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Mining the past

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Abstract

Whenever we hear of an accident elsewhere we are eager to learn what happened and what recommendations have been made to prevent it happening again. However, we can learn as much from past accidents that have been forgotten or were never widely reported. Some such accidents are described, including entry to confined spaces, the collapse of a gasholder and the collapse of a tank for an unusual reason.

Keywords: Accidents; Entry; Gasholders; Management; Simplicity; Vinyl chloride

> If you want the present to be different from the past, study the past.—Baruch Spinoza (1632–1677).

This paper describes a number of process accidents that have been forgotten or were never widely reported at the time they occurred but which nevertheless can teach us or remind us of important process safety lessons, both technical and managerial. Though the accidents occurred in the past they are still relevant as though equipment has changed people have not.

1. Entry to confined spaces

Many accidents have occurred when people were working inside confined spaces, either because the procedures for entering confined spaces were inadequate or were not enforced [1–3]. Hopkins [4] has described one of the worst cases. It was an epidemic rather than an isolated occurrence and occurred in an organization where we would not have expected it, the Royal Australian Air Force (RAAF). Hopkins' description is based on the report of a Board of Inquiry of which he was a member.

From the late 1970s onwards RAAF maintenance employees worked inside the fuel tanks of F111 bombers repairing the liners and suffered prolonged and sometimes intense exposure to the toxic chemicals used for removing old, damaged linings and replacing them with new ones. The RAAF did not realize that it had a serious problem on its hands until 2000 by which time the health of more than 400 people had been ruined.

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The protective clothing issued to the workers was grossly inadequate. It was permeable to some of the chemicals used and many of the respirators contained filters that provided protection only against dust but not against chemicals. The cooling in the buildings where the work was carried out was not in use after 4 p.m. or at weekends though much overtime was worked and this increased the already high temperature inside the tanks. Realizing that the protective equipment was useless as well as uncomfortable the workers often failed to use it.

The immediate technical causes of the ill health were thus obvious but why was nothing done about them for 30 years? Hopkins describes the main factors. It was not a simple case of management not caring about safety. Flight safety had a very high profile and the standard was high but this attitude was not carried over into the maintenance function, for several reasons:

1 *Undermanning*. During one period the young officer in charge of the fuel tank repairs was also responsible for six other groups and 170 employees but had no significant management experience. He left the supervision of the work on the fuel tanks to the non-commissioned officers and did not even know that many of the people for whom he was responsible were suffering ill health.
2 *The "can do" attitude*. Employees all levels had a strong "can do" attitude, a reluctance to admit that any task was beyond them. Such an attitude encourages initiative and self-reliance and after downsizing or an increase in workload many people try to do the best they can but managers should ensure that it does not go so far that corners are cut and safety neglected.

3 *The helicopter fallacy*. Many senior managers believe that they do not need to be involved in the detail and instead take a helicopter view. They rely on summaries of performance prepared for them by others. They are like those queen bees who are so busy producing eggs that they have no time to eat and digest and instead rely on pre-digested food prepared by other bees. It is true that managers should not duplicate their subordinates' jobs but from a helicopter we see only forests. If we want to know what is really happening we have to land the helicopter and look at some of the twigs and leaves. Managers should walk round the areas under their control, keeping their eyes open, and talking informally to other employees. This was not the practice at Amberley where the F111s were serviced. It is no defense for a manager to say, after an accident, "If I had known this was happening I would have stopped it". It is a manager's job to know.

4 *Reporting*. The RAAF, like many airlines, had a good system for the reporting of faults but in practice it applied only to faults in the aircraft. Fault reports by those who repaired the fuel tanks were ignored by the senior managers as they did not realize the seriousness of the problems and wanted to get the repairs done as soon as possible.

5 *Silos*. There was what Hopkins calls "a culture of silos" or partitions, in which different groups of people in the same organization pursued their own group objectives, failed to communicate with other groups, and did not see the whole picture. (A silo is "an air or water tight chamber" and thus, by extension, a knowledge-tight chamber.) In the RAAF this produced a very high standard of safety for some of the employees (pilots) but outrageously bad standards for others (some maintenance workers). (In many airlines the risk to maintenance workers is far higher than for passengers.)

1.1. Similar experience elsewhere

The five headings above apply, to varying extents, to many companies and other organizations though they are rarely allowed to continue unchecked for so long. The RAAF experience shows what can happen if people are overloaded after downsizing, if they have a macho attitude to getting things done, if managers ignore details and do not know what happens at the operating level, and if people work in ignorance of their colleagues. If people are told only what someone thinks they need to know they will never learn from the experience of their colleagues in other functions or departments.

During the early days of polyvinyl chloride (PVC) production operators used to enter the batch reactors to clean them between batches. During the 1970s many of these operators contracted cancer and it was realized that vinyl chloride was carcinogenetic. Methods of cleaning the reactors using high pressure water, without entering them, were then developed. This early problem has haunted the PVC industry ever since and periodic attempts are made by opponents of the industry to prohibit or limit the use of PVC in case traces of monomer are still present. While it is a hazardous chemical it is not as hazardous as some critics make out and there would be less opposition to its use today if a better method of cleaning the reactors had been developed at the start. However, once the chemical industry realized there was a problem it reacted promptly, unlike the RAAF.

An important lesson that can be drawn form the two "epidemics" is that the most effective way of overcoming the hazards of entry is to avoid the need for it. The following are the common reasons for entry, besides cleaning, and possible ways of avoiding the need:

- *To inspect or repair equipment inside the vessel*. Withdraw the equipment from the vessel.
- *To inspect the inside of the vessel*. If doctors can inspect the insides of our stomachs, bladders and bowels from outside (and display the insides on a screen while doing so), engineers should be able to do the same with vessels.
- *To operate or maintain valves on vessels in pits*. Do not put vessels in pits but, if you have already done so, consider remote operation of valves. If you insist on putting vessels in pits, provide a generous space between the vessel and the walls of the pit.
- *To avoid blockages in vessels containing solids*. Blockages often occur when solids are flowing out of a vessel by gravity. The probability of a choke depends on the shape of the lower part of the vessel which should be designed to minimize the risk of blockage [5]. If nevertheless a blockage occurs it should be cleared by a vibratory or mechanical device, not by people entering the vessel [6]. People have been asphyxiated because the solid has collapsed while they were trying to do so.
- *To construct the vessel*. Could the internal parts of low pressure vessels be constructed from the outside? In the construction of some UK railway carriages, components are fixed to the floor, roof and the two walls before these four pieces of steel are bolted together. Fitting equipment to what is going to be the ceiling is much easier when it is at a convenient height.

The worst case ever of widespread entry to hazardous confined spaces was the employment of children as young as seven to clean chimneys by climbing up them. In 1850, 800 such boys were working in London. Once machines for cleaning the chimneys had been invented a campaign to make "entry" illegal was started in 1803 in the UK but it did not achieve its aim until 1875.

2. Another accident involving vinyl chloride

This accident is a familiar one but the official report [7] described, more thoroughly than usual, the managerial causes as well as the immediate technical ones. It occurred on a boat, but similar ones have occurred in chemical and oil plants.

The 3100 t boat carried two tanks with a combined volume of 3219 m^3 and had carried 2800 t of refrigerated vinyl chloride under a moderate pressure from Rotterdam to Runcorn, UK. On arrival the chief officer, who was in charge of offloading, was asked to provide a sample. He started up the pump on one of the tanks to circulate the contents but did not check that the valves leading to the other tank were shut. Most of the valves on the piping system were duplicated in case one leaked but most had been left open and so some of the liquid entered the other tank, the pressure in it rose and the pressure control valve opened at a gauge pressure of 9 bar (130 psi) and discharged vapor through the vent which was located on the mast. Six hundred kilograms (1320 lb) of vinyl chloride vapor was discharged and it was estimated that the flammable cloud had a radius of 50 m (165 ft). Fortunately it did not ignite. No one was in a location where they could have experienced any acute toxic effects.The report drew attention to the following:

- The boat had no fixed equipment for the detection of flammable gases, though it did carry two portable detectors.
- The boat had a water spray system that could have been used to help disperse the leak. It was not used, though a hose was used to disperse ice which had formed on the deck.
- It was custom and practice to leave as many valves as possible open to save time and effort on arrival in port. The company's operating manual stated that "All valves in the cargo system not required to be open for the operation are [to be] shut." The chief officer had signed a statement that he understood the instructions. He was making only his second trip as chief officer since joining the crew of the boat.
- The previous chief officer had been promoted master of the ship though the company's policy stated that newly promoted and relatively inexperienced masters and chief officers should not sail together.
- The chief officer was trying to supervise too many jobs at once. He should have asked for assistance.
- The operating instructions required breathing apparatus to be worn during sampling but the chief officer was not wearing it.

The report concludes that "terminal and vessel operators should check and ensure that safety management systems are working in practice and that cargo operations, in particular, are always conducted in accordance with industry guidelines". Clearly in this case they were not. The report says that the company, who owned both the import and export terminals as well as the boat, carried out too few inspections and that they were not thorough, as the inspectors had no experience of marine gas carriers. They did not understand what was happening.

The main lessons for chemical and oil plants from this sorry story are the same as from the Australian report: managers should visit the areas under their control and keep their eyes open as they walk round and regular audits should be carried out by people who know what to look for. One of the reasons for the collapse, during construction, of a tunnel at Heathrow Airport, London, was that the Airport Company decided to save money by using their own auditors to monitor construction. Unfortunately the auditors knew a lot about auditing but little or nothing about tunneling [8,9].

When the cross-channel roll-on/roll-off ferry, *Herald of Free Enterprise*, sank in 1987 with the loss of 186 passengers and crew the chairman of the holding company was reported as saying that "Shore-based management could not be blamed for duties not carried out at sea" [10]. However, boats on short journeys are as easy to audit as fixed plants.

3. An unusual way to collapse a tank

Low pressure storage tanks have often been sucked in. Reference [11] lists 13 ways of doing so though the underlying reason for most of the incidents is ignorance of the fact that the tanks can withstand only a very slight fall in pressure. They are usually designed to withstand a vacuum of only 2.5 in. of water (0.1 psi or 0.6 kPa) and will collapse if the vacuum exceeds three times that amount. However, here is an unusual cause of a collapse that I have not seen described on any other occasion.

A solid layer formed in a storage tank. When some liquid was pumped out of the tank a space was left underneath the solid. Later, more liquid was moved into the tank and it rested on top of the solid layer (Fig. 1a). Some of the solid gave way and the liquid on top of it rapidly drained into the space below, more quickly than air could enter through the narrow vent pipe (Fig. 1b).

It is often good practice to make vents rather larger than the calculated value to allow for errors in the data used in the calculation or for unforeseen causes of high or low pressure.

4. Destruction of a gasholder and its root cause

In 1912 in Ilkeson, England a water-sealed spiral gasholder collapsed, releasing 7600 m^3 (about 2 million US gallons) of water, which swept several people away and partially demolished some of the neighboring houses. Fortunately, no one was seriously injured. In this type of gasholder one or more "lifts"

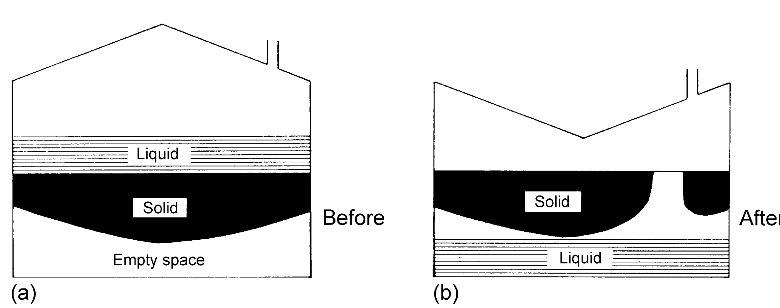

Fig. 1. (a) When the tank was emptied an empty space was formed below the solid crust. When liquid was added it rested on top of the crust. (b) The weight of the liquid broke the crust and the liquid flowed into the empty space faster than the air could enter though the vent.

rise or fall as the amount of gas in the holder changes. The lifts slowly rotate as they rise or fall and their movement is guided by wheels which move inside spiral guide rails. The accident probably started when one of the two lifts jammed and the subsequent strain caused one of the plates of the water tank to tear. However, it is possible that the tank collapsed simply because it was too weak to withstand the hydraulic pressure of the water. The escaping town gas (that is, coke oven gas) ignited but there was no explosion, only a flash fire.

According to the official report [12] the design of the water tank was too light, the plates being too thin and, in addition, “the quality of the material used was by no means all that could be desired”. There was, however, nothing fundamentally wrong with the type of design.

The underlying cause of the accident was clearly stated:

> The Town Council were somewhat ill-advised in not calling in a specially skilled Engineer to advise them in the choice of design, and the initial mistake made was the acceptance, without question, of a specification and design from a manufacturer in competition with other firms. ... This is a practice which has become increasingly into vogue during recent years [that is, about 1910], and it cannot be too strongly deprecated. It is most important and necessary that independent tests should be made on behalf of the customer, of the plates and bars, before work is commenced upon them. This is the unvarying practice with consulting engineers of standing and repute, and in important works should never be omitted. It is too often the case, however, that public and other bodies, with a mistaken idea of economy, elect to dispense with the services of a qualified adviser because, not only do they grudge his fee, but they fear that as a result of such action they might be compelled, against their inclinations, to adopt more substantial and costly works. But there is little room for doubt that in the long run, and in the interest of all concerned, it is the best and cheapest policy, and it has been amply exemplified in the present instance.

Until a few decades ago most accident reports described only the immediate technical causes of accidents – many still do – but since then there has been increasing interest in identifying the underlying or root causes and learning from them. I was therefore surprised to find that a report over 90 years old paid so much attention to the root causes. Of course, it was an official report by an outsider and company reports at the time were probably more superficial.

The remarks quoted above are still relevant. During the 1970s many incidents occurred because the wrong grade of steel or the wrong chemical was delivered. For example, liquefied air or oxygen was delivered instead of nitrogen [13]. Many companies set up positive material identification programs: all construction materials were tested before they were used and all process materials were tested before acceptance. Later, most of these programs were abandoned when suppliers obtained quality certification. Since then the wrong process material has been delivered on a number of occasions but there have been only a few published reports of the delivery of wrong materials of construction.

5. Simple explanations

I was present at a meeting where the unexpected corrosion of a pipe was discussed. A materials expert gave a long complex description, above the heads of most of those present, of possible reasons. I then asked if the material of construction had been checked before installation. We were told it had not been as the company did not have a materials identification program at the time of construction. Several of those present recalled such incidents that had occurred elsewhere, including a case where a scaffold pole, which looked similar to the process piping, was installed in a boiler.

According to Quinion [14], writing in another context, “The better [explanations] sound, the more circumstantial and detailed the background, the neater the conclusion, the less likely they are to be true. Conversely, if a story is mundane and boring, it is likely to be correct.”

Here is an example of an accident that definitely had a simple underlying cause. A manufacturer of photographic film experienced a sudden deterioration in the quality of the gelatine and asked a firm of consultant chemists for advice. One of the consultants asked the foreman if anything had changed. He replied that nothing had changed; everything was exactly as before. The consultant noticed a rusty bucket next to one of the vessels and asked what it was for. The foreman said that a bucketful of hydrogen peroxide was added to each batch of gelatine but as the bucket was rusty he had bought a new one the previous week. The consultant soon solved the firm’s problem when he found that the new bucket was twice the volume of the old one. Its linear dimensions were only 25% greater but the foreman had not realized that this doubled the volume [15].

The consultant saw the rusty bucket by chance but many people would have ignored it. To quote Pasteur, “Chance favors only the prepared mind”.

A third example of a simple cause: a man went up a ladder onto a walkway and then climbed over the handrail onto a flat fragile roof to pick up an object he had dropped. There was a warning sign that the roof was fragile. He tried to stand on the girders that supported the roof sheets but slipped off and fell into the room below.

The immediate cause of the accident was, of course, the foolish behavior of the injured man. However, the foot of the ladder was surrounded by junk, as shown in Fig. 2. It sends a simple clear message: “In this plant we don’t care about safety.”

6. Stress concentration

A check (non-return) valve intended for use at high pressure was designed so that it could be fitted to a screw-on flange. The company did not like to use screwed joints except on low pressure equipment containing non-hazardous materials so they decided to weld the valve to a weld-neck flange. The stub of the check valve was machined down so that it had the same diameter as the stub of the stub of the weld-neck flange, as shown in Fig. 3a. Note that this produced a sharp discontinuity. The high stress concentration at this point led to a fatigue crack and a leak. The stub of the check valve should have been machined so that

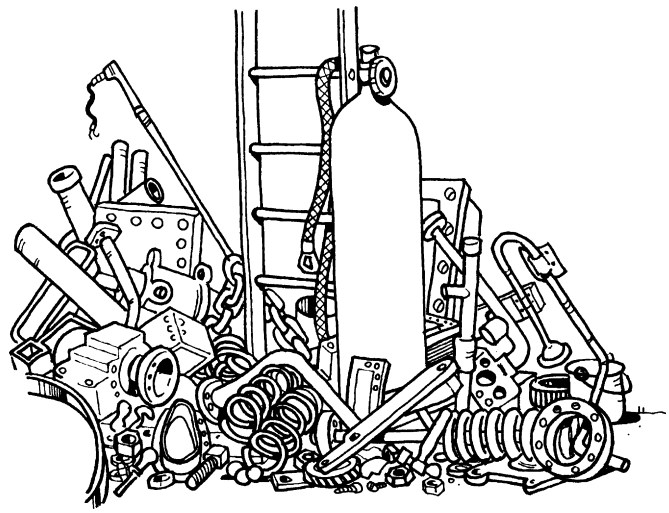

Fig. 2. What message did this give to someone who was about to go up the ladder?

its diameter was reduced gradually, at a gradient of 1 in 4 or less, as shown in Fig. 3b.

The fact that sudden changes in the shape of metal results in cracking has been known for hundreds of years. At one time church bells were tuned by chipping bits off their lips. This led to cracks which affected the sound and ultimately caused failure. Nevertheless the bells usually lasted hundred of years. The fact that discontinuities produce stress was not, however, known to the craftsman who machined the check valve, nor to his supervisor or anyone else involved.

The most famous case of failure due to stress concentration was the Comet airliner, the first jet passenger plane. Three of them crashed before the cause was discovered. The first major crash in May 1953 was blamed on an exceptional gust of wind, while sabotage was suspected as the cause of the second in January 1954. After the third crash over deep water in April 1954 the wreckage from the second crash was recovered from a shallower sea bed and it was found that stress concentrations at the corners of the square windows had caused fatigue failures. The planes were redesigned with oval windows. The story illustrates our reluctance to accept that anything is fundamentally wrong until the evidence is overwhelming [16].

7. Water in the wrong place

Many accidents have occurred because water got where it was not intended to be. The most notorious case is Bhopal where contamination of a tank containing methyl isocyanide (MIC) led to a runaway reaction, the discharge of the hazardous MIC as vapor and the deaths of many thousands of people. In this accident the water reacted chemically but most of the accidents caused by water in the wrong place have been physical rather than chemical incidents. Many, including the two described below, have been due to the contamination of oil by water and the rapid vaporization of the water when the temperature rose.

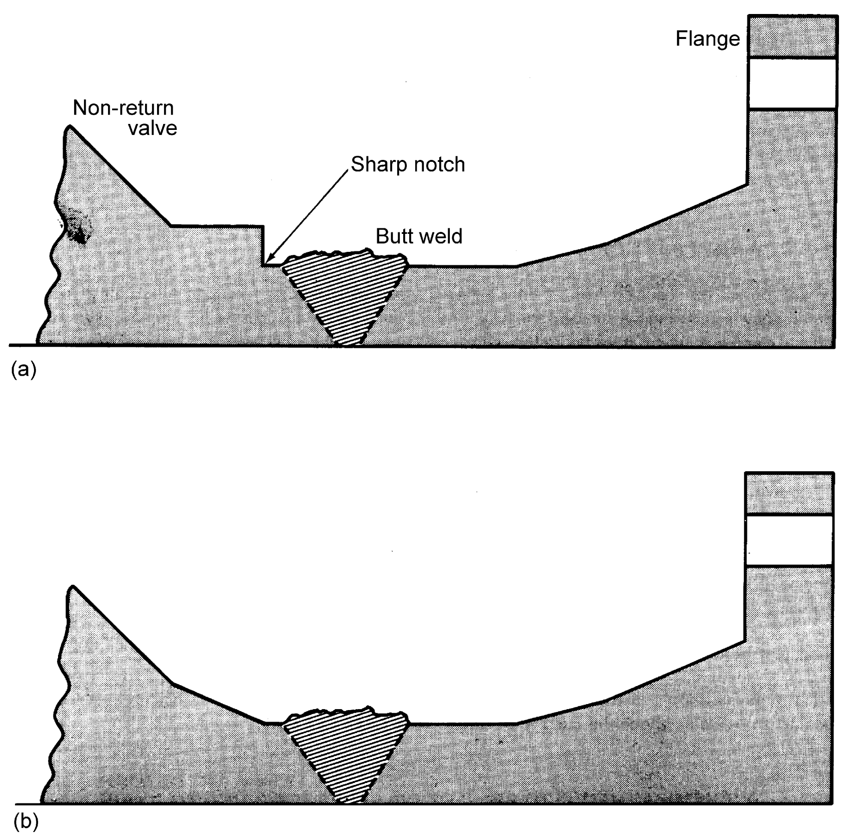

Fig. 3. (a) The stub on the check (non-return) valve was machined down so that it had the same diameter as the stub of the flange to which is was to be welded. This left a sharp notch which led to a fatigue failure. (b) The stub on the check valvet should have been machined so that there was a gradual reduction in diameter.

7.1. Heat transfer oil contaminated by water

A gas phase steel reactor, filled with catalyst, was insulated internally (Fig. 4). It was realized that cracks in the insulation or channeling could lead to hot spots so the reactor was surrounded by a jacket containing water. Experience showed that the reactor had to be operated at a higher temperature than expected, above 100 °C (212 °F) so the water was replaced by a heat transfer oil with a boiling point of 170 °C (340 °F). The water could not be used under pressure as the jacket was not strong enough. The oil entered the jacket at 120 °C (250 °F) and some of it was vaporized, condensed and returned.

The heat transfer oil, a by-product of the process, became contaminated with water, as the result of an upset on the plant. The water settled out in the base of the reactor. Its temperature rose to that of the oil, 120 °C, but it did not boil immediately as the pressure of the liquid above it raised its boiling point to about 120 °C. However, when a minor disturbance caused some mixing of the oil and the water, some of the water vaporized and blew some of the oil out of the jacket relief valve. There was a cyclone after the relief valve but it was not big enough to handle a sudden large flow, some oil escaped to the atmosphere and was ignited by a nearby furnace. The fire burnt itself out in 5 min but the damage to instruments and electric cables was extensive.

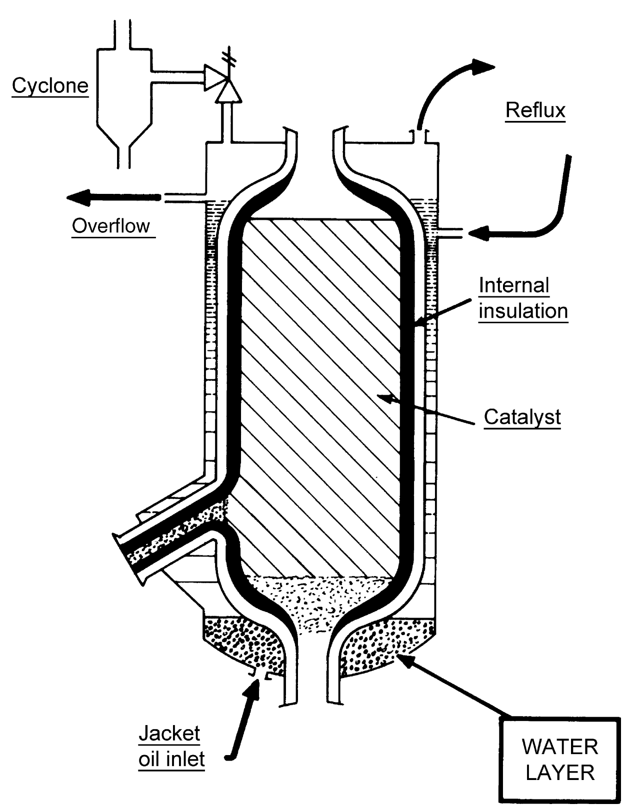

Fig. 4. The heat transfer oil in the reactor jacket was contaminated with water which settled out at the bottom. When a slight disturbance caused the water to mix with the oil (which was at 120 °C) the water vaporized with explosive violence and blew some of the oil out of the vent even though there was a cyclone in the vent line.

7.1.1. Lessons Learned

- If contamination with water is hazardous, water should, if possible, never be in a location from which it could leak into the plant. If this is not possible, any contamination with water should be automatically detected and there should be a procedure for removing it or neutralizing its effects. During Hazop, under the guide words, “other than”, always ask if contamination with water is possible.
- There had been several unexplained increases in pressure in the jacket but no one attached any importance to them. Unexpected increases in pressure, temperature, concentrations, corrosion, etc. should always be investigated as next time they may be greater.
- Replacing the water in the jacket by oil introduced a new hazard – a flammable liquid – that was more serious than any other on the plant. If the jacket had been stronger, water could have been used under pressure. When specifying the design pressure, temperature, corrosion resistance, etc. of new equipment we should ask if these may have to be changed and make some allowance for this in the design.

7.2. Water left after pressure testing

A furnace supplied heat transfer oil to four reboilers. One reboiler was isolated for repair and then pressure tested with water which was then drained out of the reboiler shell. The drain valve was 210 mm (8.25 in.) above the bottom of the shell so a layer of water was left behind (Fig. 5). When the reboiler was brought back on line the water was swept into the heat transfer lines where it vaporized instantly. The sudden rise in pressure blew the top off the surge tank (bursting pressure 30 bar gauge [450 psig]) and broke the rest of it into 20 pieces. The oil formed a fine mist which exploded forming a fireball 120 m (400 ft) in diameter.

7.2.1. Lessons learned

- When contamination with water is hazardous, another liquid, in this case the oil, should be used for pressure testing.
- The surge vessel was 90% full. If there had been more empty space in it the hammer effect of the vaporizing water would have been less serious. Filling a vessel to 90% of capacity is normal for storage but is too much for a surge vessel.
- To a design or construction engineer the location of the drain point a short distance above the base of the reboiler may not seem important so the process engineers in the design and start-up teams should pay attention to such details. During a Hazop study, when considering the guide phrase “Other than”, we should always ask if it is possible for water to be present. In considering the level in a vessel (or any piece of equipment) we should ask if it can be emptied completely.

An explosion in a furnace also occurred, in part, because a minor line was badly located. The fuel line to the burners was swept put with nitrogen when the filters in it were being cleaned but the nitrogen vent was located some distance from the burner. This made the subsequent start-up of the furnace

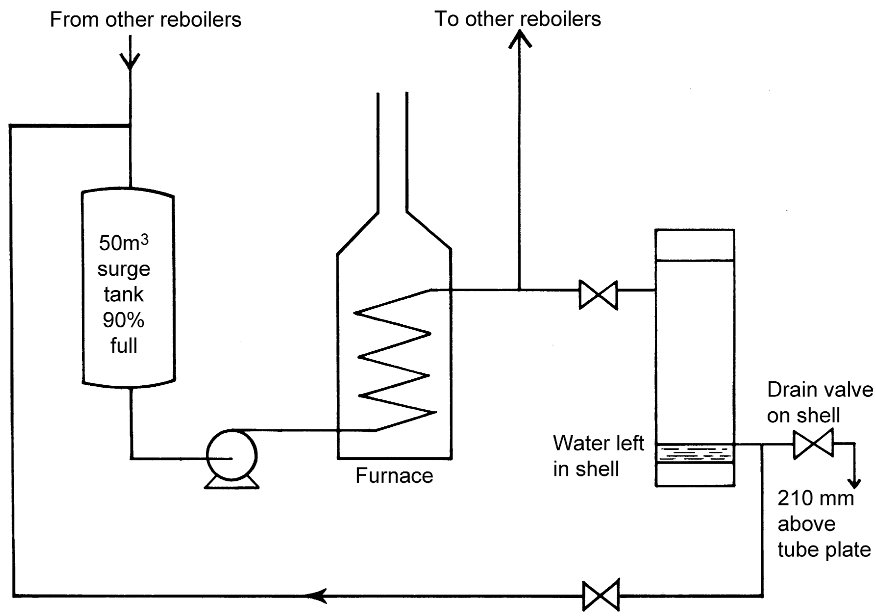

Fig. 5. The reboiler was pressure tested with water. When the water was drained about 8 in. of it was left behind. The system was filled with heat transfer oil and the furnace lit. When circulation was started the water was swept out of the reboiler and vaporized so quickly that it ruptured the surge tank.

more complicated than normal and, as might have been foreseen, short-cuts were taken [17].

8. Cheap ventilation

Many years ago I worked in a plant that included a building containing a number of compressors that handled a mixture of carbon monoxide and hydrogen. To improve the ventilation we removed the windows. It was hardly a new idea. The pioneer chemist, Robert Boyle (1627–1691), advised an alchemist friend who was experimenting with mercury, antimony and arsenic to do the same [18]. In some cases it is safer to contain leaks of toxic gases rather than disperse them, as large leaks of heavy gases may injure people outside the building.

In many buildings where flammable gases were handled we removed the walls, which were not load-bearing. This gave us for free more ventilation than ventilation engineers could have given us at considerable expense. The buildings often contained compressors and removing the walls increased the outside noise but this was overcome by fitting acoustic insulation.

9. Conclusion

The incidents described show that many, perhaps most, accident and incident reports contain valuable information obtained at great cost in money and, often, human suffering. Having paid the price we should value the knowledge we have got in return, use it to prevent similar accidents and share it with our colleagues and the industry. If your company has a policy of destroying old files after a number of years it should not apply to accident and incident reports. Destroying them is like destroying dollar bills because they have stayed in your pocket for a long time.

P.N. Lodal has shown how a reinvestigation of an explosion 40 years earlier revealed new information. Although no copy of the official report could be found the notes and photographs on which it was based were still in existence [19]. He quotes Winston Churchill, “The further backward one can look, the further forward one can see”.

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