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Learning from experience[☆]

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Abstract

Some process accidents and the actions needed to prevent them occurring again are described. They illustrate the following points:

- Some investigators are too eager to recommend changes in instructions or better observation of them than to look for ways of removing hazards or for changes in design that will make an accident less likely.
- Some people fail to calculate the effects of changes or the time required for them to take place.
- Facts that are well known in one industry or company may be unknown in another.

The incidents have been chosen because of their value as learning experiences.

Keywords: Accidents; Calculations, need for; Change; Design; Safety; Training

> *People should have to take a class on this information before they receive their undergraduate degrees in engineering. Nobody really tells us this stuff*. —A message from a chemical engineering student who found a book of accident case histories (*What Went Wrong?—Case Histories of Process Plant Disasters*) in a library.

> *We do a lot of teaching; it's just that we don't get much learning done in some of these schools*. —N.C. Rasmussen speaking at a discussion on Three Mile Island [1].

1. Changing procedures instead of designs

When we join an organization, and especially when we are young, we tend to follow and are expected to follow its ways of thinking and acting. It is usually only later, when we have gained experience, that we may start to question these default actions. The first part of this paper describes examples of a common, but unfortunate, way that many organizations react after an accident. Some of the incidents described are very simple but perhaps for this reason, no one realized that the actions taken afterwards were ineffective.

When we have identified a hazard, as the result of an accident or in some other way, there are several actions we can take to prevent it causing another accident or to mitigate the consequences if it does: our first choice, whenever "reasonably practicable", should be to remove the hazard by inherently safer design. For example, can we use a safer material instead of a toxic or flammable one? Even if we cannot change the existing plant, we should note the change for possible use on the next plant. ("Reasonably practicable" is a UK legal phrase that recognizes the impracticability of removing every hazard and implies that the size of a risk should be compared with the cost of removing or reducing it in money, time and trouble. When there is a gross disproportion between them it is not necessary to remove or reduce the risk [2].)

If we cannot remove the hazard, then our next choice should be to keep it under control by adding passive protective equipment, that is, equipment that does not have to be switched on or does not contain moving parts. The third choice is active protective equipment, that is, equipment switched on automatically; unfortunately, the equipment may be neglected and fail to work or it may be disarmed.

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The fourth choice is reliance on actions by people, such as switching on protective equipment; unfortunately, the person responsible for doing so may fail to act due forgetfulness, ignorance, distraction, poor instructions or after an accident because he or she has been injured.

Finally, we can use the techniques of behavioral science to improve the extent to which people follow procedures and accepted good practice. By listing this as the last resort, I do not intend to diminish its value. Safety by design should always be our aim but is often impossible and experience shows that behavioral science methods can bring about substantial improvement in the everyday types of accident that make up most of the lost-time and minor accident rates. The technique has had little effect on process safety but Fleming and Lardner has suggested ways in which the technique could be applied to management errors [3]. Behavioral methods should not be used as an alternative to the improvement of plant design or methods of working when these are reasonably practicable.

1.1. A simple example

To make these various ways of preventing incidents clearer, consider a simple but common cause of injury and even death, particularly in the home: falls on the stairs.

The inherently safer solution is to avoid the use of stairs by building a single story building or using ramps instead of stairs.

If that is not reasonably practicable a passive solution is to install intermediate landings so that people cannot fall very far or to avoid types of stair, such as spiral staircases, which make falls more likely. We can also mitigate the effects of falls by covering stairs with carpets or other soft materials and by avoiding sharp edges. An active solution is to install an elevator. Like most active solutions, it is expensive and involves complex equipment that is liable to fail, expensive to maintain and easily neglected.

The procedural solution is to instruct people to always use the handrails, never to run on the stairs, to keep then free from junk and so on. This can be backed up by behavioural techniques: specially trained fellow workers (or parents in the home) look out for people who behave unsafely and tactfully draw their attention to the action.

When I first quoted falls on stairs as an example of a hazard that could be removed by an inherently safer design, I did so as a simple example that is not always "reasonably practicable". In fact, since then I have become aware of the large number of people killed or injured in this way, at home, in public buildings, places of work and out-of-doors and the many passive ways in which the risk of injury can be reduced. In the United States in 1990, nearly a million people were treated in hospital for injuries resulting from stair accidents and nearly 50,000 were hospitalized. Thirty percent of the accidents were due to poorly maintained stairs. The hazards of stairs have been recognized for a long time. In Dante's *Divine Comedy*, the worst thing in the inferno is that the stairs have the wrong proportion [4].

Similarly, if someone has fallen into a hole in the road as well as asking why the hole wasn't fenced or why someone removed the fence or if the lighting should be improved, we should ask if there is a reasonably practicable alternative to digging holes in the road. Could we drill a route for pipes or cables under the road or install culverts for future use when roads are laid out? Must we run pipes and cables under the road instead of above ground?

In some companies, the default action after an accident is to start at the wrong end of the list of alternatives and recommend a change in procedures or better observation of procedures, often without asking why the procedures were not followed. Were they, for example, too complex or unclear or have supervisors and managers turned a blind eye in the past? Changing procedures is, of course, usually quicker, cheaper and easier than changing the design, but it is less effective. The following pages describe some accidents in which changes in design would have been cheap but nevertheless only changes in procedures were made.

Today designers often consider inherently safer options but the authors of incident reports do so less often. The very simplicity of the idea seems to make it hard for some people to grasp it. Perhaps they are expecting something more complex or, and this is perhaps more likely, it goes against the traditional belief that accidents are someone's fault and the job of the investigation is to find out who it was. Having identified the culprit, we are less likely to blame him or her than in the past; we realize that he or she may not have been adequately trained or instructed, and that everyone makes occasional slips, but nevertheless his or her action or inaction caused the incident. Some investigators blame a piece of equipment. It is hard for some people to accept that the incident is the result of a widespread and generally accepted practice in design and operations: changing procedures when change in design is reasonably practicable.

1.2. Misleading valve layouts

To reduce costs, three waste heat boilers shared a common steam drum (Fig. 1). Each boiler had to be taken off line from time to time for cleaning. On two occasions the wrong valve was closed (D3 instead of D2) and an on-line boiler was starved of water and over-heated. The chance of an error was increased by the lack of labeling and the arrangement of the valves: D3 was below C2. On the first occasion the damage was serious. High temperature alarms were then installed on the boilers. On the second occasion, they prevented serious damage but some tubes still had to be changed. A series of interlocks were then installed so that a unit had to be shut down and the fuel supply to a furnace isolated before a key could be removed; this key was then needed to isolate the corresponding valves on the steam drum.

Perhaps color coding of the valves, one color for C1 and D1, another for C2 and D2, etc. would have been sufficient

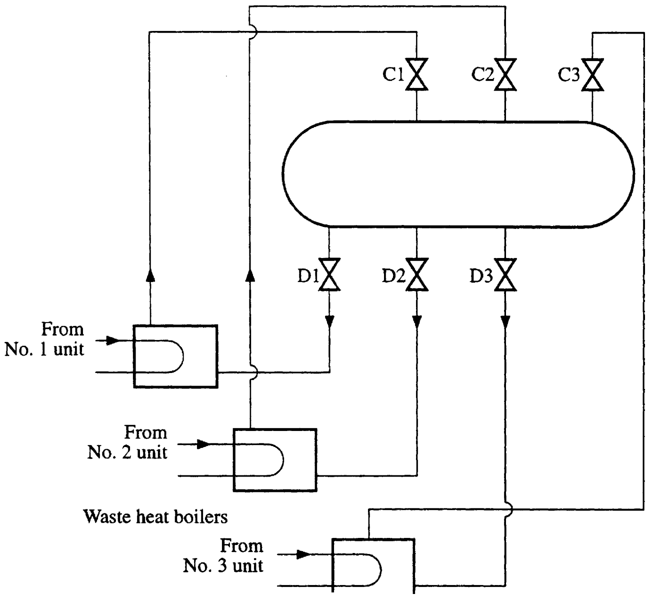

Fig. 1. Note the positions of the isolation valves on the common steam drum.

to prevent further errors. It would have been simpler and cheaper than the mechanical interlocks.

A good solution, of course, would be to rearrange the pipework so that valves in the same line were opposite each other. To do so on, the existing plant would be impracticable but the point should be noted for the future. A design engineer said, after this incident, that it was difficult enough to get all the pipework into the space available without having to worry about such fine points as the relative positions of valves. This may be so but putting valves in unexpected positions leads to errors.

The best design, used on later plants, was to have a separate steam drum for each waste heat boiler (or group of boilers if several could be taken off line together). There was then no need for valves between the boiler and the steam drum. This was more expensive but simpler and free from opportunities for error. Note that we do not grudge spending money on complexity but are reluctant to spend it to achieve simplicity.

The default action of many of the people in the company was to look first for changes to procedures (such a operator action triggered by alarms) and when that proved unsuccessful for more complex equipment and procedures (keys and mechanical interlocks). A change in design, for future plants, was considered only after the second failure. No one thought of color coding.

The incident could have been given widespread publicity, not just immediately afterward but regularly in the future, and made part of the training of operators and designers, but it was not.

When color coding is used the colors must be distinctive and easy to distinguish. Passengers on a roll-on roll-off ferry were told to return to their vehicles via the blue stairway. Someone mistook the turquoise stairway for the blue one and was seriously injured by a vehicle [5].

1.3. Simple redesign overlooked

A bundle of electric cables was supported by cable hangers. The hooks on the ends of the cable hangers were hooked over the top of a metal strip (Fig. 2, top). The electric cables had to be lowered to the ground to provide access to whatever lay behind them and then replaced. They were put back as shown in Fig. 2 (lower). This increased the load on the upper hooks. One failed, this increased the load on the adjacent ones and they also failed. Altogether, a 60 m (200 ft) length of the cables fell down. Fortunately, the only injury was minor [6].

Many people would fail to see this hazard. Training is impracticable if, as is probably the case, many years will pass before the job has to be done again. The best solution is to use cable hangers strong enough to carry the weight even if they are used in the wrong way or to lay the cables on a cable rack or on the ground (but take care they do not become a tripping hazard).

1.4. *"Just tell people to follow the rules"*

A tank containing radioactive liquid was fitted with instruments for measuring density and level. They were

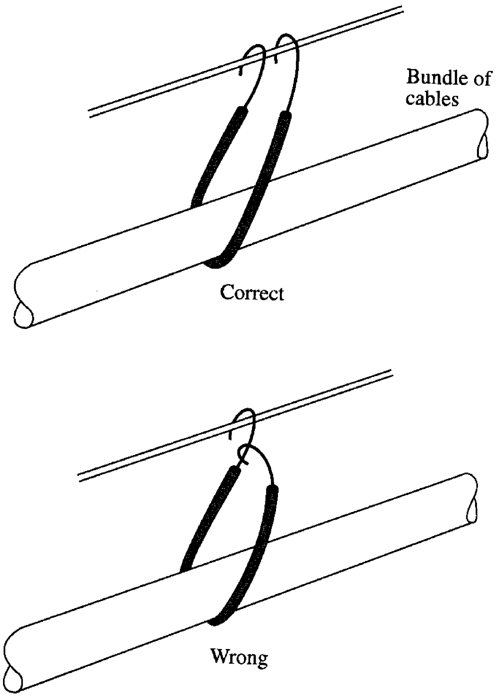

Fig. 2. Two ways of supporting a bundle of cables. When the hangers were assembled in the wrong way, the upper hooks had to support twice the design weight. The hooks opened out and 60 m (200 ft) of cable fell 5 m (15 ft) to the ground. How many people would recognise the hazard? Instead of relying on training and instructions, it would be more effective to use hangers that can support the entire weight even when they are assembled wrongly.

purged with steam at intervals. Before opening the steam valve, the operator was instructed to check that there was steam in the line by measuring the temperature of a steam trap and checking that it was over 93 °C (200 °F). However, he merely felt the trap and finding it was hot he opened the steam valve. Unknown to him, the steam line had been isolated 16 h beforehand. (Presumably conduction from beyond the isolation valve kept the trap hot.) As the steam cooled, it developed a vacuum and this sucked the radioactive liquid into the steam line. Radioactive alarms sounded, and fortunately, no one received a significant dose.

The report [7] drew attention to failures to follow procedures: the people who drained and isolated the steam line did not inform those responsible for purging the instruments; the operator who was asked to carry out the purging was not adequately trained, as he had never done the job before but only watched other people do it.

The report recommended that managers should stress the proper use of procedures, that before carrying out a task operators should stop, think about the task, the expected response and the actions required if it failed to occur, and so on. There was no suggestion, however, that the procedures might be improved, for example, by fitting a warning notice on lines that are out-of-use, or that the design could be improved by fitting a check valve in the steam line. They are not 100% reliable but can greatly reduce the size of any back flow. Check valves with moving parts would be difficult to maintain in a radioactive environment but fluidic ones would be OK. Another possibility is a catchpot to catch any liquid that does flow into the steam line.

1.5. *Blaming the operator rather than the software*

An operator was asked to switch a spare transformer on line in place of the working one. This was done remotely from the computer in the control room. He inadvertently isolated the working transformer before switching on the spare one. He realized his error almost immediately and the supply was restored within a minute. The report on the incident blamed distraction:

> It is apparent that the control room is used as a gathering area for personnel as well as a general thoroughfare for persons moving about the building to the detriment of the control room operator’s concentration.

The report also suggested greater formality in preparing and following instructions when equipment is changed over. Though not suggested in the report, it should be simple for the computer program, when the computer is asked to isolate a transformer to display a warning message such as, “Are you sure you want to shut down the electricity supply?” We get such messages on our computers when we wish to delete a file and if we have deleted it, we can recover it from the recycle bin. There is no need for control programs to be less user-friendly than word processors.

Note that the default action of the investigators was to describe ways of changing the operator’s behavior rather than to look for ways of changing the behavior of the equipment.

Similar incidents have distorted financial markets, for example, accidental pressing of the wrong key has started instant selling and the operator has been blamed [8].

1.6. *Waiting until after the fourth accident*

A mixture of phenol, formaldehyde and sulfuric acid, the raw materials for the manufacture of PF resin, was discharged on to a roadway four times before the company decided to change the design and install a catchpot after the reactor’s rupture disc.

The first runaway occurred because the operator forgot to add the catalyst, sulfuric acid, at the beginning and so added a larger amount later when a second addition of catalyst was normally made. This was an example of a common incorrect belief: that it is better to carry out an action late than not carry it out at all.

The second runaway occurred because the formaldehyde failed to react for an unknown reason. When the second addition of catalyst was made, the large excess of formaldehyde reacted vigorously. (In many other cases, a mixture has failed to react because the stirrer was not operating or catalyst had not been added. When the operator realized what was wrong, he or she switched on the stirrer or added the catalyst and a sudden violent reaction occurred.)

The third and fourth incidents had similar causes. Part of the heat of reaction was removed by a cooling jacket and part by condensing the vapor given off during reaction. The latter was ineffective as there was a partial choke in the vapor line where it entered the condenser.

The company did not ignore the first three incidents. They changed the operating procedures. After the fourth incident, they decided that this was not enough and they made a change in the design: they installed a catchpot [9].

1.7. *“Don’t assemble it wrongly”*

After an incident, many designers have said, “There was nothing wrong with the design. The maintenance (or construction) team assembled it wrongly”. Equipment should be designed so that it cannot be assembled wrongly or at least so that it is obvious if it has been.

1.8. *“Tighten correctly”*

A hose was fastened to its connector with the type of clip used for the water hoses in cars (known as Jubilee clips in the UK). The connection leaked. The recommendation in the report on the incident was, “Check tightness of Jubilee clips during maintenance.” However, these clips are not robust enough for industrial use and a better recommendation would have been to replace them by bolted clips.

Similarly, a steel plate fell from a clamp while being lifted because the bolt holding it in position was not tightened sufficiently. The incident was classified as human failing and the operator was told to be more careful in future. It would have been better to use a type of clamp that is not dependent for correct operation on someone tightening it to the full extent [10].

2. Failures to carry out calculations

Here are three examples of accidents that occurred because no one calculated the effects of changes or the time required for them to take place.

2.1. Unrecognised scale-up

In his biography, *Homage to Gaia* [11], James Lovelock describes an incident that occurred when he was working for a firm of consultant chemists. There had been a sudden deterioration in the quality of the gelatine used for photographic film and he and another chemist were sent to visit the manufacturers. They asked the foreman if anything had changed. He relied that nothing had changed; everything was exactly as before. Lovelock's colleague 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. "We soon solved the firm's problem when we 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.

Failures to understand scale-up go back a long way. Canned food was introduced in 1812. In 1845, it became part of regular Royal Navy rations. Some time later there was an outbreak of food poisoning. Larger cans had been used and the heat penetration became insufficient to kill the bacteria in the middle [12].

2.2. "It's only a minor change"

A reactor vent discharge containing 100 ppm benzene in nitrogen was sent direct to atmosphere at a rate of 8.5 m^3/h (5 ft^3/min). To meet new emission standards, the company installed an electric flameless destruction system. The vent discharge had to be diluted with air before entering this system and the air rate was set so that the total flow was 170 m^3/h (100 ft^3/min). This dilution ensured that the mixture was well below the lower flammable limit of benzene even during occasional spikes when the benzene concentration rose briefly to 15%.

Soon after installation of the destruction unit, the vent discharge from a storage tank was also directed into it. The increase in flow rate was only 6.7%. Everyone assumed that this was too small to matter and no one made any calculations. However, during the spikes in benzene concentrations in the main contributor to the flow the lower flammability limit was exceeded; the destruction unit was hot enough to ignite the vapors and there was an explosion. A high concentration of combustible gas in the gas stream sounded an alarm but it operated too late to prevent the explosion. Though damage was considerable, the explosion did not travel back to the reactor and tank as both were blanketed with nitrogen.

We should consider the possible consequences of changes before authorizing them and never dismiss a change in quantity as negligible before calculating its effects. We should consider transient and abnormal conditions as well as normal operation.

We should estimate the response time of every alarm and trip to see if it is adequate and check it during testing if there is significant delay. Most measuring instruments respond quickly but analytical instruments are often slow, though it is usually the sampling system rather than the measuring device that causes the delay.

The report [13] says that pollution control equipment should not be treated like a domestic garbage can, something into which anything can be dumped. Every proposed addition should be thoroughly evaluated. On a chemical plant or in a chemical laboratory, this applies to all waste collection equipment. Many fires, toxic releases or rises in pressure have occurred because incompatible chemicals were mixed in the same waste drum.

2.3. Cooling takes time

A coker is a large vessel, typically about 12 m (40 ft) tall, in which hot tar-like oil, after being heated in a furnace, is converted to lighter oils, such as gasoline and fuel oil, leaving a tarry mass in the vessel. On cooling, usually with steam and then water, this forms coke, which is dug out. A power failure occurred when a coker was 7% full and the plant was without steam for 10 h. The inlet pipe became plugged with solid tar and the operators were unable to inject steam.

There were no instructions for dealing with this problem although a somewhat similar one had occurred 2 years earlier. The supervisor, therefore, decided to let the coker cool naturally before opening it. Two days later, the temperature of the outside of the bottom flange of the coker had fallen from its usual value of 425 °C (800 °F) to 120 °C (250 °F) so the supervisor decided to go ahead. The operators injected some steam, presumably through a different route to the normal one, to remove volatile products and then started to open the coker. The top cover was removed without incident. The bottom cover was unbolted while supported as usual by a hydraulic jack. When the jack was lowered, hot vapor and oil gushed out and immediately ignited. It was probably above its auto-ignition temperature. Six people, including the supervisor were killed.

The immediate cause was the failure to realize that the temperature of the middle of the vessel was far higher than that of the walls, high enough to continue to covert the tar to gasoline. Afterwards calculations showed that it would take 2 weeks, not 2 days, for the temperature to fall to a level at which it would be safe to open the coker.

We have all been given, at some time, a food such as pasta or rice pudding, straight from the oven in the dish in which it was cooked. If it is too hot to eat, experience tells us that the outside bits are cooler and we eat them first. We know the outside cools faster than the inside. Unfortunately, we find it difficult to apply in one situation the lessons we have learned in another; they are kept in different parts of our minds. We do not communicate with other people as well as we might: we also do not communicate well with ourselves.

Of course, there was much else wrong besides the failure to calculate the time need for the vessel to cool. The controls for the hydraulic jack should been located further away from the coker and people should not have been allowed as near as they were.

An underlying cause was the failure to plan in advance for a loss of power even though one had occurred 2 years before and caused a serious spillage. Another underlying cause was the lack of technical support. The supervisor seems not to have been a professional engineer or recognized the need to consult one. The report [14] does not say whether or not there had been any downsizing or reduction in support.

The worst chemical industry accident in the UK, the explosion at Flixborough in 1974, was due to the failure of a large temporary pipe. The men who constructed it did not realize that they needed expert advice. The only drawing was a chalk sketch on the workshop floor [15].

2.4. Another failure to estimate the rate of heat transfer

In the last incident, the heat flow was lower than expected. In this incident, it was higher. A circulating gas stream was heated in a shell and tube exchanger. The gas was in the shell and electric heating elements were in the tubes. A high temperature trip prevented overheating. Catalyst dust in the gas stream caused a choke and stopped the circulation but the operators did not realize this as the flowmeter frequently choked and they had learned to manage without it. With no gas flow though it, the heater got too hot and the high temperature trip isolated the power supply. The operator could see nothing wrong, so after a while he switched the power back on. This happened three times in an hour, during which there was a shift change. Finally, the heater shell burst (see Fig. 3).

The trip had been set to operate at 740 °C (1360 °F), a temperature chosen to protect the heating elements but far too high to protect the shell. Either the electrical designer did not think about the need to protect the shell, that was someone else's problem, or more likely, he assumed that the heating elements would reach 740 °C before the shell reached a temperature at which it would burst.

After the accident, a high temperature trip was attached to the shell. The incident was also used as part of a training program to emphasize, in particular, the following points:

- Electric heating is not inherently safe as heat output continues at the same rate regardless of the temperatures of the material being heated. A heating medium that is not hot enough to overheat is inherently safer.

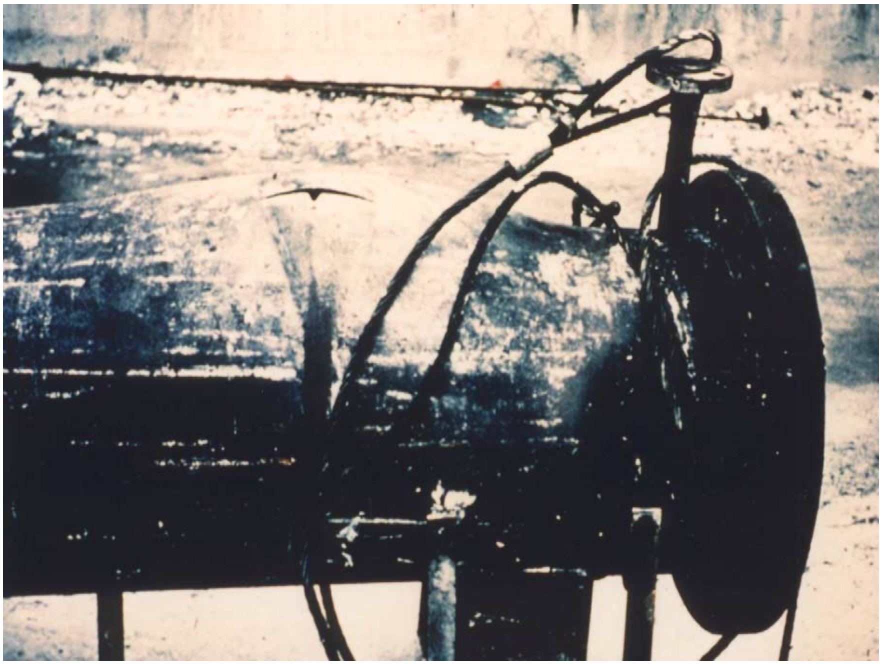

Fig. 3. The shell of an electric heater after the flow of circulating gas failed. The small "v" in the rupture is due to the removal of a sample for analysis.

- Vessels can fail at a pressure below design when they get too hot. This was not realized by everyone at the time. When the shell burst, the first reaction of the operators was to assume that the relief valve was faulty and send it for testing.
- It is better to measure directly what we wish to know (such as the temperature of the shell) than infer it from another measurement (such as the temperature of the heater).

3. Believed in one industry but not in another

The gases entering a flare stack were scrubbed with water at the base of the stack. There was a continuous flow of fresh water into the system and a continuous overflow into a covered concrete sump about 2 m (7 ft) deep from which the water was pumped to drain by a submerged pump (see Fig. 4). An explosion in the sump threw its steel manway cover about 20 m (60 ft). The fuel was oil that had condensed in the scrubber in the bottom of the stack. The source of ignition was probably overheating in the pump as the impellor was damaged and due to a fault in the level controller, the pump was barely covered.

It would have been difficult to blanket the sump with nitrogen as it was not gas-tight and as no nitrogen was available in the area so instead the steel manway cover was replaced by a lightweight one.

The designers and operators had realized that a small amount of oil might enter the sump but had assumed that it could not explode as there was no obvious source of ignition. This incident occurred many years ago, and it is unlikely that the same error would be made today. It is now widely recognized in the oil and chemical industries that it is impossible to remove every source of ignition with 100% confidence, and therefore, we should prevent the formation of flammable mixtures of gas or vapor and air.

The same is not true in the aviation industry. According to Ural [16], the vapor spaces of the centre wing tanks on large airplanes such as 747s are often located near heat sources and are flammable for more than one-third of the operating hours; as a result, a number of explosions have occurred. The vapor spaces can become flammable in three ways:

1. The flash point of the fuel can be as low as 40 °C (105 °F) and falls as the air pressure falls.
2. Cooling and vibration can produce mists, which have a lower flash point than the vapor.
3. Oxygen is more soluble in fuel than nitrogen, and therefore, the gas released when the pressure falls is enriched in oxygen.

In addition, experience shows that sources of ignition can never be completely eliminated. It is hubris to imagine that we can infallibly prevent a thermodynamically favored event [17].

There have been about 18 explosions since 1960, some while airplanes were on the ground but including the well-known explosion on TWA flight 800 in 1996.

The aviation industry at first claimed that blanketing with nitrogen would be so expensive that it would not be “reasonably practicable” (to use the UK legal phrase) though Ural claimed that it would amount to no more than a few dollars per flight. However, inerting systems for aircraft are now being developed. They are designed to reduce the oxygen concentration to 12% instead of the 10% or better usually achieved in ground-based systems, as this reduces the cost

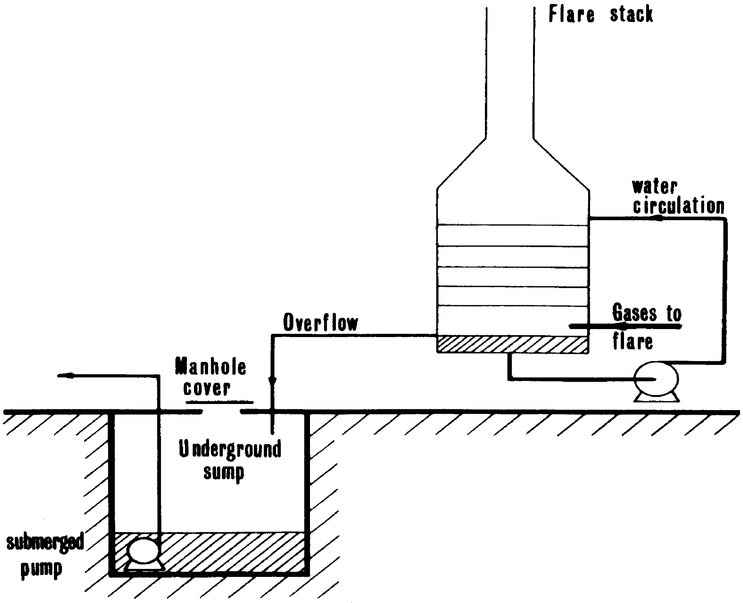

Fig. 4. Oil from the base of the flare stack exploded in the sump.

by 75%. The minimum oxygen concentration needed for an explosion is said to be just under 12% at ground level but 14.5% at 30,000 ft, so the margin of safety will be zero or small [18,19].

4. Conclusion

The incidents described as a whole show the need for senior managers to look at some accident reports in detail to see that their authors are not making errors such as those described in this paper. It is not sufficient for them to take a helicopter view that shows only the forests. They should land the helicopter and look at some of the trees and even the twigs and leaves.

If you wish to share the information in this paper with your colleagues, then I suggest that discussing the incidents with them will be more effective than lecturing or giving out copies to read. Outline the incident and then let your audience question you to find out any further facts they want to know and then let them say what they think should be done to prevent the incident happening again. More will be remembered and your audience will be more committed to the recommendations. Copies of the PowerPoint slides accompanying this paper are available on request.

Much of this paper is based on extracts from *Still Going Wrong—Case Histories of Process Plant Disasters and How They Could Have Been Avoided* (Gulf Professional Publishing, an imprint of Elsevier, Burlington, MA, 2003).

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