The ignition sources were not identified, but an electrostatic spark was considered as one possibility, a local fire or glow as another. The initial flame was transmitted immediately to the next dust collecting unit, and both units (1) indicated in Figure 5–45 exploded almost simultaneously, giving rise to the first major impact pulse in Figure 5–46(b). The explosion then propagated through the other seven dust collecting units in the central collecting plant (2) indicated in Figure 5–45, and into the pre-carding area. Here the blast wave preceding the flame had generated an explosive dust cloud in the room, which was ignited by the flame jet from the dust collectors (3). The room explosion propagated further to the carding and pre-spinning shops (4), and right up to the eastern dust collectors, where another distinct explosion (5) occurred. The final four explosion pulses were generated as the explosion propagated further into the underground linen flax stores, where it finally terminated after having traveled a total distance of about 300 m. The chain of nine explosions lasted for about eight seconds.

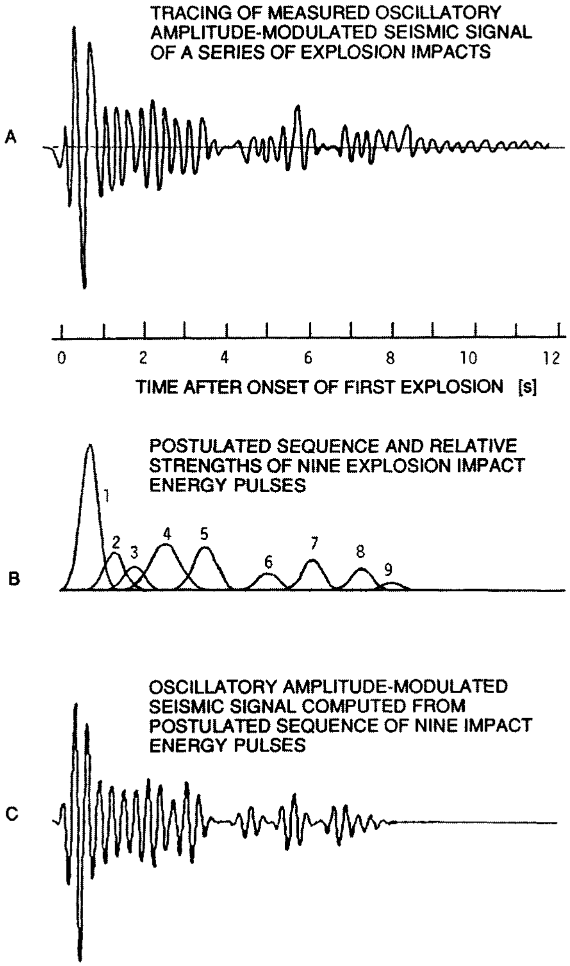

Figure 5–46 Sequence of nine impact energy pulses from nine successive dust explosions in the Harbin Linen Textile Plant, Harbin, P.R. China, 15 March 1987, postulated on the basis of a seismic record of the event. From Eckhoff (2000).

5.4.4.3 Explosion Initiation and Development, Scenario 2

This alternative scenario originates from the investigation of Zhu Hailin (1988), who found evidence of an initial smoldering dust fire caused by a live 40 W electrical portable light lamp lying in a flax dust layer of 6–8 cm thickness in a ventilation room. He also found evidence of flame propagation through the underground tunnels for the dust collection ducting. On the basis of his analysis, Zhu suggested that the explosion was initiated in the eastern dust collectors (5) indicated in Figure 5–45, from which it transmitted to the nine units of the central dust collecting plant (1) and (2) via the ducting in the underground tunnels. Severe room explosions were initiated when the ducting in the tunnel ruptured, and the resulting blast dispersed large quantities of dust in the workrooms into explosive clouds that were subsequently ignited. From the eastern dust collectors the explosion also propagated into the underground flax stores.

5.4.4.4 Final Remark

The investigation of the Harbin disaster exposed the great difficulties in identifying the exact course of events of major explosions creating massive damage. In addition to causing pain and grief, loss of life also means loss of eyewitnesses. Besides, the immediate need for fire fighting and rescue operations changes the scene before the investigators can make their observations. Also, the explosion itself often erases evidence, e.g. of the ignition source. However, the Harbin disaster unequivocally demonstrated the possible dramatic consequences of inadequate housekeeping in industrial plants where fine combustible dust is generated.

5.4.5 Major Silicon Dust Explosion in Bremanger, Norway (1972)

In this serious explosion accident, five workers lost their lives and four were severely injured. The explosion occurred in the milling section of the plant, was extensive, rupturing or buckling most of the process equipment and blowing out practically all the wall panels of the factory building. Figure 5–47 shows a view of the extensive damage. Eyewitnesses reported that the flame was very bright, almost white. This is in accordance with the fact that the temperature of silicon dust flames, as of flames of aluminum and magnesium dust, is very high due to the large amounts of heat released in the combustion process per mole of oxygen consumed. Because of the high temperature, the thermal radiation from the flame is intense, which was a main reason for the very severe burns that nine of the workers suffered.

The investigation after the accident disclosed a small hole in a steel pipe for conveying silicon powder from one of the mechanical sieves to a silo below. An oxygen/acetylene cutting torch with both valves open was

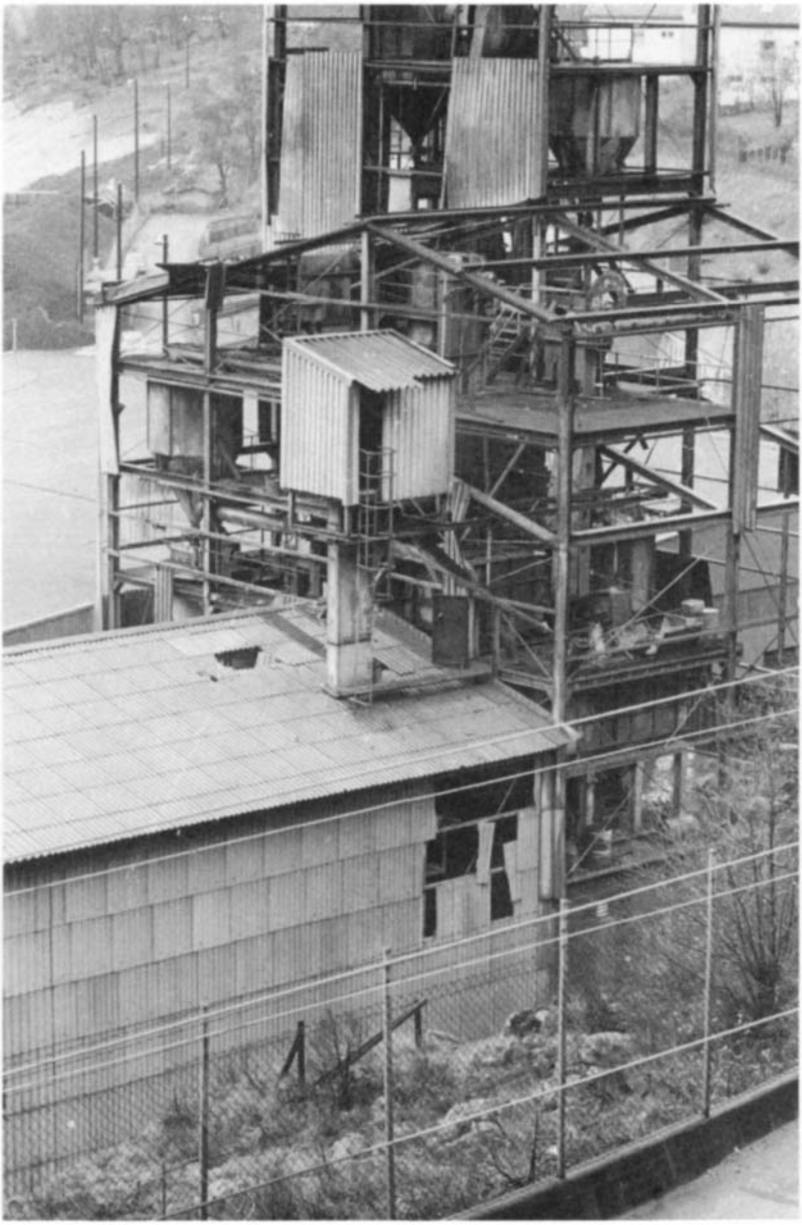

Figure 5–47 View of the extensive demolition of the silicon grinding plant caused by the silicon dust explosion at Bremanger, Norway, October 1972.

found lying on the floor about 1 m from the pipe with the hole. According to Kjerpeseth (1990) there was strong evidence of the small hole having been made by means of the cutting torch just at the time when the explosion occurred. The interior of the pipe that was perforated had probably not been cleaned prior to the perforation. At the moment of the explosion, part of the plant was closed down due to various repair work. However, the dust extraction system was operating. In view of the high temperature and excessive thermal power of the cutting torch, and not least the fact that it supplied pure oxygen to the working zone, a layer of fine dust on the internal pipe wall may well have become dispersed and ignited as soon as the torch had burned its way through the pipe wall. The blast from the resulting primary silicon dust explosion then raised dust deposits in other parts of the plant into suspension and allowed the explosion to propagate further until it eventually involved the entire silicon grinding building. The grinding plant was not rebuilt after the explosion.

5.4.6 Major Aluminum Dust Explosion at Gullhaug, Norway (1973)

The main source of information concerning the original investigation of the accident is Berg (1989). The explosion occurred during the working hours, just before lunch, while ten workers were in the same building. Five of these lost their lives, two were seriously injured, two suffered minor injuries, whereas only one escaped unhurt. A substantial part of the plant was totally demolished, as illustrated by Figure 5–48.

The premix preparation plant building was completely destroyed. Debris was found up to 75 m from the explosion site. The explosion was followed by a violent fire in the powders left in the ruins of the plant and in adjacent storehouse for raw materials. The explosion occurred when charging the 5.2 m^3 batch mixer, illustrated in Figure 5–49.

About 200 kg of very fine aluminum flake, sulphur, and some other ingredients had been charged at the moment of the explosion. The total normal charge of the formulation in question was 1,200 kg. The upper part of the closed vertical mixing vessel was cylindrical, and the lower part conical. The feed chute was at the bottom. The internal mixing device consisted of a vertical rubber-lined screw surrounded by a rubber-lined earthed steel tube. The powders to be mixed were transported upwards by the screw, and when emerging from the top outlet of the tube, they dropped to the surface of the powder heap in the lower part of the vessel. There they

Figure 5–48 Scene of total demolition after aluminum dust explosion in the premix plant of a slurry explosives factory at Gullaug, Norway, in August 1973. From Eckhoff (2003).

became mixed with other powder elements and eventually re-transported to the top.

The construction materials of the mixer had been selected so as to eliminate the formation of mechanical sparks. This was probably why both the screw and the internal wall of the surrounding earthed steel tube were lined with rubber.

During operation the 5.2 m^3 vessel was flushed with nitrogen, the concentration of oxygen in the vessel being controlled by a direct-reading oxygen analyzer at the vessel top. According to the foreman's statement, the oxygen content at the moment of explosion was within the specified limit. After the explosion, the heavy central screw part of the mixer, with the mixer end cap, was retrieved about 12 m away from the location of the mixer prior to the explosion. More detailed investigation of the part of the screw that was shielded by the steel tube, revealed that the screw wings had been deformed bi-directionally as if an explosion in the central part had expanded violently both upwards and downwards. This evidence was considered as a strong indication of the explosion having in fact been initiated inside the steel tube surrounding the screw. The blast and

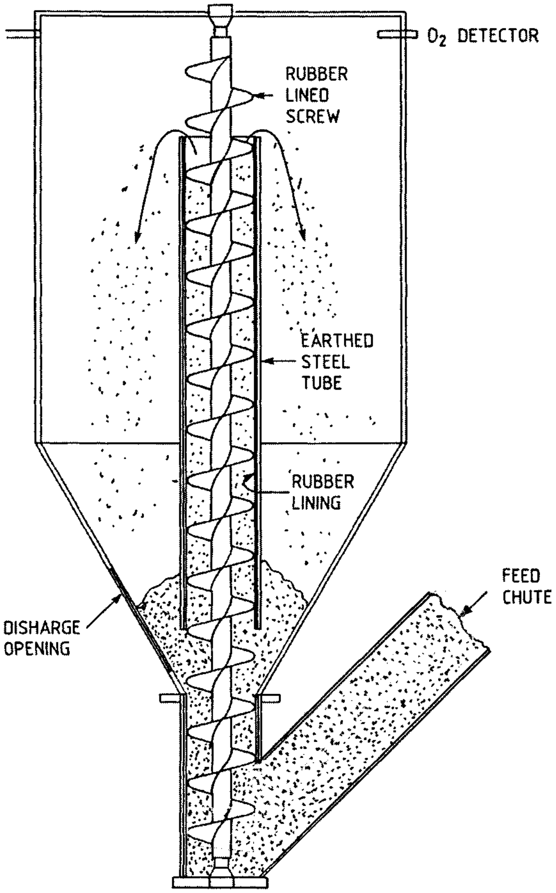

Figure 5–49 Cross-section of the mixer used for production of dry premix for slurry explosives at Gullaug, Norway, in 1973, From Eckhoff (2003).

flame from this primary explosion, in turn, generated and ignited the dust cloud in the main space inside the mixer. Finally the main bulk of the powder in the mixer was thrown into suspension and brought to ignition when the mixer ruptured, giving rise to a major dust explosion in the workrooms.

Subsequent investigations revealed that clouds in air of the fine aluminum flake powder involved were both extremely sensitive to ignition and exploded extremely violently. The minimum electric spark ignition energy was of the order of 1 mJ, and the maximum rate of pressure rise in the Hartmann bomb 2,600 bar/s. Both these values are extreme. The thickness of the aluminum flakes was about 0.1 μm, which corresponds to a specific surface area of about 7.5 m^2/g.

The investigation further disclosed that the design of the nitrogen inerting system of the mixer was inadequate. First, the nitrogen flow was insufficient to enable reduction of the average oxygen concentration to the specified maximum level of 10 vol.% within the time allocated. Secondly, even if the flow had been adequate, both the nitrogen inlet and the oxygen concentration probe were located in the upper part of the vessel (see Figure 5–49) which rendered the measured oxygen concentration unreliable as an indicator of the general oxygen level in the mixer. It is highly probable that the oxygen concentration in the lower part of the mixer, and in particular in the space inside the tube surrounding the screw, was considerably higher than the measured value. This explains why a dust explosion could occur in spite of low measured oxygen concentration.

The final central concern of the investigators was identification of the probable ignition source. In the reports from 1973, it was concluded that the primary explosion in the tube surrounding the screw was probably initiated by an electrostatic discharge. However, this conclusion was not qualified in any detail. In more recent years the knowledge about various kinds of electrostatic discharges has increased considerably. It now seems highly probable that the ignition source in the 1973 Gullaug explosion was a propagating brush discharge, brought about by the high charge density that could accumulate on the internal rubber lining of the steel screw and of the steel tube surrounding the screw, because of the earthed electrically conducting backing provided by the screw and the tube.

5.4.7 Major Polyethylene Dust Explosion, Kinston, North Carolina, U.S.A. (2003)

5.4.7.1 Introduction

On 29 January 2003, a dust explosion occurred at the West Pharmaceutical Services, Inc. plant in Kinston, North Carolina, U.S.A. Six workers lost their lives and thirty-eight were injured, including two fire fighters. Because of the number of deaths and injuries, the U.S. Chemical Safety and Hazard Investigation Board (CSB) launched an investigation to determine the root and contributing causes of the explosion and to make recommendations to prevent similar occurrences The present account is based on the comprehensive CSB (2003) report.

5.4.7.2 Company and Process

Founded in 1923, West is one of the world's largest manufacturers of closures and components for sealing drug vials and pre-filled syringes. The headquarters are in Lionville, Pennsylvania, U.S.A. The company has approximately 4,000 employees working in eight facilities in North America and ten in Europe and Asia.

The West Kinston plant had manufactured rubber drug delivery components for syringe plungers, septums, and vial seals since 1975. The rubber compounding process in use at the time of the dust explosion was started up in 1987, following a major expansion and automation project. This process was basically similar to other rubber manufacturing processes, such as tire production. Production operations included rubber compounding, molding, and extrusion. Raw materials were prepared in another area of the plant. The production was semi-continuous, producing sequential batches and operating twenty-four hours per day, five or six days per week. At the time of the explosion, 264 employees and thirty-five full time contract workers were employed at the Kinston plant.

5.4.7.3 Location and Layout of the Kinston Plant

The Kinston plant was located in a light industrial business park adjacent to the regional airport. Two private residences and the local Humane Society shelter were each located about 300 m from the facility. The plant area illustrated in Figure 5–50 was approximately 13500 m^2, and primarily single story. However; some of the rubber compounding equipment was located in a 18 m high, three storey area, which is hatched in Figure 5–50. The plant housed two main operations, viz. rubber compounding and product finishing. In the finishing process, the compounded rubber was molded and pressed into stoppers and plungers.

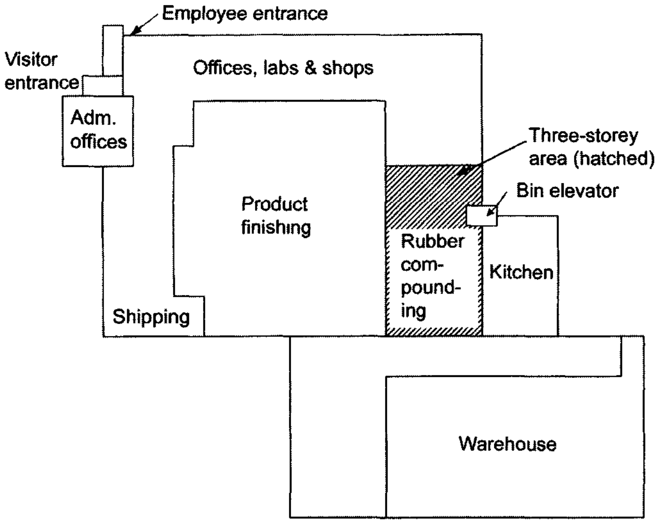

Figure 5–50 Plan of the West Pharmaceutical Services Inc., production plant in Kinston, North Carolina, U.S.A., prior to the dust explosion 29 January, 2003. From CSB (2003).

5.4.7.4 Rubber Compounding Process

5.4.7.4.1 Overview

The location of the compounding area in relation to the other facilities, is given in Figure 5–50. The automated rubber compounding system consisted of two separate production lines, each with a mixer, a roller, and a "batchoff" machine (see Figure 5–52). The compounding was done in batches, and the purpose of the batchoff machine was to cool, coat, and fold the strips of rubber from a compounded batch. The batchoff machines used were of a common design utilized in various industries.

5.4.7.4.2 Raw Material Preparation

The raw material preparation for the rubber compounding process was taking place in the "kitchen." This was a process area to the side of the rubber compounding area and separated from it by a concrete masonry firewall. Solid materials were weighed and loaded into bins. A roller conveyer transported the bins to an elevator, where they were lifted to the second floor of the compounding structure.

5.4.7.4.3 Mixing/Kneading

A conveyor carried the bins further to the mixers, where the ingredients were compounded. Ingredients were generally loaded into the mixers through an open hatch on the side. However, bulk powders used in large portions, such as calcined clay, were pneumatically transferred to weighing hoppers and automatically dropped into the mixers. Each mixer had two opposing rotors that meshed, pulled, and sheared the components to create a uniform mix. The frictional heat generated by the mixer facilitated this process. Mineral oil was used as a plasticizer for the rubber blends and was piped directly to the mixers. After the batch was loaded, the operator closed the feed door and engaged the mixer with automatic controls.

The kneading action of the mixer caused frictional heating of the rubber. Although chilled cooling water flowed through the kneading rotors, the varying speed of the rotors and the duration of the mixing phase largely controlled the temperature of the rubber. The process temperature was held by automatic controls to below the onset temperature for vulcanization. (The rubber was vulcanized later during the forming process, when the finished products were shaped by molding).

5.4.7.4.4 Rolling, Trimming, Cooling, and Drying

Once compounded in the mixers, the rubber was dropped through chutes to the ground floor, where rollers smoothed it into sheets of roughly uniform thickness. The sheets were then cut into strips, which entered the batchoff machine, where they were cooled, coated, and folded. Then the strips were trimmed, i.e. they were dipped into a tank containing a slurry of very fine polyethylene powder in water. The polyethylene powder acted as an anti-tack agent and had an average particle size of 12 μm, i.e. it was very fine. The water slurry also cooled the product to prevent premature vulcanization.

5.4.7.4.5 Air Drying of Trimmed Strips

After leaving the dip tank, the rubber passed in front of a series of air fans. The fans drew air from the room and blew it across the rubber strips to enhance drying. At the exit of the batchoff, the rubber was folded. Finally the dried strips were stacked for shipment, or for molding in the finishing area of the plant. After drying almost all of the polyethylene powder in the slurry coating adhered to the strips, but a small amount became airborne.

5.4.7.5 Housekeeping Standards

5.4.7.5.1 General

The plant management knew that the compounding process could create dusty conditions. Therefore, local exhaust ventilation (LEV) ducts had been installed at the compound mixers and in certain areas of the kitchen, primarily to limit employee exposure to airborne nuisance dusts. The LEV ducts transported the captured dust to collectors located outdoors. Efforts were also made to prevent dust accumulation in work areas by a having a continuous house keeping program. A cleaning staff worked around the clock vacuuming and wiping up dust to minimize visible accumulation on exposed surfaces. Because the plant manufactured products for pharmaceutical use, keeping the facility free of dust was given high priority.

5.4.7.5.2 Batchoff Machines

The batchoff machines were sources of fugitive emissions of combustible dust. Twelve fans blew air across the rubber strip to cool and dry it as it passed through each machine. Some portion of the anti tack agent was carried by air currents from the machine into the room, where it tended to settle on surfaces. The cleaning crew continuously wiped and vacuumed the dust from surfaces so that the area was generally free of visible accumulation. However, there was no organized cleaning program for surfaces of beams, conduits, and other features above the ceiling, where dust was known to accumulate due to the design of the dust extraction system of the machines. Partition walls partially enclosed the batchoff machines to separate them from other areas. Regular housekeeping was conducted around the machines, and de-humidifiers/filters associated with the enclosures removed some dust from the air. Witness statements and photographs submitted by the Kinston plant indicated that visible accumulation of dust in the milling area, even around the batchoff machines, was minimal. Management focused on the extent and effectiveness of housekeeping in working areas, and the effort was a matter of facility pride.

5.4.7.5.3 Hidden Areas not Covered by the Housekeeping Program

However, although the cleaning crew continuously cleaned the areas around the equipment, several employees told CSB investigators that there was a layer of dust on top of the suspended ceiling, above the room where the rolling mills and batchoff machines were located. Accumulation was reported to be widespread but heaviest in the areas directly above these machines. Accounts on the thickness of dust layers varied. Some employees claimed that dust accumulations of 6 mm were common, but other witnesses described heavier accumulations, such as 13 mm or more. One individual who had performed a maintenance job above the ceiling in the months prior to the incident recalled seeing as much as 50 mm of powder in some areas. Another person, who had been above the ceiling two weeks before the explosion, estimated an accumulation of up to 13 mm across 90 percent of the ceiling area. However, the investigation by the company management concluded that the overall thickness of dust accumulations ranged from 3 to 6 mm.

The area above the ceiling also contained pneumatic conveying lines for the calcined clay and other high-volume non-combustible powders used in the mixers. Because these lines were reported by employees to have leaked on at least one occasion, it is possible that some of the dust accumulation above the ceiling was non-combustible.

5.4.7.6 Outline of the Accidental Explosion

Interviews conducted by CSB investigators indicate that the operations on the day of the explosion were as usual. No one recalled to have noticed any sights, sounds, or odors that would have indicated a problem. The explosion occurred abruptly at 1328 on 29 January. Employees throughout the plant heard the explosion, which some of them described as sounding like "rolling thunder." After seeing the exterior side panels being blown off the second story of the compounding structure witnesses outside saw a fireball and a rising smoke cloud.

Inside the facility, employees had made different observations. Those most distant from the compounding area saw lights flickering off, and ceiling tiles and debris being blown about. Some workers saw a bright flash and felt either a pressure wave or a vacuum effect that knocked them off their feet. The entire facility was affected to some extent, though explosion damage was most severe in the rubber compounding and milling areas. Figure 5–51 shows the plant after the explosion. The elevated part of the structure in the background is what was left of the three-storey rubber compounding section (see Figure 5–50 and Figure 5–52). As can be seen, the damage was extensive.

A Kinston police officer on patrol about 1 km south of the plant noticed smoke above the tree lines that surrounded the facility. He immediately contacted his dispatch to inquire if a controlled burn was taking place at the airport. Seconds later, he observed the smoke rising into a cloud about 100 m into the air, and he reported the explosion, which was heard as far as 40 km away. He immediately proceeded to the scene and began helping victims out of the facility to safety.

5.4.7.7 Fires Following the Explosion

Fires began to develop throughout the facility. The sprinkler system designed to mitigate incipient fires within the plant was rendered inoperable from the outset of the incident because the explosion broke feeder lines to the system. Emergency responders reported hearing water freely flowing into the structure. The largest and most persistent fire, lasting for two days, developed in the warehouse (Figure 5–50 and Figure 5–52). Rubber and other raw materials were stored in the warehouse, and the thermal effect from the explosion most probably reached this area and initiated the fire. Eventually, the entire warehouse was fully engulfed in flames involving the large volume of stored baled and strip rubber. Heat from the fire caused most of the steel framing to yield and collapse. Some of the rubber continued to smolder and flare up for about a week.

Mineral oil was stored in two 28 m^3 plastic tanks located between the kitchen and the warehouse (Figure 5–50). These tanks failed, spilled their

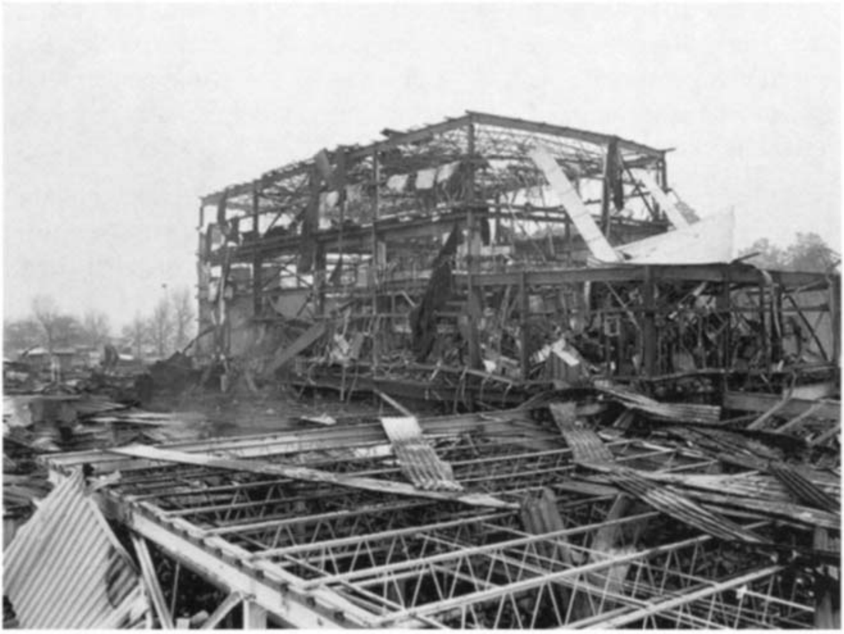

Figure 5–51 Photo of the West Pharmaceutical Services Inc., production plant in Kinston, North Carolina, USA, after the dust explosion 29 January 2003. From CSB (2003).

contents, and burned to the ground. Two additional but smaller plastic tanks containing mineral oil, located near the warehouse, also failed and contributed fuel for the fire. The concrete masonry retention walls around the tanks failed and did not prevent the burning oil from spreading.

5.4.7.8 Fatalities and Injuries

The six people who were killed were working on the ground level of the plant. Three were near one of the mills and its batchoff machine. The fourth, who died several weeks after the incident, was working at another batchoff machine. The force of the blast pushed the fifth victim east into the kitchen, and falling objects on the finishing side of the plant fatally injured the sixth person. The majority of the fatal injuries were either by thermal burns or by ejected objects or collapsing walls. When police officers entered the facility, one of the victims was trapped under a fallen girder near the end of a batchoff machine. However, because of the advancing fire, attempts at rescuing this person failed, and he died at the scene.

Immediately after the explosion, many employees were dazed or buried under debris. Responders and other employees equipped with flashlights assisted them out of the plant to triage areas. A few workers clung to the exposed frame of the building's second story and were later rescued by firefighters.

One student was injured when windows were broken at a school about 1 km away. Businesses located in the same industrial park as the Kinston plant were damaged, and windborne burning debris initiated fires in wooded areas as far as 3 km away. One home located nearby was damaged slightly, and at least two families were evacuated as a precautionary measure.

5.4.7.9 Facility Damage and Relocation of Production

The explosion and ensuing fire heavily damaged the compounding section of the Kinston facility. Figure 5–51 shows the extent of the damage. All exterior sheathing on the compounding structure was destroyed and masonry block walls were knocked down. The warehouse collapsed, and the remaining building structure was rendered mostly unusable.

Fourteen months after the explosion, the company relocated their production to an industrial facility several km south of the destroyed plant. Some equipment that was not used in the compounding process was salvaged from the original plant and is in use at the new location, and much of the workforce was rehired. When the CSB report was written, however, the destroyed facility and the compounding machinery was not in use.

The relocated production plant is not compounding rubber. Instead, rubber strips are being produced by contract manufacturers or at other West facilities and are shipped to Kinston for molding.

5.4.7.10 Analysis of Explosion

5.4.7.10.1 Fuel For Explosion

Because no other material capable of producing such a large explosion was present or used at the plant, CSB concluded that accumulated fine polyethylene dust above the suspended ceiling tiles was the main fuel in the explosion. Other possibilities were investigated, but were found to be not credible. However, CSB were unable to conclusively determine what specific mechanism dispersed the polyethylene dust to create the primary explosive cloud.

5.4.7.10.2 Center of Explosion

CSB further concluded that the primary, strong explosion occurred in the compounding section of the plant, as illustrated in Figure 5–52. Figure 5–53 shows a photograph of the extensive damage in what was assumed by CSB to be the center of the explosion (zone of maximum blast pressure).

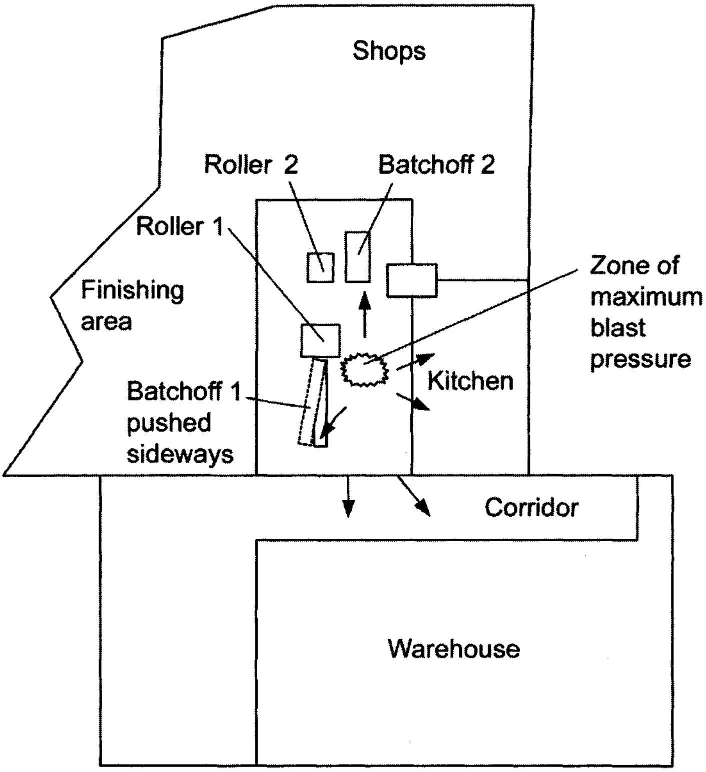

Figure 5–52 Plan of part of the West Pharmaceutical Services Inc., production plant in Kinston, North Carolina, U.S.A., showing the centre of the dust explosion 29 January 2003. From CSB (2003).

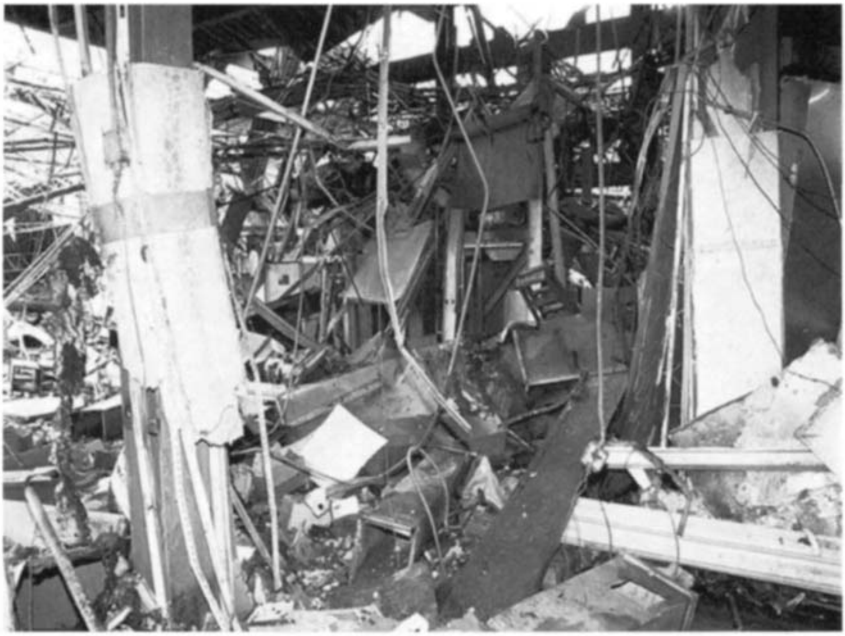

Figure 5–53 Photograph of what was assumed to be the centre of the dust explosion in the West Pharmaceutical Services Inc., production plant in Kinston, North Carolina, U.S.A., 29 January 2003. From CSB (2003).

The location of the highest pressure was determined to be close to Roller 1 on the first floor of the three-story compounding section, as indicated in Figure 5–52. Force vectors derived from observed damage to the building and surrounding equipment indicate that the largest pressure developed in the compounding section and emanated spherically outward. CSB investigators also recovered ceiling tiles debris from the suspended roof above the ground floor of the compounding section. Nearly all of the tiles appeared to be burned and splattered on top, but not on the bottom, which had faced the ground floor room below. Furthermore, some of the fluorescent light fixture pans recovered from the Roller 1 area had been flattened from above, as if they had been forcefully driven downward to the concrete floor. These two pieces of evidence give further support to the theory that the explosion occurred within the confined space above the suspended ceiling. Independent quantitative CFD simulations also concluded that the explosion occurred on the first floor of the compounding section, and that the explosion pressure from this area was the source of the extensive blast damage throughout the facility.

5.4.7.11 Initiating Events Giving Rise to the Explosive Dust Cloud and Its Ignition

CSB concluded that the accumulation of combustible dust, mainly fine polyethylene dust, above the suspended ceiling, was the most important safety issue in the West incident. The extent of damage to the Kinston facility made it extremely difficult to definitively determine the initial events that dispersed the polyethylene dust and ignited it. CSB was unable to determine whether any of the following scenarios may have been the actual initiating event:

- overheating of a batch of rubber and subsequent ignition of the vapors produced by thermal decomposition
- ignition of the dust layer by an overheated electrical ballast or light fixture
- ignition of the dust layer by an electrical spark from an unidentified electrical fault
- unsettling of dust in a cooling air duct for an electric motor and subsequent ignition of the dust by the motor

Instead the investigators focused on the most pertinent hazard, i.e. the possibility of accumulation of combustible dust in spite of a systematic housekeeping program, and considered the initiating event as a matter of secondary importance.

5.4.7.12 Previous Incident

CSB were informed that in an earlier maintenance operation involving welding, polyethylene powder in proximity to the batchoff machine had ignited, but the fire self extinguished. This incident demonstrated that the powder was ignitable. However, there was no documented investigation of this incident.

5.4.7.13 Root Causes

CSB concluded that the following root causes were responsible for the explosion and subsequent fire in the Kinston plant of West Pharmaceutical Services Inc. in 2003:

- The company did not perform an adequate safety assessment of the use of powdered zinc stearate and polyethylene as anti tack agents in the rubber batchoff process.
- The company's engineering management systems did not ensure that relevant industrial fire safety standards were consulted.
- The company's management systems for Material Safety Data Sheets (MSDS) did not identify combustible dust hazards.
- The hazard communication program at the Kinston plant did not identify combustible dust hazards or make the employees aware of such.

5.4.7.14 Some Recommendations Given by CSB to West Pharmaceuticals

- Revise policies and procedures for new material safety reviews. In particular: Use the most recent versions of MSDSs and other technical hazard information.
- Fully identify the hazardous characteristics of new materials, including relevant physical and chemical properties, to ensure that those characteristics are incorporated into safety practices, as appropriate. Include an engineering element that identifies and addresses the potential safety implications of new materials on manufacturing processes.
- Develop and implement policies and procedures for safety reviews of engineering projects. In particular: Address the hazards of individual materials and equipment and their effect on entire processes and facilities, and consider hazards during the conceptual design phase, as well as during engineering and construction phases.
- Cover all phases of the project, including engineering and construction performed by outside firms.
- Identify and consider applicable codes and standards in the design.
- Identify other production plants within the company that use combustible dusts. Ensure that they incorporate applicable recognized safety precautions. In particular: Ensure that penetrations of partitions, floors, walls, and ceilings are sealed dust tight, and ensure that spaces inaccessible to housekeeping are sealed to prevent dust accumulation there.

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- Improve hazard communication programs so that the hazards of combustible dust are clearly identified and communicated to the employees. In particular: Ensure that the most current codes of practice are in use and that employees receive training on the revised/updated information.

5.5 Means of Preventing and Mitigating Dust Explosions in the Process Industries

5.6.1 Overview

Table 5–2 gives an overview of the various means that are presently known and in use. They can be divided in two main groups, namely means for preventing explosions and means for their mitigation. The preventive means can again be split in the two categories prevention of ignition sources and prevention of explosive/combustible clouds. Quite often one has to accept the occurrence of explosive dust clouds inside process equipment as an inherent feature of the process. One central issue is then whether only preventing ignition sources can give sufficient safety, or whether it is also necessary to employ additional means of explosion mitigation. The general answer is that preventing ignition sources is not sufficient. In the following sections the various means listed in Table 5–2 will be discussed separately.

Table 5–2 Overview of Means for Preventing and Mitigating Dust Explosions in the Process Industries

<table>
<tr><th colspan="2">Prevention</th><th rowspan="2">Mitigation</th></tr>
<tr><th>Preventing explosive dust clouds</th><th>Preventing ignition sources</th></tr>
<tr><td rowspan="3">Inerting by N_2, CO_2 and rare gases</td><td rowspan="3">Smoldering combustion in dust, dust flames</td><td rowspan="2">Reduce expl. cloud size</td></tr>
<tr></tr>
<tr><td rowspan="2">Partial inerting</td></tr>
<tr><td rowspan="3">Intrinsic inerting</td><td rowspan="3">Other types of open flames (e.g. hot work)</td></tr>
<tr><td rowspan="2">Isolation (sectioning)</td></tr>
<tr></tr>
<tr><td>Inerting by adding inert dust</td><td>Hot surfaces</td><td>Venting</td></tr>
<tr><td>Dust concentration outside explosive range</td><td>Electric sparks and arcs, electrostatic discharges</td><td>Pressure resistant construction</td></tr>
<tr><td></td><td>Heat from mechanical impact (metal sparks and hot spots)</td><td>Automatic suppression</td></tr>
<tr><td></td><td></td><td>Good housekeeping (dust removal/cleaning)</td></tr>
</table>