Loss Prevention Bulletin

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Process Safety Essentials

Issue 272, April 2020

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Loss Prevention Bulletin

Articles and case studies from around the world

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Process safety essentials: BLEVE

The Feyzin Disaster

Published in LPB077, October 1987

Summary of the incident

On January 4th 1966, a spectacular fire occurred at the Feyzin refinery in France, killing 18 people, injuring 81 and causing extensive damage.

An LPG spillage occurred when an operator was draining water from a 1200 m pressurised propane sphere. The resultant cloud of propane vapour spread 150 m until it was ignited by a car on an adjoining road. The pool of propane in the bund caused the storage sphere to be engulfed in flames. The vessel became overheated and eventually a BLEVE (Boiling Liquid Expanding Vapour Explosion) occurred when the sphere ruptured. This resulted in a fireball which killed and injured firemen and spectators. Flying missiles broke the legs of an adjacent sphere which later BLEVE'd.

Three further spheres toppled due to the collapse of support legs which were not adequately fire protected. These vessels ruptured but did not explode. A number of petrol and crude oil tanks also caught fire. The conflagration took 48 hours to bring under control.

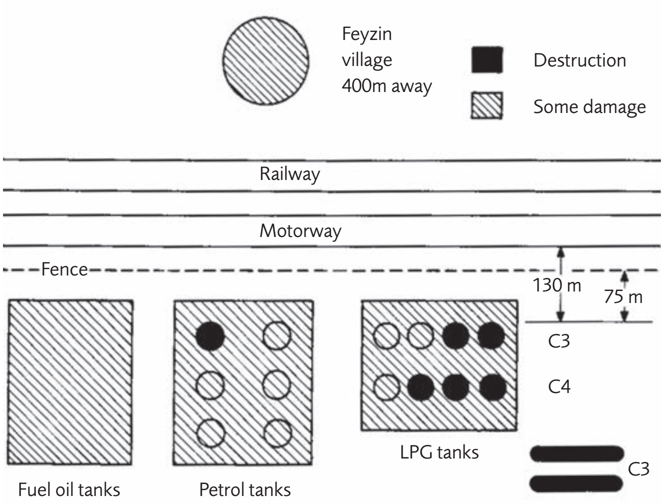

Figure 1: General site layout

General site layout

The refinery was located close to the village of Feyzin, about 10 km south of Lyons. It employed 250 personnel and its capacity was about two million tons of crude oil annually. The main refinery units were located to the north of a local road.

The main storage areas were situated to the south of this road in a 145 m wide strip adjacent to a boundary fence with a motor-way. The key area in the tank farm relates to the following units, (*see Figure 1*).

- 4 spherical pressure vessels used for propane (1200 m^3)
- 4 spherical pressure vessels used for butane (2000 m^3)
- 2 horizontal bullet pressure vessels used for propane and butane (150 m^3)
- 10 floating roof tanks used for the storage of finished grades of petrol and kerosine (2500 m^3 and 6500 m^3)

The LPG storage spheres were about 450 m away from the nearest refinery unit and about 300 m from the nearest houses in the village. The shortest distance between an LPG sphere and the motorway was 42.4 m, and the spacings between individual spheres varied from 11.3 m to 17.2 in.

Main LPG storage

The eight spherical LPG storage vessels were built inside a 114.5 m x 55 m bund with a central sub-division forming two approximately square bund halves. These each contained two propane and two butane spheres (the bund walls were 0.5 m high with the intermediate one 0.25 m high).

Each sphere was provided with fixed watersprays both at the top and at the mid-height, plus a single spray directed towards the bottom connections.

On the top of each sphere was a three-way valve beneath two identical pressure relief valves, so that one was always in service with the other isolated. The propane spheres had relief valve settings of 18.0 bar gauge and the butane spheres settings of 7.5 bar gauge.

All the spheres had "fireproofed" steel supports.

Sampling operations

Samples were taken from each of the LPG storage spheres on a routine basis every three to five days for analysis. The refinery processes led to a certain amount of sodium hydroxide solution separating out from the LPG on storage. It was thus necessary to drain off this solution prior to sampling the propane.

The main bottom flange of the sphere was about 1.2 m above the bund floor which was arranged to slope down to a catch pit under the centre of each sphere. Mounted at the centre of the spheres bottom flange was a 50 mm (2 in) connection on which were attached two plug valves with

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a short spool piece separating the valves. The valves were mounted close to the sphere bottom and terminated in a vertical pipe with an open end close to the bund catch pit (*see Figure 2*).

The spool piece between the valves carried a side 20 mm (¾") connection to a valve and a downwards facing sample connection. These draw-off arrangements were heated by small bore steam tracing beneath lagging.

Sampling instructions

An instruction had been issued on 4th March 1965 stating the sampling procedures to be followed. This had arisen because of valve freezing problems (due to propane hydrate and ice formation) which had been experienced in two previous incidents.

The instruction ordered:

(i) Put an operating lever (valve spanner) on either of both valves

(ii) Open fully the upper valve closest to the sphere

(iii) Adjust the small drawoff rate, as necessary, by operating the lower valve (or the 20 mm (3/4") sample valve).

This procedure was designed so that the cooling effect at flow throttling occurred at the lower valve, with the upper valve remaining free from freezing blockages.

Valve handles were not permanently mounted or placed near to the valves to prevent unauthorised tampering with the drainage system. Figure 2 shows a diagram of the sampling operations.

Circumstances leading to the fire

A sample was being taken from the sphere No. 443 for quality control following a correction that had been made after the propane was found to be over-rich in C2 content.

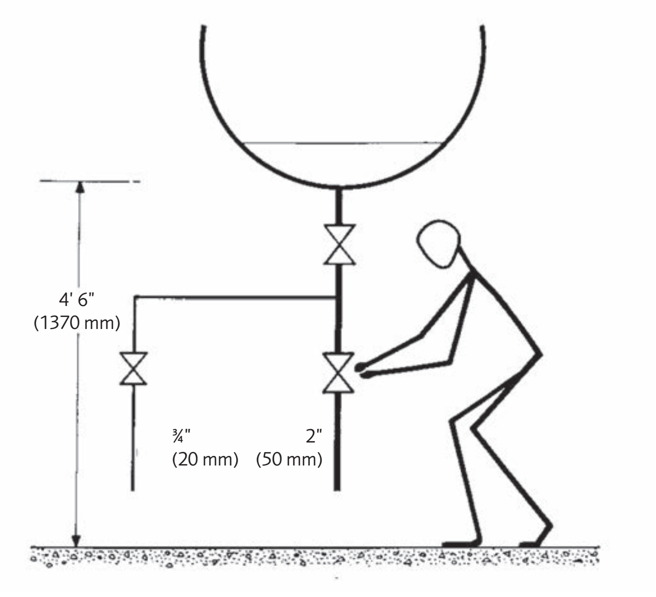
At the beginning of the 6am to 2pm shift on 4th January 1966, a team comprising a plant operator, the shift fireman and a laboratory technician proceeded by truck to sphere No. 443 to take the required sample. Unfortunately, the plant operator, who only had one valve spanner proceeded to operate the valves in the reverse sequence to that laid down in the instruction.

First, he opened the lower 50 mm (2 in) valve leading to the atmosphere almost fully, and then slightly opened the upper valve to adjust the drawoff rate. A small quantity of caustic soda solution came out, followed by a little gas.

The operator then closed the valve and opened it again. A few drops emerged, then the flow stopped. He then fully opened the upper valve. Something like a deflagration was heard, and a very powerful jet of propane gushed out, splashed up from the drain and frost burnt the operator on the face and forearm. As he fell backwards, he pulled the valve handle partly off the valve.

The fireman, seeing the escape of propane and losing sight of the operator, turned on the water supply to the sprays fitted to the sphere. The operator and fireman then attempted together to reposition the valve handle and shut the valve, but failed to do so.

Figure 2: Sampling operation



The time was approximately 06.40. All three men then set out on foot to give the alarm and seek help (about 0.8 km distance to the pumphouse). Apparently they were afraid to use the telephone in the area of the sphere or to start up their truck for fear of igniting the escaping gas. At about 06.55, the alarm was given concerning the leakage.

At around 07.10, the first refinery firemen arrived with a fire truck and a dry chemical truck and they attempted in vain to close the valves. By this time, a layer of propane 'snow' was forming in the area of the sphere and the gas cloud was moving out in all directions. The refinery had a well-rehearsed emergency plan and traffic was stopped on the adjacent motorway.

Unfortunately, one minor road was not sealed off in time and a 4CV car entered the gas cloud and stopped. The driver got out and started to walk along the road. At this point, the gas cloud was ignited (apparently from an electrical defect in the right rear light unit) and the driver was caught in the flash fire and fatally burned. The time was 07.15. The fire travelled back to the sphere within a minute, and igniting the escaping propane underneath and around sphere No. 443, resulting in flames of heights up to 60 m.

Fire fighting

The refinery fire alarm was sounded at 07.20.

At 07.30, an attempt was made by at least 10 refinery firemen and a few other personnel to extinguish the fire at the sphere using dry chemical. It was nearly, but not quite successful before the 1.5 tonnes of dry chemical were exhausted. Shortly afterwards, foam was applied without success and the water spray systems on the remaining spheres were turned on.

Between 07.30 and 07.45, municipal fire companies arrived and coupled their hoses to the refinery hydrant system. This demand overwhelmed the fixed pumping capacity which in itself was not quite adequate to keep full water flow on all eight spheres at once. Water had then to be pumped from the

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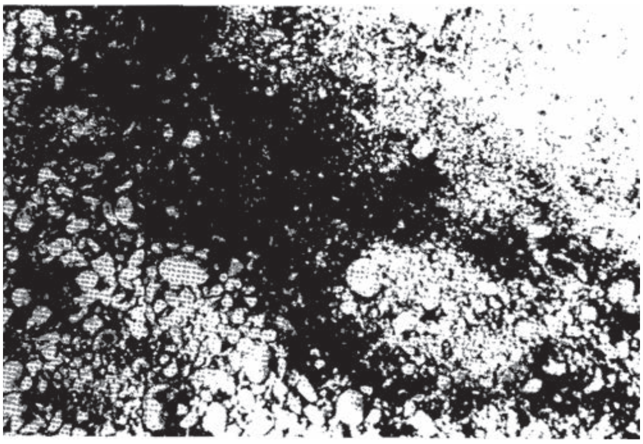

Figure 3: Carbon shadow of a man

canal to the west for firefighting use.

At 07.45, the 100 mm (4 in) diameter relief valve on the sphere opened, and the discharging gas immediately ignited as a vertical jet of flame above the sphere.

By 08.30, water pumped from the canal became available and approximately 15 hose streams came into action. These were directed at exposed spheres, tanks and piping with virtually none being used on sphere No. 443. At this time, there were approximately 150 firemen, refinery personnel and other volunteers in the vicinity of the sphere storage area.

The generally held view was that the fixed water spray system plus the relief valve would be able to protect the sphere from the surrounding fire exposure. Therefore, the main strategy was initially to cool the surrounding equipment to prevent the fire spreading.

Bleves and explosions

At about 08.40, sphere No. 443 suddenly ruptured into 5 large fragments. Approximately 340 m^3 of liquid propane were released which rapidly vaporised producing a large fireball and an ascending mushroom cloud. This killed or injured over 100 people who were in the vicinity. A considerable and dangerous operation had then to be mounted to extract the injured from the area.

One fragment from the sphere knocked the supports from under sphere No. 442 which contained 857 m of propane. Another fragment tipped over another sphere containing 1030 m^3 of butane, whilst one section travelled 240 m south and severed all the product piping connecting the refinery area to the storage area. One other fragment broke piping near four floating roof tanks and fires were started in this area.

At 08.55, firefighting in the storage area was abandoned.

At 09.30, sphere No. 442 exploded and sphere No. 441 emptied itself through broken pipework, adding to the fire intensity.

Three other butane spheres ruptured with major splits in their upper sections at undetermined times without creating any flying missiles. The fire spread to four floating roof tanks about 30 m away, and also to another similar tank 75 m away (which probably had its roof damaged by flying debris). Two horizontal LPG pressure vessels were also set on fire.

Fire fighting was resumed at around 5.00 pm, and was continued for 48 hours until the three spheres which were still intact and full of butane and propane were cooled adequately.

Fire fighting was resumed at around 5.00 pm, and continued for 48 hours until the three spheres which were still intact and full of butane and propane were cooled adequately.

Extent of damage caused

Extensive but minor structural blast damage was caused in the village of Feyzin which was centred about 500 m away from the sphere storage area. 2,000 people were evacuated from the surrounding area after the first explosion. Windows were broken in a church approximately 3 km away.

Damage to the refinery installations was estimated at $4.6 m with damage outside the refinery being estimated at another $2 m. Approximately 5,100 m^3 of LPG and 3,800 m^3 of aviation kerosine were destroyed in the affected tanks plus another undetermined quantity from broken pipework.

One man who hurled himself flat onto the ground when sphere No. 443 ruptured suffered only burns to his hands. A fire department officer who remained standing beside him was fatally burned. Some of the recovered bodies were greatly reduced in size as a result of exposure to the intense thermal radiation and in some cases (*Figure 3*), only a carbon shadow on the ground remained of a man.

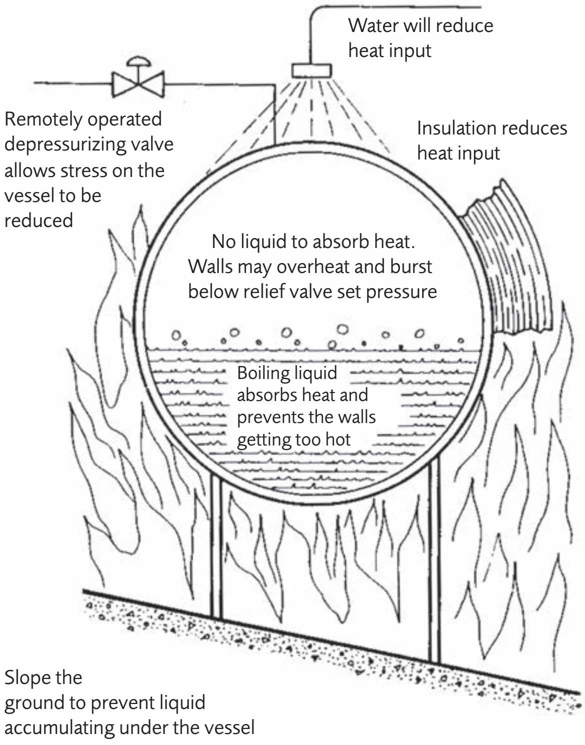

Figure 4: Preventing BLEVES in LPG vessels

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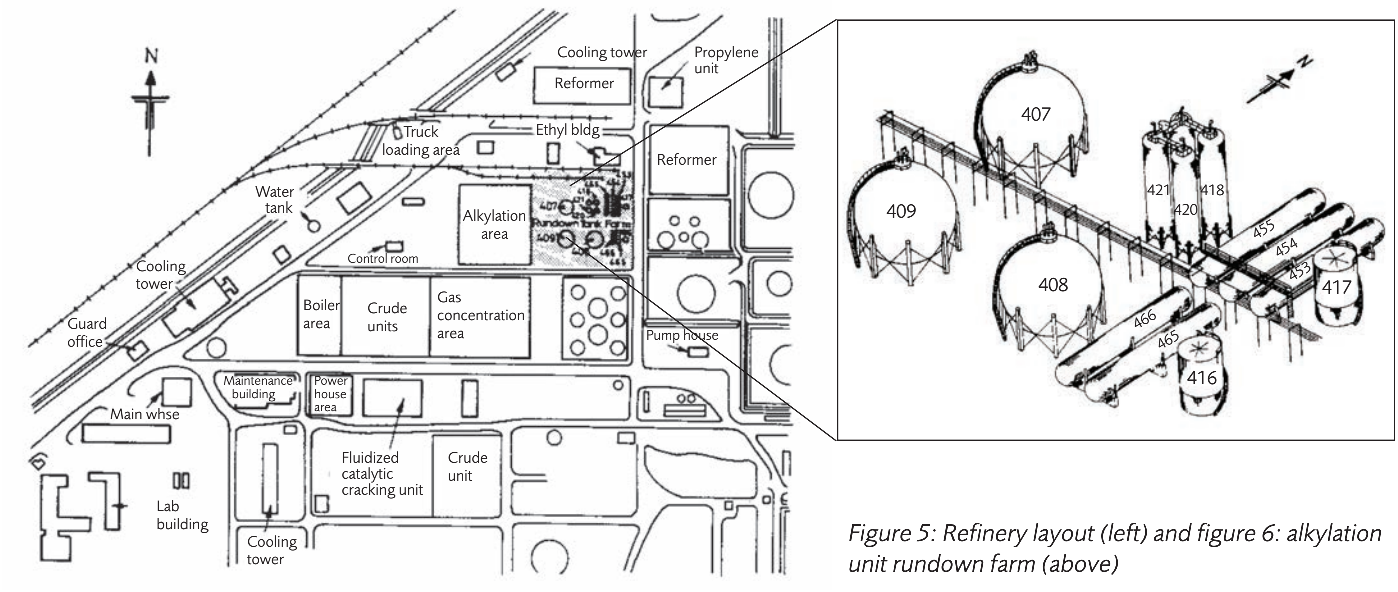

Figure 5: Refinery layout (left) and figure 6: alkylation unit rundown farm (above)

Causes of the incident

a) The propane leak

The primary cause of the propane leak was the operational fault of the plant operator; this fault was made easier by the difficult access to the valves and the lack of permanent valve spanners.

It is probable that a solid plug of ice or propane hydrate stopped the drawoff 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 the frost burns suffered by the operator and formed the cloud which made the recovery and repositioning of the valve lever impossible. Darkness and poor lighting added to the difficulties.

Where possible, the direct draining of aqueous liquid from LPG vessels should be avoided on systems which have to be regularly operated and, in particular, where large volumes of LPG at high pressure could accidentally be released.

If it is not practicable to install a closed draining system then consideration should be given to the use of a dewatering pot which may be positively isolated from the main vessel during the draining operation, and therefore minimise the quantity of LPG which could be accidentally released to atmosphere.

b) Escalation

Points which contributed to the escalation of the incident were:

(i) Delay in raising the alarm after the start of the leak.

(ii) Delay in arrival of refinery firemen:- 10 minutes for the first fireman, 50 minutes for the total force (which arrived about 30 minutes after the municipal force).

(iii) Failure to keep motor vehicles and thus sources of ignition away from the scene.

(iv) The activation of fixed water sprays on all eight spheres at once and the coupling of many fire nozzles to the water system overwhelmed the fixed pumping capacity of the refinery hydrant system.

(v) The failure of the refinery and other personnel to foresee the consequences of the fire surrounding the sphere 443.

c) Cause of sphere 443 BLEVE

The pool of leaked propane in the bund under the sphere caused it to become engulfed in flames when ignition of the gas cloud ignited.

The generally held view amongst the refinery management and other personnel was that the pressure relief valve (plus the fixed water spray system) would protect the sphere. Therefore, they decided the main problem was to cool the surrounding spheres and tanks to prevent the spread of the fire.

Relief valves are designed to protect a vessel against overpressurisation. However, if the vessel becomes too hot, it will burst at or below the set pressure of the relief valve.

Below the boiling liquid level in the sphere, the temperature of the wall would be controlled by the boiling heat transfer coefficient, and would be close to that of the propane liquid (30-35°C). Above the liquid level, however, there is no longer a medium to conduct heat away rapidly and the wall temperature would have approached the temperature of the surrounding flames. Thus, the metal above the liquid level became overheated and was unable to withstand the internal pressure set by the pressure relief valve.

It then ruptured and a BLEVE occurred. Figure 4 shows the methods that can be used to prevent BLEVEs in LPG vessels.

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Lessons from Feyzin

The Feyzin disaster was the worst accident which had occurred in petroleum and petrochemical plants in Western Europe, prior to the Flixborough disaster in 1974. Since then, many pressurised tanks containing liquefied gases have BLEVE'd. The hazards are now better understood and storage spheres are protected from fire engulfment by better design. However, so many firemen and emergency servicemen have been killed while trying to control large fires that the cautious philosophy is to evacuate and take shelter until the material burns itself out.

BLEVEs produce intense thermal radiation from the fireball. This and blast damage from the bursting pressure vessel are relatively localised compared with unconfined vapour cloud explosions. Therefore, evacuation of up to 0.5 km will usually ensure the safety of people. Burning hydrocarbon storage vessels are very spectacular but unpredictable. Therefore, newsmen and sightseers must be kept well away for their own safety.

References

For details of the standards to be used in handling LPG, see:

1 *Liquefied Flammable Gases -Storage and handling (I5/74) -* ROSPA, Cannon House, Priory Oueensway, Birmingham. B4

2 *HSE Guidance Note HS(G) 34.*

3 *LPG ITA Code of Practice No. 1.*

4 *Institute of Petroleum LPG Code.*

Advice on fighting LPG fires is given in:

Guide for Fighting Fires In and Around Petroleum Storage Tanks API Publication 2021.

Loss Prevention Panel comment

Visit any facility handling liquefied hydrocarbon gases and ask the operators "what is a BLEVE"? Probably 50% will know. Ask who has heard of Feyzin? and the proportion will probably fall to 10%. LPB has published several articles describing the Boiling Liquid Expanding Vapour Explosion (BLEVE) at Feyzin, France in 1968. A number of strands came together to exacerbate the event — design errors, operational errors and emergency response were all flawed.

The older generation of engineers are retiring or have retired but will be as familiar with Feyzin as with Flixborough, Piper Alpha and Texas City. As they leave the industry, Feyzin will become less well known (who now remembers the Nixon Nitration Works disaster of 1924?) but Feyzin still has great relevance.

The initiating event at Feyzin was the uncontrolled release of LPG caused by a sampling procedure which went wrong, causing isolation valves on the sample line being frozen open. The design and operation procedures to avoid freezing have been available for many years but there are still examples of poor design and even poorer practice in place today.

LPG trapped under a sphere will, if ignited, cause very high heat input to the vessel especially in the upper part of the sphere (where boiling LPG will not provide cooling). As the metal walls heat up they lose tensile strength and at some point the rupture pressure will be less than the design pressure – the pressure safety valve will not help. Modern practice is to drain any spillage into an impounding basin remote from the sphere and cover the spill with foam. All well and good but some recent designs include a normally-closed manual isolation valve close to the sphere. In the event of a release, an operator is supposed to approach the sphere and open the valve – a potential suicide mission.

The potential effects of a BLEVE are often not well understood. Standard modelling techniques can predict the hazard contours of a BLEVE. Despite this, emergency response plans frequently do not include hazard contours. Consequently, emergency responders are placed in conditions of danger and evacuation of exposed areas does not take place.

The value of LPB is to ensure these major events are remembered but, more importantly, to ensure that learnings from these incidents are not forgotten. In the case of BLEVEs there are alarming indications that the "lessons learnt" are becoming "lessons forgotten" with the latest BLEVE recorded in China in 2019.

Modern process design often involves much "cutting and pasting" allowing an error to be repeated and the development of designs based largely on codes and standards (without extensive independent analysis) also occurs. At the same time, operators are retiring and replacement operators lack their predecessors' years (decades?) of experience and are often doomed to make the same mistakes again

There are many examples where the lessons learnt from a previous incident have been forgotten. Relearning the lessons of past BLEVE's will likely cost many lives.

Doug Scott

The hazards of confined space operations

Tony Fishwick

Published in LPB244, August 2015

Introduction

Previous articles in this series of safety reviews have focussed on the hazards associated with potentially dangerous chemicals, and others on the same theme will follow. However, some operations present situations that are at least equally hazardous, and working in confined spaces is a particularly good example. Dangerous situations and occurrences arise extremely frequently in these circumstances, have led to many serious accidents, and continue to do so. This article looks at different types of confined spaces and the dangers inherent in them, legal requirements, methods of avoiding or minimising risks, and arrangements for dealing with emergencies. Case studies are presented to illustrate some of the potential hazards and how they were dealt with.

Types of confined space

A confined space can be defined as *'any space of an enclosed nature where there is a risk of death or serious injury from hazardous substances or other dangerous conditions e.g. lack of oxygen.*'[1] Some are easy to define, like storage tanks, silos, sewers, large pipelines, flare stacks and other enclosures with limited openings and access. Others are less obvious, such as open-topped chambers and pits, ducting, floating roofs, ship's cargo holds and congested areas with restricted air circulation. There are many other examples, as accident statistics and types verify. They exist in all areas of industry, commerce and academia, not just the process sector. Other examples are in the agricultural industry, where grain silos, slurry pits, and glass houses into which carbon dioxide is introduced to promote plant growth are just some of the items that fall into this category. The Health and Safety Executive (Great Britain) publishes advice on how to manage these safely[2]. Civil engineering, with dangers inherent in trenches, pits and culverts and the shipping industry, where confined spaces can exist in the holds and boiler rooms of vessels, are other sectors that present these hazards. The case studies describe accidents that occurred in several of these areas, with varying causes and consequences.

The dangers from confined spaces

The main hazards associated with confined space working can be summarised as follows:

- lack of oxygen – this can be caused by release of toxic gases from sludges, purging with nitrogen and reactions between oxygen and other materials resulting in oxygen depletion;
- presence of poisonous gases – these can accumulate in sewers, manholes and pits, leak from refuse tips, occur due to fires and explosions, or arise from residues and sludges;
- use of machinery – this may also require protection against dust, electric shock or fumes from welding;
- items falling from above or trench walls collapsing;
- restricted escape routes, for example through a manhole;
- liquids or solids that suddenly fill the space, or release gases into it, when disturbed (free-flowing solids such as grain, or finely divided powders, can have the same effect; these usually arise because of inadequate isolation);
- fire or explosion;
- residues inside vessels which might give off toxic fumes;
- hot conditions leading to a dangerous increase in body temperature;
- poor lighting and visibility;
- electricity, including static;
- presence of dangerous conditions and substances such as radioactivity, pyrophoric materials and bacteriological hazards;
- attempting to rescue a person without first taking proper precautions which is also a matter for emergency arrangements as discussed below;
- inadequate isolation of the confined space before work begins which, in many ways, over-arches all of the above.

Adequate isolation means:

- physical breaks in all pipework leading to, or from, any vessel or other space that is to be entered including those that are not actually 'vessels' at all for example, trenches and pits;
- if that is not possible, then at the very least, insertion of a blank spectacle plate into all pipelines;
- isolation from all sources of electricity, pressure, vacuum, excessive heat, or severe cold and moving machinery.

It is also important to recognise that persons outside a confined space can sometimes be at risk from conditions inside the space. One of the case studies exemplifies this.

The size of the problem – confined space accident statistics

Between 2003 and 2011 there were 29 fatalities due to confined space working reported to the Great Britain Health

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and Safety Executive (HSE). During the same period of time, eight fatalities occurred in Australia. In the USA, US Bureau of Statistics data shows that 350 workers died as a result of trench walls collapsing on them between 2000 and 2009 and, in some years, a further 50 fatalities occurred due to other confined space causes. Data from OSHA tells a similar story for the USA – 63 confined space worker fatalities in 2010 and a further 22 in the first half of 2011[3]. These figures show that confined space working presents significant hazards across international borders though there is a need to allow for the effects of different systems for reporting and classification. There is evidence that many of these accidents have similar causes, indicating that recurrence is a determining factor.

Although details of confined space accidents in Great Britain are not easy to find, some reliable sources estimate that actual figures are even higher than those given above. For example, the Institution of Electrical Engineering has stated a view that the true figure for fatalities might be as high as 15 per year[4]. This, if true, would indicate some degree of under-reporting or misclassification.

US Bureau of statistics also show that about 60% of confined space fatalities occur to people trying to rescue colleagues already trapped inside the space.

Recent HSE statistics[5], although not presenting confined space accidents as a specific category, lend further support to the belief that the problem is a continuing one, since it is reasonable to conclude that some, perhaps most, of the accidents summarised in Table 1 fall into this category.

Accident type	2011/12		2012/13	
	Fatal	Non-Fatal but Major	Fatal	Non-Fatal but Major
Trapped by something collapsing or overturning	14	88	6	105
Asphyxiation or drowning	8	6	3	7

Table 1: Extract from HSE Statistics for Workplace Injuries

Legal requirements

In Great Britain, the legal requirements for working in confined spaces are contained in the Confined Spaces Regulations 1997, Statutory Instrument No 1713[6] and associated Code of Practice[7]. Guidance on how to comply with this legislation is provided in HSE's document at Reference 1. Underpinning this are the Management of Health and Safety at Work Regulations 1999 which require the carrying out of a *suitable and sufficient assessment of the risks for all work activities to decide what measures are necessary for safety.* If this assessment identifies risks of serious injury from confined space working, the Confined Spaces Regulations then set out the following key duties:

- avoiding entry into the confined space if possible;
- if entry is unavoidable, a safe system of work must be followed;
- adequate emergency arrangements must be put in place.

Avoiding entry to the confined space

Consideration should be given to possible alternative ways of doing the work for example, by the use of remote equipment. It may be possible to use vibrators, rotating flails or purges to clear blockages. Inspection or sampling can often be done from outside the space. Remote cameras can sometimes be used for internal inspections of vessels.

If entry cannot be avoided – safe systems of work

The risk assessment will help to identify precautions needed to reduce the risks of injury. These will need to be put in place and everyone involved in the job trained and instructed as to how they can carry it out safely. Key points for consideration would include:

- detailed planning for, and adequate supervision of, the job;
- suitability and competence of the people doing the job – have they got sufficient experience and been adequately trained, are they claustrophobic and are they comfortable wearing respiratory protection? Are they healthy – even if they just have a heavy cold they might be more sensitive to heat stress than usual? Account must certainly be taken of more serious, or permanent, conditions such as angina or asthma;
- mechanical and electrical isolation;
- shoring up of trench walls to prevent them from collapsing inwards;
- draining, flushing, cleaning, purging and ventilation of the space;
- size of the entrance to the space and how people could be got out in an emergency; defined access and escape routes (normally minimum of two);
- adequate cleaning of the space before entry;
- testing of the air inside the space for toxic or flammable vapours and oxygen concentration all against relevant standards; making the atmosphere safe to breathe if at all possible; provision and use of adequate ventilation and respiratory protection if the air is not fit to breathe;
- emergency arrangements, including training, practice drills and provision of rescue harnesses;
- communications between people inside the space and those outside it; use of two-way radio systems; positioning of a standby person outside the space;
- a tally (or other) system for checking people in and out of the confined space;
- permit to work aimed at ensuring that all the elements of a safe system of work are in place and complied with and raised and approved by designated persons. An excellent description of the requirements of a confined space permit is included in Reference 8.

Emergency arrangements

Even with the best systems in place, things can still sometimes go wrong, and people can then be exposed to serious and immediate danger. It is because of this that effective arrangements for raising the alarm and dealing with the emergency are essential. The exact nature of these emergency arrangements will depend on the type of confined space, the job being carried out and the potential risks identified. However, some key features are common to all types of work

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and these would include:

- Effective communications so that the emergency procedures can be put into effect at any time. The different demands presented by shift and weekend working, or work during holiday periods, need to be accounted for.
- Provision of rescue and resuscitation equipment and adequate training in its use. One of the case studies that follow illustrates a potential pitfall in this respect.
- Ensuring that rescuers are fully capable and trained and fit for the work. They should be able to use any rescue equipment, for example, breathing apparatus, lifelines and fire-fighting equipment. They should be trained in first aid.
- As far as is practicable, emergency procedures should be regularly rehearsed and practised. It will not be possible to foresee all potential accidents, but there will be generic features that are common to many jobs.
- Involvement of local emergency services so that they have sufficient familiarity with the plant before an emergency occurs.
- *A golden rule* – if a person has collapsed inside a confined space *never* enter the space to help or rescue them without first putting on respiratory protection. The dangers of ignoring this rule are graphically and tragically demonstrated by one of the case studies. Rigorous training and adequate rehearsal of emergency arrangements are the key to preventing people attempting this highly dangerous procedure though it is always done with the best of intentions. The *golden rule* is necessary because, if a person is collapsed inside a confined space, then going in without respiratory protection to help them will almost certainly result in the helper suffering the same fate.

Case studies

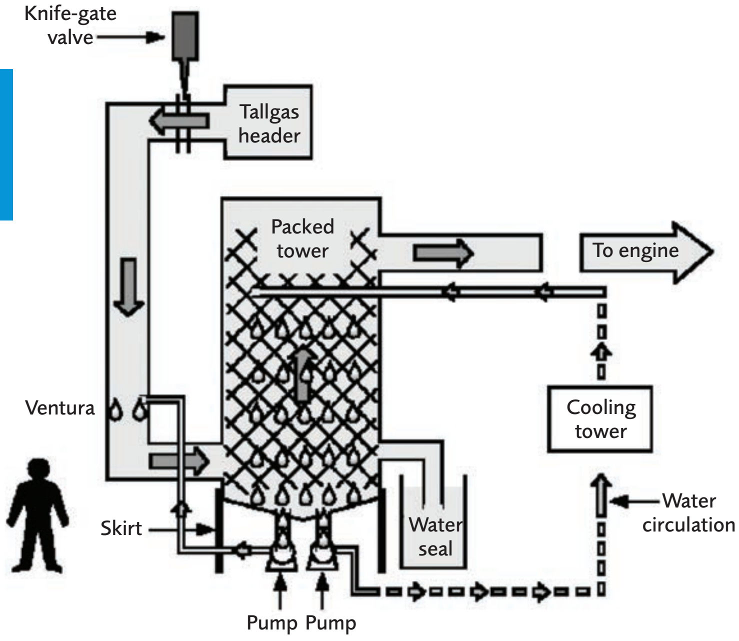

Figure 1: Waste gas tower, water seal vent valve closed

Accidents involving confined spaces are, sad to say, many and varied. A selection is presented to demonstrate the different ways in which these have happened.

Inadequate isolation and failure to recognise a confined space

An electrician and a student were working underneath a waste gas tower (Figure 1[9]). They were on their hands and knees inside the skirt under the tower. The skirt was designed to prevent any impact from passing traffic, such as fork lift trucks, with the valves, pipework and pumps under the tower. It had four arched access openings in it. The electrician became motionless and unresponsive. Fortunately, the student remained conscious and was able to get out of the skirt and pull the electrician clear. Both of them recovered. The fumes contained a mixture of carbon monoxide, dihydrogen sulphide and hydrogen cyanide and these were present inside the skirt due to a combination of inadequate isolation, poor venting and failure to recognise that, despite the openings, the skirt was a confined space. Air circulation was poor and was exacerbated by the fact that the tower was located in a congested area of the plant. The fumes were present inside the skirt because purging and venting of the tower was not carried out properly. The water seal vent was not open to allow toxic gases to be purged.

Careless use of rescue equipment

An operator was cleaning inside a reaction vessel. The vessel had been emptied, purged and correctly isolated. The operator was wearing the correct protective clothing including breathing apparatus. He had a fully functional two-way radio system to keep him in contact with the standby man stationed above the open manhole of the vessel and was wearing a harness connected to a mechanical winch designed to get him out of the vessel. It seemed that everything was in place and nothing could go wrong. He called the standby man on the radio to say that he wished to come out of the vessel in order to visit the toilet. The winch was set in motion to raise him out of the vessel. As he was being lifted, one of his arms became entangled with a cross-member beam inside the vessel and was broken in two places before the standby man could stop the winch. Mechanical winches that 'brake' when they encounter any obstruction are available commercially. They can then be reversed until the obstruction is freed. The risk assessment had been inadequate.

An accident in the civil engineering sector showing the dangers of an ill-advised rescue attempt

Four workers had the job of spray painting the walls and ceiling of a box culvert under a road carriageway (Fig 2a and b[10]). Three of them were killed as a result of acute toluene poisoning. They set up a blower at one end of cell 1, then workers 1 and 2 spray-painted for almost one hour before leaving because they could no longer stand the smell. They were replaced by workers 3 and 4. On hearing cries for help from them, workers 1 and 2 re-entered the cell but worker 1 felt nauseous, so he again left the cell but then passed out. The foreman arrived and found the three workers collapsed inside

Figure 2a: Restricted access to cell 1 under carriageway

cell 1. Emergency services removed them but they were all dead.

The cell of the culvert, a small space with access restricted by soil, was not recognised as a confined space, so a risk assessment was not carried out. Respiratory protection was only provided for the worker actually spraying and it was the wrong type, being for particulates not for aerosol solvents. Most tragically of all, workers 1 and 2 went back into a toxic atmosphere without any respiratory protection and worker 2 died as a result. Some estimates place the percentage of fatalities resulting from ill-advised rescue attempts at as high as 60% of all confined space fatalities.

Fatalities due to a fire in a tunnel

Five workers died in an accident at a hydroelectric plant. They were part of a group of 11 painters working in a tunnel and using a cleaning product that contained flammable solvent. The solvent ignited, presumably due to a spark, and the flames spread to open buckets of the solvent and other flammable material. The five workers were trapped behind the fire and died from smoke inhalation. The possibility of fire had not been anticipated. Flammable material should not have been left in open buckets, especially in a confined space.

Fatality due to total disregard of confined space entry procedures

A supervisor entered an underground motor fuel storage tank that was to be cleaned out. The tank had been embargoed for entry due to a change of plan and this had been made clear and the tank cordoned off (Fig 3[8]). He lowered a bucket and shovel into the tank to enable him to remove sand that had been put in as part of the previous plan to abandon the tank. He plugged his nose and ears with toilet paper and put one end of a rubber hose into his mouth to act as a snorkel. The other end was fixed near to the tank manhole. He lowered himself into the tank and was immediately affected by the fumes inside. He tried to breathe through the hose and climb up the rope to get out of the tank. The standby man tried to pull him out but he was too heavy so the fire and rescue services were called. By the time they arrived, the supervisor was dead.

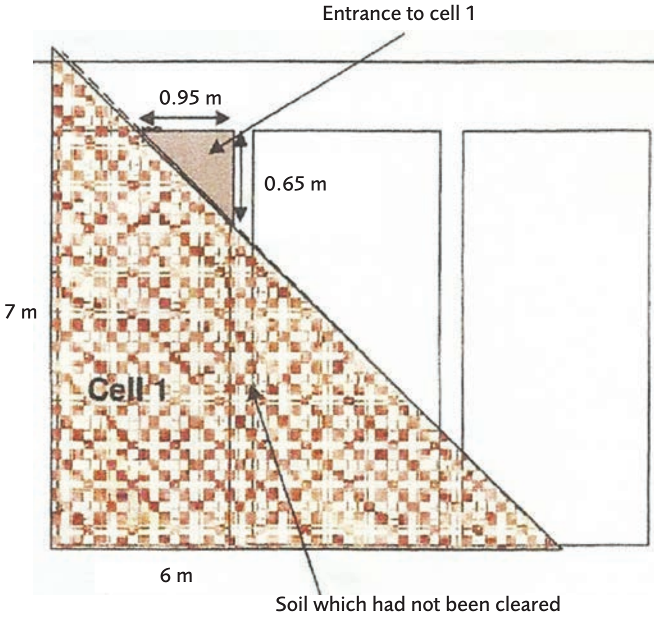

Figure 2b: Dimensions of access to Cell 1

This tragic accident was a result of blatant disregard of procedures and specific safety instructions possibly motivated by a misguided attempt to attempt to impress the project management. The accident is described more fully in References 8 and 11.

Static electricity causes a confined space fatal accident

A tank that had contained methyl tertiary butyl ether was being cleaned using a rotating high pressure water nozzle through the top manhole. An explosive atmosphere had been inadvertently created inside the tank when a vacuum truck sucked some vapour out of the tank and air was drawn in. The fine water mist generated by the pressure cleaner set up a static discharge and this ignited the explosive atmosphere in the tank. The explosion blew an operator off the roof of the tank and killed him[8]. He was outside the confined space, but he still perished.

A fatal accident in an office

A worker was re-laying plastic floor tiles inside a small

Figure 3: Underground tank with entry forbidden

cupboard in an office corridor. He was using a solvent-based, quick-setting adhesive. The fumes overcame him and he fell forwards into the adhesive, where his face became stuck. He died from inhaling the fumes[8]. This was an accident that could have happened in almost any place of work or, indeed, the home. When working in small spaces with any substance that might give off noxious fumes, respiratory protection must be worn if practicable. If not, then adequate ventilation must be ensured. Proprietary adhesives and solvents, available at any DIY shop, always display warnings about this.

A flash fire in a tanker in a shipyard

Repairs were being carried out on a tanker in a shipyard when, without warning, a huge fireball was emitted from a manhole on deck. A man, engulfed in flames, was ejected from the manhole. He was doused in water but died in hospital from serious burns. Below deck, six other workers died, four from burns and two by asphyxiation. The workforce had just returned from lunch to resume cutting away rusted parts of a tank and welding in new steel plates. A flammable atmosphere, thought to have been created by a leak from acetylene cylinders, was ignited and led to a flash fire. When workers leave a confined space for a period of time, for example a meal break, gas tests should be carried out before they re-enter the space, to check that conditions are still safe[8].

Avoiding or minimising the risks from confined spaces

In principle, the means of avoiding accidents in and around confined spaces are very similar to those associated with any other type of accident. Thorough planning and preparation, adequate isolation, use of appropriate personal protective clothing, an effective risk assessment and emergency plan are key factors, as is not attempting rescue unless properly equipped. All this is common knowledge, but confined space accidents continue to occur and, more importantly, *recur.* Why should this be so? The late, highly respected, safety practitioner Trevor Kletz, identified the loss of 'corporate memory' as a significant reason and there is a lot of evidence to support this[12]. The lessons learned from accidents are not always properly recorded and passed on. Experience and skills are lost when people retire or staff cuts are made. Greater use of contractors can increase hazards if they are not properly trained. Overloading supervisors, who are the vital interface between management and the workforce, can result in ineffective control and leadership. Understaffing often results in people taking dangerous short cuts. A good 'accident avoidance' plan, would be to collate all these, and other, factors as they apply to confined spaces, into a comprehensive package to be used for training and information.

Getting the message across effectively is the next step forward. Proper training is essential, and thought needs to be given to the best techniques, as these will vary from situation to situation and place to place. However, there are a few tools that can be helpful across the board. These include:

Tool box talks (TBT)

A TBT is an informal way of informing the workforce and getting their views in an interactive manner on topics related to safety. A TBT on confined spaces (of which IChemE has an available example) would typically include case studies, lessons learned, prevention of recurrence, types of confined space and how to make them safe. Heavy emphasis would be placed on the extreme dangers of entering confined spaces without respiratory protection in order to rescue colleagues. The group should be encouraged to map out a way forward to be applied to their own specific circumstances.

Mental imaging

Participants should be asked to imagine the worst possible outcome from a particular set of circumstances, then what they would do to avoid it. Visual aids depicting real outcomes from previous accidents can be used to support the discussion. The technique yields best results when used as part of a step-by-step package incorporating interactive stages such as examining the reasons for unsafe behaviour, encouraging suggestions for safer behaviour and others. When used in this way quantified reductions in accident rates over a period of time can usually be observed[13].

Emergency planning

As already stated, different situations will require different responses to any emergency but there will be some common themes including risk assessment, fire fighting skills, isolation from noxious substances and sources of pressure or electricity, rescue techniques and use of effective PPE.

Whatever means are chosen, there must be a single, common objective – be a 'what if' person and avoid the accident, not an 'if only' person after it has happened.

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Dear Editor

As a member of the Loss Prevention Panel, may I offer a few words on two confined space incidents?

The first incident occurred at ICI's Wilton site between about 1978 and 1980 when I was the plant manager (aged ~30) on T7 Oxidation. This was a plant which made crude terepthalic acid (an intermediate in the production of polyester) from the oxidation of paraxylene in a catalyzed acetic acid medium. The vessel in question carried out a crude separation of the catalyst to recover the solvent and had a slow moving (~ 15rpm) anchor agitator which scraped the walls of the vessel. The plant was 'high maintenance' i.e. it shut down regularly and during one of these shutdowns we decided to carry out repair work inside the vessel (I can't remember what, but it involved 15-20 people working inside the vessel at the same time). All the usual isolations were carried out and vessel entry permit issued (by myself) under reg 7. The requirement for electrical isolation was that there should be two barriers. At the agitator motor we had a choice of either removing the coupling or disconnecting and wrapping the cables, we chose the latter. The second level of isolation was to lock off the MCC (motor control centre). On the day of the incident, the first day of the entry, it was raining very hard and the cable managed to connect between the junction box and earth (the handrail) and the motor kicked. We had isolated the wrong MCC. No one was injured.

As the plant manager it was my job, under reg 7, to inspect the isolations and issue the entry permit. All the rules were followed but:

Lesson: You see what you expect to see.

Another incident occurred around 1986 in New Zealand. I was the technical manager at the time so on the fringe of the entry.

An entry was required on a very long steam drum which had a small oval manway at each end. Time was short and it was decided that the vessel had cooled sufficiently to permit an entry. The entry was performed and the work carried out, but when things heat up they swell – which the human body does also. The man inside found himself unable to get out of the manway and he was beginning to show signs of claustrophobia. The solution required him to strip naked, be greased all over with margarine from the mess room, have his hands tied together and be pulled through the manway. He came out like a cork from a bottle!

Lesson: All things expand with increasing temperature and margarine is better than butter!!

Colin Feltoe FIChemE

Loss Prevention Panel comment

As the reference article[1] notes, accidents involving confined spaces continue to occur with depressing regularity. It provides some shocking statistics from across the world relating to accidents from confined space working. The LPB archive is littered with articles recounting tragic accidents involving them[2]. John Bond[3] gives a historical perspective on the subject. He describes an accident from as early as 1828, in which three men met their deaths in a well in Marton near Middlesbrough. One had entered it to retrieve a piece of stolen beef and had succumbed to toxic fumes, whilst the other two had most likely gone in to rescue him and were also overcome. Sadly, this event displays a common trait of many confined space accidents, i.e. an noble but ill-considered attempt to effect an immediate rescue, often resulting in yet more casualties[4].

The article upon which this editorial is based comprehensively addresses:

- the general nature of a confined space;
- the hazards posed by confined spaces;
- legislative requirements; and the need for a suitable and sufficient risk assessment before entering a confined space, the key considerations of which are:
- if possible, avoid entry into the confined space and do work from the outside;
- if entry to the confined space is unavoidable, a Safe System of Work (SSoW) must be in place and be followed; and
- adequate emergency arrangements must be in place before the work starts.

These are each discussed in some detail.

Finally, the article asks the question: Why do accidents recur? and goes on to consider ways that recurrence of accidents more generally can be avoided.

As Dr Fishwick notes at the beginning of his article, the hazards of confined space working are 'virtually universal' and can happen 'almost anywhere'[5]. With this in mind, he strongly advises that any workplace should be proactively examined, to determine any parts of it which could potentially pose a confined space hazard, and to have pre-prepared SSoWs to address them.

Geoff Gill

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Acrylic acid runaway

Published in LPB126, December 1995

The accident

On 27 November 1994 a breakdown of operations occurred at Wacker-Chemie's Burghausen plant caused by the bursting of an acrylic acid tank. This resulted in a largescale fire fuelled by the escaping acrylic acid/ polyacrylic acid. The polyvinyl alcohol storage facility nearby also caught fire. One worker died and 13 were injured. Twelve of the injured people had left hospital care by 13 December, but one casualty remained in hospital for follow-up treatment.

The equipment involved

The 16 m^3 storage tank, filled at the time with 10 m^3 acrylic acid, was located in the yard in front of two rectangular adjoining buildings: a single-storey storage facility; and an un-roofed production unit with five floors. The figure shows a simplified drawing of the tank and its associated plant.

The tank's contents were circulated in two pipe circuits. This arrangement was designed to ensure uniform distribution of the inhibitor which avoids polymerisation reactions of the acrylic acid and also to stabilise the temperature in the acrylic acid tank.

The 'large circulation pipeline' led to the acrylic acid outlet points and continued on over a heat exchanger located on the fifth floor of the production facility, then back into the tank. This pipeline was equipped with a temperature control surveillance system and an overflow pipe. The heat exchanger regulated the temperature of acrylic acid to a constant 22°C. The pumping rate was around 20 m^3/h

The bypass pipeline' was designed to receive acrylic acid from road tankers and circulate the tank contents. During normal operations on the pump around setting, a partly throttled valve passed around 5 m^3/h of acrylic acid through to this bypass pipeline.

The storage tank was equipped with an overflow safeguard and a venting system. The unit operated without problems for 15 years.

The investigation

To reconstruct the cases and the sequence of events during the incident, assumptions have to be made, which cannot be proven beyond doubt, but are supported by a high probability and by circumstantial evidence. The investigators depict the sequence of events during the accident as follows.

On Wednesday, 23 November 1994 the plant experienced a power cut for about 30 minutes when the electricity supply for the above-mentioned buildings ceased. The circulation pump was also affected. All appliances were stopped without incident. The heating system in the building shut down due to the power cut. The lack of heat combined with a cold north wind (wind speed of around two m/s and outside temperature of around 5°C) led to a rapid cooling of the whole building.

Due to the low temperatures and the shutdown of the circulation pump of the pipelines, acrylic acid in the non-insulated part of the pipeline froze — the freezing point of acrylic acid is around 12 °C. However, the pipeline in the sector of the temperature control system did not freeze — it was situated in an area shielded from the weather — therefore the low temperature alarm was not triggered and the blockage in the large circulation pipeline remained undiscovered. Apparently, at the same time a plug of acrylic acid formed inside the bypass pipeline. After power was restored the circulation pump started up again and ran against blocked pipelines. This led to a large temperature increase of the acrylic acid inside the pump. It seems that the warm-up of the acrylic acid in the pump must have triggered a first polymerisation reaction. Since the acrylic acid in the throttle valve of the bypass pipeline (around 50 cm away from the pump) would not have thawed, the pump would have come to a standstill after a few minutes due to the polymerised material. Investigators found that the pump sensors had indicated a period of overheating.

As the bypass pipeline thawed, polymers that had formed were flushed through the throttle valve into the acrylic acid tank. This led to a very slow polymerisation to start with. Polymerisation continued slowly during the period from 23 November to 27 November 1994 but speeded up dramatically on the morning of 27 November This was confirmed by investigators who took samples from containers of acrylic acid extracted from the tank on 24 November 1994. Small amounts of polymerised materials were found in the samples.

The large circulation pipeline, where the temperature control and cooling system was installed, failed to thaw. The temperature reading on this pipeline showed small differences during the routine checks, but values always remained within normal parameters. Deceptively, the system appeared to operate normally. As no acrylic acid was taken from the tank on Sunday, the actual state of affairs remained undiscovered. Due to the blockage of this pipeline, temperature increases in the storage tank remained unnoticed. The very slow polymerisation at the beginning of the incident, with the slow addition of energy to the system by the circulation pump running normally, gradually heated the acrylic acid in the tank. On Sunday, 27 November 1994 a high enough temperature was reached to accelerate the reaction to such an extent that it led to the bursting of the tank, and the spontaneous ignition of the escaping mixture.

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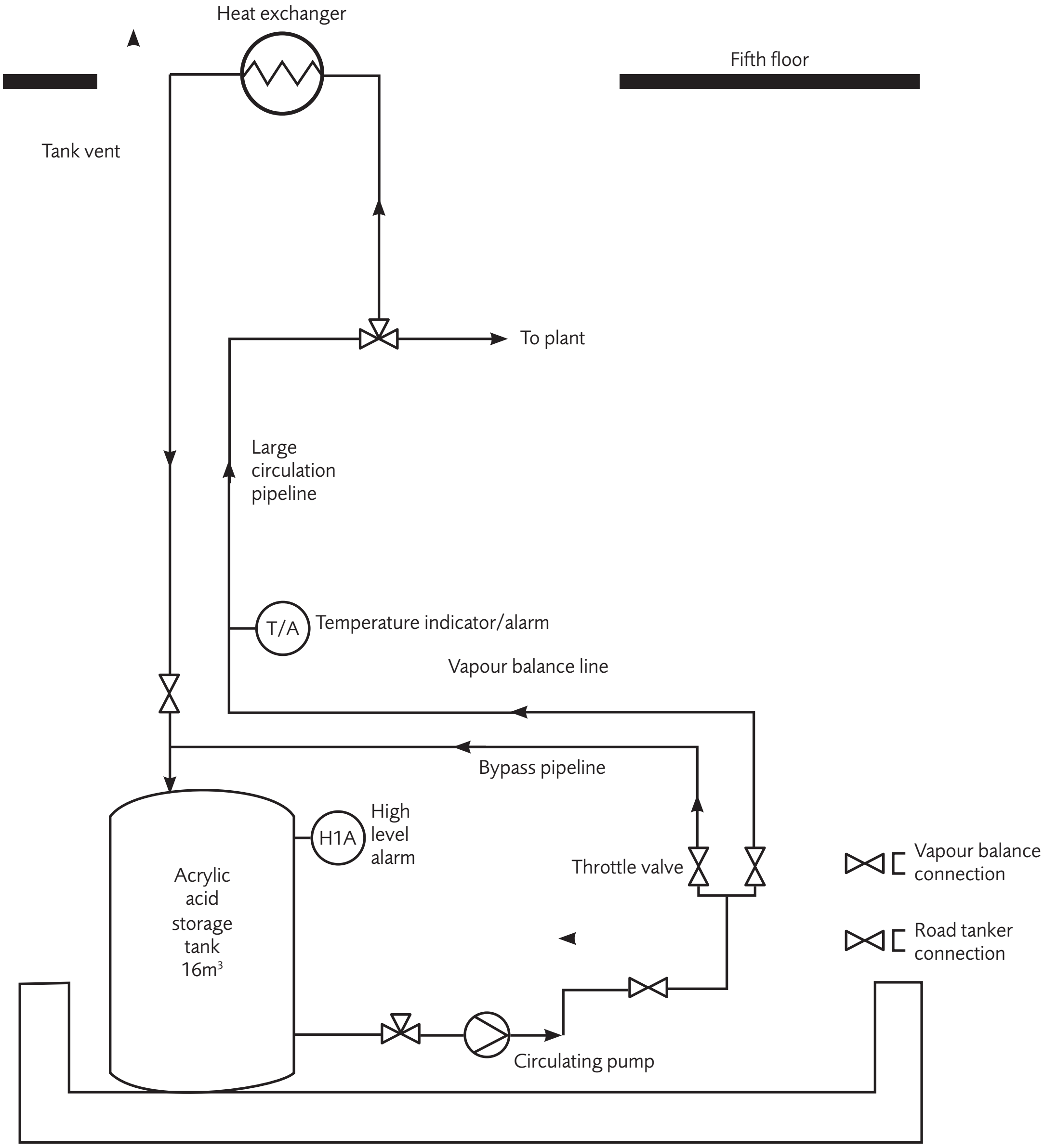
Figure 1 –Connections to the acrylic acid tank



Conclusions

The temperature increase that led the polymerisation to propagate originated from two sources.

The circulation pump, with a pumping throughput of 20 m^3/h worked against the throttle valve —the flow rate in the bypass pipeline was around 5 m^3/h. This might have caused the warm-up of the total contents of the tank by around 0.5°C/h. This probably resulted in a warm-up of the acrylic acid to above 60 °C during the period from 23 November to 27 November.

Polymers which formed in the pump on 23 November flowed into the tank and triggered polymerisation acting as 'living polymer'. Although very slow at first, polymerisation accelerated at higher temperatures, and an adiabatic reaction occurred. Adiabatic reactions can promote a rise in temperature to between 450 °C and 500 °C.

The following combination of events lead to the accident:

- a power cut
- external temperature of around 5 °C with a north wind
- the open-topped building
- crystallizing out of the acrylic acid in both pipeline circuits
- warming-up and polymerisation caused by the pump working against a blocked delivery route
- thawing of the crystallized acrylic acid in the bypass pipeline
- transfer of polymers into the acrylic acid storage tank
- slow warming of the tank's contents by around 0.5°C/h, due to the pump passing against a throttled valve
- ineffectiveness of the temperature monitoring system, since the large circulation pipeline remained blocked all the time.

The following safety procedures were introduced to avoid the reoccurrence of a similar incident:

- A continuous independent temperature measurement of the tank contents will be provided.
- The circulation pump will be equipped with a temperature control safety switch.
- Safeguards put in place to ensure that temperatures in acrylic acid storage facilities and in rooms containing acrylic acid pipelines do not fall below a certain level. This will avoid crystallization of the acrylic acid in the event of a power failure.
- Analytical surveillance will ensure that the inhibitor concentration within the acrylic acid does not fall below 200 ppm.
- A measuring device will be installed to monitor the throughput of the major pipework.
- An emergency reaction inhibition system will be installed.

Editorial discussion

There have been a number of acrylic acid runaways over the years, including several reported in Loss Prevention Bulletin[1,2,3] but there are measures which can be taken to help prevent incidents. It may be useful to outline the main ideas from various suppliers' literature.

External loops

Many suppliers of acrylic acid (and its homologue methacrylic acid) recommend only a single recirculation circuit. Almost all agree that the circuit must be as compact and simple as practically possible. The pipes must be protected against lower temperatures, to prevent freezing in cold weather. Since the melting points of acrylic acid and methacrylic acid are 12°C and 16 °C respectively, even mild ambient conditions can lead to freezing.

Temperature measurement

In acrylic acid storage, temperature measurement is needed both to control the storage temperature, and to warn of impending danger. It is possible to use a single temperature probe in the recirculation line for both needs. But if the recirculation line is blocked for any reason, the probe is useless.

Suppliers suggest use of more than one temperature probe, including:

- some in the body of the tank
- on the recirculation pump head
- in the recirculation line, and
- in the temperature management system, whatever form that may take (e.g. heat exchangers, tempered water mixers etc).

Even with many probes, it is still possible for polymerisation to take place in dead spots in the tank

Temperature control system

Most suppliers now advocate the use of coils inside the tank to warm and cool the acid. The heat transfer medium preferred is indirectly heated tempered water, arranged so that steam cannot enter the coils if the cold water fails. Most recently, one supplier suggests that the tank is located in a warm room, and the coils are served with water (temperature >15 °C) for cooling only. As well as adopting this inherently safer approach, they also suggest comprehensive temperature recording with Hi/Lo and HiHi/LoLo alarms. Alarms on high rate of change of temperature may be useful in detecting the start of an incident.

Tank outlet

It is strongly recommended that tank floors slope down to the outlet, which is in the floor of the tank, or even in a small well in the floor of the tank. This helps to ensure that there are no dead spots in the tank, where the inhibitor system can become depleted with time, and allow the formation of polymer seeds. Returning the acid to the tank through a jet mixer nozzle improves agitation in the tank, and helps to eliminate dead spots.

Inhibition

The acid is normally delivered with a safe level of inhibitor already dissolved. Once the inhibitor, PMP (methyl ether of hydroquinone, or p-methoxy phenol) is dissolved in the acid, it is difficult to see what effect the circulation will have on its distribution. Recirculation is necessary though to keep the levels of dissolved oxygen in the stock adequately high and evenly distributed. Without oxygen, PMP is not an effective stabiliser for acrylic acid.

Some inhibitors don't need oxygen to work (e.g. phenothiazine), but these inhibitors can make the acid unusable if subsequent processing involves polymerisation. A bubble-type level meter fitted to the tank and fed with air will ensure that the small amount of oxygen needed for inhibition is always present in the tank stock. Circulation will then ensure that the oxygen levels are adequate throughout the acid. If acid is to be stored for any length of time (e.g. weeks), then regular analytical checks on the levels of both inhibitor and dissolved oxygen are necessary. In any event, storage of acrylic acid for more than six months is considered by many suppliers to be unwise.

If the monomers are allowed to crystallize on cooling, the crystals that form are pure acrylic acid containing no inhibitor. There is a danger that when these crystals melt a liquid layer low in inhibitor concentration may form. This region of purer monomer is capable of initiating a runaway polymerisation.

Emergency inhibition or short stop

For acrylic acid storage emergency inhibition has a major drawback: spotting the start of the polymerisation. If the inhibitor is added too soon, an entire tank of raw material could be ruined needlessly. If added too late, the viscosity of the polymerising material would be so high (and rising) that mixing the inhibitor with the acid would be practically impossible.

Vent pipes and flame arresters

Glacial acrylic acid is volatile, and will evaporate from the (warm) body of the stock and condense in (cold) vent pipes and on the roof of the tank. This material is effectively distilled, and so uninhibited. Droplets of acrylic acid formed in this way polymerise quietly, and over extended periods can accumulate to block vent pipes. The only sure way of keeping vents free of blockage is regular preventive maintenance, in the form of inspection and cleaning. Most suppliers suggest that such vent lines are as short as practically possible and heated, to prevent condensation of acid vapour. Many suggest that the vents are designed to stop polymer dropping back into the tank. Flame arrestors are particularly prone to blockage with polymer.

Formation of small beads of polymer on the underside of the tank roof is also undesirable. The polymer so formed can eventually fall back into the tank contents, and seed further polymerisation.

Logistics

Since acrylic acid is a reactive chemical, the safest storage method is to store only material which is intended for immediate use. This is the inherently safer way and carries the smallest risk.

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Loss Prevention Panel comment

The rate of a chemical reaction increases with temperature. If the reaction is exothermic, and the heat released is kept within the reaction mixture, the temperature rise will accelerate almost until the reaction has gone to completion. Many such mixtures contain gases or vapours or are liable to evolve them with rising temperature. In a fixed volume, the pressure exerted by gas is directly proportional to the absolute temperature. Even without the not uncommon prospect of triggering further, unintended, exothermic reactions at elevated temperatures, it is clear that, unless the heat of reaction is removed as fast as it is generated, the containing vessel or reactor is at risk of turning into a bomb.

The hazard can be eliminated by designing the vessel to withstand the theoretical maximum pressure that can be generated, taking into account possible errors in mixture composition, starting temperature etc. This solution is, in fact, widely used in the study of gas combustion phenomena. In general, however, chemical reactors are protected by cooling circuits, continual mixing, venting in case of overpressure and emergency injection of inhibitors or dumping of liquid contents.

Unfortunately, there are many ways for protective systems to fail – and, when they do, to fail catastrophically. To begin with, the positive feedback loop between reaction temperature and reaction rate enables exothermic reactions to run away suddenly and very quickly from any operator interventions. Failure of cooling[1] or agitation[2] are common immediate causes. Emergency vents have often proved to be undersized, failing to prevent a vessel burst[3]. Provision of emergency dumps is the exception, not the rule. Runaway reactions can take place unexpectedly in the storage[4] or transport[5] of unstable substances, in the complete absence of protection or mitigation. Even small quantities, such as are stored in laboratories, are potentially lethal[6].

Severe consequences can ensue even when venting protects the vessel, unless flammable or toxic vented material is routed to secure containment. The Bhopal disaster, the worst ever caused by the process industries, involved a massive toxic cloud vented from a runaway reaction[7].

Mischarging of reactants or catalysts is the most common immediate cause of reaction runaway, followed by ignorance of reaction chemistry/thermochemistry, poor temperature monitoring/control and inadequate agitation[8]. Mischarging includes over or undercharging reactants or catalyst, undercharging solvent, adding the wrong reagent, omitting a reagent completely or adding reagents in the wrong sequence[9].

Nearly all of the three dozen or so case studies of runaway reactions in the LPB archive describe batch processes. For economic reasons, these generally involve substantial inventories – and hazards – not necessarily the case with continuous processes. The risks inherent in batch processes are enhanced by their relative busyness, with far greater scope for operator errors[10]. Process intensification can markedly improve safety by converting a batch process to a continuous one with a much smaller inventory[11].

Ivan Vince

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Explosions and fires involving dusts

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Introduction

Fires in industrial plant are shown by experience to be caused frequently by combustible dusts or powders. Dust explosions can be caused by the rapid burning of suspensions, giving damaging pressure effects, whereas at the other extreme, smouldering dust deposits can give very slow fires. The combustion processes depend on both the extent of subdivision of solid and also on the ratio of solid to surrounding air.

The dispersion of the dust or powder into a suspension in air can, after ignition, lead to extremely rapid burning with explosion effects. Dusts involved include common foodstuffs like sugar, flour, cocoa; chemicals, dyestuffs and pharmaceuticals, plastics, metals such as aluminium and magnesium and traditional fuels such as coal and wood. For a cloud dispersed in the open air, the result of ignition is a flash of flame, probably developing no hazardous pressure. If the dust cloud is confined, as in a plant or a room, then pressure effects would be expected depending on the size of the cloud, the nature of the dust, and the ease of discharge to atmosphere. Dust explosions can be in surroundings of atmospheric temperature, as in ducting and bins, hoppers, silos or in heated surroundings as in furnaces, and driers. This type of dust explosion can be regarded as a primary explosion, but dusts are notable in that they can easily cause secondary explosions. A secondary explosion results from a primary explosion (which might be relatively mild) dispersing further dust and igniting it (sometimes giving severe explosion). An example would be an explosion in a process plant which burst out and dispersed dust which had accumulated in a badly maintained workroom, causing a secondary explosion in the room.

Unless specially designed, much plant and buildings can withstand pressures of only 7-15 kN^2/m (1-2 lb/in^2), without damage. As a dust explosion in a closed vessel can develop pressures of 700 kN/m^2 (100 lb/in^2), or even more, damage to plant by a dust explosion is likely unless precautions have been taken. The hazard to plant and operatives due to dust explosions is therefore clear.

Combustible dusts can cause fires provided sufficient dust and oxygen to support the combustion are present. There are obvious differences in the appearance of dust fires and explosions. The characteristics of the dust explosions: the rapid rate of flame propagation and the generation of damaging pressure, are absent from dust fires. The quantity of dust in unit volume in the layer is far greater than in the same volume of the explosible suspension, and the total amount of heat released when a layer is completely burned is correspondingly greater than with a suspension, and in addition, the duration of the fire is considerably longer. Further, certain dusts which are not explosible, such an anthracite or coke, can be ignited and cause fires. The fires can be combustion without flame (i.e. smouldering), which may either be on the surface or within the dust deposit or layer or burning with flame which propagates over the surface of the layer. Some dusts are able to undergo both forms of combustion, but those which liquefy at combustion temperatures tend not to smoulder, at least in thin layers. A burning dust layer can cause damage to the surfaces on which it rests, can ignite neighbouring materials, and if dispersed can cause a dust explosion. Dispersion may simply be the result of the layer losing adhesion on a vertical surface and falling under gravity within a large enclosure.

For further information a book on dust explosions and fires is now available.[1]

Characteristics of dust explosions and fires

Since not all combustible dusts can cause explosions, if dispersed in air in the presence of an ignition source, tests have been devised to classify dusts according to their explosibility[2]. Dusts are classified by HM Factory Inspectorate into two groups as follows[3]:

- Group (a) — Dusts which ignited and propagated flame in a test apparatus.
- Group (b) — Dusts which did not propagate flame in a test apparatus .

If the dust has not been tested and listed[3], or its composition is not known, it will be necessary to classify it according to the standards tests. If the dust is known to be explosible, i.e. is in Group (a), or is shown by tests to be so, further tests are available to measure the explosion properties[2]. The choice of test carried out is related to the hazard envisaged in the proposed method of protection. The available tests are:

- Minimum ignition temperature (hazards of hot surfaces)
- Minimum ignition energy by electric spark (static electricity)
- Minimum explosible concentration (exhaust ventilation)
- Maximum explosion pressure and rate of rise (relief venting)
- Maximum permissible oxygen concentration to prevent explosion (use of inert gas)

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Results obtained from these tests, and by comparable tests in the United States and Germany, have been published and a collected list is available[1]. The tests are necessarily of laboratory scale and care is needed in their interpretation. Particular attention should be paid to problems associated with the scaling up to the dimensions of industrial plant, and for conditions where the dust is not initially at atmospheric temperature but is heated. The explosibility classification relates to dust dispersed at ambient temperatures, and is not directly applicable to dispersions at appreciably higher temperatures. Some discussions of the problem is available[1] which takes account of the different test methods in various countries.

Dust fires can be initiated by various sources, see below, and the ease of ignition is usually increased by a draught provided that disturbance of the dust is not caused. The ease of ignition also generally increases with finer dusts. The initiation of dust fires by hot surfaces, or by dust deposits in hot environments, is an important hazard and attention has been devoted to it both by experiment and by theory. In broad terms, three types of situation are likely to arise in practice and give dust fires from these causes:

- Dust deposits or heaps. Typical situations would be thick accumulation in a drier or oven, heated material in a hopper, or a very large heap on the ground exposed to the atmosphere for a long time.
- Dust layers, which, are relatively thin, in a heated environment . These may be found as deposits on the wall of driers.
- Dust layers which are relatively thin on a hot surface, with the other surface of the dust exposed to atmospheric temperature. Relevant situations include deposits on pipes, lighting fittings and on hot bearings

Two conditions of burning can be distinguished. In the first, the flame or smouldering propagates over the surface of the dust deposit, or if the deposit is thin, can burn across the layer involving practically the whole thickness in the process. The second condition is ignition of smouldering within the deposit, the smouldering propagating through the deposit, mainly upwards, until it reaches the surface. Propagation across the surface then proceeds as in the first condition. Knowledge of smouldering rates is of particular importance because it enables realistic estimates to be made of intervals between ignition and the outbreak of flames. Smouldering rates can be drastically increased by the action of an air flow over a dust layer. For air movement in the same direction as the propagation of smouldering, the rate may be increased by an order of magnitude. The effect is of practical importance because it is the means whereby smouldering is most likely to be converted to flaming and the subsequent rapid spread of fire.

Sources of ignition

Although there are a vast number of different sources of ignition having various temperatures, energies, durations, etc . they can be conveniently grouped as follows:

- Flames
- Glowing combustion and smouldering
- Hot surfaces
- Welding and impact
- Electric sparks
- Spontaneous heating

The flames produced from the burning of gases, liquids or solids, are potent sources of ignition for dusts. This applies whether the flames are diffusion, that is, unmixed fuel burning in air, or premixed, in which the air and the fuel are mixed before entering the flames. Because flames are such effective ignition sources, little investigation has been made into the minimum size and duration of flames needed to ignite dusts, because these minima are likely to be so small as to have little practical application. As a general conclusion, if a dust can be ignited, flame is likely to cause ignition and should be regarded as extremely hazardous.

Glowing or smouldering can arise in a variety of ways which include direct heating of the material, ignition of the material by flame followed by extinction of the flame, contact with another smouldering material or friction of impact. The subsequent ignition of a dust suspension can then be caused by:

- The dust suspension coming into contact with glowing or smouldering material deposited on the surface.
- The smouldering being converted to flaming by the action of an air flow, the flame then igniting the dust suspension.
- The glowing or smouldering material itself being dispersed into a dust cloud producing a flame.

Because of the ease with which glowing or smouldering can be converted into flame, they should be regarded as ignition sources of comparable hazard to flames.

Ignition by hot surfaces may be appreciably slower than with flames, etc. but the dust may be in contact with the surface for a much longer time. For surfaces whose temperatures can be controlled, such as heaters and driers, a maximum permissible surface temperature may be definable[1]. Account must be taken of the fact that the ignition temperature of dust layers falls as the layer thickness is increased. In situations where the surface temperature cannot be controlled, as with an overheated bearing, accumulations of dust should be minimised. The use of temperature sensors to detect overheating is advisable. Lighting fittings and lamps, particularly of the filament type, can be expected to heat appreciably whilst running and permanent fittings should be mounted external to the room, bin, etc. containing the dust, separated by a dust-tight armoured glass window. Inspection lamps attached to wander leads are hazardous and should not be provided; the hazard arises because the heated lamp may come into direct contact with dust whilst inspections are being made and also because the lamp may be inadvertently left switched on in the enclosure and subsequently buried in dust.

Welding and cutting lead to localised heating of plant, which is known to have caused dust explosions and fires. Similar hazards arise from operations such as soldering, burning and the use of power tools. It is important that an adequate safety procedure should be laid down when welding and cutting are to take place because of the known explosion and fire risks entailed.

Sparks arising from friction or impact are usually considered

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together because of the difficulty of differentiating between them in many practical cases. There is strong evidence from industrial experience that such sparks are able to ignite dust suspensions, particularly where machinery or powered tools are involved. Sparks can also arise because of the introduction of foreign objects such as metal or stones into mills, etc or by the breakdown of plant so that the fragments from it are subject to mechanical action.

Electric sparks can arise from two principal origins, electric power and electrostatic charging. Electric power, from the mains or batteries, is a powerful source of ignition because the energies available are usually greatly in excess of those required to ignite dusts unless special precautions have been taken in the design of the equipment. The production of hazardous sparks from electrostatic charging of dusts has been studied for many years. It is common knowledge that in the processing, transportation and general handling of dusts, electrostatic charges are generated. Although dust particles in suspension are very likely to be charged, there is no definite experimental evidence to prove that a discharge from one particle to another in the suspension can cause ignition and lead to the generation of explosions throughout the suspension. But this mechanism has not been definitely disproved either and so must remain a possibility, particularly in large scale installations. The greatest danger from static electricity probably arises because of the transfer charge to isolated metallic conductors that are not bonded to earth. Such conductors can store enough electrical energy to exceed the minimum ignition energy of the dust, and so can cause ignitions on sparking to earth. Isolated metal units in a dust handling plant are hazardous and must be prevented, by stringent bonding of all components to earth.

Spontaneous heating can arise if a dust undergoes chemical reaction with the surrounding atmosphere, or if it is unstable and decomposes producing heat in the reaction. The extent to which the heat can raise the temperature of the dust depends upon its rate of generation and the rate of loss to the surroundings. Under favourable conditions, heat generation can exceed the rate of loss so that the temperature of the dust rises, and reaction then accelerates. If heat generation always exceeds heat loss, the rate of heating accelerates to a runaway condition and eventually spontaneous ignition will occur. From tests on dust specimens heated in an oven, mathematical analysis now permits predictions to be made of the spontaneous heating behaviour of large heaps such as may be deposited on the walls of a drier .

Protection against dust explosions and fires

The main methods of protection against dust explosions are the prevention of its development, by automatic suppression or by the use of inert gas, or the control of the explosion pressure to a safe level by relief venting. The choice of approach depends upon the design of the plant, its situation and economic factors. Generally, relief venting is relatively cheap, provided the plant is of convenient design and situation. It is likely to be considered every time a new plant which needs this protection is designed.

Relief venting involves provision of apertures on the plant, or in a building, so that if an explosion occurs and the pressure starts to rise, the increase is limited to a predetermined value. This limiting pressure is related to the strength of the structure. Both the area and the distribution of the vents are important. For normal working, the vents should be closed, to prevent emission of dust, but should open quickly as soon as the explosion is initiated. The combustion products must be discharged to a safe place. Vents should be situated near positions where the sources of ignition are likely to be.

At present in the United Kingdom, the area of vent prescribed is on an empirical basis using the vent ratio, which is the area of relief vent per unit volume of plant. Guidance on the value of vent ratio can be obtained from the test giving measurements of the maximum rate of pressure rise, and from Table 1. If the rate of pressure rise is greater than 85000 kN/m^2s (12000 lb/in^2s), serious consideration should be given to alternative methods of protection. For other dusts, it is customary to reduce the vent ratio as the volume of plant is increased much above 30 cubic metres. If, because of difficulties in the geometry, the full area of vent cannot be provided, then the strength of the plant may be increased to withstand the pressures expected from smaller vents. The extent of strengthening cannot at present be classified accurately but there is evidence that the explosion pressure would vary inversely with the square of the vent ratio. The matter is discussed in more detail elsewhere[1].

Table 1 – Guide to vent ratios for dusts of different explosibilities

Maximum rate of pressure rise		Vent ratio	
kN/m^2 s	*lbf/in^2 s*	*m^{-1}*	*ft^{-1}*
< 35,000	< 5,000	1/6	1/20
35,000 -70,000	5,000 -10,000	1/5	1/15
>70,000	>10,000	1/3	1/10

The vent ratios in Table 1 are of mainly empirical origin, although some data have also been obtained from experiments on cubical enclosures up to 6 cubic metres volume. For other geometries, such as long ducting, connected vessels, cyclones and filter units, a limited amount of experimental information is again available but each instance is best dealt with individually.

If the conveying gas in a collector system can be recycled, the use of inert gas instead of air to convey the dust can be considered. The technique is specialised and great care should be taken in the positioning' and design of appropriate oxygen monitoring equipment. These monitors are particularly necessary if it is not possible to displace all the air from the plant, and a reduced oxygen level is used. Specialist advice should be obtained for any such installations, particularly as great reliance has to be placed on the instrumentation, and it may be desirable to ensure that the plant should shut down automatically in the event of any malfunction.

Automatic explosion suppression systems work on the principles that the flame is detected at a very early stage, a fraction of a second after it has been generated, and a suppression agent is injected into the plant to quench the explosion. Detection is usually by pressure sensors or radiation from the flame, and the suppressant is either a halogenated hydrocarbon or a gas such as nitrogen under high pressure. As soon as the explosion is detected the suppressant is discharged into the unit by the firing of detonators. Using this technique, explosion pressures can be kept sufficiently low to protect weak plant, even though no venting may be present. A system is available commercially and its installation is usually commissioned from the manufacturers. It has the advantage that warning is automatically given of any incipient explosion, and the system can be designed to shut down the plant automatically. Additional facilities enable the spread of explosion from one unit to others to be prevented and for valves to be actuated automatically. Installation is a job for a specialist because it is most important that the incipient explosion is completely quenched and cannot propagate, even slowly, into neighbouring units which are not adequately protected.

Protection against fires in dust layers is obtained firstly by attempting to avoid the presence of sources of ignition such as flames, hot surfaces, sparks, etc. This approach cannot, however, give complete protection and further consideration must be given to the fighting of fires should they develop.

The most common extinguishing agent for dust fires is water, but all agents should be applied with caution to avoid disturbing the dust into a cloud because burning material is present and may cause an explosion. Water should not be applied from high pressure jets to dust, but a low pressure spray should be used instead. The spray wets the deposit and causes it to become more cohesive, thereby reducing the likelihood of accidental dispersion of the dust. With thick layers, water applied as a spray may not penetrate into the mass of the dust, and it may be necessary to resort to digging with the continued use of the spray in order to extinguish all burning material. Attempts to speed up fire fighting, by disturbing the dust, are likely to increase the hazard due to explosion and should be avoided. With certain dusts, particularly metals, the use of water would be hazardous and it may be necessary to contain the fire and to allow it to burn out over a period of time.

Case histories

1. Whilst the premises of a kitchen equipment manufacturer were closed for the annual holidays, a maintenance man carrying out repairs in the metal polishing shop lit a cigarette and carelessly discarded a lighted match. The standard of housekeeping was inadequate and dust on the floor caught alight, the fire spread rapidly to machinery. Three firemen were injured when a dust explosion occurred in the dust extraction ducting. Most of the machinery in the section was severely damaged and part of the roof destroyed. Slight damage by fire occurred to other parts of the building.

   Note: Highly flammable dust and fluff can be produced by the tools for metal polishing, in addition to metal dust from the workplace. Management had not ensured that maintenance staff were aware of the high explosion risk.

2. During milling, a chemical caught fire in a mixer installed directly after the mill. The cause was probably a piece of metal which passed through the preliminary crusher and entered the mill. The fire was extinguished immediately by the permanently installed quenching system, so that no serious damage was done.

   Note: Although the primary cause of the fire was frictional impact in the mill, the fire was established in the next unit. It is common for fires or explosions originating in mills to produce their most damaging effects in other plant units downstream.

3. An explosion occurred shortly after starting up a fluidised bed drier. No-one was injured but considerable material damage was done. The charge in the drier weighed about 120 kg and contained approximately 12 kg of ethanol as well as various chemicals, sugar and sodium bicarbonate. The drier was fitted with a relief vent, opening into the work area (not a good idea). A large number of earthing rods were fitted in the inside of the drier and the nylon filter bags were provided with separate earthing wires. A large filter box for fine dust was installed after the drier. The suspected cause of ignition was a screw, which become loose in the roof of the drier and fell into a filter bag where it may have acted as a condenser which provided a hazardous electrostatic spark.

   Note: Static electricity is a particular hazard where a flammable solvent, which has a relatively low ignition energy, is present with powdered solids which act as static electricity generators when moved.

4. Several fires have occurred in the spray drying of human and animal foodstuffs. Layers of dried material can build up on the upper part of the walls or on the roof of the drier although the atomiser and the flow of drying air should direct the product downwards. Unless deposits are removed regularly, they may overheat and eventually spontaneously ignite, even though the oxygen concentration in the drier is depressed by steam formed during the drying process. Burning dried product can also be transferred downstream to further plant units.

   Note: Black specks in the product from a spray drier are important evidence of malfunction.

5. In a sugar refinery, the product was conveyed the full height of the 13-storey building by two bucket elevators. Two minutes after one of the elevators had been switched on, following a nine-day shutdown, an explosion occurred. It appeared that sugar had accumulated in the elevator boot from another part of the plant. This put abnormal strain on the elevator which had to dredge through this accumulation, causing a maladjusted tensioning device to fail. The elevator ran severely out of alignment and rubbed hard against the bucket guides and was struck heavily by the sprocket wheels. The heat generated by friction between the various metal surfaces was sufficient to ignite a cloud of sugar dust. The elevator duct and parts of the associated ventilation and sieving plant were severely damaged in the explosion. Some window frames and many of the windows were blown out and internal partitions were damaged by blast. Two employees were severely burnt.

   Note: If not properly adjusted and maintained, bucket elevators can generate friction and impact, and as there is often a cloud of dust in suspension in the casing, the conditions for dust explosion are readily obtained.

6. During the maintenance of a spray drier for dairy products, the atomiser was given too much lubricating oil. The oil

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soaked into powder deposited on the underside of the roof of the drier and during subsequent operation, the oil-soaked powder spontaneously ignited. The burning material fell to the bottom of the drier, but fortunately no explosion occurred. However, the entire batch of product had to be discarded.

Note: There was insufficient supervision of the maintenance staff, who were unaware of the potentially serious consequences of an apparently slight mishap.

7. Men returning from a meal break smelled burning and saw flames coming from the base of a 100-ton silo, which was on the eighth storey of a building and extended to the tenth storey. The silo was being filled by a worm-screw with animal feedstuff, thus creating a dust cloud. The men's immediate reaction was to switch off the silo light, as it was a common occurrence for the dust to ignite on contact with a lit silo light bulb. However, before this could be done, the dust cloud inside ignited and an explosion occurred. The light bulb was situated in a well, but the thick protective glass was missing and dust therefore came into contact with the hot bulb. The fire subsequently spread over four storeys of the 11-storey building and further explosions occurred.

Note: Ignition of dust by electric light bulbs, particularly those on wander leads, has often been reported. Bulbs overheat when insulated with dust, but the hot glass can ignite the dust before the filament burns out.

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Loss Prevention Panel comment

I have been responsible for something over 1,000 dust explosions. The responsibility for that lies, at least in part, with LPB and the first article on dust explosions published in the eighth edition of LPB in April 1976. I should hasten to explain that "my" explosions were all small scale and nearly all were done inside laboratory apparatus for testing and characterising the explosive properties of dusts. The others were done using custard powder, a large tin can with a push-fit lid, an old football, a long length of plastic instrument air piping and a candle. The trick there was to seal the burning candle and custard powder in the can and then — at a safe distance — jump on the football with the far end of the piping pointing at the custard powder. The candle ignites the dust cloud and the lid of the can flies a satisfying distance into the air followed by a significant fireball. It was great fun but, more to the point, served as an excellent way of demonstrating to operational staff the danger, and power, of dust explosions.

I joined the chemical industry in late 1976 and the safety officer had a subscription to LPB with copies passed round all the professional staff. The company made or used lots of powders and — at least in part from reading about dust explosions in LPB — it was realised that for many, perhaps most, there was no good dust explosibility data. As a new recruit I got the job of setting up a testing facility and then found myself with the job of working through the powders handled on site.

One of the first materials I tested (meta Nitro-Paratoluidene - mNPT) was a bright yellow, solid compound. It was produced as a flake but sold as a powder, produced by grinding in a pin mill. I tested the material and found the powder was highly explosive. Whilst I was writing up my report at the end of the month the plant, after ~20 years of operation, blew up on the night shift. Fortunately there were no casualties but there was a large, singed yellow stain on the outside of the (bent) production building. And no production for several months. Lesson 1: if you find something is a significant hazard, let people know straight away!

Throughout LPB's history and my working lifetime, dust explosions have continued to be destructive and deadly. In the early years of LPB's existence there were quite a number of articles on the developing understanding of dust explosions and codification of protection methods. The basic science of testing materials for their explosive properties and the provision of passive protection by fitting appropriate explosion relief vents (venting to a safe place) has not changed much and the early articles continue to be worth reading. The very first article[1] remains a readable introduction to the subject, it opened my eyes to something I knew nothing about. The author is not credited but I wonder if it was Ken Palmer of the UK Fire Research Station (FRS)? His book "Dust Explosions and Fires" was published in 1973 and was a first in this field.

The 1970s and 1980s were a period of active research and development around dust explosions, particularly in Germany, Switzerland and the UK. Germany published guideline VDI 3673 on dust explosion testing and venting in 1977, with a US NFPA guide (NFPA 68) following in 1978. In Switzerland, Sandoz and the Swiss Federal Institute worked together to improve testing methods and that led to W Bartknecht's book "Explosions: Cause, Prevention and Protection" in 1981. Peter Field from the FRS followed that with his book "Dust Explosions" in 1982.

Finally IChemE collaborated with HSE and the British Materials Handling Board to produce a three volume "Guide to Dust Explosion Prevention and Protection", with sections by Clive Schofield, John Abbott and Geoff Lunn which surveyed the whole field. LPB covered these developments in articles by G Butters[2] and P Field[3]. The articles are accompanied by a typical "phlonce" cartoon which makes a good point (It's very often the dust outside the equipment that kills) in a memorable way, but also serves to remind us how male dominated and sexist engineering was only a generation ago!

LPB has reported on numerous dust explosion incidents; perhaps the chemical industry has learned something as most of them seem to be in food or other industries. Martin Glor's paper[4] does cover two chemical industry events caused by static. It also includes a useful method for analysing incidents where static is thought to be the cause. The destructive power of dust explosions is emphasised by Frederic Gil's paper on the Blaye grain silo explosion in 1997. That explosion killed 11 people in Bordeaux, destroyed or damaged 28 reinforced concrete silos, and projected debris over 140m, damaging the adjacent chemical company[5]. The way incidents can repeat when we fail to learn is emphasised in the article on explosions in sugar refineries in the "Lessons not learned" series[6]. The two accidents are distressingly similar both having the familiar double explosion scenario: a small explosion shakes a building with poor housekeeping; that raises all the dust present into a building-filling cloud; this second, larger cloud ignites with devastating consequences. Keith Wilson's article about a fire in custard powder handling plant[7] underlines this point — the plant's scrupulous cleanliness meant that no secondary cloud was formed and this almost certainly saved the lives of those in the plant.

Finally, two papers which emphasise the relationship of dust explosions to process safety. The first by Andrew Dickens[8] discusses the need for dust explosion data when formulating the basis on which safe plant operation will be achieved. The second, from Stephen Rowe and colleagues[9], emphasises the need for process safety systems in the food manufacturing industry, referring to what is probably many people's favourite product - chocolate!

Ken Patterson

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Flixborough: Lessons which are still relevant today

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Summary

After 40 years, Flixborough still ranks as the worst mainland process plant disaster in the UK. The paper will review the official report into the disaster and, drawing on current standards and more recent incidents, will consider how relevant the lessons are to the process industry today. Aspects which will be covered include:

- the control of modifications;
- understanding of vapour cloud explosions;
- occupied buildings;
- competence and organisational change;
- safety culture.

Particular emphasis will be given to issue of management competence and the organisational changes that took place on the site before the incident occurred. It will question whether the systems advocated today would be fully effective in dealing with the unplanned changes that were at the root of the disaster.

Keywords: Flixborough, modification, management of change, explosion

Introduction

Flixborough was not the first serious accident to occur in the process industries during the 60's and 70's. It did however result in a step change in the consideration of process safety and introduced changes that are still relevant forty years later.

Interest in process safety had started before 1974. The IChemE Hazards series of symposia started in 1960 and the first symposium of the European Federation of Chemical Engineers (EFCE) Loss Prevention Working Party was held in May 1974. The Loss Prevention Journal was being published by the American Institution of Chemical Engineers; within ICI HAZOP was already a well-established procedure in the design of new plant and Trevor Kletz was producing his Safety Newsletters.

Flixborough was not only the most serious incident to have occurred in the UK process industry, it was also one of a series of serious explosions and fires that occurred during the 1970's in both Europe and the USA. As noted in the reports of the Advisory Committee on Major Hazards the capacity of some hydrocarbon processing units had increased tenfold in the twenty years prior to 1975 (ACMH First & Second Reports[1]).

Following Flixborough there was a significant increase in the attention given to process safety. The Loss Prevention Bulletin (LBP) was first published in the months following Flixborough[2]. The Health and Safety at Work Act was introduced into the UK and the Advisory Committee on Major Hazards was established towards the end of 1974 to advise on '...measures to control.. such installations'. This led to the establishment of the Notification of Installations Handling Hazardous Substances Regulations, a predecessor to the Seveso Directive and the UK COMAH Regulations.

This paper is based primarily on the findings of the Court of Inquiry[3] established following the explosion and will attempt to show how the lessons learned from the event relate to current good practice in process safety.

The explosion

A massive explosion equivalent to between 15 and 45 tons of TNT occurred at 4:35pm on Saturday 01 June 1974. The consequences were severe with 28 of those working on the site being killed, together with 36 onsite and 53 offsite injuries. It resulted in almost complete destruction of the plant and extensive offsite damage to approximately 2000 buildings. A brief recap of the main elements leading up to the accident is as follows.

The plant was operated by Nypro Chemicals which at the time of the accident was owned jointly by Dutch State Mines and the National Coal Board (NCB). The plant had been commissioned in 1967 to produce caprolactam, an intermediate in the production of nylon, a revised process introduced in 1972. A key part of the revised process involved the oxidation of cyclohexane by air in a series of six large reactors at a pressure of 8.8 kg/cm² and a temperature of 155°C, above its atmospheric boiling point. These reactors were inter-connected by 700mm diameter, metal expansion bellows to accommodate thermal expansion.

Two months prior to the accident at the end of March a crack was noticed on number 5 reactor and the plant was shut down. A meeting of the site management team agreed that the reactor would be removed and, to enable production to continue, a section of pipe was inserted between the bellows to take the place of the missing reactor. The modification was fabricated onsite without any engineering drawings, calculations or hydraulic testing, the new pipe was inserted, supported by scaffolding, and the plant restarted. No account was taken of the turning moment that would be placed on the new pipe due to flow of fluid and the process pressure or the fact that the bellows would be subject to shear forces for which they were not designed. The scaffolding support was completely inadequate to resist these forces.

The plant then ran without further problems until at the end of May when it was shut down again to repair a leak. Whilst the plant was being restarted the temporary bellows/piping failed, the temporary pipe jack-knifed and many tons of boiling cyclohexane were released. This rapidly created a vapour cloud which ignited with a force estimated to be equivalent to between 15 and 45 tons of TNT.

The inquiry examined in detail an alternative scenario involving the initial failure of an 8" (200mm) pipe. Examination of this alternative scenario, which was dismissed by the inquiry as highly improbable, has been discussed elsewhere and is beyond the scope of this paper.

Management of change

The Court of Inquiry found the direct cause to be the release and explosion of cyclohexane

> *'….. caused by the introduction into a well designed and constructed plant of a modification which destroyed its integrity.' As noted above there was little or no engineering consideration of the way in which this pipe should be designed and installed or of the fact that the bellows were being subjected to forces outside of their design range.*

Two of the Court's recommendations key recommendations were:

> *that any modifications should be designed, constructed, tested and maintained to the same standards as the original plant.*
>
> *that all pressure systems containing hazardous materials should be subject to inspection and test by a person recognised by the appropriate authority as competent after any significant modification has been carried out and before the system is again brought into use.*

Whilst these are important recommendations, they do not cover all the factors that need to be considered when making changes to a plant or process. The first reference to the importance of having a robust Management of Change procedure is an article in issue 1 of LPB *Are your Plant Modifications Safe?*[2] This article includes a range of case studies covering changes to piping and valves, change of process materials and incorrect materials of construction. It finishes with a recommendation that:

> *On each works there ought to be a system for checking expenditure proposals, however small, to make sure that the correct materials are specified and that there are no unforeseen effects on the relief and blow-down system, trip system, area classification, and other safety systems.*
> *Such formal systems should require that all plant design, minor modifications, changes in process conditions, changes in operating procedures, changes in material composition are subject to thorough Hazard & Operability Studies.*

The above is extremely close to the MOC procedures used today. The application of such a system at Flixborough, together with measures recommended by the Court to ensure that sound design principles were applied to changes, would almost certainly have prevented the disaster.

The importance of robust MOC procedures is now well understood in the process industry and current best practice, such as in an IChemE training module[4] would include all of the above with the addition of changes to computer programmes, temporary changes as well as organisational change (an issue touched on later in this paper).

Despite this, incidents due to poor control of changes continue to occur, recent examples being those at Texaco, Milford Haven refinery in 1994[5] and at the Conoco Phillips Humberside refinery in 2001[6].

Understanding of Unconfined Vapour Cloud Explosions

Whilst there had been unconfined explosions causing significant damage before Flixborough, such as that which resulted following the failure of a LNG storage tank in Cleveland Ohio in 1944[7], methods for estimating the potential consequences were not in common use.

As noted in the by the Court of Inquiry:

> *"Although unconfined vapour/air explosions have been known to happen in other parts of the world, there is a marked scarcity of information about the conditions under which an unconfined vapour cloud can result in an explosion or what is the mechanism leading to such an explosion. We do not know to what extent it is practicable to obtain this information but if it can be obtained it would clearly be useful.*

One of the earliest approaches to determine the consequences of an explosion relied on the TNT equivalent method first described by Brassie & Simpson in 1968[8], six years before the Flixborough Explosion. In the days shortly before Flixborough took place, a paper was presented at the first International Symposium on Loss Prevention and Safety Promotion in the Process Industries exploring a vapour cloud explosion in 1968 at a Shell refinery in Rotterdam[9]. The subject was very unclear at the time. In their paper, Brassie & Simpson described the results obtained by studying the records of damage from a number of large scale explosions in order to estimate an empirical efficiency factor that could be used to convert the energy contained in gas cloud into a TNT equivalent. Tables derived from the explosion of munitions were then used to determine the extent of damage at various distances from the point of explosion. Flixborough spurred further work on flammable gas clouds and the understanding of these events, which was still incomplete even up to time of the Buncefield explosion in 2005.

Three years after Flixborough, at Hazards VI, papers on flammable gas clouds were presented by Clancy & Burgoyne[9] as well as Marshall and Burgoyne. In Clancy's paper, a method is developed to calculate the maximum quantity of vapour within the flammable region from the quantity of flammable gas or vapour released. The differences between condensed phase explosions and vapour cloud explosions means that, whilst the TNT equivalent may be used to estimate damage in the far field, it will overestimate overpressure in the near field since the peak pressure in the high density, solid explosive is roughly a thousand times higher than in an exploding gas, although the blast duration is relatively very short.

Research into vapour cloud explosions continued in the USA, UK and France during the 1970's. These provided the first indications that overpressures resulting from unconfined gas and vapour cloud explosions were generally low unless there was a strong ignition source coupled with some form of congestion, such as that provided by piping, vessels and steelwork, to introduce turbulence into the flame front. This is the basis of the multi-energy method developed by TNO. This overcame the limitations of the TNT equivalent method and provided the basis for a number of

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widely used computational fluid dynamic (CFD) models. The EU supported further work in the field throughout the 1980's and 90's which resulted in the validation of the Gexcon computer CFD code FLACS.

However these methods were not initially able to describe the extent of the damage which resulted from the Buncefield explosion in 2005. More detailed work was required in order to demonstrate how a number of factors, including the composition of the gasoline, the tank overflow arrangements, the weather at the time of the release as well as the trees inserted to provide a visual screen, all interacted to accelerate the flame, and thus contributed to the severity of the event. Whilst work carried out post-Buncefield greatly improved the methods available to estimate the consequences of a vapour cloud explosion the question as to whether the cloud produced a fast deflagration or a detonation is still not resolved. Large scale releases of flammable materials continue to occur resulting in flammable vapour clouds and explosions as for example at Conoco/Phillips (1989), Texas City (2005) and Jaipur (2009), see Johnson[10].

It is clear that great caution and expertise must still be used before concluding that severe consequences cannot arise following a large flammable release.

Occupied buildings

Prior to 1974 unconfined explosions on the scale of Flixborough were not generally taken into account in the design and location of control rooms and other occupied buildings. In addition there were features in the design of the buildings at Flixborough which contributed to the high number of fatalities, features which were common in many plants designed up to that time.

The control room was located close to the plant for operational reasons. However the building offered no protection against even small overpressures and the design of the building, with brick walls and the control room located on the ground floor beneath a heavy concrete floor, exacerbated the condition leading to such a high death toll. None of the 18 people in the building escaped. The plant laboratory suffered from similar deficiencies. The fact that the accident occurred at a weekend when the office block, which was also destroyed, was unoccupied prevented a much higher toll of casualties.

In their report the Court of Inquiry referred the topic of occupied buildings to a special committee (ACDS) noting that:

> *"Many suggestions were made to us as to the consequences which should follow from taking account of such a possibility. These included: the siting of offices, laboratories and the like well removed from hazardous plants; the construction of control rooms on block-house principles….."*

Following Flixborough, the Chemical industries Association developed guidance on the location and design of occupied buildings, the first edition being published in the late 1970's. Protection against overpressure was commonly incorporated into control rooms designed post-Flixborough and many control rooms on existing facilities were rebuilt to provide similar protection. Despite this, explosions and fires caused fatalities in occupied buildings in the case of Hickson & Welch[11] and BP Texas city Refinery[12].

Development of the CIA Guidance has continued with the 3rd edition being published in 2010, an overview being provided by Coates & Patterson at Hazards XXII [13,14]. Current good practice, as defined in the guide, recommends that organisations have a policy on occupied buildings incorporating the following hierarchical approach linked to inherent safety, an example of such a policy being given below.

> *The protection of people on chemical manufacturing sites should adopt the following principles:*
>
> *Wherever possible, locate people away from chemical processing and storage unless their presence is required for safe, effective operations*
>
> *Control the risks during storage and all operational phases by efficient and effective process safety management*
>
> *Ensure that the on-site buildings are located and designed to minimise the risks to the occupants by:*
>
> - *Carrying out an appropriate risk assessment for the buildings, and*
> - *Applying the results of the risk assessment to the design and continued operation of the buildings.*

The latest guidance makes it clear that all buildings which may be occupied even for limited periods of time, such as maintenance facilities, shift laboratory facilities and small on-plant control stations, need to be considered and an Occupied Buildings Risk Assessment prepared where appropriate. Whilst protection against explosion overpressure remains an important consideration the assessment also needs to consider other hazards such as thermal radiation and toxic gas.

The explosion and fire at BP's Texas City refinery highlighted the importance of considering explosion overpressure in the location and design of temporary buildings as well as the importance of reducing the number of personnel exposed during high risk periods such as plant start-ups.

Management competence

The Court of Inquiry highlighted the deficiencies in management at Nypro Chemicals which contributed to the incident. The Works Engineer, who had been a chartered mechanical engineer, had left the site some time before the incident. The Services Engineer, who was a non-chartered electrical engineer with an ONC qualification, was given a co-ordination role managing day to day maintenance activities; however, his training did not equip him to assess even straightforward mechanical engineering issues. Although arrangements had been made to make expertise in mechanical engineering available from the NCB these were not called on when the modification was made.

During the meeting to discuss what action to take following the discovery of the cracked reactor:

> *No-one appears to have appreciated that the connection of No. 4 Reactor to No. 6 Reactor involved any major technical problems or was anything other than a routine plumbing job, and the possible design problems and design alternatives were not discussed. Even the fact that the inlet and outlet of the by-pass pipe were at different levels was not appreciated at the meeting;*

To quote from the report:

> *'….none of the senior personnel of the company, who were chemical engineers, were capable of recognising the existence of what is in essence a simple engineering problem let alone solving it'.*

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It is also surprising that the plant was restarted without any action being taken to assess the cause of the crack in reactor 5. The crack was massive, 1.8 metre long and extending through the full 95mm thickness of the vessel wall. As noted by the Inquiry a crack of this size could have led to a disastrous failure of the vessel with a major loss of containment and consequences as severe as the eventual explosion.

The report notes that:

> *...no-one at the meeting, save Mr Blackman, (the engineer responsible for areas 1 & 2) was seriously concerned about the wisdom of restarting without both:*
>
> *(a) ascertaining the cause of the crack to Reactor No. 5 and*
>
> *(b) stripping and inspecting the other five reactors to ascertain whether any of them exhibited similar faults, albeit not yet sufficiently developed to cause actual leakage;*

The inquiry was clear that good practice, exercised by a properly qualified engineer, would have called for the plant to be shut down until it had been established that the other reactors were sound and free from defects. Such a shut-down would have provided more time to consider the design of the by-pass.

The Court made two recommendations in this area.The first recommendation was that:

> *'... when an important post is vacant, special care should be exercised when decisions have to be taken which would normally be taken by or on the advice of the holder of the vacant post.'*

It also recommended that:

> *... it is essential that the management structure should be so organised that the feedback from the bottom to the top should be effective to ensure not only that instructions given are effectively carried out (although that is essential) but*
>
> *(a) that persons given certain responsibilities are competent to carry out those responsibilities,*
>
> *(b) that top management has a clear understanding of the responsibilities of individuals and the magnitude and type of demand made upon them, and*
>
> *(c) that top management has a clear knowledge and understanding of the total work load placed on each individual in relation to his capacity. Even good and competent individuals have increased potential for errors of judgement when overworked. Also, in times of crisis and extreme demand it is easy to overwork the willing horses some of whom may not know their own limitations.*

These recommendations are likely to have been influenced by the findings of the collapse of a spoil tip in Aberfan in 1966, which took the lives of 116 children and 28 adults[15]. The lack of technical competence was also at the heart of this disaster:

> *' .... the Aberfan Disaster is a terrifying tale of bungling ineptitude by many men charged with tasks for which they were totally unfitted, of failure to heed clear warnings, and of total lack of direction from above. Not villains but decent men, led astray by foolishness or by ignorance or by both in combination, are responsible for what happened at Aberfan".*

The Courts recommendations are still relevant today with the current recognition that sound management systems are at the heart of process safety. It is reflected in the OECD guidance for senior leaders in high hazard industries *Corporate Governance for Process Safety*[16] where competence is one of the five key areas with a recommendation that:

> *'CEO and leaders assure their organisation's competence to manage the hazards of its operations, and:*
>
> *Ensure there are competent management, engineering, and operational personnel at all levels. '*

As noted previously, the control of organisational change is as important as the control of changes to the plant or process. The management deficiencies at Aberfan were the result of a reorganisation and would be identified by the procedures for control of organisational change advocated today[17]. The changes at Flixborough were however imposed on the organisation by the resignation of the works engineer and would not necessarily trigger a MOC review. It is therefore important that the organisation has the resilience to ensure that the required technical competencies are available when required. Absence of one individual, whether due to resignation, accident or illness, is to be expected and the management organisation must be able to cover such situations. Within large organisations, the necessary expertise may be available from elsewhere in the organisation but smaller organisations may need to call on consultants.

Competence is still a topic of concern and an HSE report[18] notes that:

> *'a review of major accidents across hazardous industries found that a lack of competence contributed to many of those incidents including:*
>
> *Southall Rail Crash; BP Texas City; Piper Alpha explosion and fire; the Esso Longford Gas plant explosion; and Buncefield.'*

An important aspect of competence is an understanding of the limits of that competence and the recognition of those situations when the advice of others needs to be sought. The integrity of the other reactors should have been confirmed by an expert before restarting the plant. In addition, those involved in fabricating the temporary pipe did not recognise the need to evaluate the turning moment which was imposed on the pipework from the fluid flow and the internal pressure nor the fact that the bellows should only be subjected to axial loads.

This is covered by the HSE in its guidance to inspectors[18], which requires that

> *'The Operator has arrangements in place to ensure that individuals only perform activities that they are competent to carry out. Personnel and their line managers should know which activities personnel have been assessed as being currently competent and authorised to undertake. Personnel should be made aware of the importance of only carrying out those activities for which they have been assessed as competent and for which their assessment is current.'*

Had such arrangements for staff competence been in place at Flixborough at the time of the disaster, coupled with an effective management of change procedure, it is highly unlikely that modifications would have been made without adequate mechanical design, and the disaster would have been prevented.

A second, longer term, recommendation of the Court of Inquiry was that

> *'All engineers should therefore learn at least the elements of other branches of engineering than their own in both their academic and practical training.*

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Traditionally engineering courses have required a certain amount of basic engineering, mechanics etc. as part of the first or second years. Whilst many universities retain this, there are many pressures on the curriculum as process engineering increasingly includes more computing, management and elements of life science. An associated problem is that with the increasing importance of research in university funding, academic staff are much more likely to be employed because of their research speciality rather than a practical knowledge of engineering. In addition few mechanical, electrical or civil engineering courses include any consideration of process safety. It is therefore questionable as to whether university courses can be relied on to equip a graduate with all the skills necessary for work in the process industry. This demonstrates the importance of post-graduate training, such as IChemE's *Fundamentals of Process Safety* course.

As fundamental science becomes more important, engineering institutions, such as IChemE, may need to review whether their membership requirements continue to ensure a competence in basic engineering.

Safety culture

The importance of an organisation's safety culture was first recognised following the Chernobyl nuclear reactor explosion and meltdown in 1986, so it is not surprising that it is not mentioned in the Court's report. Whilst we must always be cautious in applying current standards to actions carried out in the past it is interesting to attempt to assess the safety culture which applied at Flixborough.

The Court's report makes a number of references to the level of safety at the Flixborough site, many of which appear contradictory to today's reader.

There are a number of positive comments:

> *There can be no doubt that Nypro were very safety conscious and that Mr Brenner (Safety & Training Officer) was an able and enthusiastic safety and training manager. He had created a proper system for dealing with normal hazards*
>
> *At no point in the inquiry was there any evidence that the chemical industry or Nypro in particular, was not conscious of its responsibilities relative to safety. On the contrary, there were indications that conscious and positive steps were continually taken with this objective in mind.*
>
> *We repeat that there was no evidence whatsoever that Nypro placed production before safety.*
>
> *We entirely absolve all persons from any suggestion that their desire to resume production caused them knowingly to embark on a hazardous course in disregard of the safety of those operating the Works.*

The above comments do not align with other comments in the report and at no point is there any mention of systems to manage process safety. There were serious omissions during the management meeting which decided to install the by-pass and despite the above comments it is clear that at certain critical times process safety was either not considered at all or given a lower priority than production.

> *the emphasis at the meeting was directed to getting the oxidation process on stream again with the minimum possible delay. no-one at the meeting, save Mr Blackman, was seriously concerned about the wisdom of restarting without …inspecting the remaining reactors.*
>
> *We have no doubt, however, that it was this desire (to resume production) which led them to overlook… that it was potentially hazardous to resume production without examining the remaining reactors.…*
>
> *We have equally no doubt that the failure to appreciate that the connection of Reactor No. 4 to Reactor No. 6 involved engineering problems was largely due to the same desire.*

We cannot rewrite history and neither Nypro nor its management were accused of breaking any of the laws or regulations in place at the time, prior to the implementation of the Health & Safety at Work Act with its wider management responsibilities. However recent inquiries, such that into Texas City or the Haddon-Cave Inquiry[19] into the explosion of an RAF Nimrod aircraft in 2006,have been much more critical of management deficiencies.

A commonly used model for assessing the safety culture of an organisation is the five step Safety Culture Maturity Model[20], developed for the HSE.

Level 1 Emerging
Level 2 Managing
Level 3 Involving
Level 4 Cooperating
Level 5 Continually Improving

Currently operators responsible for high hazard operations would be expected to be at or aspire to levels 4 or 5. However looking at the information available in the Inquiry report, Nypro, and possibly many other organisations in the 1970's, would appear as level 1 or level 2. From the information in the report the management at Nypro do not seem to have appreciated or understood the full extent of hazards of the process they were operating. There are no references to the characteristics one would expect to see today in a high reliability organisation, such as the lack of complacency, the feeling of paranoia that the next accident is just around the corner, the striving to be better and the drive to find better ways of improving hazard control mechanisms.

Conclusions

Flixborough, and the other serious incidents that occurred during the 1970's, contributed to significant changes in the understanding, management and regulation of major hazard processes.

Regulations for the control of major hazard processes, introduced through the Seveso Directive and COMAH, are now well established with a further revision due to be implemented in 2015.

Management of Change procedures are now common across the process industry and cover a wider range of changes such as organisational change, although this has not eliminated incidents.

Comprehensive guidance on the location and design of occupied buildings covering both permanent and temporary buildings is now available.

Work carried out in recent years has improved the understanding of unconfined vapour cloud explosions. However large flammable releases continue to occur and the complexity of the problem will continue to require great expertise.

Guidance for board members and senior management includes the importance of ensuring that appropriately qualified, competent staff are employed. Authorities, such as the HSE have developed detailed guidance. However the disperse nature of much of the industry and ongoing re-organisations means that this is an area which will continue to require close attention.

The importance of an organisation's safety culture is now appreciated and there are indications that the safety culture of organisations today is generally much better than it was at the time of Flixborough. However much still needs to be done, particularly to ensure that the board's perception of the organisations safety culture matches that at the operational level.

Acknowledgements

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Loss Prevention Panel comment

The Flixborough disaster is one which is engrained in the minds of all safety professionals. As Robin Turney's article[1] explains, it is still is and, I believe will always remain, a stark reminder of the consequences of ill-conceived and poorly executed plant modifications. The modification was not risk assessed. Indeed, there was nobody on site who had the mechanical engineering skills to properly assess the significance, the Chief Engineer having left the site some time before the incident. This catastrophic event highlights both the need to adequately risk assess plant modifications, and similarly to risk assess changes to an organisation. The article refers out to other accidents such as that at the Texaco, Milford Haven refinery in 1994[2] and at the Conoco Phillips Humberside refinery in 2016[3] where inadequate management of change was a causal factor.

The LPB archive has many more examples of accidents, which, whilst smaller in scale, still provide important lessons concerning the need to thoroughly assess the potential consequences of plant or organisational changes. This began as early as the first issue of LPB in the article 'Are your Modifications Safe?'[4] Other examples are: 'Lessons from a Management of Change Incident'[5], 'Beware Subtle Changes'[6] and 'Small or Big Changes, Managing them can be risky'[7]

In addition to articles which derive lessons learned from accidents, there are many which describe examples of good practice. Examples of these are: 'Organisational Change'[8] and 'Small or Big changes-managing them can be risky'.

Making changes to plants and organisations are an inevitable part of running a profitable business. They are carried out with the best of intentions, either to improve efficiency or safety. However, experience has shown how vital it is to have management systems designed and implemented by suitably qualified and experienced persons, which as far as possible, identify and adequately assess all the potential consequences of a change.

Geoff Gill

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Explosion at the Phillips' Houston chemical complex, Pasadena, 23 October 1989

Dr J Bond

Published in LPB097, February 1991

An abstract of the Report to the President by the US Department of Labour, Occupational Safety and Health Administration, April 1990

The plant

High density polythene is manufactured in Plant IV and V from ethylene gas dissolved in isobutane and reacted in long pipes under elevated pressure and temperature. Various chemicals are added to modify the polyethylene to meet the desired product characteristics. The polyethylene forms particles which settle out in legs of the reactor pipe and are drawn out of the legs through valves.

At the top of each leg is a ball valve (Demco brand) where it joins the reactor pipe loop. This ball valve is kept open during normal operation. Clogging of the settling legs occurs periodically and on these occasions the top Demco ball valve is closed and the leg removed to clear the blockage. The reaction is continued during this operation as the product is able to settle out in adjacent settling legs.

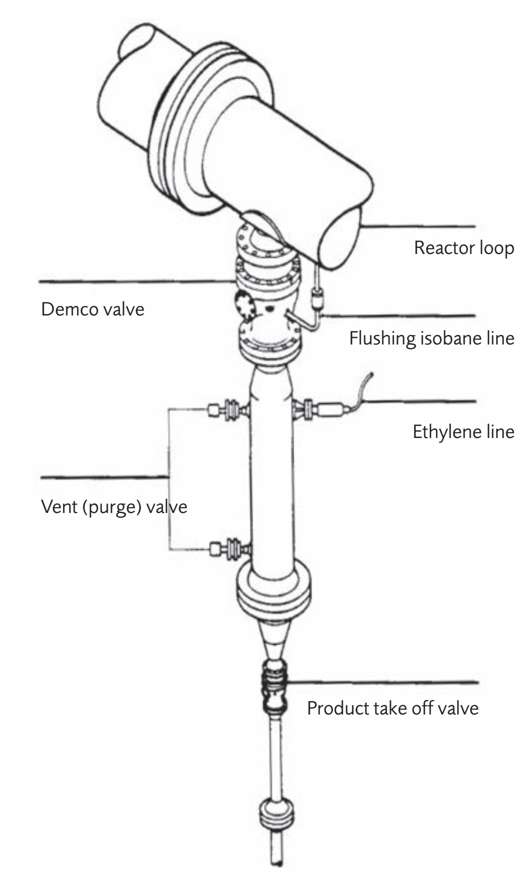

Figure 1: Typical piping settling leg arrangement

The accident

On Sunday 22 October, a contractor's crew began work to unplug three of the six settling legs on reactor 6. All three legs were prepared by an operator according to procedure with the Demco valve shut and their air operating lines disconnected. The maintenance crew dismantled the first leg and removed the blockage without incident. On Monday 23 October, work began to remove the second leg. Part of the blockage was removed but there remained a further blockage 30cm to 45cm below the Demco valve. A contractor went to the control room to seek the assistance of an operator when vapour was seen to be coming from the open pipe. 38,690kg of hydrocarbon came out in a very short space of time and formed a large semi-confined vapour cloud.

Within about two minutes the cloud was ignited by an unidentified source. Two other major explosions occurred after the first, one 10 to 15 minutes later when two 90,920 litre isobutane storage tanks exploded, and the other when a further reactor loop failed catastrophically about 25 to 45 minutes after the initial event.

Twenty three workers on the site were killed and more than 130 injured. All those who died at the scene were within 75m of the initial release.

Missiles from the explosion were thrown up to 9.5km into the neighbouring area. Two production units were completely destroyed causing $750 million of damage. The initial explosion had the force of 2.4 tonnes of TNT and measured 3.5 on the Richter Scale.

The response

The Phillips fire brigade provided the initial response with fire fighting equipment and first aid. Additional help was provided by the local emergency response units and by the Channel Industries Mutual Aid organisation which included municipal fire brigades, US Coast Guards and County Fire Departments.

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There was no dedicated water system for fighting the fire, only that which was tied into the process. Fire hydrants were sheared off by the explosion and the water system became ineffective. Water supplies had to be established from remote places including a neighbouring plant. Of the three diesel driven pumps on the site for fire purposes, one was out of service and one ran out of fuel. Electric cables supplying power to fire service pumps were damaged by the fire and could not be used. The fire was put out in 10 hours.

More than 100 employees escaped from the administration building by being ferried across the Houston Ship Channel by the US Coast Guard. Their normal route would have been through the area of the explosions.

The environment

Environmental tests were carried out during the fire by a mobile Air Control Board unit. There were no significant increase above normal levels and airborne levels of asbestos did not exceed the exposure limits.

24 sealed radiation sources were removed. It was determined that no employee or member of the public was at risk from radiation.

The investigation

The investigation was carried out by OSHA and established that the Demco valve was open at the time of the release. The air hoses which supplied air pressure to actuate the ball valve were found to be connected in a reverse manner such that the air pressure would open the valve even though the actuator switch called for the valve to be closed. The established procedure for carrying out maintenance work did not call for a backup isolation system.

Additionally, the following conditions were noted:

- The Demco valve actuator mechanism did not have its lock out device in place.
- The air hoses that supplied air to actuate the ball valve could be connected at any time even though the procedure required them to be disconnected during maintenance work.
- The connectors for the open and closed side of the valve were identical.
- The air supply valves for the actuators were in the open position so that on connection air would flow and cause the valve to rotate.
- The lockout mechanism for the valve was such that it could be locked in either position.
- The site layout with the proximity of normally high occupancy structures contributed to the severity of the event.

The findings

- The process hazards had not been identified nor the potential for malfunction established.
- The procedure for maintenance on the settling legs was inadequate.
- An effective safety permit system was not enforced for contractors or their own employees.
- There was no hydrocarbon detecting equipment to give early warning of release.
- Ignition sources were introduced into high hazard areas without testing for flammable gas.
- Buildings with people were not separated from process units in accordance with accepted engineering principles.
- Ventilation systems for buildings were not designed to prevent the ingress of gas.
- The fire protection system was not maintained in a state of readiness.

The citations

Citation for wilful violations with proposed penalties of $724,000 has been issued to the maintenance contractors for failing to obtain the necessary permits. Citations for serious violations for hazards involving inadequate respiratory protection and deficiencies in hazard communication programme were proposed.

Citations were made to the contracting company and to the Phillips 66 Company.

Pasadena and Flixborough compared

	Flixborough	Pasadena
Date	1/6/74	23/10/89
Substance	Cyclohexane	Ethylene/isobutane
TNT Equivalence	32 tonnes[1]	4 tonnes[2] 10 tonnes[3]
Fatalities	28	23
Injuries	89+	130
Lethal radius	125 metres[1]	75 metres[2]
Damage (trended)	$412 million[3]	$500 million + [3]

These two petrochemicals disasters seem to lie within the same severity bracket. Flixborough was probably the more violent explosion but property damage at Pasadena is likely to prove to be appreciably higher.

Pasadena would be a more sophisticated plant and a comparison of photographs suggests that the capital invested per unit area was higher than on the Flixborough site.

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Loss Prevention Panel comment

There have been many major incidents where maintenance work was a contributing factor to the incident. The fire and explosion at the Phillips site in Pasadena, Texas[1] resulted in 23 fatalities, 130 injuries and caused $750 million of damage. Maintenance work was being undertaken on three settling legs on Reactor 6 to remove blockages. Whilst work on settling leg 2, a large release of hydrocarbon vapour occurred which subsequently ignited. A key finding of OSHA was that the procedure for maintenance on the settling legs was inadequate. This article also compares the Phillips explosion to another well-known major industry accident – Flixborough[2]. Whilst that incident is always remembered as a prime example of how not to manage plant modifications, poor maintenance management practices were also a factor.

Another Loss Prevention Bulletin article 'The implication of maintenance in major accident causation'[3] discusses how maintenance activities have contributed to six other major accidents including Piper Alpha[4] and Texas City[5]. In both these cases, key deficiencies in the maintenance programs, including the planning and execution phases, were identified during the incident investigations.

As early as Loss Prevention Bulletin 004 (1975) important lessons from incidents relating to maintenance activities were being shared. The article 'Engineering Maintenance'[6] included examples of poor lock-out practices and lack of identification of equipment prior to maintenance. Other examples of maintenance related accidents in the LPB we can learn from are: 'A Pump Explodes'[7], 'Acid Burns to Face……. During Preparation…. for Maintenance'[8], 'The fire at Hickson and Welch'[9] and 'Communication – in brief'[10].

There are also several LPB toolbox talks on the LPB website (www.icheme.org/lpb) with examples of accidents and of good practice relating to isolation of equipment before maintenance and identification of equipment for maintenance.

Maintenance on a chemical plant is undertaken for a range of reasons – regulatory compliance, to ensure mechanical integrity and to maintain production rates or quality. Whatever the reason for the maintenance activity it can introduce hazards during all the phases of the work – from planning and preparation, through the maintenance work itself and following the restart of the equipment. These hazards must be properly risk assessed and then managed. If not managed appropriately there is the potential for a major accident resulting in serious injury or loss of life and environmental damage in addition to reputational damage.

Doug Reid

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Permits-to-work in the process industries

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Introduction

'Permits save lives — give them proper attention'. This is a startling statement made by the Health and Safety Executive (HSE) in its free leaflet IND(G) 98 (Rev 3) PTW systems. The leaflet goes on to state that two thirds of all accidents in the chemical industry are maintenance related, with the permit-to-work (PTW) failures being the largest single cause. Given these facts, it comes as no surprise that PTW systems are a key part in the provision of a safe working environment.

Over the past four years Environmental Resources Management (ERM) has been auditing PTW systems as part of its key risk control systems audits. Numerous systems have been evaluated from a wide range of industries, covering personal care products manufacturing to refinery operations. These evaluations have identified a number of common failings and with the same recommendations repeatedly being made. Interestingly, recently published guidance from the HSE (HSE 2005) has not addressed many of these failings. These failings and recommendations are summarised below.

Audit protocol

The audit protocol used by ERM is based on the HSE guidance (HSE 1997) *Successful Health and Safety Management*. The protocol breaks the risk control system into the six key elements described in the guidance. This structure is illustrated in Figure 1. The organisational element is further subdivided into four activities that are necessary to promote a positive health and safety culture. These four activities are:

- methods of control;
- means of securing co-operation between individuals and groups;
- methods of communication;
- competence of individuals.

Control, co-operation, communication and competence are collectively known as the four 'C's of safety culture. Information on these activities in one risk control system is often applicable to the organisation's whole safety management system and safety culture.

This format is also used for the assessment checklist in HSE's PTW guidance (HSE 2005). This format has been used in this paper to describe generic PTW failings and list commonly made recommendations.

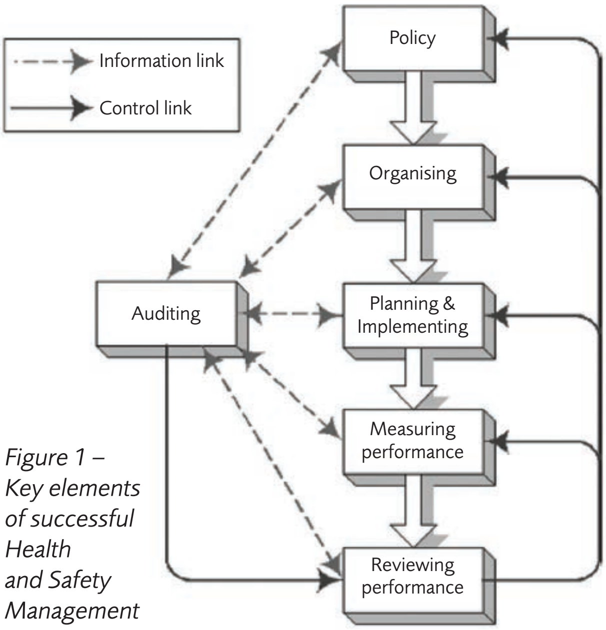

Figure 1 – Key elements of successful Health and Safety Management

Policy

The policy commonly referred to as aims or purpose, sets down the basis of the risk control system. A PTW system is a formal and recorded process to control hazardous work. The PTW system is much more than the permit form(s). A PTW system that fails to document its purpose is vulnerable to misinterpretation. It is common for the PTW policy (purpose/aim) not to be documented. Well-developed quality assurance systems often fail to address this failing, falling into the trap of describing the purpose of the document rather than the purpose of the PTW itself.

A PTW system without a documented purpose or aim can degenerate into an authorisation to work, or worse a 'legal' document whose primary aim is to transfer responsibility to the lowest level possible, usually the permit receiver.

The policy needs additional detail in the form of objectives. These objectives provide a framework for developing the PTW system. They are also the basis for identifying key performance measures and targets. The HSE PTW guidance (HSE 2005) suggests ten objectives for PTW systems. These are suitable as the basis for developing site-specific objectives. Site management needs to consider what it expects from its PTW system when deciding objectives.

***Common finding 1**: Permit-to-work systems should have documented purpose and objectives.*

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Organising

The responsibilities and relationships of those personnel who have roles in the PTW system need to be defined in terms of their control, co-operation, communication and competence. The permit system will often involve personnel not directly employed by the organisation (such as contractors and visitors). Special attention needs to be made to organisational arrangements for these groups since they may not be familiar with the site or its hazards.

Organising — control

The PTW system needs clear lines of responsibility for the operation and ownership. Responsibility of the PTW system can rest with the safety or quality teams. However, operation or manufacturing groups are heavily involved with the PTW system and should have some control on its development. Ideally, ownership of the PTW system should rest with a named person who has sufficient time, resources and authority to actively pursue improvements.

> *Common finding 2: Responsibility for the permit-to-work system should be clearly allocated.*

There are many roles within a PTW system. These include:

1. specifying work;
2. identifying the work area and equipment;
3. examining the work site;
4. identifying how the work may interact with the surroundings or nearby activities;
5. identifying the hazards;
6. identifying the preparation work to allow the job to start;
7. specifying the precautions;
8. specifying ongoing tests or checks to allow the work to continue safely;
9. communicating the information to the work team and equipment operators.

The level of authority for the various tasks needs to balance knowledge of the task and those personnel who have an overview of the whole area. Operators and leading hands may have greater equipment specific knowledge than the area or plant manager. However, junior grades can miss interactions with nearby activities. Junior grades occasionally lack authority and can be put in a very difficult position when permits are being sought by strong-willed individuals who can influence the permit issuer. The most common resolution is to set the level of authority based on the hazards associated with the work. Hot work and confined space entry often require a higher level of authority than other work.

The most common failing found by the audits is allocating the permit issuing role without allowing the time to issue permits. Permit issuers are regularly asked to issue ten to thirty permits in the space of one or two hours. At this rate, the issuer is given an impossible task and unable to spend sufficient time for each permit.

Often roles within a PTW system are allocated to personnel who have insufficient time to perform the duties expected of them.

> *Common finding 3: Consideration must be given to an estimate of the time for each permit and the maximum number of permits that need to be issued.*

Organising — co-operation

The nature of the PTW system means that it operates at the interface between various groups. Operations, engineering, contractors and managers all have roles in the PTW system. One surprising finding is the expectation of senior managers that groups will co-operate without their active encouragement and support. Consultation mechanisms beyond the legal requirements are not common. Those systems that do operate, are often ineffective and overlook simple questions such as what do you think of the permit system. They frequently miss out contractors who may have important contributions to make (for example, contractors may have recently experienced several different types of permit systems as they move from site to site and this can provide a valuable insight).

Those responsible for the PTW system need to seek out comments from all groups involved in the PTW system. This can be achieved through focus groups but there is no substitute to going to the workplace and talking to the workforce.

> *Common finding 4: Development and review of the permit-to-work systems must include consultation with all relevant groups, especially contractors.*

Organising — communication

One of the objectives of a PTW system is to aid communication between those in control of the area and those carrying out the work. Good communication will only occur if the conditions are suitable. The permit issuing points are often an afterthought in planning the layout of the site. Most permits are issued in an office. Although this is a good environment for issuing permits, if more than one group needs a permit it is rare to find a suitable place for the other groups to wait without putting undue pressure on the issuer. An office with five to ten engineers all waiting impatiently is not conducive to good permits.

A key part of the communication process is the identification of the equipment. This is closely related to plant labelling. There are many advantages to having all the equipment tagged, lines colour coded, and the direction of flow marked. Even with all this in place, it is easy for the incorrect line to be opened or the wrong pump removed. The workforce at one facility had tackled this problem by tying coloured ribbons to mark the equipment. This excellent idea only needed to be made formal and the good practice promulgated over the whole facility.

The permit design plays an important part in communication. The permit is a record of the conversation between the issuer and receiver. Most permits use check lists as part of specifying the hazard and the controls. Simple planning, such as deciding if the site standard personal protective equipment should be included on the permit, will avoid confusion.

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If the permit is going to be an effective communication beyond the issuer and receiver, then it needs to be displayed. Keeping the permit in the pocket of the worker or retaining it within the permit issuing book does not aid communication. Permits should be displayed at the work location. A copy also needs to be displayed at the issuing point. The permits are best displayed on board that reflects the layout of the plant. This allows the permit issuers to be aware of others permits that may interact with the permit being issued.

Many modern plants have central control rooms. The operators in these control rooms need to be made aware of the work being undertaken in the plant they are operating. If the permit copy is not displayed in the control room then some other system of communication needs to be made.

Organising — competence

Competence is the part of the PTW system that has been found to have the least deficiencies. Most organisations recognise the need to train their permit issuers and receivers. The training courses are normally very good, tested at the end and regularly updated. The weak area is the training of contractors who do not sign on permits and senior managers who may have to countersign permits for high hazard work.

Common finding 5: All site personnel should be familiar with the PTW system. The depth of knowledge and training should be proportionate to their involvement.

Planning and implementation

There is one recommendation that is almost universally applicable: Reduce the number of permits issued.

Large numbers of permits dilutes the attention from the high-risk work where concentration on detail is essential. Too often permits have been used to control access of personnel on the plant. Unnecessary permits devalue the whole system and can turn the whole PTW into a paper exercise. When considering the scope of a permit system, it is useful to ask what value the permit adds to the work.

The number of permits can be reduced by:

- controlling routine jobs with standard operating instructions and competency;
- controlling access (where no work occurs) through personnel reporting to the control room and if necessary a register;
- revalidating permits with work that continues without change for more than one day.

Common finding 6: Reduce the number of permits issued by ensuring permits are only issued where necessary.

The second most common finding that has the potential to undermine the PTW system is transfer of authority. The workforce may view the permit as a legal document or a piece of paper that transfers authority from managers. This can lead to issuers over-prescribing personal protective equipment to 'cover their backs'. When this occurs, individual workers are left to pick the most appropriate personal protective equipment from the comprehensive list highlighted on the permit.

Every opportunity should be taken to emphasise the safety function of the permit. Permits should be valued for the information they provide to the individual and the control to the operational group.

Common finding 7: Promote the permit system as adding value to completing the job safely.

Measuring performance

Industry invests significant resources in PTW systems. Given this, the lack of attention generally paid to measuring the performance of this safety critical and expensive activity is surprising. The common difficulty is often associated in identifying what to measure.

The incident reporting and investigation system must be able to identify where failures in the PTW system have been a contributory factor to the incident. This is not the case in most of the incident reporting and investigation system examined. This deficiency breaks an important feedback loop that would identify where the PTW system is failing in its safety function.

HSE have been promoting leading indicators in their initiative on safety performance measures (HSE 2004). Identifying performance measures is closely related to setting objectives. Objectives should detail desired outcomes. The first objective for a PTW system suggested in the HSE guidance (HSE 2005) is:

- *clear identification of who may authorise particular jobs (and any limits to their authority) and who are responsible for specifying the necessary precautions.*

Measures can be identified by considering what success would look like. For the above objective, the following outcomes may be evident if it was successfully implemented:

1. a responsible person appointed to authorise permit issuers;
2. the authorised permit issuers informed in writing;
3. a system to inform permit users (list of permit issuers and the limit of their authority);
4. the permit users informed of the list;
5. no permits issued outside the authority of the individual (failure to meet objective).

Many of these successful implementations can be measured. Examples of measures are:

1. a relevant person is appointed;
2. an up to date list of permits issuers is produced;
3. each permit issuing point has a list of issuers posted;
4. the current list and their location is included in the induction training;
5. permits examined and found to be issued outside the authority.

This process can be repeated for each objective and many more measures may be identified. Not all the measures are suitable as performance measures. Some will be too trivial, whilst others may be too difficult to measure. The whole

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process should arrive at a small number of performance measures that are relevant and have data that is easy to collect. From the examples above, displaying an up to date list of permit issuers would be a good performance measure. This could be measured every month.

Success criteria can be set against these measures. There are difficulties in setting the success level. For example, is it reasonable to expect the list always to be current? Personnel change and lists quickly become out of date. A more realistic expectation that the list would be correct for 80% of the time would allow slippage for one month per year.

***Common finding 8**: Use the objectives to derive appropriate performance measures for the permit-to-work system.*

One measure from the example requires the completed permits to be examined. Completed permits are a valuable resource that is often ignored. Reviewing permits is an essential feature that is missing from many PTW systems. Some reviews should be by the line managers conducted on live permits. Completed permits can be peer reviewed by other permit issuers. This has many benefits including:

- a learning exercise for the reviewer;
- the review can include an assessment of effectiveness;
- the issuer will know some of their permits will be scrutinised;
- provides an opportunity for informal peer pressure to produce good permits.

An excellent PTW monitoring checklist is provided in the HSE guidance (HSE 2005).

***Common finding 9**: A sample of live and completed permits should be examined and assessed for quality and compliance.*

Auditing

Too often managers view performance monitoring as audits. The definitions (HSE 1997[2]) of measuring performance and audits are:

- **audit**—the structured process of collecting independent information on how well the safety management system is performing;
- **measurement, monitoring, and checks**—the collection of information about implementation and effectiveness of plans and standards.

Collection of information by managers cannot be considered audits since they are not independent. Such information gathering cannot assess the adequacy of the PTW system. However, it is essential as a performance measure.

There are many audit protocols and it is beyond the scope of this paper to review them. However, many audits protocols concentrate on compliance and fail to make judgments on the adequacy of the system.

Reviewing

The review process is an essential element within many quality systems. The review process closes the loop in the plan-do-check-act cycle. This cycle is illustrated in Figure 2. Most reviews concentrate on compliance. This fails to fulfil health and safety policies that have a commitment for continual improvement. Sadly, reviews are often not scheduled, they consider limited information, and they rarely produce plans for improving performance.

HSE's best selling publication *Successful Health and Safety Management* (HSE 1997[2]) provides little guidance on the review process. However, good guidance is given on the planning process, most of which is directly applicable to the review. Reviews should consider information from the following sources:

- monitoring performance;
- audits;
- consultation with stake holders;
- benchmarks and industry guidance.

The review should consider the following questions:

- is the system working as intended (compliance)?
- are we measuring the right things?
- are the measures adversely affecting the performance?
- have informal practices been introduced (and why)?
- is the system adequate?
- is the system proportional to the risks?
- can we do better?

The answers to these questions should lead to a plan for the following year including setting objectives and where appropriate targets.

***Common finding** 10: The whole permit-to-work system should be reviewed for effectiveness and compliance. These reviews should lead to annual improvement plans.*

Figure 2: Plan-Do-Check-Act health and safety cycle

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Conclusion

The PTW system is a key safety system. Many of these systems have significant weaknesses and scope for improvements. The most common failing is the issue of too many permits. This leads to a devaluing of the PTW system and a loss of control on high hazard work.

The common failure that prevents continued improvement lies within the review process. Many PTW systems are not reviewed, and where they are, it only identifies changes that affect the written arrangements.

Reviews should be scheduled regularly (yearly) to assess the whole system. They should drive improvement at every level. Closing the plan-do-check-act loop is the only way to ensure the PTW system remains effective.

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Loss Prevention Panel comment

This paper, published in LPB in 2007, contains several important and current lessons for the process safety professional. In the paper the author describes how auditing permit to work systems across numerous sites had yielded common findings and highlighted several pitfalls.

One pertinent common finding reported in the paper was that permit to work systems should have a documented purpose and objectives. In other words what is the system trying to achieve? It is not always obvious which leaves some to conclude that writing a permit transfers all responsibility for safety from themselves to the permit receiver — and the very opposite of the intention of a safe system of working.

Alongside a documented purpose and objectives another common finding was that the responsibility for the permit to work system should be clearly allocated. This finding is especially relevant to what I heard recently at a conference when an HSE inspector described how during a visit to an operator that they were pushed from pillar to post when trying to speak to the individual responsible for the permit to work system.

How a permit to work system works on the ground is also of importance and in this respect the paper identifies a pair of common findings which are especially relevant. The first is that consideration must be given to an estimate of the time for each permit and maximum of number of permits that need to be issued. In other words what is the system capable of with the finite resources available? And remember that work requiring a permit is rarely ordered for the convenience of the permit writer. Work may be held up for permits and little wonder then that in a fast-moving industrial environment that there may be a conflict between the production of and the quality of permits.

Coupled with resource planning the paper identifies the need to reduce the number of issued permits by ensuring that permits are only issued where necessary. One could also add where permits add value. The indiscriminate issue of permits is more likely to bring the system into disrepute rather than promote safe working.

The investigation into the Piper Alpha offshore accident revealed that a primary causal factor was the degradation of the permit to work system which allowed a line to be restarted without any over-pressure protection in place. The accident has been the subject of several papers in LPB but it is likely that one or a combination of the general pitfalls identified in the Gould paper will have led to the system breakdown and ultimately the world's worst accident offshore.

Lee Allford

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