Loss Prevention Bulletin

Improving process safety by sharing experience

Issue 251, October 2016

The great explosion of 1916

Fire and explosion of LPG tanks at Feyzin

Seveso – 40 years on

Chernobyl – 30 years on

The Sandoz warehouse fire – 30 years on

The Challenger Space Shuttle disaster

Risk and safety management of ammonium nitrate fertilizers

IChemE Safety Centre

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Loss Prevention Bulletin

Articles and case studies from around the world

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Cover photo of burnt out storage spheres, Feyzin is courtesy of Collection Bibliothèque municipale de Lyon, Fonds Georges Vermard, P0702 B02 07 618 00001
Seveso photo courtesy of Roche

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Editorial

Major accidents of the past – what have, and haven't, we learnt?

This year, 2016, sees the 350th anniversary of the Great Fire of London. Since then urban building codes, fire protection requirements and firefighting techniques and technology are very different. Lessons indeed have been learned. Large-scale fire in towns and cities, which were commonplace in mediaeval and renaissance Europe, appear to be a thing of the past in the industrialised Europe of today — although it should not be forgotten that the Great Fire of Chicago, IL, USA occurred in 1871.

Anniversaries are important for commemorating events that have taken place; for recalling the past and for reflecting on their significance. As such, 2016 marks a number of significant anniversaries of important major accidents:

100 years	Faversham, UK
50 years	Feyzin, France
40 years	Seveso, Italy
30 years	Schweizerhalle, Basel, Switzerland (Sandoz)
30 years	Chernobyl, USSR (now Ukraine)
30 years	Challenger Space Shuttle, USA
15 Years	Toulouse, France (together with 95 years Oppau, Germany)

These are well known events, which are covered in their own individual articles in this anniversary edition.

However there are other less familiar accidents which should also not be forgotten.

- **Manfredonia, Italy, 1976**
  The explosion of a scrubbing tower for the synthesis of ammonia at the ANIC petrochemical plant led to the release of several tons of potassium carbonate and bicarbonate solution containing arsenic trioxide. One hundred and fifty people were admitted to hospital for arsenic poisoning. The symptoms were greater amongst the inhabitants of the town of Manfredonia than amongst the factory workers. As with the Seveso incident in the same year, this incident was one of the motivating events leading to the development of the European directives on the control of major accident hazards.

- **Danvers, MA, USA, 2006**
  The vapour cloud explosion and subsequent fire at an ink and paint manufacturer destroyed the facility and heavily damaged dozens of homes and businesses. Twenty-four homes and businesses were completely destroyed. The accident was caused by a complete disregard for fundamental controls to manage flammable liquids safely. There was also inadequate inspection and enforcement by the local authorities.

- **Syracuse, Italy, 2006**
  A leak due to corrosion in a pipe transporting crude oil from the tank farm to the process field ignited, impacting the other pipes in the pipe bundle which contained a variety of chemical products. Some of the pipes suffered a BLEVE and the accident led to the hospitalisation of ten firefighters. Major causal factors were the lack of maintenance and inspection together with the poor design of the pipe bundle, which meant that there was inappropriate separation between the pipes, leading to difficulties in identifying and shutting down the pipes. As well as hydrocarbons, there was also high pressure steam and firefighting water transferred in this bundle.

- **Evangelos Florakis Naval Base, Cyprus, 2011**
  The explosion of 98 containers of explosives which had been stored for 2½ years in the sun was the worst peacetime military accident recorded on the island. The explosives had been confiscated in 2009 but not disposed of, despite protests by concerned citizens. The explosion killed thirteen people, including six fire-fighters, and injured 62. The explosion severely damaged hundreds of nearby buildings including the largest electrical power station which supplied over half of the electricity for the island. The costs of the explosion were estimated to be just over 10% of Cyprus' GDP.

This is a small selection of incidents to indicate that there is still much to be learned and that very often the same key factors are listed amongst the causes:

- inadequate design;
- poor identification of hazards and appropriate measures to manage the risks;
- poor maintenance and inspection;
- inadequate considerations to human factors and safety management;
- inadequate inspection and enforcement by public authorities.

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This anniversary edition is expected to perform a number of roles. Firstly, by way of a reminder, it brings together the information on a number of important accidents and thus can be used as a teaching or training aid, in particular for those who have become involved in the process safety world since these accidents took place. Secondly, it provides an opportunity to review current practices. Reoccurrences indicate that the lessons from the "milestone events" have not been learned by all sections of the chemical processing and handling community, or have simply been forgotten. In particular, exothermic chemical reactions are still running out of control with significant impact on workforce and the surrounding communities, and accidents involving the storage of ammonium nitrate, in particular as fertilizers, leads to enormous devastation and numerous fatalities.

This edition of LPB is not just a historic review, but also an opportunity to take stock and assess whether the lessons really have been learned and the appropriate measures taken. The LPB editorial panel also hopes to enable the fraternity within the chemical and allied industries to recognise that we all have a very important role to play in preventing accidents and saving lives. This is to ensure that those who sadly lost their lives rest in peace.

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Chairman,
Loss Prevention Panel

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News in brief...

Initial results revealed in Florida explosion

Preliminary results have been released by US safety officials investigating an explosion that killed one worker at an Airgas production facility in Florida on 28 August.

The US Chemical Safety Board (CSB) said the explosion involved nitrous oxide tanks in the loading bay, where the incident is said to have taken place.

Vanessa Sutherland, chair of CSB offered "condolences to the family suffering this tragic loss", adding that "the CSB's accident investigation will determine the root cause of this fatal incident."

The Florida State Fire Marshal reported that there was a nitrous oxide holding tank and two tankers involved and that the focus of the investigation was to determine if the explosion originated with the holding tank and tankers, or started elsewhere and spread to them.

Airgas makes nitrous oxide using gases supplied by the nearby plant operated by performance materials specialist Ascend. The company said its facility may have sustained some damage as result of the explosion; however it did not report any fatalities or injuries.

The investigation will be handed over to the US Occupational Safety & Health Administration (OSHA). Airgas has been subject to 37 inspections by the federal body over the last five years resulting in 22 citations from 11 of the inspections.

Air Liquid completed its US$13.4bn purchase of Airgas in May.

Eight firefighters killed in Moscow warehouse fire

Eight firefighters have lost their lives while extinguishing a fire at a warehouse in Moscow.

Rescuers found the bodies in the remains of a large warehouse that was engulfed by fire late on Thursday 22 September.

The fire covered an area of 4,000 square meters and caused a 1,500 square meter section of the building's roof to collapse. It is understood that the victims had been conducting a search inside the building when its roof collapsed.

Earlier, they had managed to lead to safety more than 100 workers at the warehouse where plastic items and other goods were stored. The fire was extinguished early in the morning on 23 September and a search is continuing at the site in Golyanovo, north-east Moscow.

Firefighters prevented the explosion of 30 cylinders of household gas in the warehouse, as well as discharging 67kg (148lb) of ammonium from a compressor facility, the emergency ministry also said, quoted by Tass news agency.

There are suspicions that radiators had been left on, overwhelming the building's electricity circuit.

This is the latest deadly inferno to hit the Russian capital, where safety standards are often low.

On 27 August, a fire at a Moscow printing house in Moscow killed three Russian citizens and 14 Kyrgyz migrant workers.

Four killed in Chinese MDI unit explosion

At least four people have been killed by an explosion at a 600,000 t/y methylene di-phenylene isocyanate (MDI) unit owned by Wanhua Chemical in Yantai, China.

According to reports, the incident occurred on 20 September when the company was shutting down the plant for scheduled maintenance. The explosion hospitalised a total of eight people, with four of them dying of their injuries.

The scheduled month-long maintenance at the unit will likely be extended and further details will only be confirmed after the incident investigations are complete.

Wanhua Chemical's 750,000 t/y propane dehydrogenation (PDH) and 240,000 t/y propylene oxide (PO) 800,000 t/y methyl tertiary butyl ether (MTBE) production in Yantai were not affected.

China has suffered a series of chemicals-related explosions in recent times, most notably the August 2015 Tianjin blast that killed a total of 165 people. Nine workers were killed in an explosion at a chemical plant in Shandong Province in October 2015, and 21 were killed at a coal power station explosion last month.

Greenpeace said in a statement today that the incident in Yantai now adds to a total of 232 chemicals-related incidents that have occurred in China this year from January to August, an average of 29 per month. The environmental group says the incidents have caused a total of 199 deaths and 400 injuries.

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Valero Energy fined following serious accident at Pembroke Refinery

Valero Energy UK Limited has been fined £400, 000 following a serious accident at its Pembroke Refinery.

The Court heard how, on 05 March 2012, an access tower walkway that provided gangway access to a stationary tanker vessel had dropped 3.5 metres, causing the operator to be trapped by a slack wire rope. He suffered fractures and lacerations to both legs and a dislocated knee as a result.

The HSE investigation found multiple failings leading up to the incident including:

- failure to carry out a sufficient risk assessment of the use and operation of the access tower, with the result that the dangers of jamming, slack cable, and personnel accessing the walkway without engaging the scotching pin were neither identified or addressed and the hierarchy of risk control was not applied
- failure to provide adequate information, instruction and training to employees as to the safe use and operation of the access tower
- failure to carry out adequate investigations into the previous and related incidents of September 2011, February 2011 and, in particular, August 2010
- failure to review the check-list risk assessment in light of those incidents
- failure to act on the recommendations of their inspection contractor, particularly in respect of the jamming problem and the absence of any access gate interlock and ignored comments on one report that there was a ''potential fatal accident waiting to happen''.
- failure to install any means of detection or prevention of slack cable in the mechanism
- failure to detect that the access tower was neither CE marked, nor subject to a Declaration of Conformity, as required.

Valero Energy UK Limited (previously known as Chevron), of Pembroke Refinery, Pembrokeshire, pleaded guilty to a single charge of breaching Section 2(1) of the Health and Safety at Work etc Act 1974 at a previous hearing. It was fined £400,000 and ordered to pay costs of £60,614.

Speaking after the hearing, the HSE inspector said: "It was particularly disappointing to find that although the company knew there had been problems with the operation of the access tower the company had failed to investigate these properly and had relied on changes to instructions, rather than taking action to modify the defective hardware, as required by the hierarchy of risk control.

"This was even more surprising in view of the fact that the company operates a major hazard refinery site where you would expect such problems to be taken more seriously and effectively investigated, with suitable corrective actions implemented."

Six killed in NW China factory blast

Six workers were killed and one is missing after an explosion at a chemical plant in northwest China's Qinghai Province.

The explosion occurred on 18 September in a dust collection device at a cement production line belonging to Qinghai Salt Lake Haina Chemical Company when 26 workers were on site, said Liu Yunzhou, head of the administration commission of Ganhe Industrial Park in the Xining economic and technological development zone.

Two workers were killed instantly in this explosion and a further twelve were injured. Four of the injured workers later died in hospital. The other eight were treated and are described as stable.

A search is underway for a missing worker, while the cause of the accident is being investigated.

The company started production in 2013 with a daily capacity of 2,500 tonnes of cement.

Saudi Aramco fire injures eight workers

State-owned oil company Saudi Aramco reported eight workers have been injured as a result of a fire at its oil terminal facility in Ras Tanura, Saudi Arabia.

The company said in a statement that the incident occurred on 20 September at around 09:00 (local time). The company also reported that the injured, including six contractors and two employees, were receiving medical treatment.

Aramco said it will conduct a full investigation to determine the cause of the fire.

Oil and gas operations at the 550,000 bbl/d terminal were not impacted as a result of the fire.

In January 2014, three workers were killed on an oil rig belonging to Saudi Aramco which sank in the Persian Gulf.

Aramco said it will release additional information as it becomes available.

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Incident

The great explosion of 1916

Phillip Carson

Summary

The main industrial uses of ammonium nitrate are in explosives and in agriculture as a high-nitrogen fertiliser. Many industrial accidents involving ammonium nitrate have been described in LPB; but this paper focuses on an industrial accident 100 years ago in the UK explosives industry. On 2 April 1916 a fire and explosion at a munitions factory on the Kent marshes killed 108 people, injured 97, and caused extensive on-site damage. The explosion was heard over 80km away. The initial fire and explosion involved ammonium nitrate and TNT. Domino effects affected other munitions all being prepared urgently for the war effort. The following description leans heavily on the sources listed in the bibliography.

Keywords: Explosion, explosives, domino effect

Introduction

Gunpowder, established in medieval times, remained the principle propellant for military purposes up to WW1. It comprises a mixture of carbon, sulphur and potassium nitrate. The Kent marshes proved an ideal location for the gunpowder industry because:

- The streams could be dammed at intervals to provide power for watermills;
- The land was well suited for growing alder and willow as a source of charcoal;
- The creek could be used for shipping in sulphur and transporting out finished product;
- Of the close proximity of the arsenals in London and the naval ports on the south coast from where it could be loaded for use or export.

As a result, the Home Works gunpowder mill was established at the head of Faversham creek in the 16th century. The Oare Works was developed towards the end of the 17th century and a third opened in 1787 known as the Marsh Works, built by the British government approximately 1km north-west of Faversham to augment output at its Home Works. This also had access to the sea via Oare Creek. The more dangerous operations were transferred from the Home Works to the Marsh works following an explosion.

The industry continued to expand and diversify. Guncotton (and its successors) were most suited to the Marsh plant since it was more remote from towns and was first manufactured under licence at the Marsh Works in 1847. Because the process was poorly understood a serious explosion resulted in 21 fatalities (only ten of whose bodies could be identified) and the factory subsequently shutdown. Guncotton was not made again in Faversham until 1873, when the Cotton Powder Company (CPC), independent of the gunpowder mills, opened on a remote virgin site about 4km northwest of the town centre alongside the Swale, a deep-water channel dividing mainland Kent from the Isle of Sheppey. Deliveries of raw materials (cotton waste and sulphuric and nitric acids) and despatch of guncotton could readily be made by water.

The explosives archipelago continued to develop and by the turn of the century, the CPC site at Uplees became one of the largest works in Britain producing 35 types of explosive. Cordite (a mixture of nitroglycerine and guncotton) soon became the main propellant for the British army and navy but the material proved somewhat uncontrollable. By the onset of the war, the main high-explosive used in British shells was based on picric acid (Lyddite) which was superseded by trinitrotoluene (TNT). In 1912, the Explosives Loading Company (ELC) joined the CPC at its western end specifically for filling shells with TNT (see Figure 1). The outbreak of WW1 created a vast, urgent demand for high explosives, met chiefly by the manufacture of amatol comprising 60% ammonium nitrate and 40% TNT, or 80% ammonium nitrate and 20% TNT mixtures. Since ammonium nitrate (AN) was cheaper than TNT its inclusion "stretched" the TNT and provided an internal source of oxygen. Following the "shell crisis" in 1915, the need for munitions became ever urgent and the Prime Minister established the Ministry of Munitions to control all explosives factories by coordination of production and distribution of munitions.

The Uplees site

The ELC plant was established in 1912 under an amending licence granted to the CPC to fill charges with TNT for shells, torpedoes, and mines. However, management also used Amatol. The entire site was complex with about 200 workers and comprising hundreds of buildings including processing plants, stores, offices, mess rooms, power houses, etc., the majority being of light construction. Most of the CPC factory was built on a floating crust above the marsh but magazines were on more solid ground built into the hill and screened by mounds. Buildings were linked by a tramway. The ELC was the smaller company with around 30 buildings, almost all of wooden construction with no mounds because each was separated from others by approximately 60m. Because of the explosion risk, the special safety arrangements reportedly included:

- No metal buttons were allowed on garments — buttons were all made of wood.

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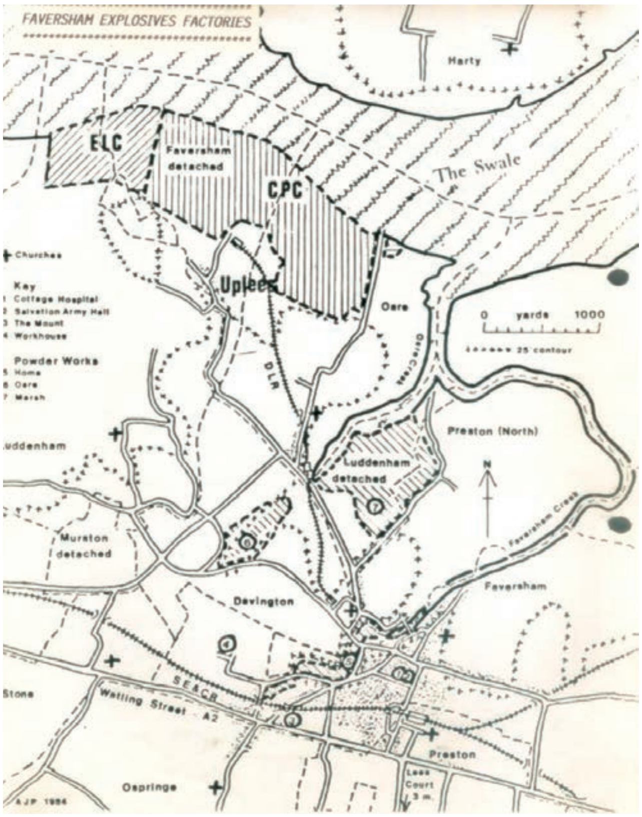

Figure 1 – Faversham explosives factories
ELC=Explosives Loading Company
CPC=Cotton Powder Company

- Women were not allowed metal hairpins or grips and had to have their hair tied up in a net.
- No pockets on overalls in which items could be kept were allowed.
- No pipes, matches or cigarettes were allowed into the works. These had to be put into pigeon holes by employees as they arrived for work.
- Tramway rails were made of wood close to buildings.
- Horses had brass horseshoes instead of steel to reduce the risk of sparks.
- Buildings were constructed of wood and well-spaced out. No metal nails were used.
- Security precautions included a military guard of 128 men and 24 patrolmen for the two factory sites. The CPC had its own part-time fire brigade, plenty of hydrants and hoses and a pump always at the ready to raise extra water. The ELC had only one four-man pump, 100 or so chemical extinguishers and a supply of fire buckets. Water was available from the dykes. High pressure mains water had been laid up to the factory and the hydrants were ready for installation but contractors had failed to deliver the pumps.

On 31 March 1916, H.M. Inspector of Explosives (Major Cooper-Key) undertook an unannounced inspection of ELC. In order to meet the nation's demand the Ministry of Munitions had stocked the factory with levels of raw materials far beyond the plant's production capabilities, despite complaints from management. About 40 tonnes of AN and 60 tonnes of TNT passed into the factory each week. Building No 833 contained stocks of AN plus 150 tonnes of TNT; an additional 50 tonnes load of TNT had recently been received for which there was no storage accommodation and it was therefore stacked in the open outside building 833. The TNT was packed in linen sacks inside the wooden crates. Empty AN barrels and TNT sacks had accumulated in spaces between offices, production units and boiler houses. He noted the absence of hydrants and fire buckets in various ELC buildings; the nearest fire-brigade was in Faversham. Nevertheless, the inspector concluded that he was satisfied with the general conditions, recognising the need for urgent production to meet government expectations.

The accident

Just after noon on Sunday 2 April 1916 it was noticed that some empty linen sacks leaning against the matchboard wall of building 833 had ignited. The alarm was raised immediately and the assistant manager took charge and attempted to extinguish the fire. Men with buckets formed a chain to the nearest dyke but the action proved futile and the building was well alight when the manager arrived. Problems were encountered in gathering sufficient fire hoses across the site to reach ELC buildings from CPC hydrants, and firefighters were unable to approach the buildings because of the intense heat. Three Faversham fire brigades turned out but were unable to reach the site in a timely manner through the narrow country lanes. Building 833 became a lost cause and the men agreed to move cases of TNT to a safe distance in an attempt to prevent fire escalation to other buildings including the CPC cordite plant. They tried to remove cases from within the building but were prevented by smoke and so concentrated on crates lying around three sides of the outside walls. The building was burning fiercely and the bulk of AN was alight. Fire trucks inflamed 35m away and sparks spread to other buildings. During the fire when a fire officer asked the deputy plant manager if there was any danger that the store of AN and TNT could explode he was reassured that it would only burn. For over an hour water was poured over the fire to no avail and the manager gave the order for everyone to evacuate. At 14:20, during the evacuation, the contents of building 833 detonated, followed immediately by explosion of the washing/filtering houses of the nitroglycerine plant, 110m away. Explosions of two further buildings followed. Five buildings were destroyed without trace, leaving behind craters some 10m wide and 4 – 6m deep (see Figure 2). All buildings of light construction within a radius of 200m of the epicentre of the initial fire were demolished and in total over 25 buildings belonging to the ELC were destroyed. The extent of the destruction is illustrated by examples shown in Figure 3. The human toll amounted to 108 deaths (including the entire works fire brigade) and 97 injuries. As the explosion occurred on a Sunday, no women were at work. The bodies of seven victims were never found and 70 of the corpses were buried in a mass grave at Faversham Cemetery on 6 April with the Archbishop of Canterbury in attendance. Letters of sympathy were received from the King and Queen.

The explosion was heard across the Thames estuary and as far away as Norwich and Great Yarmouth. In Southend-on-Sea, domestic windows and two large plate-glass shop windows were broken. This was the British explosives industry's worst industrial accident: others around this time included the

knowledge and competence
engineering and design
systems and procedures
culture

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explosion at the Barnbow shell-filling factory in Leeds on 5th Dec 1916 which resulted in 35 women losing their lives and many injuries.

Investigation

A few days after his unannounced inspection of ELC, Major Cooper-Key returned to the site this time to investigate the accident. His report puts the casualties at the time as 106, of whom 20 were CPC employees and four were military guards. Another source suggests all but five victims (who were members of the military) were employees helping with the emergency, or spectators, despite being warned to leave. The inspector confirmed the location of the initial explosion and suggested possible sources of ignition as cigarettes, sabotage, spontaneous ignition, or sparks from the powerhouse chimney. After giving reasons for dismissing the first three, he concluded that sparks were the most likely source. The three flues from the powerhouse were each fitted with a spark-catcher but they were of dubious efficiency and the wind was blowing almost directly from the boiler house towards the heap of bags just 15m away. Also, on the night before the accident, two patrolmen reported extinguishing a fire from this source between the boiler house and TNT store.

The report focussed on the vast quantity of stocks on site and concluded that had the store contained only TNT as per the licence, it was likely the contents would have simply melted and burned. However the amount of combined TNT and AN was equivalent to 75 tonnes of high explosive. (A further 3000 tonnes of explosive apparently remained in unaffected sheds after the accident suggesting the outcome could have been even more catastrophic).

In terms of accountability, the inspector acknowledged that management could not be completely exonerated from blame but he was clearly sympathetic of their plight. Thus:

- In permitting high levels of hazardous materials on site management were aware of the danger and had complained, but were over-ridden by government officials. (The inspector himself had raised the matter of congestion several times with the Ministry but given the necessity of immense scale of manufacture it was practically impossible to maintain the orderliness and method considered so essential in normal times);
- In departure from the conditions of the license he agreed that rapidity of output was the first priority and that it was extremely difficult, if not impossible, to strictly adhere to the exact letter of the licence.
- The inspector suggests it was government officials who either failed to recognise the risk of storing AN and TNT in the same building or had considered the risk justified by the urgency of national requirements.
- Attempts to fight the fire and move stocks from the scene could have put lives at risk, but the inspector singled out the manager and works manager for bravery including their success in extinguishing fires on the roof of the magazine containing 25 tonnes of TNT, thereby preventing another explosion, which would have taken out the cordite plant. (An inquest acquitted the managers of all blame).

Because of stocks of similar ingredients elsewhere in the UK the inspector had tests performed to ascertain whether TNT and AN together in unmixed states posed greater explosion risk than premixed amatol. Results, however, were inconclusive probably because of the inadequacy of the test facilities.

The inquest recommended more efficient appliances be installed in explosives factories but the inspector's report emphasised the difficulties of laying high-pressure water mains during war and although this had not been done at the present sites, it was due to no lack of effort by management. As a substitute, he recommended a four-man manual pump supplemented by fire-buckets and over 100 chemical fire extinguishers.

Lessons learned

The Minister of Munitions set up a standing committee to establish the causes of explosions in Government and controlled munitions factories. In May 1916, they issued a "secret" report making the following eight recommendations:

- Boiler-houses should be located as far as possible from danger buildings;
- Plenty of buckets filled with water should always be available in all buildings, and proper fire hydrants provided where possible;
- Part-time works fire brigades to be formed and trained by qualified firemen in use of various appliances at their disposal;
- Accumulations of empty boxes, bags, refuse of any flammable substances to be forbidden;
- Stocks of explosives or their ingredients for which proper storage was unavailable but which had to be stored on site should be placed as far away as possible from other buildings;
- TNT and AN must never be stored together in the same building;
- All conditions and terms of licences to be strictly adhered to, and
- If prompt use of fire buckets or hydrants fails to extinguish a fire at once then everyone should be withdrawn to a safe distance.

Nowadays, additional recommendations may be expected in terms of organisational considerations (for example, the appointment of the Ministry of Munitions represented a significant top-down organisational change which impacted the risk), management responsibilities, training staff in hazards, plant design (including boiler-houses, stores), process safety from cradle to grave, minimising inventory of hazardous materials, review of legislation, access for emergency services, etc. The fire on the night before the accident was a near-miss and was a lost opportunity to recognise the risk posed and thereby possibly circumvent the accident. Indeed, current day requirements are for zero tolerance to even the most minor fire within major hazard facilities.

Conclusion

This tragic but fascinating case study illustrates the difficulty of using hindsight to criticise human factors at times of war.

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The heroic attempts to dowse the fire and salvage explosives may be considered foolhardy nowadays, but the mentality to fight to save the plant could be linked to the workers' national pride in their contribution towards the war effort. Indeed, Lord Kitchener (The Secretary of State for War) wrote to the company's management in 1914 instructing the workforce on "the importance of the government work upon which they (were) engaged". "I should like all engaged by your company to know that it is fully recognised that they, in carrying out the great work of supplying munitions of war, are doing their duty for their King and Country, equally with those who have joined the Army for active service in the field." The inspector's report on the accident concluded that those who died at their posts gave their lives for their country in the fullest sense in trying to save a national disaster. Nevertheless, in the present case, this act is also attributable to lack of training, preparedness and provision of adequate equipment.

It is appreciated that under war conditions, time may not allow careful process development. However, one lesson highlighted by this accident is the need to fully understand the physical, chemical and hazardous properties of materials being used or formed, and of the processes adopted during manufacture. All involved should then be trained to appreciate these under normal and emergency conditions. At the time of the accident the physical and physiochemical properties of AN were poorly understood, which raised problems with its handling, storage, and the preparation of the various mixtures with nitro explosives, and on dealing with fires and explosions (as illustrated by the wrong advice given by the deputy plant manager to a fire officer). This is pivotal to the accident.

In mainland Europe, AN tended to be incorporated into nitro explosives at or below 40% when the nitro compound could be melted and mixed with dried AN to form a slurry which was poured into shells. In the UK, however, when blending higher concentrations of the cheaper AN component, problems were encountered in forming homogenous mixtures and in the storage and handling of bulk quantities. Large masses of AN could set rock-like and crates frequently had to be broken-up with pickaxes. This was eventually overcome by shipping the salt containing small quantities of water with subsequent drying in situ at the filling factories. It was also crucial for the shell contents to be above a minimum density so as to ensure complete and effective detonation, achieved by use of hydraulic presses to compact the mass by means of rams. This hazardous operation was housed in a separate building surrounded by mounds to minimise the effects of possible explosion, and the control levers and recording instrument were operated from outside the building. Mixtures filled into shells in a hot state tended to contract on cooling and recede from the immediate neighbourhood of the detonator and primer so that the fuse became ineffective. This was overcome by redesign of the shell and modification to the method of filling and inserting the fuse.

Whether risk assessments should result in higher levels of acceptable risk during wartime is a debatable topic. Production targets were driven by survival and military success rather than solely financial profit. In general the level of risk accepted by military personnel tends to be higher than that acceptable to civilian operators, and the rank of the chief inspector and that of some employees may suggest a military culture within the industry.

Today, where the number of inspectors allow, they should be rotated on a regular basis to avoid "regulatory capture" by management due to over-familiarity. Also, it would be wise to use a different inspector to investigate a significant accident than the person providing a routine regulatory service.

Material properties

TNT

TNT, manufactured by the (usually two-stage) nitration of toluene with a mixture of fuming nitric and sulphuric acids, is a relatively expensive explosive. It is an oxygen deficient explosive to which oxygen-rich substances (such as AN) are added to enhance its explosive power and it is one of the more stable high explosives. When pure the product is a colourless crystalline solid at room temperature melting at 81°C and boiling at 240°C. It detonates around its boiling point but can be distilled safely under reduced pressure. It may also detonate when subjected to strong shock. Small, unconfined quantities will burn quietly but sudden heating of any quantity may cause it to detonate.

TNT may enter the body via ingestion or inhalation of dust or fume but the main route of concern is by skin absorption. Target organs include the blood, liver, nerves and muscles. AN is hygroscopic and keeps the skin moist and as a result assists the passage of TNT through the skin thereby making amatol more dangerous than TNT alone. Over-exposure may result in a range of adverse health effects including skin irritation, cyanosis, atrophy of the liver, anaemia, muscular pains, menstrual irregularities etc. and, for some workers, the materials turned their hair, face, hands, forearm and legs orange/yellow from jaundice earning the ladies the name 'canary girls'. (This was also seen in WW2 but was less prevalent due to improved occupational hygiene controls).

Ammonium nitrate

Ammonium nitrate is manufactured by the exothermic reaction between ammonia gas and concentrated nitric acid

$$NH_3\,(gas) + HNO_3\,(liquid) = NH_4NO_3\,(solid)$$

Ammonium nitrate is a white crystalline solid freely soluble in water when it absorbs tremendous amounts of heat. On heating it transforms between its many crystalline forms and melts.

$$\text{Tetragonal} \overset{-17^{\circ}C}{\leftrightarrow} \text{Rhombic 1} \overset{32.1^{\circ}C}{\leftrightarrow} \text{Rhombic 2}$$

$$\overset{84.2^{\circ}C}{\leftrightarrow} \text{Rhombohedral} \overset{125.2^{\circ}C}{\leftrightarrow} \text{Cubic} \overset{169.6^{\circ}C}{\leftrightarrow} \text{Liquid}$$

At 185–220°C it decomposes to nitrous oxide and water vapour; the decomposition becomes violent at 250°C

$$NH_4NO_3 = 2H_20 + N_2O$$

Nitrous oxide

Nitrous oxide is a colourless gas, stable at ordinary temperatures. However, above 600°C, it decomposes to oxygen and nitrogen and so supports combustion of burning substances just as vigorously as does oxygen. Whether this had any influence on the Faversham accident is unknown.

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Figure 2 – Crater created by explosion of building 217 (note man in centre)

Figure 3 – Remains of building 844

Pure AN may be locally heated to red heat without explosion and the decomposition does not spread. It may, however, explode violently on contact with flames or other ignition sources and can be induced to decompose explosively by detonation. Whilst pure AN is stable under "normal conditions" and can be stored in bulk, stockpiles pose a fire hazard due to its highly-oxidising properties, for example, when in contact with hydrocarbons such as oils. Since commercial AN often contains 1% hydrocarbon oil or 5% kaolin to prevent crystals sticking together these mixtures decompose explosively when heated locally and the explosion may spread throughout the entire mass.

Cordite

Cordite is manufactured by the nitration of purified, dry, cotton waste and the product ('nitro-cellulose' or 'guncotton') thoroughly washed before working into a uniform very loose state and pumped as a slurry and pressed to afford material of 50% water content (dried nitro-cellulose is dangerous to store and easily ignites and explodes). When ready to use, dried material is mixed with nitroglycerine into a paste to which mineral jelly and solvent are added and worked up to dough and extruded through orifices to form spaghetti-like cord known as Cordite. Dried product contains 65% nitro-cellulose, 30% nitroglycerine and 5% mineral jelly.

Postscript

Both Swale-side factories closed permanently in 1919. However, in 1924 a new venture, the Mining Explosives Company, opened a factory on the east side of Faversham Creek, not far from the site of Faversham Abbey — hence 'Abbey Works'. After a fatal accident in 1939, the proprietors abandoned the manufacture of high explosives to concentrate on making an explosive-substitute based on a reusable steel cartridge filled with carbon dioxide. The premises continued to be licensed under the 1875 Explosives Act, as gunpowder was used in the initiator. Manufacture continues today under the name Long Airdox.

All three gunpowder factories closed in 1934. ICI, then the owners, sensed war with Germany, and realised that Faversham would become vulnerable to air attacks or possibly invasion. Work, staff and machinery, were transferred to Scotland. Most of the Marsh Works was later developed for housing and the Oare works is now a nature reserve.

The UK Explosives industry has been regulated under the Explosives Act 1875 and its subsequent revisions until The Manufacture and Storage of Explosives Regulations 2005, which replaced most of the 1875 Act. The most recent legislation is the Explosives Regulations 2014.

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Incident

Fire and explosion of LPG tanks at Feyzin, France

Adrian Bunn, Aker Solutions, UK; Mark Hailwood, LUBW, Germany

On 04 January 1966 at the Feyzin refinery in France an uncontrolled release from a propane storage sphere ignited, caused a fire that burned fiercely around the vessel and led to a series of BLEVEs.

This disaster was the worst accident to have occurred in a petroleum or petrochemical plant in Western Europe prior to the Flixborough disaster in 1974. Since then, many pressurized tanks containing liquefied gases have been subject to a BLEVE. The hazards are now better understood, and storage spheres are protected from fire engulfment by better design. However, so many firefighters and emergency responders have been killed while trying to control fire engulfed pressure vessels that the cautious philosophy is to evacuate and take shelter until the material burns itself out rather than attempting to extinguish the fire.

The LPG storage installation

Eight LPG storage spheres were positioned inside a bund with a central sub-division which divided the bund in two groups each made up of two propane (each 1200m³) and two butane spheres (each 2000 m³). Each sphere was provided with fixed water sprays and on top of each sphere was a three-way valve beneath two identical pressure relief valves.

Samples were taken from the spheres routinely every three to five days for analysis. The sampling line was located on a ¾" sampling tap positioned between two 2" purge valves which were used to drain production residues (oily salt/hydroxide solution) from the spheres. The purge valves were positioned about 260 mm apart and the pipework in between was fitted with rudimentary steam heating and lagging (see figure 1).

The accident

Early on the morning of 04 January, a product sample was due to be taken from one of the spheres, which was being filled by the site's production units. Before 6:40 a.m., whilst it was still dark, the laboratory technician entered the LPG bund to sample the sphere. The tank had to be purged of residues before the product sample was taken, and plant operator and a shift fireman accompanied the technician in order to carry out this task.

The sampling valves which branched off the purge line were often frozen and difficult to access; therefore sampling was regularly carried out via the purge line.

Uncontrolled releases had occurred previously under a butane sphere in August 1964 and under a propane sphere in February 1965. The releases were eventually brought

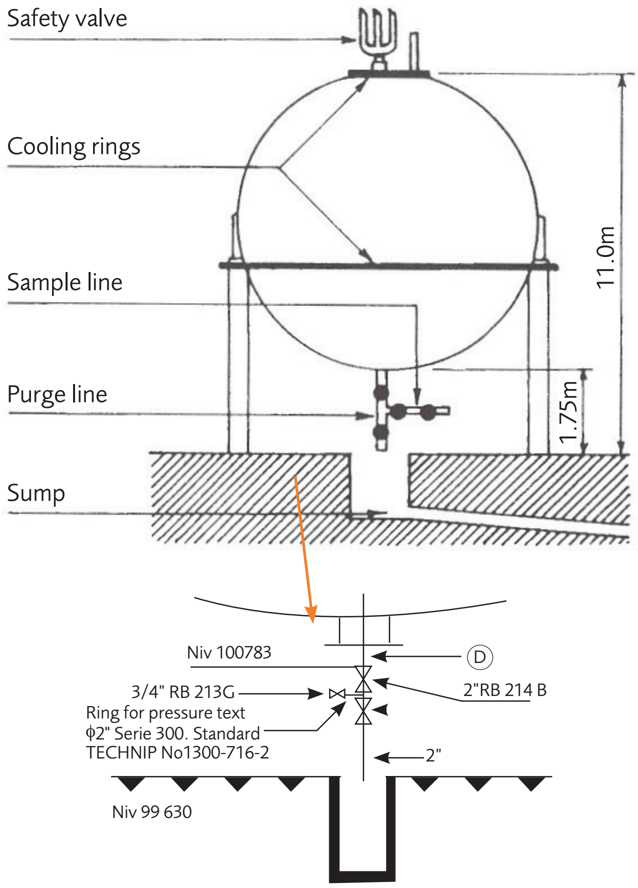

Figure 1 – Schematic representation of the purge valve configuration, Source – N° 1 - 04/01/1966 - FRANCE - 69 - FEYZIN

under control without ignition. These two incidents led to the operating procedure for sampling being drawn up which stipulated that the upper valve should be opened quarter-way and then the lower valve should be progressively opened, but never fully.

At 6:40 a.m., the operator opened two valves in series on the bottom of the sphere in order to drain off an aqueous layer. Firstly, he opened the lower valve half-way, then the upper valve even further. This was the reverse sequence to that laid down in a recently issued operating procedure.

When this operation was nearly complete, he closed the

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upper valve and then cracked it open again. There was no flow and he fully opened this valve. The blockage, which was presumably a hydrate or an ice plug, suddenly cleared, and propane gushed out, but the operator was unable to close the upper valve because it had frozen. He did not think at once to close the lower valve and by the time he attempted this, this valve had also frozen open. The leaking propane splashed up from the drain and frost burnt the operator on the face and forearm.

The alarm was raised and steps were taken to stop traffic on the nearby motorway. According to witnesses, a propane vapour cloud, spread towards the road. It is believed that a car about 160m away on a small road adjacent to the motorway may have been the source of ignition. It was later found that its engine was not running but its ignition was on and it may have stalled by taking in a propane rich mixture into the air intake. Flames appeared to flash back from the car to the sphere in a series of jumps.

At around 7:15 a.m. the sphere was enveloped in a fierce fire. Its pressure relief valve lifted at 7.45 a.m. and the escaping vapour ignited. Following the ignition at the pressure relief valve the firefighters stopped spraying the sphere, as they considered the opening of the valve as positive and assumed that the tank would burn itself out over a period of the next two to three hours. They then concentrated instead on cooling the other spheres. At around 8.45 a.m. the sphere ruptured, killing the men nearby. A wave of liquid propane was flung over the compound wall and flying fragments cut off the legs of the next propane sphere, which toppled so that its relief valve began to emit liquid and then exploded. Further BLEVEs occurred at around 9.30 a.m.

Eighteen people (eleven firefighters, two refinery employees, three subcontractor workers, one employee from the neighbouring company who came to help and the driver of the car that entered into the cloud) were killed because of the accident, and another 84 were injured. The explosion and subsequent fires caused the destruction of five of the spheres, two horizontal cylindrical tanks and four floating roof jet fuel and gasoline tanks, as well as other damage. The accident affected 1475 homes and other constructions off-site.

BLEVE

Boiling Liquid Expanding Vapour Explosions are a particular hazard where flammable substances are stored in pressure vessels. A BLEVE generally occurs when such a pressure vessel is exposed to fire, and the metal loses strength and ruptures (this is often below the maximum design pressure of the vessel). Particularly vulnerable are those parts of the vessel only in contact with the vapour phase as the bulk liquid absorbs some of the thermal energy.

The essential features of a BLEVE are:

- the vessel fails;
- flash-off of vapour from the super-heated liquid;
- combustion of the vapour.

A BLEVE usually generates missiles, which may be fragments created in the course of the rupture, but also the shell of the vessel itself. The mechanical energy released is high at the moment of bursting and this can lead to the vessel rocketing.

Burnt out storage spheres, Feyzin. Courtesy of Collection Bibliothèque municipale de Lyon, Fonds Georges Vermard, P0702 B02 07 618 00001

Large missiles may be projected several hundred metres. The resulting flash-off and combustion is experienced as a fire-ball with a short but intense release of thermal energy.

BLEVEs are not only experienced with storage vessels such as spheres and cylindrical tanks (bullets), but also in transportation tanks (road tankers and rail tank cars) as well as gas bottles. Unfortunately, even today, many accidents involving a BLEVE lead to fatalities and serious injuries amongst fire-fighters and emergency responders.

Causes

The primary cause of the propane leak was the operational failure by the plant operator; this was made easier by the difficult access to the valves and the lack of permanent valve spanners. It is likely that a solid plug of ice or propane hydrate stopped the draw-off line above the upper valve. This plug released when the upper valve was fully opened. The discharge from the drain line was directed downwards in the immediate vicinity of and under the valves, instead of to the side. This caused frost burns suffered by the operator and formed the cloud, which made the recovery and re-positioning of the valve lever impossible.

Lessons learned

- Where possible, the direct draining of aqueous liquid from LPG vessels should be avoided on systems that have to be regularly operated and, in particular, where large volumes of LPG at high pressure could accidently be released. If it is not practical to install a closed draining system then consideration should be given to the use of a de-watering pot, which may be positively isolated from the main vessel during the draining operation.

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- **Design considerations:**
  - Fit a remotely controlled emergency isolation valve in the drain line.
  - Install flammable gas detectors to provide early warning of a leak.
  - Provide deluge systems with sufficient water supply to flood the surface of the storage vessels. These systems must be regularly maintained and tested.
  - Slope the ground so that any spillage runs off to a collection pit and does not accumulate under storage vessels.
  - Insulate vessels with a fire resistant insulation, such as vermiculite or mound the vessels with sand or similar.
  - The legs of spheres should be protected against fire and impact with missiles.
- **Operating considerations:**
  - Management and supervisors must ensure that operators apply the correct operating procedures. This involves regular training and observation of work practices.
  - Consideration must be given to the work conditions for hazardous operations. This should include access, lighting, and availability of tools, as well as effectivity of intended operating procedure.
- **Emergency response**
  At facilities handling LPG or similar products firefighters must be trained in the correct approach to dealing with a storage vessel engulfed by fire. The time to BLEVE is difficult to assess and depends on a number of factors, which are not readily determined in an emergency. The principles to be applied are to cool the affected tank, cool installations in the vicinity and ensure that emergency responders (and their vehicles) are kept at a safe distance as far as possible.

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Incident

Seveso – 40 years on

Mark Hailwood, LUBW, Germany

Saturday 10 July 1976 was a day that changed the face of chemical process safety in Europe and linked a small northern Italian town with a European Directive and with a particular chemical molecule.

Introduction

The ICMESA factory in Meda, near Milan was founded in 1946 as a part subsidiary of the Swiss Givaudan SA of Geneva for the production of synthetic fragrances. In 1963, F.Hoffmann-La Roche AG bought Givaudan SA and two years later Givaudan became the majority shareholder of ICMESA, going on to buy up the remaining shares. By this time, in 1969, the production of trichlorophenol had begun at the ICMESA factory. Trichlorophenol was an intermediate in the production of hexachlorophene, a disinfectant used in the medicinal soaps of the Roche group.

1,2,4,5-tetrachlorobenzene was reacted with sodium hydroxide to give 2,4,5-trichlorophenol (TCP). This was a two stage process yielding 2,4,5 sodium trichlorophenate and NaCl after the first stage, which was then acidulated with HCl to obtain the final product. A side reaction, which occurs in particular at elevated temperature is the condensation to 2,3,7,8-tetrachlorodioxine (TCDD) (*see Figure 1*).

Two modifications were made by ICMESA to the original Givaudan process. Firstly the concentration of NaOH was increased from 17.5% to 31.6%, and secondly the xylene was distilled off before acidification. The results of these modifications increased the contact time between NaOH and the ethylene glycol.

The chemical process

A 10,000 litre reactor with a steam heating coil system, which could also be used to circulate emergency cooling water, was used for the batch process. The reactants were heated using ethylene glycol as the solvent and the addition of xylene to facilitate the removal of water through an azeotropic distillation. The ingredients were heated at ca.150 °C until no further water was formed. The temperature was then slowly increased to ca.170 °C to remove xylene, and ethylene glycol was subsequently removed under vacuum. Following the removal of ethylene glycol the reaction was quenched by the addition of a large excess of cold water. A schematic representation is shown in Figure 2.

The safety philosophy followed by the operator was careful control of temperature with the goal of preventing the formation of TCDD. The main protection device for the reactor was a bursting disc set at 3.8 bar, which was designed to provide protection during the initial stages of the reaction. The ethylene glycol removal could be protected through the addition of excess water which would cool the reaction.

The accident

On the day of the accident, the reaction was shut down with only 15 percent of the solvent removed. This was a direct violation of the operating procedures, which stipulated that either no solvent should be removed or that the removal should be completed and the reaction quenched before the reactor was shut down. The shutdown occurred at the end of the shift on the Saturday morning at 6.a.m., which was the end of work as the ICMESA plant was not operating over the weekend.

With the shutdown, the reactor was no longer stirred or heated (or actively cooled) and it was left to its own devices with its temperature at 158°C. Some six and a half hours later the bursting disc ruptured, releasing the contents of the reactor to the atmosphere. The aerosol cloud that escaped contaminated an area of about 1800 ha., encompassing four municipalities of the Lombardy region namely the townships of Seveso, Meda, Cesano Maderno and Desio.

At around 1 pm the deputy head of production was informed of the incident through a telephone call by a foreman. The deputy head of production then arrived ten minutes later, and having inspected the area immediately surrounding the plant noticed nothing out of the ordinary. At 7 pm he instructed the factory porter to contact the local public health officer for Seveso and Meda. The public health officer was however absent and it was not possible to identify his deputy. The incident was then reported to the carabineri at 8 pm. It was not until after 4 pm on the Sunday that representatives of ICMESA met the mayor of Seveso and an hour later the mayor of Meda to warn the population not to touch or eat the local fruit and vegetables. Only on the evening of 15 July, five days later, the

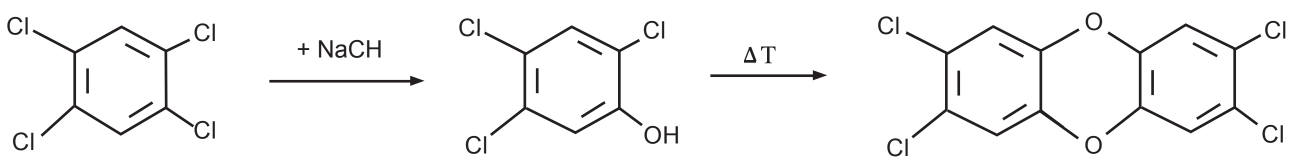

Figure 1 – Reaction of tetrachlorobenzine to produce TCP with side reaction leading to TCDD

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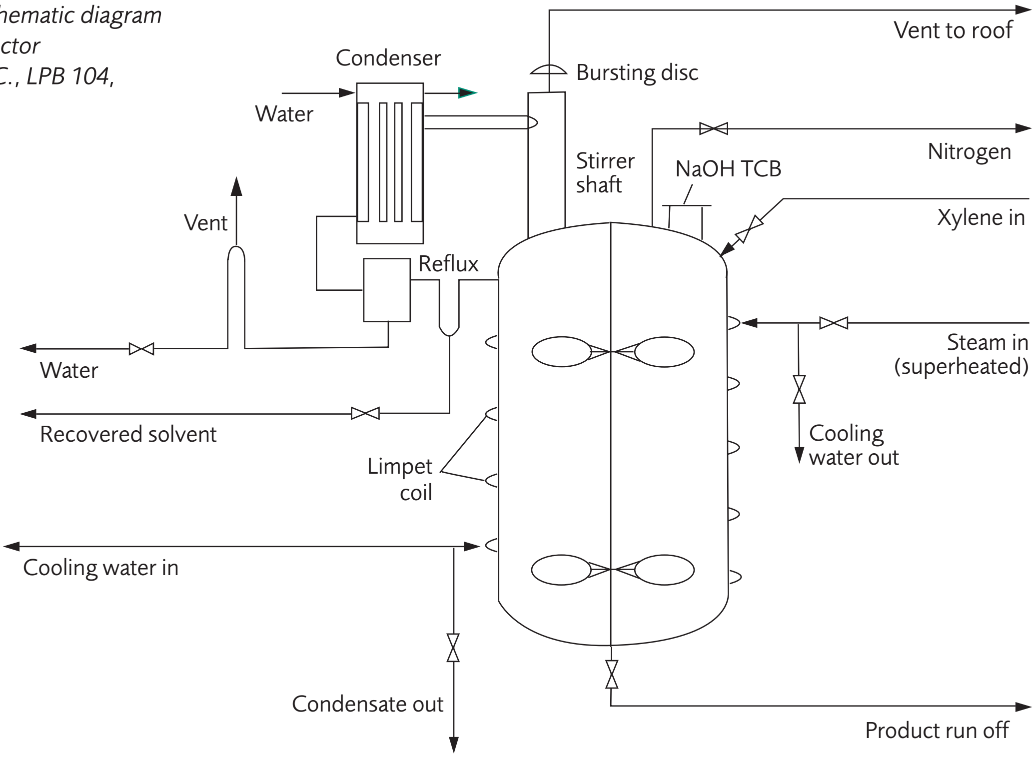
Figure 2 – Schematic diagram of Seveso reactor (Marshall, V.C., LPB 104, April 1992)



mayors of Meda and of Seveso designated a danger zone and prohibited the consumption of fruit and vegetables from this zone. By Wednesday 21 July it had become clear that parts of the neighbouring communities of Cesano Maderno and Desio were also contaminated and that the levels of TCDD detected were relatively high.

Experts from the companies Coalite (GB), BASF (DE), Philips-Duphar (NL), Chemie-Linz (A) and Dow Chemicals (USA), which had all had dioxin accidents, all recommended evacuation of the population. The first evacuation started on Monday 26 July and involved 208 people from 37 houses (Zone A) (*Figure 3*). Eventually Zone A (Concentrations > 50µg TCDD /m²) was extended and affected 736 people who were all evacuated. Zone B (5-50 µg/m²) included 4,700 people and Zone R (0-5 µg/m²) 31,800 people. Zone B was not evacuated. Over a period of several years buildings were demolished or decontaminated and as far as possible the land returned to agricultural and horticultural use. The most heavily contaminated area, Zone A, was decontaminated in April 1984 and a park laid out by the Region of Lombardy.

Causes of the accident

One of the significant causes of the accident, the initiation of the exothermic reaction, was for some time a puzzle. Initiation of the exotherm occurs at 220°C; however, the last known temperature of the reactor before the operations were shut down was 185°C, which is sufficiently below the onset temperature. In 1981 Theofanous published a paper in which the radiated heat from the reactor walls and its effect on a thin top layer of the reaction mixture was considered. From the technical detail available the reactor was only charged to just over a third (1.25 m height) and the heating was with superheated and not saturated steam. That meant that the upper two-thirds of the reactor initially had a temperature of ca.300°C. Experimental evidence indicated that, without stirring, the radiation from the vessel walls was able to elevate the temperature of a thin surface layer to 220–230°C. This would provide sufficient energy to initiate the exothermic reaction. This mechanism was not understood at the time of the accident. The production instructions did however stipulate that the reaction should be left in a form which would not have been as sensitive to this radiated heat.

Within the Italian prosecution documents it was claimed that

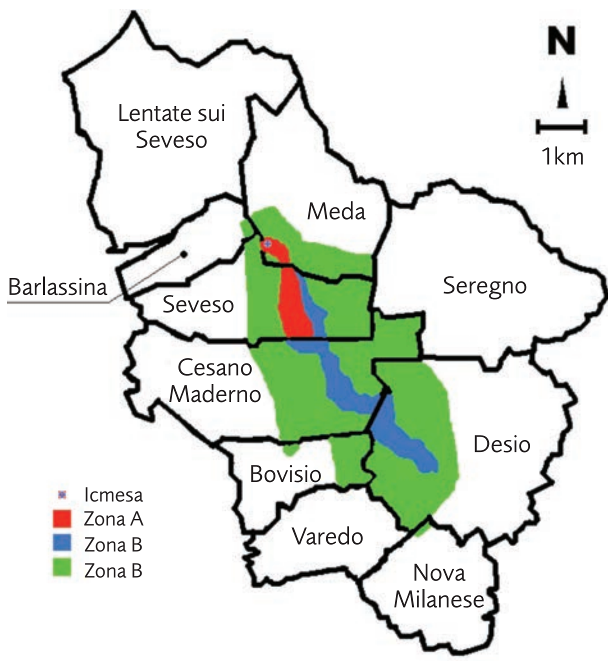


Figure 3 – Contamination zones (it.wikipedia.org, public domain)

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the reactor had never before been left in this unusual state. The claim was undisputed. However had appropriate consideration been given to the knowledge and understanding of the workforce (including the management and supervisors) and possible deviations from normal operation, then the possibility that the process was stopped part way was realistic.

Readers need to be aware that in 1976 concepts of "safety culture" and "human factors" were not well developed in the chemical process industries — in fact, in numerous industrial operations today, these issues present a considerable challenge.

Lessons learned from the Seveso accident

1) It is important that operators of facilities handling hazardous chemicals understand the thermodynamics of the reactions carried out. This includes side reactions and decompositions which may take place under plausible deviations from the intended reaction procedure.
2) Operating personnel must adhere to standard operating procedures. Production planning should be designed so that operations can be concluded safely within the available time-frame. Supervisors and management personnel should make themselves aware of the real operating practices and take appropriate action to ensure that training is carried out and expectations are communicated effectively. The safety management system should be devised to provide an appropriate structure to ensure that safe operation is a reality.
3) Batch reactors should as far as possible be provided with pressure relief systems that exhaust to containment systems to prevent either a release to the working environment or to the external environment. Modern blow-down systems exist which use tanks, bags or other forms of suppression.
4) In the event of a loss of containment event the alarm and emergency plan should be activated immediately and the internal and external communication channels provided with all of the relevant data and information to enable the correct response decisions to be taken. The operating company should draw up such plans well in advance and communicate them to the local authorities and coordinate them with external emergency responders. Regular exercises should be conducted. These should also cover the transmission of information through the various communication channels so as to ensure that information is provided, and that it is understood and acted upon appropriately. Operating companies cannot assume that they will be communicating with experts in the field of chemistry or toxicology; therefore the messages must be timely, clear in their interpretation as well as in the necessary measures to be adopted.
5) External emergency responders need to develop emergency response plans in advance and to train their implementation, including the communication channels. Should an emergency occur, then coordination and liaison with the law enforcement agency should take place to ensure that access to vital information and expertise is not inhibited through legal proceedings. As far as possible information on the appropriate measures to be taken in an emergency should be made available to the public in the area which could possibly be affected by a major accident. This information should be designed so that it can be readily understood and is likely to be read and implemented in an emergency.

Many of these lessons have become parts of the requirements of the so called Seveso Directives which are implemented within the Member States of the European Union and the European Economic Area. Other countries such as Australia and New Zealand have also adopted similar regulations. However regulations alone do not guarantee that accidents will not occur. It is necessary that the industrial operators are conscious of their responsibilities and that the public authorities carry out effective enforcement. For jurisdictions without effective chemical accident prevention, preparedness and response programmes there is a need to consider the risks posed in carrying out chemical operations without a robust framework. Guidance for establishing such programmes has been developed by the United Nations Environment Programme as well as the OECD and the EU.

Further events with loss of control of exothermic chemical reactions

Unfortunately, history has shown that the loss of control of exothermic chemical reactions still leads to major accidents. Within this selection it is clear that the lessons listed above have not been learned throughout the chemical processing community. Particularly vulnerable are toll manufacturers, which manufacture but do not always have the background in the chemistry, reaction kinetics or chemical engineering. Indeed some of this information might not be supplied by the customer under claims of commercial secrecy. Toll manufacturers often produce a range of chemicals for a number of different customers utilising a variety of reactions and processes, but with a limited set of equipment. Typically these are batch or semi-batch reactions together with mixing, blending, solvation, distillation, filtering and drying. Small-scale operations usually do not have access to process safety specialists in the same way as larger operations. Thus the available resources for carrying out risk assessments or executing management of changes processes, if at all available, may be so thinly spread that they are ineffective.

The following section documents briefly a few examples of exothermic runaway reactions.

22 February 1993 Hoechst, Frankfurt-Griesheim, Germany

A release occurred of almost 10 tonnes of ortho-nitroanisol from the pressure relief valve of a reactor, leading to a sticky, yellow precipitation (of ca. 1 t) over an area of 1.2 km length and 300m width. A residential area for 1000 people and allotments were affected. About 40 individuals received medical treatment for breathing difficulties and, skin and eye irritation. Initially the company's communication referred to a safety data sheet with a classification as "harmful" – in German "mindergiftig", which translates as "not really toxic". The company did however have data available which suggested that o-nitroanisol should be classified as a possible carcinogen. The public health authorities stated on the day of the incident that due to the low concentration, no acute health risks arose from the chemicals released. This did little to calm public fears, particularly as the workers carrying out the extensive decontamination work were

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wearing protective suits and face masks. An epidemiological study over 30 years is still on-going, however the public health authorities have come to the opinion that no instances of chronic, asthmatic or neuro-dermatitis cases can be attributed to the incident.

The cause of the exothermic release was that the reactor was charged with two reactants. However in violation of the instructions, stirring did not take place during the addition and therefore the expected exothermic reaction (for which cooling was foreseen) did not start. Because the reaction was not initiated the operator had heated the reactant being added. Some two hours after charging the reactor and not having achieved the reaction, the stirrer was started and a spontaneous exothermic reaction occurred.

19 December 2007, T2 Laboratories Inc., Florida, USA

On 19 December 2007, four people were killed and 13 others were transported to the hospital when an explosion occurred at T2 Laboratories Inc. during the production of a gasoline additive called methylcyclopentadienyl manganese tricarbonyl.

The CSB determined insufficient cooling to be the only credible cause for this incident, which is consistent with witness statements that the process operator reported a cooling problem shortly before the explosion. The T2 cooling water system lacked design redundancy, making it susceptible to single-point failures. Interviews with employees indicated that T2 ran cooling system components to failure and did not perform preventive maintenance.

22 April 2012, Mitsui Chemical, Iwakuni-Ohtake Works, Japan

An explosion and fire at the resorcinol production facility led to one death and 21 injured, two of which seriously.

Due to problems with the steam supply system during the night before the accident, all plants using steam were ordered to be shut down. This "emergency shut down" triggered the interlock system switching the air supply to nitrogen and cooling water to emergency cooling water; agitation continued. About 70 minutes later it was determined that the temperature in the resorcinol oxidation reactor had not dropped, therefore the interlock was released and cooling returned to circulating water. With the release of the interlock the nitrogen supply was stopped and agitation ceased. The upper liquid phase of the reactor did not have a cooling coil and decomposition heat from the organic peroxide could not be removed, resulting in a gradual rise in temperature. In the lower liquid phase the temperature continued to fall. One and a half hours after the interlock had been deactivated the decomposition of the organic peroxide accelerated, the temperature rose and gas was generated. The pressure relief valve was activated, however pressure continued to rise. Five minutes later the reactor burst leading to the fire and explosion.

01 December 2014, Pirna, Germany

A serious explosion in a chemical factory caused the death of one person and seriously injured four others. Debris was strewn over the surrounding area. The reactor which exploded was producing the first, larger scale batch of a flame retardant for textiles. The investigations are still ongoing. However, there are indications that modifications to the originally intended production process may have been made.

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Incident

Chernobyl – 30 years on

Fiona Macleod

On Saturday 26 April 1986 the citizens of Pripyat were outside enjoying the hot weather — in the school playground, planting out the garden, fishing in the river, sunbathing in the park, completely oblivious to the plume of radioisotopes drifting towards them from the nearby Chernobyl nuclear power plant.

After Saturday lessons finished, a few enterprising children cycled up to the overpass to get a better look at all the excitement a mile away. Across the lake — an artificially created cooling pond for the power plant — they watched fire engines, planes, helicopters, and truckloads of soldiers. In the evening people came out onto their balconies to marvel.

> *"I can still see the bright crimson glow...We didn't know that death could be so beautiful".*[1]

At 01.23, earlier the same day, No 4 reactor had exploded during a safety test that went horribly wrong. A series of explosions led to the rupture of the containment and fifty tonnes[3] of nuclear fuel were ejected from the core of the reactor, hurling uranium dioxide, iodine, caesium, strontium, plutonium and neptunium radioisotopes into the air — orders of magnitude greater than the radioactive release after the bomb dropped on Hiroshima. And the fires were still burning, yet no one had alerted the population or evacuated the town that lay only one mile away.

Before his suicide on the second anniversary of the accident, one of the expert investigators, Valery Legasov, wrote:

> *"... the (Chernobyl) accident was the inevitable apotheosis of the economic system ... in the USSR ... Neglect by the scientific management and the designers ... When one considers the chain of events ... it is impossible to find a single culprit, a single initiator of events, because it was like a closed circle."* [2]

So was this accident unique to the nuclear industry of former Soviet Union at the height of the Cold War? Or are there wider lessons to be learned?

Too much haste, too little speed

Picture the scene: a meeting between a project team and the sponsors. The Chairman opens the meeting.

> *"Give us an update on progress."*

The project manager rolls out a plan and begins his presentation on the critical path for completion. After two minutes, he is interrupted.

> *"When will you start up?"*
> *"No earlier than August."*
> *"That is unacceptable. The deadline for start-up is May."*

The project manager bites his tongue. He is not going to remind the steering group that the original project plan showed start-up in December, that a May deadline was imposed by someone in a remote office without any conception of what needed to be done. Instead, he shrugs his shoulders and spreads his hands.

> *"Some equipment will only be delivered in May."*

The Chairman slams a fist on the table.

> *"Then make sure it is delivered earlier!"*

He turns to the boss of the project manager.

> *"Your project team has failed again."*

The project manager is side-lined and new blood is brought into the team.

The plant starts up in December.

That was the gist of an exchange in the Kremlin in 1986, discussing another nuclear plant project, reported by Grigori Medvedev[3] because it was so unusual for a chief of construction to challenge unrealistic deadlines in front of ministers. After his dressing down, the project manager was reported to mutter:

> *"We lie and teach others to lie. No good will come of this."*

Such an exchange could never happen today in the board room of a multinational chemical company. Senior leaders may not know the fine detail of every complex project, but they always hire, trust and empower people who do.

Or do they?

Start up first, test later

Chernobyl Reactor 4 started up before the end of 1983 in order to meet a deadline for energy production targets. Because some of the commissioning tests were bypassed, a worrying problem emerged. How to run the main water circulation pumps in the event of a loss of power.

Active cooling is required in nuclear reactors, running or idle, to remove the heat generated by radioactive decay. In the event of a reactor shutdown, back up diesel generators were designed to start up automatically in order to provide power to the instruments and main water circulation pumps, however they took over 60 seconds to reach full speed. Too long for the core to be without cooling.

[1] *Nadezhda Vygovskaya quoted in Voices from Chernobyl*

[2] *Testament - Valery Legasov, leader of the Soviet delegation to the IAEA Post-Accident Review Meeting*

[3] *G. Medvedev Chernobyl Notebook*

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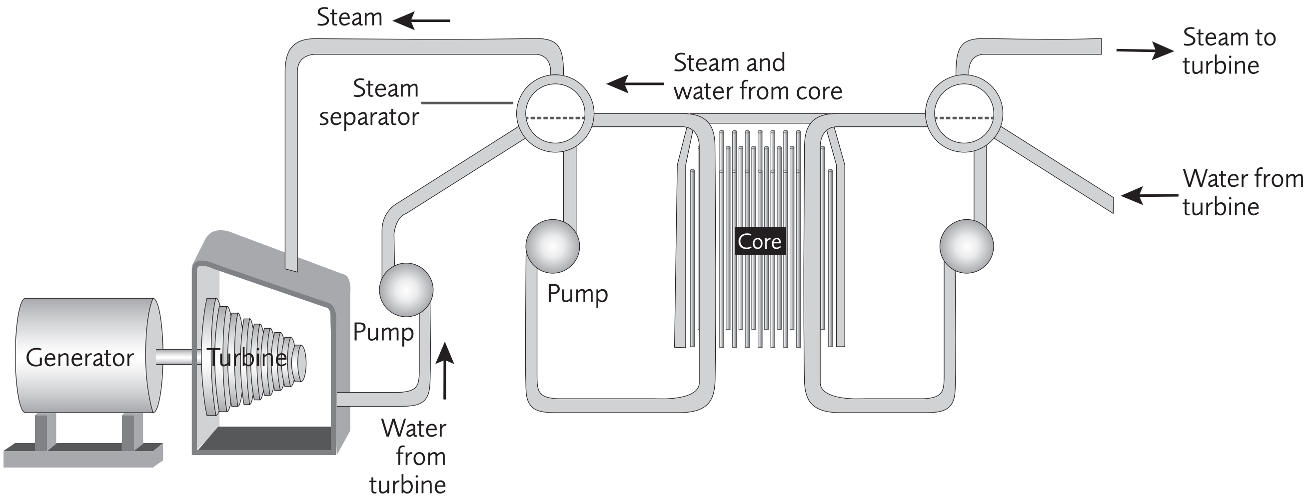

It was suggested that the steam turbines, which would continue to spin after a reactor shutdown, might generate enough electrical power as they were coasting down to run the main water circulation pumps while the back-up diesel generators were winding up, elegantly bridging the power gap.

Previous tests had proved unsuccessful, but a fourth test was scheduled for 25 April 1986, in advance of a planned shutdown on Reactor 4.

Opinions are divided on the risk of running such an experiment on a nuclear power plant. However the additional measures that the plant management took in order to make the experiment "pure"[3] added the most extraordinary risks.

The emergency cooling system was disabled: the pump fuses removed and the valves chained and padlocked shut. This seems to have been due to a belief that there was a danger of heat shock if cold water was allowed to rush into the hot core of the reactor, despite the fact that this was a fundamental part of the design.

The test was to be carried out live. Instead of shutting down the reactor and measuring the electrical energy generated by the coasting steam turbine, the plan was to keep the reactor operational so the test could be repeated if necessary.

Most of the reactor emergency shutdown systems were disabled. In part this was to allow the test to be repeated if it failed the first time.

These extraordinary violations, the removal of the very back-up systems on which the safety of the plant depended, were planned and documented and sent to the government regulator in January 1986, well in advance of the test[3]. The plant management took the lack of reply as tacit approval to proceed. It became clear after the accident that nobody who understood the operation of a nuclear reactor had reviewed or understood the planned tests.

According to the expert investigator, Valery Legasov[2], the test was

> *"like airplane pilots experimenting with the engines in flight"*

But even with these fundamental systems overridden, the test might just have proceeded without incident, had it not been delayed from day shift to night shift.

Before looking at what else went wrong, it is worth taking a moment to understand the fundamental design flaws of the RBMK nuclear reactor.

The difficult we do right away, the impossible takes a little longer

The experts recommended a pressurised water reactor design (VVER) for the Chernobyl complex. The VVER design was said to be superior — intrinsically safer with lower emissions than the boiling water graphite moderated reactor (RBMK). See Table 1 for a comparison of the two technologies.

The technology chosen by the expert design team was rejected. Why? Was it just a question of cost? Rouble per kilowatt? Bang for Buck? It appears not.

By 1965 it was clear that mass production of the VVER reactor would be difficult. Only one factory, the Izhora works in Leningrad, had the necessary technical expertise to manufacture such large and complex pressure vessels. On the other hand the inferior RBMK could largely be constructed on site with local suppliers of concrete and piping. Even the graphite blocks could be transported and assembled from modules.

> *"Soviet scientists, engineers and planners did not take decisions of such magnitude lightly (but)...instead of choosing technically outstanding designs...they chose designs they thought would meet ambitious plan targets for nuclear power generation"*[4]

In the end, one overriding factor trumped all the others. How fast could the nuclear energy program be implemented?

The decision was made. The council of ministers approved the RBMK, declaring it the safest and most economical. An aspiration rather than a fact.

"*No matter, we will adopt it...The operators have to work it out so that ...* (the RBMK design) *is cleaner and safer than the Novovoronezh* (VVER) *design*." (Reference 3).

Such an impossible task — take an inferior design which can be built faster and magically remove the flaws — would never be given to the design engineers in a modern chemical company.

Or would it?

[4] *Producing Power: The Pre-Chernobyl History of the Soviet Nuclear Industry by Sonja D. Schmid*

engineering and design

systems and procedures

culture

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Technology[5]	VVER	RBMK
	Pressurised water reactor	Graphite moderated water cooled reactor
	Novovoronezh Водо-водяной энергетический реактор	Reaktor Bolshoy Moshchnosti Kanalniy Реактор Большой Мощности Канальный
Emissions	100 curies/day	4,000 curies/day
Turbine driven by	Steam from Secondary circuit – primary water is pressurised to remain liquid in core and exchanges heat with water in secondary circuit which boils to drive turbine	Steam from Primary circuit – water boils in core and drives turbine
Moderator	Water	Solid Graphite
Coolant	Water	Water
Loss of coolant	Intrinsically Safer - The neutron moderation effect of the water diminishes, reducing reaction intensity	Unstable - The neutron moderation by graphite continues, no loss of reaction intensity leading to overheating
Void coefficient of reactivity[5]	Negative (good)	Positive (bad)
Fuel	Enriched Uranium dioxide	Enriched Uranium dioxide
Refuelling	Full shutdown required	On-line. Multiple independent fuel channels.
Containment	Steel pressure vessel	Leak-tight (explosion prone) concrete box with bubbler pool underneath
Other	Design favoured outside USSR	Originally designed to provide Plutonium for military use
Construction	Construction in specialised fabrication shop. High quality factory based steel forging	Modular. Assembly on site. Graphite, cement and piping
Capital Cost Rouble/ kW Power output	190-210[6]	250-270[6] (actual) 190[7] (aspirational)

Table 1: Comparison of VVER and RBMK designs

RBMK design flaws

Design flaw 1 – positive void coefficient of reactivity

In a nuclear chain reaction, a neutron collides with a nucleus, splitting it to release heat and more neutrons (nuclear fission). The neutrons must be slowed down (moderated) to increase the probability of the next fission and sustain the chain reaction. Extra neutrons must be removed (absorbed) to prevent a runaway reaction and core meltdown. The power of the reactor is controlled by inserting and withdrawing control rods containing a neutron absorber, in this case boron.

In the RBMK design, the moderator and coolant are of different materials. Water is a more efficient coolant and a more effective neutron absorber than steam (see Table 2) Excess steam reduces the cooling of the reactor, but the graphite moderator allows the nuclear chain reaction to continue. As steam bubbles (voids) form, the reactor power increases, releasing more heat and more steam and so power continues to increase in a vicious spiral. This is known as a positive void coefficient of reactivity.

In the VVER design where the water circuit is both moderator and coolant, excess steam generation reduces the slowing of neutrons necessary to sustain the nuclear chain reaction. More steam means lower reactor power, less heat and less steam, returning the reactor to stability. This is known as a negative void coefficient of reactivity.

[5] *http://users.owt.com/smsrpm/Chernobyl/RBMKvsLWR.html*
[6] *The Economics of Nuclear Power in the Soviet Union. William J. Kelly, Hugh L. Shaffer and J. Kenneth Thompson, Soviet Studies. Vol. 34, No. 1 (Jan., 1982), pp. 43-68*
[7] *Semenov*

	Neutron scattering Cross-section (σs) in barns Moderates speed of neutron, Promotes fission	Neutron absorption cross-section (σc) in barns Stops fission	Moderating Ratio[8] (Slowing down power vs Macroscopic absorbtion cross section)
Water (H_2O)	~100	0.66	70
Graphite (C)	4.8	0.004	170
Boron 10	~0	3800	~0

Table 2: Properties of water, graphite and Boron 10

Design flaw 2 – Control rods

The designers of the RBMK understood the first design flaw. A supervisory control system continuously calculated and displayed the operating reactivity margin (ORM). The secondary safety systems were beefed up — a minimum number of control rods were to remain in the core at all times, the AZ-5 emergency button which inserted further control rods in 20 seconds and independent emergency cooling.

But there was another problem with the RMBK design that was less well known, a design flaw that was first noticed in December 1983 during the commissioning of Ignalina Unit 1 (Lithuania was then part of the USSR). As the control rods descended into the core, the operators observed a surge in the power. The tip of the control rod was made of graphite. As the control rod descended it displaced water, so instead of

[8] *Nuclear Power Generation: Incorporating Modern Power System Practice edited by P.B. Myerscough*

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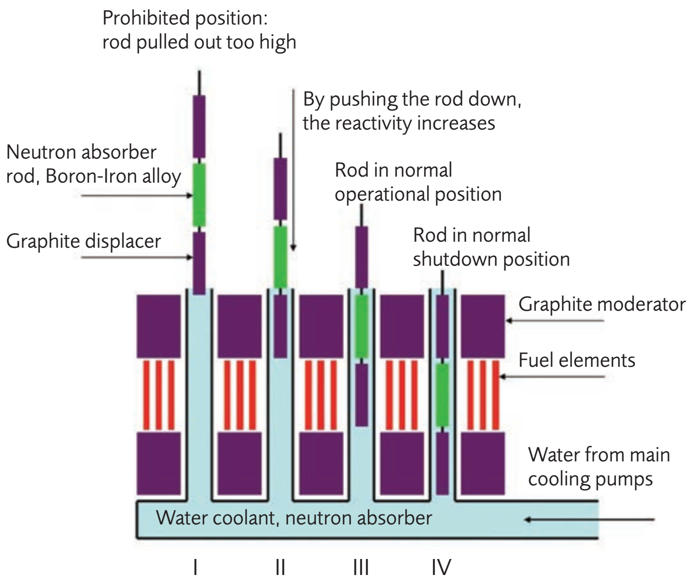

Diagram from http://consumedland.com/page_06_en.html

reducing the power of the reactor, the power increased.

In 1983 in Ignalina Unit 1, the reactor was stable; the cooling water was flowing and the automatic control was regulating. The temperature and pressure did not soar, the channels did not warp, the control rods did not get stuck and over 20 seconds the graphite tip continued to descend beyond the core allowing the boron section of the control rods to slip into place and stop the nuclear reaction.

But in 1986 in Chernobyl the reactor was unstable; the incoming night shift had allowed the power to drop to a dangerously low level and the primary water circuit was surging uncontrollably. The reactor operator attempted to stabilise the reactor manually. When his supervisor realised that control had been lost, he hit the emergency AZ-5 button. The control rods started to fall. The entry of the graphite tip of the control rod into an already unstable reactor was the final straw.

The first explosion happened seconds later.

Не пили сук, на котором сидишь – Don't saw through the bough you're sitting on

Plant Manager Bryukhanov (a turbine specialist) and Chief Engineer Formin (an electrical engineer) had approved the unsafe-safety test. It appears that their interest in assessing the electrical power from a coasting turbine had blinded them to the dangers of operating of a nuclear reactor with safety systems disabled. Formin had only recently returned to work after major spinal surgery as a result of a serious car accident and was reported to be distracted and in constant pain (Reference 3).

The unsafe-safety test was ready to start at 14:00 on 25 Friday April 1986. Over the previous twelve hours, the reactor power had been slowly reduced. At the last minute, the controller of the electricity grid refused to allow the plant to reduce power further due to a generation problem elsewhere. All the senior managers went home and the reactor remained at 50% power for another nine hours. At 23:10 the electrical grid controller called to say that the supply/demand balance was back to normal.

At midnight, the new shift took over.

Although there are many alternative versions, the description of events that follows is largely as described by Grigori Medvedev's book (Reference 3) and dramatised in an excellent BBC documentary[9].

Deputy chief engineer Anatoly Dyatalov, a physicist by training, came with them. According to colleagues, he was a difficult man to get along with and had little respect for his subordinates.

Yuri Tregub from the previous shift remained on site, handing over to shift supervisor Aleksandr Akimov and reactor operator, Leonid Tuptunov (26 years old and 3 years out of college). All had the necessary training in nuclear reactors, but were repeatedly overruled and threatened by their superior, Dyatalov.

The reactor was not designed to run at low power, and the operator overshot the test target, the reactor power plummeting to 30MW thermal at 00.28. Akimov and Toptunov wanted to abort the test but were overridden by Dyatalov who forced them to continue, threatening to have Tregub take over.

Toptunov began to withdraw the control rods as instructed, and was able to raise the power to 200 MW thermal at around 1:00 am.

With only a few control rods in the core, the reactor's capacity for excursion now exceeded the ability of the remaining safety systems to shut it down (Reference 3).

At 01:19 alarms showed that the water level was too low. Toptunov tried to increase the water flow manually, by now all eight recirculation pumps were running, but with small temperature changes causing large power fluctuations the reactor was increasingly unstable.

By 01:21, the caps on the fuel channels were reported to be jumping in their sockets. The control room printout of core reactivity showed the excess reactivity required immediate shutdown — the warning was ignored and the test initiated.

At 01:23:04 the experiment began by closing the steam to the turbine. As the momentum of the turbine generator decreased, so did the power it produced for the pumps. The water flow rate decreased, leading to increased formation of steam voids (bubbles) in the core.

The reactor power increased. Toptunov reported a power excursion to Akimov.

At 01:23:40 Akimov decided to ignore Dyatalov and abort the test. He pressed the AZ-5 emergency button to insert the control rods and shut down the reactor.

As the graphite tips descended, the rate of fission increased, the reactor power surged. The control rods stopped one third of the way down. In desperation, Akimov disconnected the motor clutches in the hope that the rods would descend into the core under their own weight, but the rods did not move. The intense heat had ruptured the fuel channels. The rising pressure from the excess steam broke every one of the pressure tubes.

The first explosion at 01:23:44 ruptured the reactor vessel,

[9] *BBC Drama Documentary "Surviving Disaster" (https://www.youtube.com/watch?v=njTQaUCk4KY)*

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lifted the 1000 tonne upper reactor shielding slab and rotated it by about 90°. This was followed by a second, more powerful explosion. Lumps of fuel and graphite were ejected from the core catching fire as they hit the air.

Thirty one people died as a direct result of the accident: reactor operators, fire fighters and emergency responders. One man died immediately, killed by the explosion and forever buried in the rubble, one of a heart attack, the others suffered unimaginable pain as they succumbed to acute radiation exposure over the following days and weeks.

The total number of causal deaths (premature deaths due to radiation exposure) and injury is hotly contested and will not be covered here.[10]

The blame game

A first report[11] into the accident blamed the night shift operators.

> *"...the primary cause of the accident was the extremely improbable combination of rule infringement ... (intentional disabling of the emergency protection equipment) ... plus the operational routine allowed by the power station staff."*

Many disagreed.

> *"In the process of operating nuclear power plants... (operators)...have to make a large number of independent and responsible decisions... Unfortunately you will never have instructions and regulations that envisage the entire diversity of every possible combination of states and maladjustments."* (G. Medvedev Reference 3)

> *"The operator activated...the reactor emergency shutdown system...but...(it)...thrust the reactor into a prompt critical state."* (Minenergo expert Gennaddi Shasharin as reported in Reference 4)

And even if his actions had contributed to the accident.

> *"Human error can never be fully eliminated, even among highly qualified specialists. If one operator's mistake could lead to a reactor explosion... then nuclear power should be abandoned."* (Reference 4)

A later report into the accident[12] took account of the design flaws and misguided planning of the test and absolved the hapless operators Toptunov and Akimov who, through acts of extraordinary selflessness and bravery, helped to prevent the disaster spreading and paid with their lives.

So what of the designers? They knew about the flaws. Were they responsible?

> *"Complex technological systems usually have innumerable problems ... We all operate and use imperfect systems on a daily basis. We know about flaws and how to work around them... but it does require knowledgeable, skilled operators who understand how to compensate for the flaw, know their limitations and are committed to safety above everything else, including plant targets, bonuses and yes, orders."* (Reference 4)

Mushroom management: Keep 'em in the dark...

Accidents in Soviet nuclear power plants were kept secret from the public in the USSR. Worse, they were kept secret from the designers, engineers and operators of nuclear power plants.

Even the widely publicised details of the Three Mile Island Accident in the USA on 28 March 1979 (core melt after loss of cooling water to the reactor) were not made available to scientists and engineers inside the former Soviet Union (Reference 3).

If the management and operators of the plant had known about the power surge in Igualina and the partial core meltdowns in other RBMK units, would they have allowed the unsafe-safety test to proceed?

We will never know.

The people of Pripyat were not evacuated on the morning of Saturday 26 April because senior managers could not believe what had happened. Eye witness accounts of an exposed, burning core were ridiculed. Dosimeters that read off-scale for radioactivity were declared faulty. The nuclear power complex had been producing energy for ten years without a major offsite incident. It was all perfectly safe.

The evacuation of Pripyat took place on Sunday 27 April. On Monday 28 April 1986, after radiation levels set off alarms at the Forsmark Nuclear Power Plant in Sweden, hundreds of miles from the Chernobyl Plant, the Soviet Union finally admitted publicly that a serious accident had occurred[13].

But could such secrecy happen now?

Over my working life, I have seen a shift away from sharing process safety stories, not only outside but also inside companies. The short term fear of litigation outweighs the moral duty of disclosure. Company lawyers are increasingly forbidding technical staff to share detailed information, even internally. While most major accidents involving fatalities are independently investigated (what went wrong) sharing near misses (what nearly went wrong) is every bit as important.

As chemical plants become safer, do we forget just how dangerous they can be? Are we sometimes guilty of a willing suspension of disbelief when things are going well? Do we listen to those willing to speak truth to power?

"A leader who ... doesn't welcome bad news will get told everything is ok even when it isn't... We need leaders who can live with a chronic sense of unease and who can spot the warning signs of complacency creeping in." Judith Hackett[14]

If the Chernobyl accident reminds us of nothing else, it is the danger of complacency.

Conclusion

The 1986 Chernobyl accident has lessons that extend beyond the nuclear industry and the former Soviet Union. These lessons are directly applicable to today's international chemical industry.

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[10] *http://www.unscear.org/docs/reports/2008/11-80076_Report_2008_Annex_D.pdf*
[11] *IAEA Report INSAG-A 1986*
[12] *IAEA Report INSAG-7 1993*
[13] *Wikipedia Accessed 29th Jan 2016 (wikipedia.org/wiki/Chernobyl_disaster#Announcement_and_evacuation)*
[14] *http://www.hse.gov.uk/aboutus/speeches/transcripts/hackitt221013.htm*

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- artificially imposed deadlines lead to shortcuts;
- simplified targets in complex environments will lead to perverse incentives and unintended consequences;
- real experts tell leaders things they don't want to hear;
- good leaders listen;
- you don't get safety by rules and regulation, it starts with the design and evolves with experience;
- good design is iterative — it takes time, expertise and feedback;
- things happen differently on night shift;
- whatever the designers intended, sooner or later the operator will do something unimaginable — often on night shift;
- sharing process safety information means sharing what went right (near misses) as well as what went wrong (accidents);
- sharing process safety stories widely and acting on the lessons they teach us is the way we shore up our defences faster than the changes can overwhelm us;
- management of change, and a sense of chronic unease, stops only when the field is green again.

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Incident

The Sandoz warehouse fire – 30 years on

Ivan Vince, ASK Consultants, UK

Incident summary

On 28 October 1986, an official fire inspection was carried out on a chemical warehouse on the Sandoz site in Schweizerhalle, Basel, Switzerland. The warehouse contained bulk quantities of a number of powerfully toxic and ecotoxic substances, including over 800 tonnes of organophosphorus insecticides and, of even more concern, 11 tonnes of water soluble mercurial fungicides. The inspection deemed everything to be in order.

A fire broke out shortly after midnight on 1 November.

The official investigation by the Zurich City Police Science Department[1] concluded that the fire was probably caused by operator error using a blowtorch for shrink wrapping paper sacks of the oxidising agent Prussian blue (Iron(III) hexacyanoferrate(II)). Paper impregnated with Prussian blue is capable of smouldering undetected for several hours, without visible flame or smoke, before a sudden outbreak and rapid spread of open fire.

The speed with which the fire advanced through the warehouse overwhelmed attempts to extinguish it with foam.

Following a fatal fire (initiated by a shrink wrapping blowtorch) a programme of large-scale trials by the UK Health and Safety Laboratory has shown that a wide range of flammable dusts stored in pallet stacks or on racks is likely to present severe fire risks with rapid escalation[2].

Firefighting appliances, including tugs on the adjacent Rhine, eventually used over 10,000 m^3 of water at up to an estimated 24,000 litres per minute. The site drainage could not cope with these quantities and flow rates, and so most of the run-off entered the Rhine.

Due apparently to confusion among the Swiss authorities, the international alarm system for Rhine accidents was only activated after a delay of nearly 24 hours.

Short-term consequences of the incident

The incident was one of Western Europe's worst environmental disasters. Contaminated firefighting water killed nearly all aquatic life for a significant distance downstream – dead eels were found up to 200 km from the incident. Significant pollution was detected all the way to the North Sea. The environmental impact was in places aggravated by delays in transmission of the alarm. The contamination of the Ijssel River and Holland's northern waterways probably could have been avoided if the Dutch authorities had been given an additional twenty-four hours in which to respond to the crisis[3]. Recovery, though more rapid and complete than initially predicted, took several years.

In their enthusiasm, the firefighting tugs also inadvertently spread the contamination around a large area of land, to a depth of up to 14 metres, thus potentially impacting the groundwater. Much drinking water downstream was derived from the river, so impacted communities had to rely on tankers for up to three weeks after the incident. A considerable number of livestock drinking from the river died.

Firefighters and others exposed to smoke from the fire suffered acute health effects of varying severity – mainly respiratory, eye irritation and nausea. No long-term effects were recorded.

Decontamination involved a workforce of over 200 and took nearly three months. Thousands of tonnes of contaminated material were removed from the site and surroundings, including the river bed. Direct costs arising from the incident totalled approximately €90 million, including €27 million paid in compensation to government authorities, fishing organisations and private individuals.

Lessons learned

Building standards for chemical warehouses should be reviewed with regard to fire resistance, prevention of flammable vapour accumulation, and ease and safety of firefighting operations.

Hazardous substances should be segregated into appropriately sized compartments, with due regard for fire risks. Following the incident, Sandoz voluntarily reduced its inventories of the most hazardous substances, eliminating altogether the storage of mercury compounds.

The magnitude and nature of fire risks in the bulk storage of hazardous chemicals need to be understood by workers and communicated to the emergency services.

Provision needs to be made through the use of ditches, dykes, embankments and sloping terrain – tertiary containment – to prevent firefighting water leaving the site. The design of tertiary containment should be based on realistic worst-case water application rates and quantities.

Fire and explosion hazard management (FEHM) at hazardous installations should be formally planned, beginning with a scenario based analysis and a comparison of consequence reduction measures – including controlled burn-down.

Transmission of warnings downstream following a pollution incident needs to be timely and effective. Following the incident, the Rhine Warning and Alarm Plan[4] was improved by the development and validation (using chemical tracers) of a computer model to predict in three dimensions the progress of pollutant waves.

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Legacy

The Seveso Directive was amended (Council Directive 88/610/EEC, 24 November 1988) to strengthen requirements for the storage of hazardous substances, in particular, to bring isolated storage into the scope of the Directive (i.e. storage not associated with an industrial operation).

Seveso II (96/82/EC, 9 December 1996) had an increased emphasis on environmental protection, including consideration of transboundary effects. While resisting pressure following the accident to accede to the Directive, Switzerland (which is not a member of the EU) did in 1991 adopt regulations to control risks, including risks to the environment, from major accidents[5].

According to the International Commission for the Protection of the Rhine (ICPR), *"The Sandoz accident became a turning point for environment and water protection in the Rhine catchment"*. In 1987, environment ministers of the seven countries bordering the Rhine adopted the three-phase Rhine Action Programme, coordinated by the ICPR, with ambitious targets including the halving of inputs of dangerous substances by 1995 and the return of salmon by 2000.

The UNECE Convention on the Transboundary Effects of Industrial Accidents 1992, which came into force in 2000, obliges the contracting parties to prevent as far as possible accidents with transboundary effects, to reduce their frequency and severity, and to mitigate their residual risks. It promotes active international cooperation between the parties before, during and after an industrial accident.

Postscript

In 1987, the Sherwin-Williams warehouse in Dayton, Ohio, USA, containing over 5.5 million litres of paint and paint-related products, caught fire and the installed sprinkler systems and fire wall were quickly overwhelmed. The warehouse was situated over an aquifer that provided drinking water to approximately one-third of the local population of 400,000.

The warehouse was allowed to burn down. The decision was taken following early consultation among company representatives, fire responders, air and water pollution experts and public officials. The consensus was that the risk of contaminating the underlying aquifer with firewater run-off far outweighed that associated with the smoke plume if the fire was allowed to continue with minimal intervention. Only as much water was applied to manage the burn-down safely as could be retained on site[6].

Unfortunately, the lessons from Sandoz, fresh in the minds of the Dayton responders (the incident report appended a summary of the Sandoz disaster), seem to have been forgotten a few years later. The fire at Allied Colloids (Bradford, UK) in 1992 resulted in considerable environmental damage to the local Aire and Calder rivers, largely due to firefighting activities. The incident highlighted a number of shortcomings both in technical/safety precautions and FEHM measures including management of firefighting run-off[7]. In fairness, these errors were largely made prior to the incident; the fire service had no option but to fight the fire, which threatened nearby warehousing and very large storage tanks of highly flammable liquids.

Following the December 2005 explosion and fire at the Buncefield UK oil terminal, which led to contamination of groundwater despite the provision of considerable tertiary containment, the investigation report recommended that controlled burn down should be considered in the site specific planning of firewater management, together with bund design factors such as firewater removal pipework[8].

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Incident

The Challenger Space Shuttle disaster

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Summary

The space shuttle Challenger disintegrated 73 seconds after launch on 28 January 1986 killing all seven astronauts aboard. An O-ring seal in the right solid rocket booster (SRB) failed at lift off causing a breach in the SRB joint seal. This let pressurised hot gas escape and ignite, affecting nearby SRB attachment hardware and an external fuel tank leading to structural failure. NASA management knew the design of the SRB had a potentially catastrophic flaw in the O-rings but did not address this effectively. They also appeared to have disregarded warnings from engineers and not to have passed on their technical concerns.

Keywords: Production pressure, culture, risk assessment, design, hindsight bias

This review is based on:

- the original (brief) LPB coverage[1] in a wider review of communication failures;
- the original US Presidential Commission's report of the investigation (the Rogers report)[2];
- the US Congress Committee on Science and Technology's review[3] of the Roger's report and NASA's own investigation;
- the seminal account by Diane Vaughan (published in 1997 but recently republished as an enlarged 2016 edition — the only change is a new foreword on Columbia)[4]; and
- the subsequent Columbia Accident Investigation Board's (CAIB) report of the 2003 Columbia space shuttle disaster[5].

In considering the disaster on this 30th anniversary, the author has aimed to stand back from the later Columbia accident. Since 2003 Challenger is mostly seen and studied through the lens of Columbia (as an example of an organisational learning failure) but it is worth looking at what was known before this so that the original accident is seen more clearly. Even though the CAIB report acknowledges this risk explicitly, there is inevitably a risk of hindsight bias and selectivity in such post-Columbia accounts of Challenger. Therefore, the focus here is more on Vaughan's original and exhaustive account of Challenger alone.

Like Andrew Hopkins (of 'Lessons from Longford' fame) Vaughan is a sociologist, appropriate enough for the socio-technical systems involved both in space travel and in the process industries. Explaining major accidents of any kind requires both engineering / technical expertise as well as an understanding of how organisations (as social structures) and people work. This sociological input produces better learning from such events and improves the chances of avoiding future disasters. This paper summarises the accident, its technical and immediate causes and the contributing organisational factors. Clear lessons emerge for the process industries. One of the big enemies of learning from accidents is a defensive 'checklist' approach e.g. 'we don't have that equipment, that process, that goal – so this doesn't apply to us'. This approach screens out potential learning opportunities. It is much better to say 'OK, this doesn't look like a direct correlation, but what can we learn?' This turns learning into a potentially much more productive process rather than a checklist approach.

The accident

Challenger launched at 11.38 a.m. EST on 28 January. It disintegrated 73 seconds into the first two minute ascent stage killing all seven astronauts on board. They included the well-publicised presence of Christa McAuliffe, a teacher due to teach elementary pupils from space. Rather like the Space Lab today, the shuttle launches were then seen as sufficiently routine to allow such diversity.

The technical explanation for the disaster is relatively straightforward. There were two Solid-propellant Rocket Boosters (SRBs) attached to the space shuttle. The Solid Rocket Motor (SRM) was contained within the four main central segments of the assembled SRB. The SRBs provided 80% of the thrust required at lift-off to get the whole shuttle assembly off the ground and into space. The shuttle itself initially consisted of the orbiter vehicle, the external fuel tank and the SRBs. The solid fuel in the SRBs was reacted to produce very hot high-pressure gas which expanded and accelerated on moving through the rear nozzle to provide thrust. The SRBs were jettisoned two minutes into the ascent and were later recovered and reused. The use of solid fuel was a well-recognised solution to provide the necessary extra thrust required to get the shuttle off the ground and into space. It was also a relatively cheap choice. The third attachment to the shuttle for lift-off was the external liquid fuel tank consisting of a hydrogen tank, an oxygen tank and an inter-tank which fed the three main shuttle rocket engines with a hydrogen-oxygen mix. The external fuel tank was jettisoned once the shuttle had escaped the earth's atmosphere and was not recoverable.

The SRBs were prefabricated by Morton Thiokol (the contractor who designed, manufactured and maintained the SRBs) from seven original sections into four cylindrical segments each with factory-sealed joints. Propellant was poured into each segment where it solidified. The four segments were assembled after transport to the Kennedy Space Centre and so the remaining joints were known as 'field'

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joints. The pressure generated at lift-off ignition created a very small gap in the SRB joints. The O-rings were designed to seal these gaps against the high pressure hot propellant gases developing inside. The seal was achieved by using quarter-inch diameter Viton rubber-like O-rings. There were two of these, the primary and secondary O-rings, the secondary acting as a back-up in case any of the hot propellant gases generated on ignition should erode and pass the primary.

The air temperature at the launch was the lowest recorded for any previous shuttle lift-off. This hardened the O-rings and adversely affected their ability to achieve an effective seal. On the previous coldest launch in January 1985, a primary joint was breached and eroded but the secondary seal worked as intended. For low temperature to impact on the seated seals fully required about three days' exposure — a relatively rare event. On Challenger's launch in January 1986, the hot combustion gases produced on ignition inside the SRM on the right-hand SRB were able to erode and then 'blow by' both the primary and secondary O-rings on the aft field joint. Cameras captured the resulting smoke puffs at the joint showing that the grease, joint insulation and O-ring material were being burned and eroded by the hot propellant gases.The escaping gases ignited and the ensuing flame started to damage the adjacent SRB aft field joint attachment hardware and then was deflected onto the external fuel tank. The hydrogen tank located aft within the external fuel tank either failed or was weakened and the liquid fuel inside subsequently leaked and started burning. The original flames by this time had also caused the SRB lower strut connecting it to the external fuel tank to break. The SRB then rotated away and the external fuel tank itself failed leading to a major release of hydrogen and a subsequent fireball (not an explosion)[4[p39]]. The shuttle was also by then breaking up mechanically in the normal atmospheric turbulence associated with the launch because the external fuel tank was a key structural part (the 'backbone') of the whole shuttle assembly.

Lessons learned

The lessons are listed here but the detail which underpins the organisational causes is discussed further below.

Lessons for the process industries

- External pressures on organisations, such as the production pressures on NASA, can establish ways of doing things in the organisational culture, structure and processes which incrementally align reality with what the organisation wishes for — its goals. Managing these pressures and being mindful of their potential distorting effects is difficult and requires vigilance over time and a proper sense of chronic unease.
- To prevent such pressures distorting an organisation's arrangements it is important to establish a clear baseline or rationale for e.g. engineering and technical decisions, so that any incremental movement away from this can be spotted.
- Incremental changes can lead to the normalisation process so that each individual anomaly is explained or justified but the full picture is not seen until after a significant adverse event. Each event is rationalised and validated against e.g. risk assessment processes but not evaluated ("Is this really doing what we want? Against what baseline?")
- Risk assessment should not be about maintaining or defending the status quo — the process should not take over from the purpose. A questioning attitude and mind-set is required. There is always the possibility that something new is happening which designers could not foresee.
- Organisations need sufficient checks and balances for safety to ensure that safety is not over-ridden by organisational structures and processes. These can include: sufficiently independent and resourced safety oversight and an adequate baseline for key arrangements such as engineering and design decisions. If key decision makers cannot see the baseline (or if the baseline is wrong) they cannot easily spot significant deviations from it, especially when these are incremental.
- Whether a new design is developed or an old one used or modified, there are risks to be managed. New designs bring in more potential for 'Unknown unknowns'. In the case of the SRBs, the existing designs (such as the Titan rockets) were not a straight 'read across' to the space shuttle, and introduced misunderstandings about redundancy.

Lessons for investigators

- If the full underlying causes (organisational and some extra-organisational) are not understood and learned from, and the organisation's structure and arrangements changed and maintained accordingly, then accidents can and will repeat.
- Just relying on the official investigation reports for major accidents can be misleading and incomplete. Even with good investigations and reports, what the press and others choose to focus on is not necessarily the full picture, and nor is a company digest or flyer. Companies need to think for themselves and exercise judgement about the full range of lessons learned and consider the full picture presented. This implies that they know what good looks like for an investigation and what the underlying organisational factors may be.
- Learning is a process and not just an outcome. Organisations can learn something from most incidents if they view learning in this way. Using a screening out or defensive checklist approach will inhibit learning.
- The hindsight bias can warp investigator judgements and skew the lessons drawn from accidents like Challenger. Investigators need to establish the full baseline against which key decisions and actions occurred. The history of O-ring anomalies and how to interpret them may look obvious after the Challenger failure but was not obvious to those involved at the time. Based on what they knew or was available to them they acted rationally and in line with the prevailing safety processes.
- Investigations which produce stereotypes (heroes or villains in whatever guise, such as 'management') are good stories but unlikely to change anything or produce real learning. People generally behave in ways that make sense to them at the time. The first job in an investigation is to understand things from their viewpoint.
- The full impact of human factor issues on issues such as critical communication arrangements (like those affecting

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the final teleconferences) and fatigue can be missed if investigators either do not prioritise human factors or do not value them sufficiently. These factors can be major contributors to poor decision-making.

The organisational causes

The underlying causes of the disaster are complex and organisational. These are discussed below.

Launch delays

The launch was put back five times from the original 22 January date before the disastrous launch on 28 January. The shuttle before this was delayed seven times over 25 days before finally launching on 12 January. This affected the subsequent Challenger launch. The last two delays were due to weather and a fault respectively. Delays were a major concern for NASA because the launch schedule had become central in their competition for scarce funding. Production pressures were at their peak before the Challenger launch.

The O-rings and the launch decision

The problem with the O-rings was documented from 1977, long before the first shuttle flight in 1981. Evidence accumulated from 1977 to 1985. During a final teleconference running up to around midnight of the day before the launch, engineers from Morton Thiokol, the SRB manufacturer, and NASA managers debated whether the launch should go ahead because of the predicted very low temperatures expected and the likely effect on the O-rings. As the Commission, the Committee, the press and others investigated "*...they created a documentary record that became the basis for the historically accepted explanation of this historic event; production pressures and managerial wrongdoing.*" [4[pxxxiv]] The Rogers Commission "*...found that NASA middle managers had routinely violated safety rules requiring information about the O-ring problems be passed up the launch decision chain to top technical decision makers...*" [ibid[pxxxiv]] The top-down pressures on NASA included competition, scarce resources and production pressures. These led finally to a flawed and deliberate launch decision.

Vaughan's very thorough investigation provides a more nuanced view, and ultimately a more convincing one. Her conclusions also make more sense in the light of the subsequent Columbia disaster. Rather than the simplistic popular account derived from the Rogers Commission and the Committee's reports, she argues that "*No extraordinary actions by individuals explain what happened: no intentional managerial wrongdoing, no rule violations, no conspiracy. The cause of the disaster was a mistake embedded in the banality of organisational life and facilitated by an environment of scarcity and competition, elite bargaining, uncertain technology, incrementalism, patterns of information, routinisation, organisational and interorganisational structures, and a complex culture.*" [ibid [pxxxvi]]

The normalisation of deviance

Vaughan divides this into three elements: the production of culture; the culture of production; and structural secrecy. The gradual and incremental acceptance of the O-ring anomalies was the 'produced culture'; the scarcity of resourcing and the demands of competition over a long period conspired to establish a culture of production; structural secrecy prevented key information from flowing effectively through the organisation. All of these elements affected decision-making including the final fatal launch decision.

- **Accepting more risk**

  The normalisation of deviance helps explain:
  - why the evidence of risk in the SRBs was originally accepted in the selected design;
  - why it was assessed as safe when the shuttle was declared operational in 1984;
  - why it continued to be assessed as safe; and
  - why the final launch took place despite some key engineers having and expressing misgivings.

  More risk was accepted incrementally over a long period. The risk was seen as acceptable (and accepted) and anomalies were explained for each case after launch and recovery. Each successful launch reinforced this. Those involved in decisions on the SRB and the launch acted and made decisions that made sense to them (was normal) at each relevant time. Morton Thiokol, Marshall (The Marshall Space Flight Center (MSFC), NASA's rocketry and spacecraft propulsion research centre, who had technical oversight of Morton) and others followed the NASA rules, arrangements and structures for the twin key safety management system procedures — the Acceptable Risk Process (ARP) and the Flight Readiness Review (FRR). There were compounding errors e.g. flawed base data on O-ring temperature limits, no effective demonstration of the correlation of temperature data against O-ring previous failures and in communications such as on the understanding of O-ring redundancy between Marshall and Morton and the way that the O-ring risk was categorised.

- **Redundancy misunderstood**

  The baseline for the redundancy misunderstanding was that the SRB seal design was seen as a significant improvement over previous designs such as the earlier US Titan rocket which only had a primary seal. Failure of a primary was not seen as so significant when a secondary was in place to protect against this. The problem arises through dependency such as the cold temperature issue. In the process sector nowadays, the triggering of any safety or protectives system – such as a pressure relief valve – is a safety event in itself. In the latter case, maintenance could be a common cause factor affecting both operational and safety valves.

  NASA processes, procedures and structures incrementally accommodated the O-ring anomalies to align with the overall goal — of timely and repeated successful shuttle launches and recoveries. These weak signals were seen but were expected and on a case-by-case basis accepted — engineers did risk assessments and communicated the results to managers. The latter were also mostly engineers but with different goals and priorities set by the culture of production. Hindsight does not show so clearly that the context for tuning in to weak signals was against a much wider range of anomalies detected after each launch.

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- **Structural secrecy**
  A large organisation generating huge amounts of information, specialised engineering roles and language, the acceptance of risk on a case-by-case basis against established (but flawed) technical criteria and in accord with established risk processes — all of these conspired to prevent key technical information from flowing through the management chain. No individual was hiding anything but the organisation's own structure was acting as a barrier.
- **Oversight**
  The final barrier should have been the safety oversight but NASA's safety programme was famously described as 'silent'. In fact, this was drastically reduced and especially after the shuttle programme entered its operational phase. Internal regulation was also subject to the effects of interdependence, i.e. being part of the same organisation the internal bodies were regulating. The external regulator was even smaller and had a narrow scope. These bodies had in truth little chance of finding the O-ring issue and not least because it was seen and maintained as an acceptable risk.

Design and culture

Design is an inherently uncertain process, the more so in areas of risky technology such as innovative space missions. However, designers in any industry make trade-offs all the time and also are conservative — adopting the solid fuel option for the SRBs was conservative at the time because it was a better tried and tested approach. The fact that there were known risks associated with this was in that sense good because they were 'Known knowns' and could in principle be managed. New designs would potentially have 'Unknown unknowns'. For the SRBs and the shuttle as whole such 'Unknown unknowns' were bound to emerge in such a risky area of technology but NASA generally expected these and was vigilant for them.

There is also the well-rooted view that the transition from an experimental space vehicle to an operational one was somehow also deviant. In terms of the overall space shuttle programme, this was simply an in-built project milestone and the criteria for passing this were met. Hindsight suggests this was a flawed decision and that such an inherently risk enterprise could never be truly seen as operational. Therefore, the original programme could perhaps be criticised but in that context, the decision was rational. In its own terms the mission was a success story. NASA have also been accused of being too 'can do' but if that is reworded as 'being good at solving problems' then it doesn't sound so damming, and problem-solving is what NASA engineers, managers and others were very good at. Culture and control were also eroded by the need to be business-like and put work out to contract. However, the latter was not 'wrong' in itself. Provided that safety, quality and sufficient technical oversight were maintained, this can and did work. The larger problem was that of the ensuing organisational and project complexity — complex organisations can produce surprises, and tightly-coupled systems such as those involved in space flight are particularly prone to this.

Cost cutting and mission safety

One widely-held view of key contributing causes to the accident were NASA cost / safety trade-offs, prompted by budget cuts and other pressures on the organisation. These decisions are held to have adversely affected safety programmes, hardware testing and technical design. Vaughan found it difficult to find concrete evidence that the first two affected mission safety but she investigated the extensive paper trail for the third. The example she chose was the original award of the SRB contract to Morton Thiokol and the consequent decision to not pursue a proposed safety feature, escape rockets. Her conclusion is that despite their apparent salience in hindsight "*...these were not the cost / safety trade-offs they appeared to be after the tragedy.*"[4[p423]]

The SRBs were a cheaper option. Rockets using solid fuel have fewer moving parts and so are cheaper to use than liquid fuelled ones even though solid fuel is more expensive. However, solid fuel rockets could not be shut down after ignition which had major implications for mission safety. Previous rockets had escape rockets to allow crews to escape during the dangerous first two minutes of SRB-assisted ascent. Orbiter was too large for this option without significantly reducing its payload so the proposed escape rockets were scrapped.

On the face of it, this looked like a pure cost or business decision that compromised safety but in fact NASA had done an extensive assessment of the option and concluded that escape rockets were simply not viable. Any trigger event that could provide warning that escape was necessary would in effect be the event itself or closely co-incident with it. There was also no practical means identified which would both cover all scenarios during the first two-minute ascent and also significantly increase crew survivability.[4[p424]] NASA concluded that instead "*...that first stage ascent must be assured*. [ibid] In other words they just needed to get this stage right — for example, through conservative design and other tried and tested means. All design involves trade-offs of course, but this example just became more visible than most after the disaster.

The same argument is made in the choice of a segmented over a seamless design for the SRB. Straightforwardly, if a design with no joints is selected, then joints cannot fail — and a joint failed so. But NASA had had the four contract bids and proposals assessed by a source Evaluation Board (SEB) against four 'mission suitability' criteria. There were three segmented designs and one seamless / monolithic one proposed by Lockheed.

However, Vaughan points out that segmented SRBs were more widely used at the time so the bid ratio looks understandable in this 'social context'. [4[p430]] Her closer examination of the SEB assessment also shows that the Lockheed seamless design was rejected not just because it was more expensive than Thiokol's but because the design was inadequate in ways that were significant and not easily correctable. The Thiokol design had issues but these were assessed as 'readily correctable' and the segmented design itself as 'not sacrificing performance quality'. This was confirmed by a subsequent further Governmental Accounting Office (GAO) review after a Lockheed protest that the costs were miscalculated. The GAO agreed a reduction in the original $122 million cost estimates for Lockheed (but did not find any new issue with the Thiokol design) but this was still $56 million more than Thiokol's. The original SEB bid assessment was repeated and found still valid.

Vaughan acknowledges that her analysis of the cost / safety trade-offs is necessarily incomplete even for the SRB contract example despite her painstaking research and analysis. However she concludes that "*...what I found did not affirm either decision [escape rocket scrapping and contract award] as an example of organisational misconduct and amoral calculation on the part of NASA senior administrators.*" [4[p431]] She also strikingly states that *"Production pressures became institutionalised [in NASA] and thus a taken-for-granted aspect of the worldview that all participants brought to NASA decision-making venues."* [4[pxxxvi]]

The hindsight bias

Hindsight is tricky to recognise and deal with and after the hugely public failure of one of Challenger's segmented SRBs, the social context looked very different to observers — but all that had changed was that Challenger was lost. People are wired to find stories, to make sense out of events quickly (this is what Daniel Kahneman calls System 1 thinking[6]) — it is a highly automatic, quick and sometimes dirty process but it has evolutionary advantages. People also like stereotypical characters just as many stories have, so casting heroes and villains (even if labelled collectively as 'NASA Management') is intuitively appealing and inclined to stick in observers' and the public's imagination. The heavier-duty and very effortful System 2 thinking which takes time, energy, patience and application — as shown by Vaughan's epic study over nearly ten years — can really test the evidence, reconstruct the events and look more widely to make sure that the full context is understood. Typically, System 2 thinking comes into play when the world as we think we know it surprises us and System 1 has to look to it for help.

Despite the very unpleasant 'surprise' of a disaster like Challenger however, as Sidney Dekker makes very clear[7[p82]], the hindsight bias can lead investigators and others to be misled by System 2 and ask 'Why didn't people act (think, react, decide etc.) differently?' instead of 'Why did they act as they did?' — a subtle but very important difference. Those involved all acted rationally in the circumstances they found themselves in and with the knowledge, competence and so on that they then had. Only asking the second question will elicit the full context against which to judge causes and contributions, and from which to extract the full lessons. One of the big dangers of hindsight is in not establishing the baseline for what happened — the full landscape in which decisions were made and actions carried out. The O-ring anomalies needed to be seen against a background where anomalies were expected on each flight, and not just for the O-rings. The later Columbia investigators specifically address this issue: "*Rather than view the foam decision only in hindsight, the [CAIB] tried to see the foam incidents as NASA engineers and managers saw them as they made their decisions.*" [5Vol1: [p196]]

The investigation reports

The Congress report was produced by the Committee on Science and Technology (the Committee) in the US House of Representatives based on the Rogers' Commission investigation and report on the disaster, the NASA investigation, and on its own additional hearings and review. The Committee "*...which authorised the funds and reviewed the lengthy development process which led to the successful Shuttle program, has a responsibility to insure that the tragic accident, and those events that led up to it, are understood and assimilated into all levels and activities of NASA so that safe manned space flight can be resumed.*"[3p2] Clearly this either did not happen or it happened and then the improvements degraded over time. The Committee certainly did not miss

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the wider implications of the event at the time: "...*the lessons learned by the Challenger accident are universally applicable, not just for NASA but for governments, and for society*."[3p3]

Neither of the reports are that easy to read and it is difficult to cross-check between them or to find clear and succinct conclusions and recommendations. They are quite discursive e.g. though the use of direct extracts from the hearing testimonies. Although such direct testimony is quite powerful in places, it is not always easy to follow, and the sometimes adversarial nature of the questioning does not help clarity.

The Rogers Commission report itself is separate and the Committee states that it does not always agree with the Rogers' findings[3p4]. For example, the Committee did not agree that NASA middle managers violated rules but the Committee's report came later and did not receive the same level of publicity as the Rogers report.[4[p72]] The Committee also makes some further recommendations of its own to NASA as well as repeating the Rogers' recommendations. It is interesting to look back and see the Committee coming to some significantly different conclusions (and recommendations) to those in the Rogers report. The Committee saw this as their role and felt able to disagree with Rogers (and the report left some areas open for the Committee to conclude on). This is something that did not happen after the CAIB's report. All that said, the conclusions and recommendations make sense even if they ultimately did not prevent the Columbia accident (but may of course have prevented others unknown).

Following the Challenger investigation, when the CAIB investigated Columbia they set a new benchmark for clarity and completeness along with a thorough treatment of the organisational factors, but this is still rare. More recent accidents, such as Macondo, re-emphasise the difficulty of relying solely on official reports — Macondo has multiple reports and the US CSB report is imminent.

Human factors in the Rogers report

The 'Human Factors Analysis' carried out for the Rogers Commission is relegated to an appendix[4]. It is worth quoting the rationale in full: "*The Commission staff investigators reviewed the work schedules of NASA and contractor personnel involved in the launch processing of the Challenger at Kennedy and of the Marshall managers involved in the 27 January teleconference discussion of low temperature effects on the Solid Rocket Booster joint. The results of the review are presented herein. Although major accident investigations now include human factor analyses, the Commission avoided drawing specific conclusions regarding the effects of work schedules on work performance or management judgment. However, with the concurrence of NASA officials the Commission agreed that the results of the review should be included as an appendix to the Commission report. An evaluation by NASA of the consequences of work schedules should be conducted as part of its effort to reform its launch and operational procedures.*"[4]

Work scheduling, the lack of understanding of what is lost without face-to-face communication, the final teleconferences and other human factor aspects did not receive a sufficient weighting. What is lost in not having limited or unreliable face-to-face communication can be partly compensated for if understood and planned for. In simple terms key decisions were taken by people trying to communicate in a degraded situation (a teleconference or unreliable videoconferences rather than a full face-to-face meeting) and across time zones and after working long hours, sometimes repeatedly.

Final analysis

Vaughan's account of the Challenger disaster is the most complete and sets the background and baseline very thoroughly and widely — indeed the subsequent Columbia investigation draws heavily on it. Her final analysis is worth repeating here: "*No extraordinary actions by individuals explain what happened: no intentional managerial wrongdoing, no rule violations, no conspiracy. The cause of the disaster was a mistake embedded in the banality of organisational life and facilitated by an environment of scarcity and competition, elite bargaining, uncertain technology, incrementalism, patterns of information, routinisation, organisational and interorganisational structures, and a complex culture.*" [ibid [pxxxvi]]

The 2003 Columbia disaster is eerily signalled in Vaughan's book i.e. written before the book's publication in 1997. She notes that economic pressures were again increasing on NASA, and those at the top were largely not the same people who underwent the Challenger experience and aftermath. She warns that "History repeats, as economy and production are again priorities." [4[422]] These external influences again degraded the NASA culture and its organisation over time despite the lessons learned from Challenger. Even a high reliability organisation may struggle against such forces and weak signals may again be missed.

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Risk and safety management of ammonium nitrate fertilizers: keeping the memory of disasters alive

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This paper is aimed at keeping the memory of disasters alive, assuming that risk awareness and implementation of safety measures are facilitated by case histories. There have been several accidents and a few disasters in the ammonium nitrate fertilizer industry, and it is worthwhile to review these from time to time, beyond the regulation and practice changes which they triggered.

BASF plant, Oppau, 1921

On 21 September in 1921, two consecutive explosions occurred in a silo in the BASF plant in Oppau, Germany, creating a 20m deep, 90x125m large crater. The entire area was covered by dark green smoke and there were several additional fires and small explosions. At the time of the event 4500 tonnes of ammonium sulphate nitrate compound fertilizer (ASN) were stored in the silo. The explosion killed 507 people and injured 1917. The plant and approximately 700 houses nearby were destroyed[21].

The introduction of a new, spray drying process was one of the reasons for the explosion. This particular process modified some physical parameters of the ASN such as the density, the crystalline structure and humidity. Therefore the ASN, dried with the new process had fractions with higher ammonium nitrate (AN) content and this inhomogeneous mass was stored together with the ASN that was dried with the old process. Due to higher AN content, lower density, lower water content (reduction from 4% to 2% with the new technique) and changed crystalline structure, the accumulated fine fraction was explosive. In addition, the operational issue was that the storage in large quantity lead to caking. The anti-caking procedure at that time was to use dynamite! It was repeated over 20,000 times with no large explosion before that day. Similar risky procedures were at the origin of other accidents in Kriewald in Germany in 1921 (26 July)[25] and Tessenderlo in Belgium in 1942 (29 April)[26].

Texas City disaster, Texas, 1947

Another tragic accident, involving two ships loaded with thousands of tonnes of ammonium nitrate and sulphur, occurred on 16 April in 1947, on the ship SS Grandcamp docked in Texas City, Texas, USA[2]. In that event, 500 people died and 3500 people were injured, which was 25% of Texas City's population at the time. Also, serious damage was caused in the nearby refineries, ripping open pipes and tanks of flammable liquids and starting numerous fires. The blast

Figure 1: Oppau – The consequences of the explosion[1]

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occurred when a small fire, perhaps caused by a cigarette, broke out on the Grandcamp. There were two additional factors that worsened the situation of the first explosion. First of all, in the ensuing chaos, nobody payed attention to the ship docked about 200m away (SS High Flyer) which was also loaded with sulphur and thousands of tonnes of ammonium nitrate and exploded sixteen hours after the first explosion on the Grandcamp. The first explosion ignited the High Flyer. However attempts to release the ship from its moorings and thus reduce potential damage in the event of an explosion failed. The second factor that contributed to the high number of fatalities was the fact that large numbers of people were allowed to stay in the close vicinity of the fire and therefore could not escape from the subsequent explosion.

Another ship accident occurred in the French port Brest in 1947 (28 July) — an explosion occurred after a large fire, killing 26 people and injured 500[20].

AZF site, Toulouse, 2001

Exactly 80 years to the day after Oppau, a severe explosion occurred in a temporary storage for off-specification and downgraded ammonium nitrates at 10.17 a.m. on 21 September in 2001 at the AZF industrial site in Toulouse, France. The detonation, felt several kilometres away, corresponded to a magnitude of 3.4 on the Richter scale. A 7m deep crater (65x45m) was observed outside the plant and a large cloud of dust and red smoke drifted to the north-west. The accident resulted in 30 fatalities, with up to 10,000 people injured and 14,000 people receiving therapy for acute post-traumatic stress. The cost was estimated by insurers to be in the region of 1.5 billion Euro[3].

The direct causes of the explosion of the storage of roughly 400 tonnes of off-specification ammonium nitrate (AN used for technical and fertilizer grade) in the plant have still not been officially established. Investigators, representing the company and the legal authorities, have not yet agreed on the origins of the accident. An appeal has been made and the trial will be reopened in 2017. However, the final legal expert report concluded that the explosion occurred due to an accidental combination of sodium dichloro-isocyanurate and downgraded ammonium nitrate. The key controversial element is the ignition source of the stored AN. Investigations showed that its origin was neither a fire nor an initial explosion followed by the mass explosion[4].

Figure 2: The area affected by the explosion (Source: Archives Grande Paroisse[17])

Regardless of these uncertainties, the following important findings could be recognised[5]:

- The safety report of the AZF factory did not take into account the off-specification and downgraded ammonium nitrate waste storage since it was not regulated (no Seveso classification). Their higher sensitivity was not recognised, and their waste status did not help.
- Although the explosion risk of AN was known, fire risk was considered more probable in open storage operations, and as the reference scenario by the industry. The safety report did not describe each possible accident scenario.
- Urbanisation had spread out considerably near the site since the launching of the chemical activities after World War One. At the time of the accident, the chemical site was surrounded by business parks, hospitals, and dwellings[6].
- Twenty-five subcontracting companies worked continuously on the site. Three different subcontracting companies worked in the warehouse (the downgraded AN was picked up, unloaded and removed by them) and another subcontractor carried out the maintenance of this warehouse. The legal expert assumption is that the waste of some chlorinated compounds manufactured in the other part of the plant was inadvertently mixed with other AN waste and poured on the AN waste storage.
- The storage building involved in the accident did not have nitrogen oxide detectors although other facilities were equipped with such sensors around the facility.

West Fertilizer Company, West, 2013

More than 60 years after the Texas City disaster, a significant explosion of fertilizers shook the inhabitants of Texas again. On the evening of 17 April 2013, a fire of undetermined origin broke out at the West Fertilizer Company in West, Texas, USA. After their arrival, firefighters started to fight the fire when a detonation occurred. Although the firefighters were aware of the hazard from the tanks of anhydrous ammonia, they were not informed of the explosion hazard from the 30 tonnes of fertilizer grade ammonium nitrate with a 34 percent total nitrogen content, which was stored in bulk granular form in a 7 m high bin inside the wooden warehouse[7]. As a consequence of the explosion, the shock wave crushed buildings, flattened walls, and shattered windows. Twelve firefighters and emergency responders were killed along with three members of the public who were volunteer firefighters. The accident also resulted in more than 260 injured victims, including emergency responders and members of the public, and more than 150 buildings were damaged or destroyed in the accident. The cause of the initial fire remains unknown; nonetheless, the US Chemicals Safety Board investigated the factors that likely contributed to the intensity of the fire and detonation of the ammonium nitrate fertilizer. They found two possible scenarios as following:

- contamination of ammonium nitrate with materials that

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served as fuel;

- the nature of the heat buildup and ventilation of the storage place.

The scenarios are presented in the final investigation report with further analysis on the detonation[12].

A similar accident occurred in a smaller facility (an agricultural storage building with 3-5 tons of AN fertilizer in a big-bag) in 2003 in Saint-Romain en Jarez (ARIA No. 25669) with 23 firefighters injured.

In the light of the facts above, the common pitfalls are:

- initial lack of knowledge and remaining low awareness about the hazardous characteristics of fertilizers (inherent explosive risk);
- no hazard identification and poor risk assessment (use of explosives for anti-caking procedures, contamination with organic materials, off-specification and downgraded higher sensitivity);
- inadequate risk management for storage and transportation of ammonium nitrate;
- deficiencies in the emergency response planning and management;
- deficiencies in the learning from past accidents;
- pitfalls in the regulation;
- lack of adequate land-use planning restrictions.

Based on the findings and the causes of the accidents, the following recommendations can be identified:

BASF, Oppau

- The assumption that past successes will work again in the future takes no account of the consequences of failure. Safety is more than reliability. Risk management scope should be enlarged and usual practices should be questioned from different perspectives.
- Although the incident occurred in 1921, it highlights management of change issues. For example, the influence of the change on the sensitivity of the product had not been realised. Hazard identification and risk assessment should be carried out before making changes in the process or the physical properties of the handled substances.
- There was lack of knowledge of the characteristics of the ASN fertilizer. Overall knowledge of the dangerous substances used in the facility is crucial. This knowledge should be updated by monitoring scientific work. The safety behaviour of materials should be studied beyond the product quality knowledge.

Figure 3: West explosion aerial photo (Source: Shane Torgerson)

Texas City disaster

- Adoption and implementation of procedures and instructions for safe operation is crucial.
- Lack of concern with failure or disaster was a big problem in this case, as no risk was estimated. Also, no-one seemed to be aware that the fertilizer was hazardous[22]. The scientific opinion about fertilizer was that it was inert and could not catch fire.
- Large numbers of people were gathering around the dock to see what was happening, which highlights the poor knowledge of the nature of the fertilizer and the fire and explosive risk. Information to the public is an emergency management and educational tool that can help in preventing more severe consequences in case of an accident. The issue with controlling the public at major emergencies and the role of social media is a new version of this problem.
- Even though risk zones were formed around the dock, the effect of a potential accident was underestimated. Apparently 20% of the industrial area was estimated to be exposed to a fire, meanwhile the two explosions and resulting fires inflicted damage to 90% of the area. It is imperative to maintain appropriate safety distances between establishments and the residential area to prevent major accidents or mitigate the consequences.
- Safety culture as a concept was not around in 1947 and employers and their workers also in the neighbouring refineries and chemical factories had only basic knowledge of the hazards.
- Texas City was a boomtown in those years and the priority appears to have been economic growth over safety. Appropriate balance should be created between economic development and process safety. Also, land-use planning was not considered as a priority.

AZF, Toulouse accident

- Given the variety of ways in which ammonium nitrate can cause an accident, there are many accident scenarios that operators must consider. The site risk assessment should include all possible major accident scenarios including low probability high consequence ones. It should address domino effects relating to the dangerous substances stored, transported or produced on-site.
- Operators should have full knowledge of the inherent hazards associated with the handling and storage of ammonium nitrate fertilizer, especially off-specification and downgraded fertilizers and technical grade, and regularly review operating procedures to ensure they are being followed.

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- The ammonium nitrate storage facilities were not directly managed by the AZF company employees but by subcontractors, whose knowledge of the products and the site could sometimes be incomplete. When contracting out a technical process to a third-party the operator should ensure that all risks in the area and associated with the contractor's work have been identified and controlled[8, 9].
- In order to cause as low impact as possible on the population, land-use planning or urban development control zone limits should be applied, even retroactively.

West, Texas

- The only scenario which was considered as dangerous in the storage facility was the accidental release of anhydrous ammonia. Conducting comprehensive hazard identification, analysis and risk assessment where hazardous substances are stored or handled is a basic requirement when operating dangerous establishments. For small and medium enterprises lacking expertise, stricter regulation should be applied and enforced.
- Separation of combustible materials from organic substances is needed to reduce potential conflagration and explosion once an ammonium nitrate fire has started.
- It is unacceptable for a site storing ammonium nitrate in bulk quantities to operate without proper fire prevention, protection and mitigation measures.
- Development should be restricted around sites that handle or store ammonium nitrate, and in the case of existing development in close proximity to the site, appropriate prevention and protection measures should be in place to reduce the risk as much as possible.
- Local authorities should be aware of the dangers associated with ammonium nitrate hazards and oversee the sites in their jurisdiction as appropriate to the level of risk. Even sites with relatively small quantities can be significant risks if they are in close proximity to human development[4].
- Local responders should also be aware of all ammonium nitrate storage sites in the area and the maximum quantities that might be present. They should be trained on how to fight ammonium nitrate fires in accordance with the current best practice.

Changes in the legislative system following these events

1. After the accident at BASF in Oppau, use of explosives to loosen solidified salt was forbidden. Treatment of ASN with anti-caking additives to prevent caking is required.
2. After Texas City disaster the following recommendations[1] were made:
   Anyone dealing with or handling ammonium nitrate should be fully advised of the hazardous nature of the chemical and of the proper methods of storage and handling. Also, these materials should be stored only in brick or fireproof sprinklered buildings on skids or pallets on concrete floors with at least one foot clearance from walls. Storage should preferably be in separate fire divisions from highly combustible commodities or well-segregated. Spilled material from broken bags must be re-sacked immediately and, to avoid contamination to the contents, must not include floor sweepings.
3. Following the AZF accident, a significant modification in the Seveso II Directive[18] was introduced and the categories of fertilizers were extended under this legislation to cover off-specification and downgraded AN fertilizer and technical grade. Furthermore, in France, the accident itself initiated a review of the safety studies to better address low probability high consequence scenarios[10]. It also lead to the development of a new land-use planning approach and the implementation of governance tools at the level of company (involvement of workers and subcontractors) and at the level of the territory (involvement of stakeholders such as neighbours, public parties)[11].
4. West, Texas
   The investigation was completed and the final investigation report with a list of recommendations was published on 28 January 2016 by the US Chemical Safety Board[12]. In the aftermath of the accident, President Barack Obama issued EO 13650 (Executive Order), "Improving Chemical Facility Safety and Security"[23]. By the second anniversary of the accident, in April 2015, three bills regulating storage and inspection of ammonium nitrate and a fourth bill to create a state-wide notification system alerting the public about any hazardous chemical leak at a manufacturing facility were introduced in the Texas Legislature. Also, the NFPA 400 Hazardous Materials Code was reviewed after the accident[19]. Furthermore, in December 2014 the OSHA Directorate of Enforcement Programs issued investigatory and citation guidance on elements of the OSHA standard 29 CFR 1910.109(i) on explosives and blasting agents[24]. Because the current version of 1910.109(i) has limited enforcement in some areas – and because NFPA 400 (2016 Edition) includes updated provisions, the US Chemical Safety Board states in the investigation report that OSHA should update 1910.109(i) to include requirements similar to provisions in NFPA 400 (2016 Edition). In total, ten organisations made recommendations on the accident. These recommendations were published in the investigation report on the US Chemical Safety Board website.

Conclusion

It is a common practice that, following a major accident, a thorough investigation is carried out with great involvement of experts in the field, creating reports and listing recommendations and lessons learned. Yet, history shows that there are difficulties in learning those lessons, in discovering the hidden remaining risk to anticipate some atypical scenarios[13] or the next accident, or take on board the recommendations. Therefore, similar accidents reoccur from time to time with similar, but also new recommendations. However, some of the new recommendations in accident investigation reports do not take into account lessons learned or recommendations made from past accidents. Whatever the technical scenario involving AN[16], some flaws are found in safety management, regulation, oversight and land use planning. The legislation may be modified and some standards are changed over the years but they are not implemented everywhere with the same pace and enforcement. The

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inherent risks of AN fertilizer are still high[14] which require further regulation especially for small and medium enterprises. It may be a solution to introduce more hazard than risk based standards on the storage of AN fertilizers to prevent further accidents. This should then allow the storage of, for example, off-spec material and accidental contamination to be included in the requirements.

After an accident, the memory fades and people tend to forget some lessons or the momentum to implement corrective actions. As repeatedly stated by Trevor Kletz[15], "organisations have no memory, only people have", it is therefore imperative that process safety experts have memory and remember these major events. Similar or new triggering initiators can happen everywhere, and therefore, learning from past mistakes remains a requisite to avoid a recurrence or the next disaster. Reducing exposure by reducing risk at source and vulnerability by using land use planning approaches remain parts of a global strategy.

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