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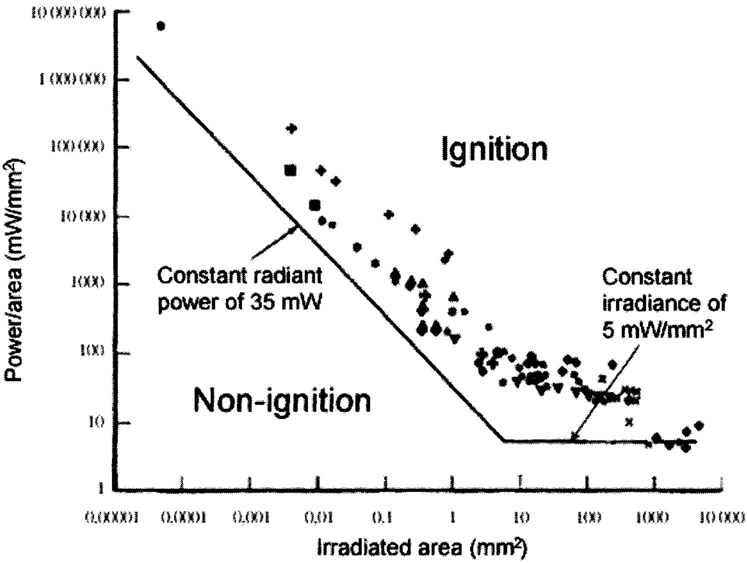

Figure 2–52 Summary of experimental data of minimum radiated power per unit target area (mW/mm²) for igniting a range of explosive mixtures of combustible gases/vapors and air, as a function of the irradiated area (mm²). From Thowle (2000).

of just one value for a given explosive gas, based on a highly conservative laboratory test, irrespective of the actual industrial situation, may in some cases put industry to considerable unnecessary expense.

2.3 Case Histories of Accidental Gas/Vapor Cloud Explosions

2.3.1 Motivation for Section

Experience has shown that "learning by doing" is an effective way of acquiring new knowledge. Unfortunately, this also applies to learning about explosions, which can give rise to much human suffering and grief, as well as material damage and loss of profit. People who have experienced an explosion accident, whether as workers or management in industrial plants, or elsewhere, have a profound appreciation of the realism of this hazard, beyond the reach of those who have only heard or read about accidental explosions in general terms. Real understanding in turn produces the proper motivation for minimizing the probability of occurrence of such events in the future. Clearly, accidental explosions are highly undesirable in any situation, and one therefore seeks less dramatic means of transferring knowledge and motivation. One way is the use of case histories, i.e., detailed accounts of explosions that have actually occurred.

This section describes a number of gas explosion accidents in different types of industry and equipment, with emphasis on ignition sources, propagation mechanisms, and destructive effects. Most of the material is taken from Eckhoff (1996a).

2.3.2 Historical Perspective: Methane Explosions in Coal Mines

As coal mining developed in Europe during the 17th and 18th centuries, severe mine explosions became common. It was soon discovered that the origin of the explosions was the ignition of mixtures of flammable gas, or *firedamp* and air, which accumulated in the mines. Firedamp is essentially methane liberated from coal when pressure is released. In early coal mining in Europe, testing of mines for possible explosive gas was undertaken by volunteers creeping into the mine galleries wrapped in wet blankets and carrying an open flame on a stick. This is illustrated in Figure 2–53.

In 1815 the UK's Sunderland Society for Preventing Accidents in Coal Mines asked Sir Humphrey Davy to carry out systematic research on the causes of ignition of and flame propagation in firedamp/air mixtures. As Davy recorded:

> The great object was to find a light, which at the same time that it enabled the miners to work with security in explosive atmospheres, should likewise consume the firedamp.

As pointed out by McQuaid (1990), one of the striking features of this investigation was the speed with which Davy moved from receiving the problem to producing a successful solution. However, when the task of finding a safe source of light in coal mines was first put to Davy, he was not optimistic. It appeared to him that there was very little hope of finding an effective solution. Earlier attempts at finding a safe source of light had

Figure 2–53 A fire fighter igniting methane under the roof of a mine gallery prior to the miners being admitted to the gallery. From McQuaid (1990).

not met with much success. Designs of safety lamps in existence relied either on complete confinement so lamps could burn only for a short time, or else the air supply was pumped through water seals so lamps were not practicable and the flame could easily be extinguished.

Despite his initial pessimism, Davy embarked on his research. He first investigated the chemical composition of the firedamp and then carried out numerous experiments on the circumstances under which it combusts. He established the limits of flammability of the firedamp in air and also established that it was much less easy to burn than other flammable gases. Under the test conditions used, it could neither be ignited by red hot charcoal nor by red hot iron. The heat produced by it in combustion was less than that of most other flammable gases.

Davy found that in glass tubes one quarter of an inch in diameter and one foot long, more than a second was required before the flame had traveled from one end to the other. When the tubes were one seventh of an inch in diameter, flammable mixtures could not propagate a flame to the open end. Metallic tubes prevented flame propagation better than glass tubes.

He now reasoned that the effect of the surfaces of small tubes in preventing combustion depended on their cooling powers, that is, upon their lowering the temperature of the burning mixture so much that it was no longer sufficient for continued combustion. He proceeded to conclude that a metallic tissue or gauze would offer the perfect barrier to flame propagation. He experimented until he found the geometry of the gauze and its material which was safe in all possible varieties of flammable mixtures, not only of firedamp but also of coal gas. His final design was produced in January 1816 and was immediately adopted in the coal mines. Figure 2–54 shows an early version of the Davy lamp.

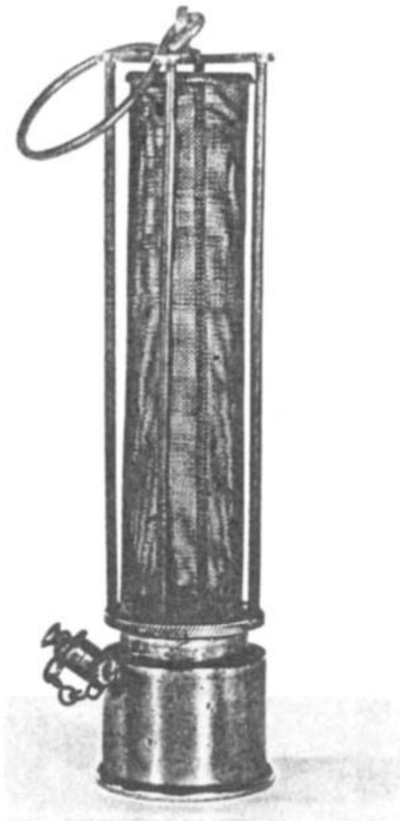

Figure 2–54 Early version of the coal mine lamp developed by Sir Humphrey Davy about 1815.

Davy had achieved his objective less than six months after receiving the letter from the Sunderland Society for Preventing Accidents in Coal Mines. And he did this without any of our modern analytical facilities. However, it seems reasonable to assume that this highly efficient and successful research was not only due to Davy himself. His young and extraordinarily talented assistant, whose name was Michael Faraday, must also have played a major role. Much later, in 1844, he was the first researcher to realize that also coal dust played a crucial part in many of the severe coal mine explosions that Europe experienced in the growing coal mining industry at that time.

The excellent performance of the Davy lamp was confirmed in a letter from Mr. George Morris, Plas Issa, Wales, dated 27 January 1817, to his mine owner (from McQuaid, 1990):

> Sir: You will be pleased to recollect that some time in the month of June last, I applied to you with a request you would send me immediately some of Sir Humphrey Davy's safety lamps, in consequence of an explosion of the firedamp taking place in one of your coal mines, by which several of the men were dreadfully burned and bruised. On the arrival of the safely lamps no accurate account of their use accompanied them. But I at length obtained (I think) the Edinburgh Review, in which was a detail of some experiments. This I read to the colliers, which gave them some confidence in the lamps, prior to which they secretly treated them with silent contempt; and I found, notwithstanding these interesting details, that a great doubt existed in their minds.
>
> The men had no sooner descended than the enemy (methane) was discovered (by ignition and combustion inside the Davy lamp), which they say very much alarmed them. They would have retreated if they could, but finding that impossible, took courage, and soon found they had destroyed the enemy so far; advancing a little farther, they found him again, and again destroyed him, and so on through the whole work. Thus the first alarm was got over, when all the knowing men in the neighbourhood were got collected together to hear the result, all of which were astonished and amazed, that so simple looking an instrument should destroy and defy an enemy, heretofore unconquerable. The same precaution and use of the lamp, was gone through the second day, and when the firedamp was destroyed, we began working and continued to work in this way for some weeks.

However, in spite of this and other great achievements, methane and coal dust explosions continued to represent a severe hazard in coal mines.

Cybulski (1975) summarized the major mine disasters that occurred world wide during 1900–1970. In 135 major explosions worldwide, more than 20,000 miners lost their lives; that is an average of about 150 in each of the disasters. Cybulski also described much of the extensive research that had been conducted in many countries up to about 1970, in order to reduce the explosion hazard in coal mines.

2.3.3 Previously Published Reviews of Major Accidental Gas/ Vapor Cloud Explosions

Gugan (1979) published a comprehensive review of one hundred major gas/vapor cloud explosions in the process industries, up to the late 1970s. One of the main sources of information was the preceding account by Davenport (1977). Gugan concluded that because of incomplete records, only 29 of the 100 incidents could be analyzed in any depth. Of these, only eight of the incidents that gave significant blast effects were documented sufficiently well to permit reasonably comprehensive analyses. Gugan (1979) gave a fairly detailed discussion of five of the eight explosions.

In his book, Marshall (1987) presented 11 reviews and collections of case histories of major gas/vapor cloud explosions up to 1984, including the book by Gugan (1979) and the updated report by Davenport (1984). Marshall gave quite detailed case histories of the major di-methylether explosion at Ludwigshafen, Germany in 1948; the propane explosion at Port Hudson, Missouri, USA in 1970; the cyclo-hexane explosion in Flixborough, UK in 1974; and the iso-butane explosion at Decatur, Illinois, USA in 1974.

Gow (1991) provided brief abstracts of published records of vapor/gas cloud explosions, including the explosions with propane (Sweden, 1981); vinyl chloride (USA, 1971); acetylenic alcohol (USA, 1967); ethanol (USA, 1972);1-pentol (USA, 1967); hydrogen-rich treat gas (UK, 1983); methanol synthesis gas (USA, 1983); natural gas (USA, 1986); hydrogen (USA, 1989); a mixture of ethane, propane, ethylene, and propylene (USA, 1967); ethylene oxide (USA, 1968); butadiene (USA, 1971); propylene (USA, 1976); propylene (USA, 1977); and hydrogen (Norway, 1989).

2.3.4 The Flixborough Explosion, UK (1974)

2.3.4.1 Summary

Some central data of this catastrophic event are given in Table 2–13.

Table 2–13 The Flixborough Explosion

Place:	Flixborough, Humberside, England
Date:	June 1, 1974
Fuel:	Cyclohexane
Type of plant:	Congested process area of cyclohexane oxidation section of caprolactam production plant (basic raw material for Nylon 6)
Fatalities:	28
Injuries:	89
Material Loss:	Entire plant demolished. 1821 houses and 167 shops in nearby residential areas suffered various degrees of damage

The Flixborough disaster is probably the most well documented major accidental industrial vapor cloud explosion world wide. The comprehensive public report by Parker et al. (1975) contains references to about sixty detailed reports on various aspects that were available by early spring of 1975. A further considerable number of articles, scientific papers and reports were published after the public report had been issued. Examples are the paper by Warner (1975) and the papers by Sadee et al. (1976/1977), Roberts and Pritchard (1982), and Berg (1985). Extensive reviews and analyses of the Flixborough disaster, containing further references to papers and reports, were given by Gugan (1979) (12 pages); Lees (1980) (20 pages); and Marshall (1987) (20 pages). Marshall includes an interesting analysis of blast damage of dwelling houses in the surroundings of the industrial plant, as a function of the assumed explosion epicenter.

Roberts and Pritchard (1982) estimated the maximum explosion loads at various locations in the Flixborough explosion, on the basis of the degree of deformation and damage on process equipment, lamp posts and other mechanical structures.

Lees (1994) provided a detailed account of the various aspects of the Flixborough disaster, a summary of which follows.

2.3.4.2 The Process and the Plant

The cyclo-hexane oxidation plant shown in Figure 2–55 consisted of a train of six reactors in series in which cyclo-hexane was oxidized to cyclo-hexanone and cyclo-hexanol by air injection in the presence of a catalyst. The reactions are exothermic. The feed to the reactors was a mixture of fresh cyclo-hexane and recycled material. The product from the reactors still contained approximately 94 percent of cyclo-hexane. The liquid reactants flowed from one reactor to the next by gravity. In subsequent stages, the reaction product was distilled to separate the unreacted cyclo-hexane, which was recycled to the reactors, and the cyclo-hexanone and cyclo-hexanol, which were converted to caprolactam. The operating conditions in the reactors according to the design were 8.8 bar(g) and 155°C.

2.3.4.3 Events Prior to the Explosion

On the evening of 27 March 1974, it was discovered that Reactor No. 5 was leaking cyclo-hexane. The following morning, the decision was taken to remove Reactor No. 5 and to install a bypass assembly to connect Reactors No. 4 and 6 so that the plant could continue in production. The diameter of the openings to be connected on these reactors were 28", with bellows on the nozzle stubs, but the largest pipe which was available on site, which was considered to be suitable for making the bypass, had a diameter of 20". Furthermore, the two flanges were at different heights so that the connection had to take the form of a dog-leg of three lengths of 20" pipe welded together with flanges at each end, which were bolted to the existing flanges on the stub pipes on the reactors. The bypass assembly is indicated in Figure 2–55. Calculations were done to check that the pipe was large enough for the required flow and that it was capable of withstanding the same pressure as if it were a straight pipe.

However, as pointed out by Lees (1994), no drawing of the bypass pipe was made other than in chalk on the workshop floor. The existing stub pipes were connected to the reactors by bellows, as indicated in Figure 2–55. No calculations were done to check whether the bellows would withstand the forces caused by the dog-leg pipe. The bypass assembly was supported by a scaffolding structure, which was intended to support the pipe and to avoid straining of the bellows during construction of the bypass. It was not suitable as a permanent support for the bypass assembly during normal operation. No pressure testing was carried out

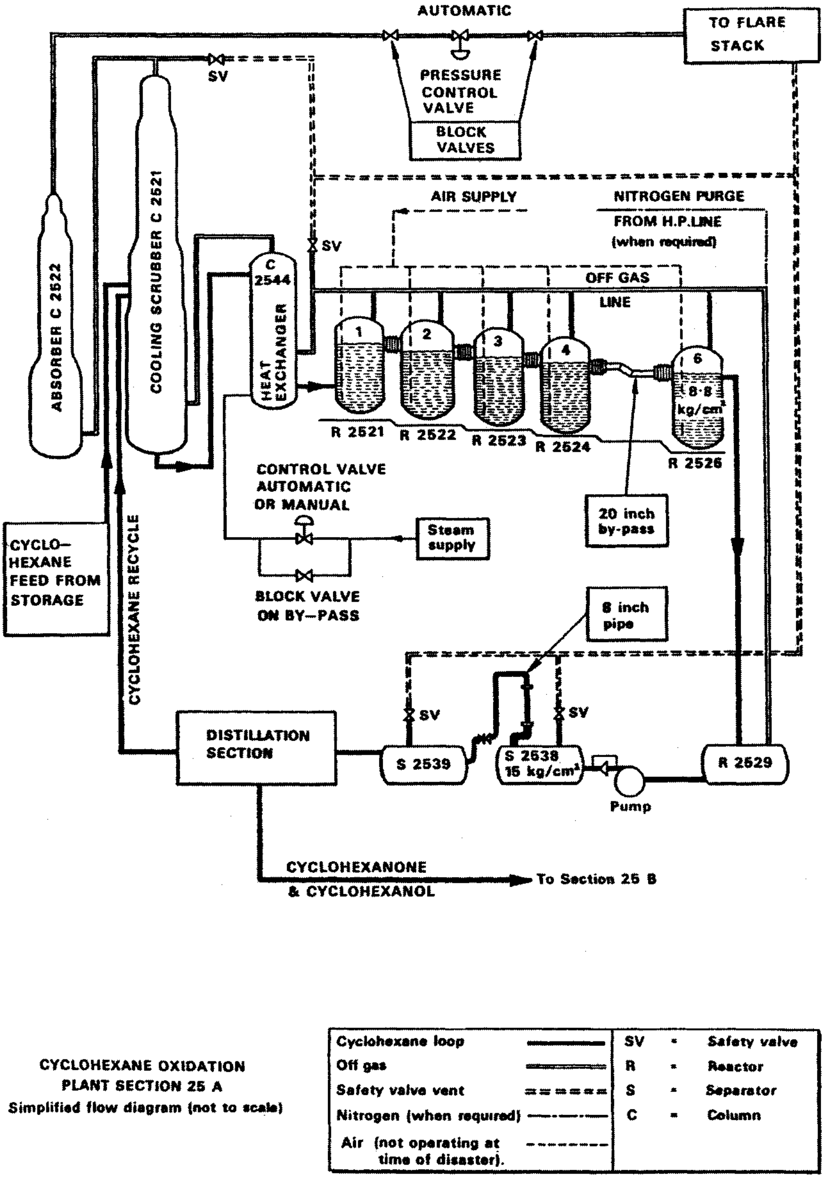

Figure 2–55 Simplified illustration of section 25 A of the cyclo-hexane oxidation plant of the caprolactam production plant at Flixborough. From Parker at al. (1975).

either on the pipe or on the complete assembly before it was fitted. A pressure test was performed on the plant, however, after installation of the bypass. The equipment was tested to a pressure of 9 bar(g), but not up to the safety valve pressure of 11 bar(g). The test was pneumatic, not hydraulic.

Following these modifications, the plant was started up again. The bypass assembly gave no trouble. There did appear, however, to be an unusually large usage of nitrogen on the plant, and this was being investigated at the time of the explosion. On 29 May, the bottom isolating valve on a sight glass on one of the reactors was found to be leaking. It was decided to shut the plant down to repair the leak. On the morning of 1 June, start up began. The precise sequence of events is complex and uncertain. The crucial feature, however, is that the reactors were subjected to a pressure somewhat greater than the normal operating pressure of 8.8 bar(g). A sudden rise in pressure occurred early in the morning when the temperature in Reactor No. 1 was still only 110 °C and that in the other reactors was less. Later in the morning, when the temperature in the reactors was closer to the normal operating value, the pressure reached 9.1–9.2 bar(g). The control of pressure in the reactors could normally be performed by venting the off-gas, but this procedure involved the loss of considerable quantities of nitrogen. Shortly after warm-up began, it was found that there was insufficient nitrogen to begin oxidation and that further supplies would not arrive until after midnight. Under these circumstances, the need to conserve nitrogen probably inhibited an attempt to reduce pressure by venting.

2.3.4.4 The Explosion

During the late afternoon of the day of the explosion, the provisional 20" bypass system ruptured, without or with a contribution from a fire on a nearby 8" pipe. This resulted in the escape of a very large quantity of cyclo-hexane. The cyclo-hexane formed a vapor cloud (and possibly also a liquid-droplet spray cloud, see Section 3.5.1), and the flammable part of the cloud found a source of ignition. At about 4.53 p.m. there was a huge, catastrophic vapor cloud explosion.

The explosion caused extensive damage and started numerous fires. The blast and the fires destroyed not only the cyclo-hexane plant but several other plants also. Many of the fires were in the tank farm. The blast of the explosion shattered the windows of the control room and caused the control room roof to collapse. Of the twenty-eight people who died in the explosion, eighteen were in the control room. Some of the bodies had suffered severe injuries from flying glass. Other victims were crushed by the roof. No one escaped from the control room. The main office block was also demolished by the blast of the explosion. However, since the accident occurred on a Saturday afternoon, the offices were not occupied. If they had been, the death toll would have been much higher. The fires on the site burned for many days. Even after ten days, the fires were hindering rescue work on the site.

2.3.4.5 The Investigation

Some of the possible causes of failure of the bypass assembly were outlined early in the inquiry. They included failure of the 20" diameter pipe due to a small pressure rise in the system. Several possible causes for a pressure rise in the 20" diameter pipe were suggested, viz. entry of high pressure nitrogen into the system due to instrument malfunction, entry of water into the system, temperature rise in the system due to excessive heating by steam in re-boiler of the heat exchanger C2544, leakage of steam from a tube in C2544, explosion of peroxides formed in the process, and explosion due to air in the system.

The overall conclusion of the final inquiry was that the disaster was due to "ignition and rapid acceleration of the resulting deflagration, possibly to the point of detonation, of a massive vapor cloud formed by the escape of cyclo-hexane under a pressure of at least 8.8 bar(g) and a temperature of 155 °C, and that the escape was from Section 25A of the cyclo-hexane plant." There was no dispute that the main part of the cyclo-hexane came from the 20" bypass assembly, but there was some uncertainly as to whether the mechanical failure of the assembly was the primary failure or whether it was a secondary failure caused by a preceding one.

2.3.5 The Beek Explosion, the Netherlands (1975)

2.3.5.1 Summary

Some central data of this event are given in Table 2–14.

Table 2-14 The Beek Explosion

Place:	Beek, The Netherlands
Date:	November 7, 1975
Fuel:	C3-C4 hydrocarbon fractions
Type of Plant:	Congested process area of naphta cracker installation
Fatalities:	14
Injuries:	104
Material Loss:	Entire plant and a nearby tank farm destroyed. Window breakage in surroundings up to 2.5 km from explosion centre.

Reviews of this accident were given by Gugan (1979) and Lees (1994). A comprehensive two-part report of investigation in the Dutch language (Anonym, 1976) was issued by the Directorate of Labour of the Ministry of Social Affairs, in the Netherlands. This report contains quite detailed maps and photographs of the damaged plant, including a map indicating the contours of the explosive cloud prior to ignition.

2.3.5.2 Process and Plant

According to Wingerden et al. (1995), the explosion occurred in a naphtha cracker installation, covering an area of approximately 160 m × 80 m. Naphtha was cracked in furnaces, resulting in hydrogen, ethylene, and other hydrocarbons, ethylene being the main product. Separation of the products was accomplished by distillation, compression, and cooling. The plant was subdivided in seven process sections, viz. the furnaces for cracking, various separation and distillation processes, a compression section, and cooling sections. Transport of raw materials, and products between the various parts of equipment within sections, and between sections, occurred in pipes gathered in pipe-racks. Most process sections were densely packed with equipment. In some, the equipment was located on elevated grated, or concrete floors.

2.3.5.3 Events Prior to the Explosion

In the morning on the day of the explosion, a leakage of a mixture of C3 and C4 hydrocarbons occurred from one of the process sections. The most likely cause was low-temperature embrittlement at a weld in a feed drum.

The prevailing wind caused the flammable vapor cloud to drift into the congested process area. After approximately two minutes from the start of the leak, the visible part of the cloud was approximately 2 m high. It was estimated that in total approximately 5,500 kg of gas had escaped. At this point, the cloud was ignited by one of the furnaces near one corner of the process area.

2.3.5.4 The Explosion

The resulting explosion caused severe damage inside the process area. Overpressures of up to 1 bar must have existed to account for the damage produced. Pipelines and beams were bent over and several pipelines had ruptured, resulting in fires. Vessels had become dented and pushed away from their original locations. Part of a concrete platform had fallen down and another had tilted. Severe damage occurred to the concrete walls of the control room. The engineers' room was totally demolished. Fire broke out in a tank farm north of the process installation. Outside the plant area, damage was limited to window breakage up to a distance of 4.5 km (5 mbar). The fourteen fatalities occurred in the control room and engineers' room.

2.3.5.5 Computer Simulation

Twenty years after the accident, Wingerden et al. (1995) were able to perform a series of unique computer simulations of the Beek explosion disaster, using the comprehensive CFD-based simulation code FLACS, developed in Norway from 1980. A comparison of local peak pressures estimated from the damage picture generated by the actual vapor cloud explosion in 1975, and the corresponding local peak pressures produced by the FLACS simulation, showed similar trends in the peak pressure distribution across the process area. The simulations indicated that the explosion occurred with a fuel that was more reactive than pure propylene. Significant amounts of ethylene or butadiene must also have been present. The simulations also showed that for land-based process installations in the open, where partial confinement is mainly due to process equipment, the reactivity of the fuel is important with respect to the violence of an accidental explosion. The simulations further revealed that in an exploding heavy (flat) vapor cloud, a stoichiometric mixture of fuel and air is not necessarily the worst case. Over-stoichiometric mixtures can be even more dangerous due to the rapid mixing of air above the cloud with the gas mixture in the cloud during the explosion process.

2.3.6 The Arendal Explosion, Gothenburg, Sweden (1981)

2.3.6.1 Summary

Some central data of this event are given in Table 2–15

2.3.6.2 The Site of the Event

Details of this accident have been obtained from the Special Working Group (1981), Brandsjö (1988), and Nilsson (1991). The site of this explosion is not, strictly speaking, a process plant, but the event provides valuable information that is relevant even in the present context. Figure 2–56 gives a view of the explosion site and indications of the local damage caused by the explosion. The site was a large obstacle field in the open characterized by pipe tracks, bridges, buildings, cars, and trees, acting as turbulence-generating obstacles.

Table 2–15 The Arendal Explosion

Place:	Arendal, Gothenburg, Sweden
Date:	May 8, 1981
Fuel:	Propane
Type of Plant:	Pipe track through urban area. Rupture of pipeline
Fatalities:	1
Injuries:	1
Material Loss:	15 mill. SEK

2.3.6.3 Leak and Vapor Cloud Formation

The gas leak giving rise to a large explosive gas cloud was probably caused by sabotage. A 5 km long 6 inch diameter pipeline, transporting liquid propane at 8-9 bar(g), became perforated, presumably by an explosive charge placed and detonated intentionally on the pipeline wall. About 95 m^3 of the liquid propane was flashed to the atmosphere through the

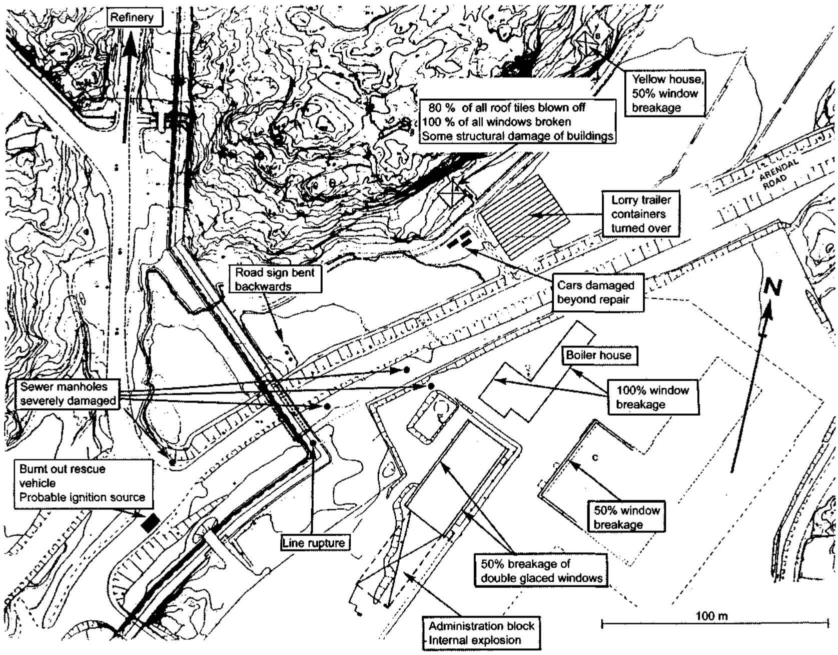

Figure 2–56 Plan of site and consequences of propane vapor cloud explosion at Arendal, Gothenburg, Sweden, in 1981. From Nilsson, 1991.

resulting 90 cm^2 hole in the pipe wall. The gaseous propane mixed with the ambient air, and a major explosive cloud was generated in the surroundings. The report of the Special Working Group (1981) provides estimates not only of the leak rate of propane from the perforated pipeline, but also of the total amount that escaped to the atmosphere. Visual observations of the size and shape of the vapor cloud prior to ignition are also included. However, Nilsson (1991) pointed out that the visible part of the cloud was due to water droplets generated by condensation due to cooling of the air by the propane evaporation, and that the extension of the real propane gas cloud could not be observed visually.

2.3.6.4 Ignition and Explosion

Ignition of the cloud occurred about fifty-five minutes after the pipeline had been perforated. The ignition source was probably a fire appliance that was driven into the explosive cloud. There was a series of distinguishable explosions, extending over about thirty seconds. The major fireball had a diameter of 300 m. Maximum explosion overpressures at various locations, e.g. in the sewer manholes indicated in Figure 2–56, were estimated from damage analyses.

2.3.7 Methane Explosion in 17,000 m^3 Coal Silo at Elkford, British Columbia, Canada (1982)

Storage of coal can present a gas explosion risk, due to spontaneous release of methane from some types of coal. An account of such an explosion in British Columbia, Canada, in 1982 was given by Stokes (1986).

2.3.7.1 Plant and Process

The silo that exploded, of height 48 m, diameter 21 m, and capacity of 15,000 tons, was used for storage and load-out of cleaned, dried metallurgical coal. Prior to the explosion, a methane detector had been installed in the roof of the silo. The detector activated a warning light in the silo control room when a methane concentration of 1% was detected, and an alarm light was activated when detecting 2% methane. A wet scrubber was located in the silo head house to remove dust from the dust-laden air in the silo during silo loading. A natural ventilation methane stack was also located in the silo roof to vent any build-up of methane gas from the silo.

The silo was full of coal twenty-four hours prior to the explosion. However, during the evening before the explosion, 10,000 tons of coal was discharged, at the same time as conveying of deep-seem coal into the silo had been started. This continued until the explosion occurred. At the moment of the explosion, there was approximately 12,300 tons of coal in the silo, of which 7,600 tons was deep-seam coal. Testing had shown that this quality of coal had a high methane emission rate and produced a low volatile coal dust. Clouds in air of this dust could not be ignited unless the air was mixed with methane.

2.3.7.2 The Explosion and Its Consequences

The explosion occurred early one morning in May. Witnesses stated that a flash was noticed in the vicinity of the head house, followed seconds later by an explosion displacing the silo top structures. This was followed by an orange-colored fireball that rolled down the silo walls and extinguished prior to reaching the base of the silo. Fortunately, neither injury nor death resulted, and damage to surrounding structures was minimal, although large blocks of concrete and reinforcing steel had been thrown several hundred meters from the silo. However, the plant itself had suffered substantial damage, including a devastated silo roof, head house, and conveyor handling system.

2.3.7.3 Possible Ignition Source

The ignition source was not identified, but three possible sources were considered: spontaneous combustion of the stored coal, an electrical or mechanical source, and hot coal from the thermal dryer. Spontaneous combustion had never presented a problem during ten years of operation, with coal being stored in different environments for varying lengths of time. Consequently spontaneous combustion was not considered to be a probable source of ignition. During demolition of the damaged silo, all electrical and mechanical components were recovered and inspected and did not show any evidence of having been the ignition source. Therefore, Stokes (1986) concluded that the remaining possibility, i.e. hot coal from the thermal dryer, was the most probable source of ignition.

2.3.8 The "West Vanguard" Explosion, The North Sea (1985)

2.3.8.1 Summary

Some central data of this event are given in Table 2–16.

2.3.8.2 Site of Explosion

A detailed discussion of this accident is given in the report by the Public Commission of Investigation (1986). The explosion occurred on board

Table 2-16 The "West Vanguard" Explosion

Place:	Haltenbanken, Norwegian continental shelf
Date:	October 6, 1985
Fuel:	Natural gas
Type of Plant:	Mobile drilling platform
Fatalities:	1
Injuries:	0
Material Loss:	Several hundred mill. NOK

the comparatively new, well equipped and well maintained mobile oil drilling platform "West Vanguard", while performing test drilling on Haltenbanken on the Norwegian continental shelf in the North Sea. The main platform structure is illustrated in Figure 2–57.

2.3.8.3 Events Leading to the Explosion

An uncontrolled blow-out of natural gas occurred during the early stages of a normal drilling operation. The blow-out was a so-called "shallow-gas kick" and happened before the blow-out preventing valve had been mounted. Shallow gas pockets were expected in this area, but at greater depths than the 263 m below the sea bed that had been reached when the blow-out occurred. According to the Public Commission of Investigation (1986), a series of unfortunate circumstances led to the uncontrolled blow-out, including inadequate reporting, partial lack of confidence in the process monitoring instruments, deficiencies in the well program, and reluctance to increase the mud weight. The gas pressure in the shallow pocket was of the order of 50 bar, and the velocity of the uncontrolled upwards gas flow was very high. The gas diverter equipment was unable to withstand the heavy erosion by the sand and other solid particles in the flowing gas. Consequently, after a few minutes, the gas flow had perforated the equipment and started to flood the entire platform structure. The gas was effectively distributed to most parts of the platform via the ventilation system. Eventually it reached an ignition source and got ignited.

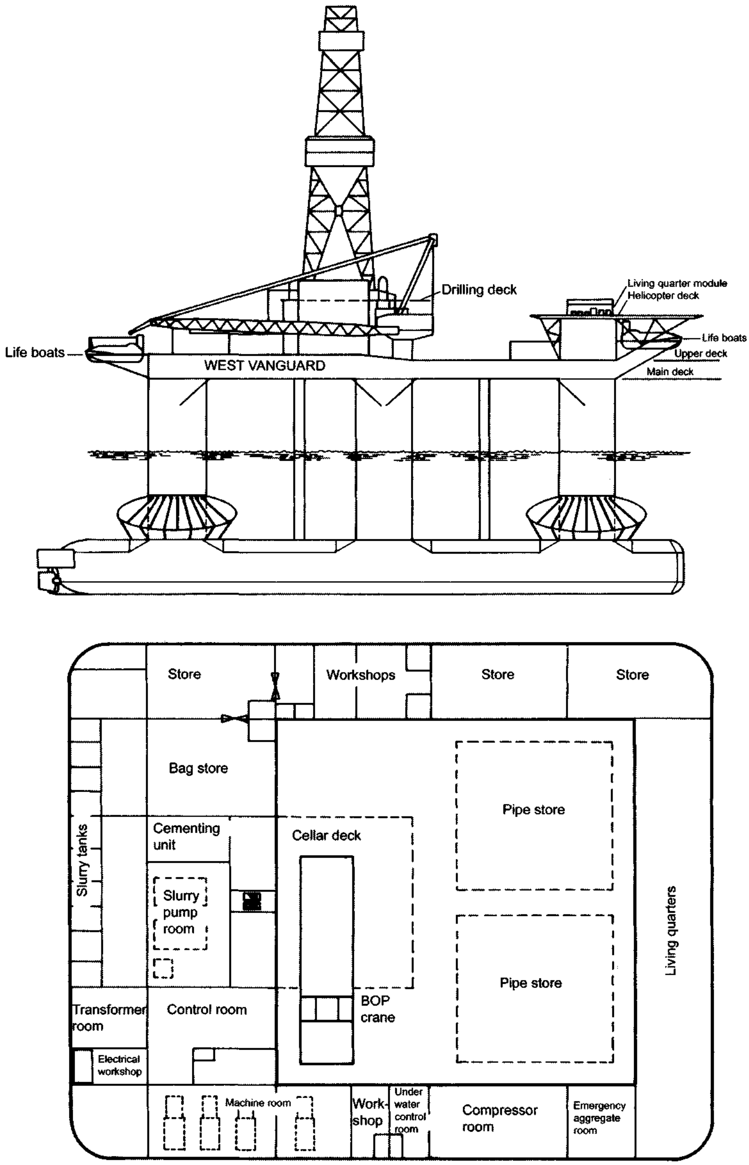

Figure 2–57 Illustration of the mobile drilling platform 'West Vanguard', with a side view of the entire platform, and a top view of the main deck. The main deck is 85 m long and 75 m wide. The platform was kept floating by means of two 100 m long pontoons. From Public Commission of Investigation (1986).

2.3.8.4 Ignition Sources

The ignition sources were probably metal sparks or a hot surface generated in the cellar deck area during the intense erosion of metal during the blow-out, and some electrical or other ignition source in the engine room of the platform. The former source was considered the most likely possibility for the first, strong explosion.

2.3.8.5 The Explosions and Their Consequences

At least two distinct explosions were heard. The first and most powerful produced a large flameball in the area of the drilling tower and across the pipe deck. According to most witnesses, this explosion probably occurred in the cellar deck. The second major explosion probably occurred in the engine room about one minute after the first explosion. Fortunately, as soon as the blow-out got out of control, and only a few minutes before the first explosion, the rescue operation had started, and 79 of the 80 persons on board were able to get into the lifeboats from which they were picked up by the standby ship before the explosion occurred. Large amounts of natural gas were bubbling through the sea to the sea surface, and from the stand-by ship it was observed that natural gas was burning across the sea surface in some areas around the platform, but fortunately not in the area from which the people were rescued. The platform suffered severe damage from the explosions and subsequent fires, mainly in the after part, including the area around the drilling tower and the adjacent areas and rooms. Roofs, bulkheads and bolted steel doors were blown up or heavily deformed by the explosion pressures.

2.3.8.6 Computer Simulations of Gas Explosions

As part the investigations after this accident, numerical simulations of explosions in various parts of the platform, were performed by means of the FLACS code developed in Norway. This made it possible to compare the observed actual structural damage with that to be expected from various ignition scenarios. This work was discussed in more detail by Bjorkhaug et al. (1985).

2.3.9 Catastrophic Gas Explosion in Taegu, South Korea, April 1995

2.3.9.1 Overview

This gas explosion catastrophe did not occur in the process industry, but in the middle of the busy city Taegu in South Korea (see Figure 2–58). However, the lessons to be learned are also indeed relevant for the process industries. The following provisional summary is taken from the brief report by Spaeth (1995) published shortly after the accident:

> At 0750 hours on April 28, 1995, an immense fireball tore through the heart of Taegu, South Korea's third-largest city, of a population of 2.3 million. Cars were hurled aloft, chunks of steel beams landed atop buildings and 250-kg steel plates that had covered a subway excavation, rained down on vehicles and pedestrians. A bus from the Youngnam Middle School pitched into the hole, killing all the students aboard.

Figure 2–58 Site of the LPG explosion disaster in Taegu, South Korea, April 28, 1995, which killed 100 people, and injured 117. Ten buildings were completely demolished and 48 others partly damaged, while 80 vehicles were destroyed or damaged. From Fire Investigation Report (1995).

The descriptions of the cause of the catastrophe in magazines and newspapers shortly after the accident were somewhat diverging. According to Spaeth (1995):

> The explosion occurred when a drill operator working at a department store building site near the subway construction pit mistakenly drilled into a fuel pipeline. The liquid (LPG) poured out into the pit for about 20 minutes, vaporized and the resulting vapor cloud was ignited, probably by a workers blowtorch.

Korea Times, a few days after the explosion, reported that:

> A 100 mm diameter gas pipeline was ruptured during digging near a department store adjacent to the explosion site. The pipeline was buried 1.3 meters deep under the road. Gas leaking from the ruptured pipe flew into the subway construction site through a sewage line and got ignited by a spark from nearby welding work. Subsequent investigations disclosed a 7 cm hole in the gas pipe.

However, the comprehensive Fire Investigation Report (1995) concludes that the exact cause of the explosion disaster could not be found. The following is a brief summary of the findings given in this report:

2.3.9.2 Circumstances before the Explosion

The residents living near the construction site had, since the night of 27 April, smelled gas several times and reported this to the City Gas Corporation and nearby police station, but the responsible persons had not responded to the reports. As late as 20 minutes before the explosion in the morning of 28 April, workers on site again reported to the Corporation about the gas leakage, but no immediate action was taken. It later turned out that after receiving similar messages from the workers at the site about a gas leaks both in January and March, the City Gas Corporation had not taken any significant measures. Fortunately, in these two cases there were no explosions.

2.3.9.3 Possible Causes of Explosion

The exact causes of the explosion were not resolved, but three scenarios were suggested.

2.3.9.3.1 Scenario 1

Gas leaked from a loosened joint or a crack on one of the LPG pipelines passing through the construction site, and the gas cloud produced became ignited and exploded. The construction company in charge insisted that, before the explosion occurred, they had reported several times to the City Gas Corporation about the smell of gas on the site, without any actions being taken. There were indications of poor quality of the work done when the pipelines were first laid.

2.3.9.3.2 Scenario 2

Generation of the explosive gas cloud was due to workers on the site having damaged the underground gas pipelines during their works. The City Gas Corporation received a report from a worker on the site saying that gas was leaking due to their mistakes during excavation work just before the explosion. In this scenario, the gas cloud was probably ignited by sparks or embers from welding operations. However, the company in charge of the whole subway construction strongly rebutted this hypothesis by claiming that the explosion had been initiated early in the morning before the work on the site had started. Furthermore, the gas pipelines were hanging about 15 m above the base of the working site, just below the perforated steel plates acting as a provisional road cover across the site. Therefore, it would not have been easy for the workers to touch the pipelines accidentally.

2.3.9.3.3 Scenario 3

Another possible cause of the gas leak might be formation of one or more cracks in the pipelines due to the continual vibrations induced by the heavy traffic across the perforated steel plates acting as the provisional road across the construction cavity.

2.3.9.4 The Extent of the Explosion and Its Consequences

Besides the violent noise of the explosion, a huge flameball extending 50 m above the road level was observed. Numerous perforated steel plates used as provisional road cover for a road length of about 300 m were flung into the air. One of these, weighing 280 kg (270 cm × 70 cm × 2 cm), was found hanging on a church cross on top of a three-story building near the explosion site. The explosion severely deformed and displaced the heavy duty H-beams supporting the provisional road cover within 1 km of the explosion centre. This caused numerous other steel plates to collapse under the load of all the vehicles, and thirty cars and buses were plunged into the 18 m deep construction cavity. Other cars soared to 10 m above road level. In all, eighty vehicles were damaged by the explosion. Ten buildings were completely demolished and forty-eight others partly damaged. Gas pipelines, water pipes, and underground cable pits were also destroyed, and the whole area was flooded, and the electrical power was cut off in thousands of homes. Rescuers found 97 people killed, three people missing, and 117 people injured.

2.3.9.5 Rescue Operations

A total of thirty fire trucks, ten cranes, and about 2,500 rescue personnel were dispatched to the explosion site. However, because of the possibility of further explosions of remaining unburned gas in the underground, rescue personnel could not be admitted to the site immediately after the explosion. Flooding due to the broken water pipes delayed the rescue operations even more. Rescue operations could not start fully until about twelve hours after the explosion.

2.3.9.6 Lessons to be Learned

The overall cause of this catastrophe was an inadequate governmental bid system for construction work, including inadequate quality assurance of technical and managerial safety matters. The workers on the site did not have adequate understanding of the technical standards applying to the work they were doing, and the responsible authorities had not given sufficient guidance. The company in charge of the construction work had not checked the underground pipelines drawings prior to starting the excavation works. Furthermore, the construction site was not provided with any gas alarm system. The investigations also disclosed lack of updated maps of underground gas pipelines, electric cables etc.

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2.3.9.7 The "Human Factor"

The following story, also from Spaeth (1995), illustrates the important part played by human behavior, not only in the chain of events leading to accidents, but indeed also in the subsequent investigation to disclose what actually happened:

> Five days after the explosion a local fire fighter told reporters that the gas leak had been reported to the local fire station by a street sweeper four hours before the explosion. According to the fire fighter, the complaint was entered in the station's log, but destroyed after the accident had occurred. When journalists found the sweeper, he said he reported a gas smell to a police box at 2100 hours in the evening before the blast and again at 0400 hours the following morning. After the tragedy he was confronted by officials who threatened to have him fired from his job unless he repudiated his reports. He did so, and the retraction was videotaped. When his story was made public, however, the prosecutor general in Seoul ordered an investigation.

2.4 Means of Preventing and Mitigating Gas/Vapor Explosions in the Process Industries

2.4.1 Introduction

Explosions and fires involving combustible gases and vapors constitute a major hazard in process industries and other environments where such materials are produced, used and handled. Therefore, the efforts to minimize the risk of explosions and fires in these industries continue nationally as well as internationally, and much work is spent on preventing and mitigating accidental gas and vapor cloud explosions.

Explosion risk is often defined as the product of the probability of an explosion and its expected consequence. Therefore the basic principle of gas explosion risk management is to minimize the explosion probability as well as the expected explosion loads, which are in turn related to the explosion consequences. Reduced gas explosion consequences can be obtained by active as well as passive measures. The most important means of prevention and mitigation/control are summarized in Figure 2–59.