ELSEVIER

Journal of Hazardous Materials 104 (2003) 95–105

Journal of Hazardous Materials

www.elsevier.com/locate/jhazmat

Equipment that cannot do what we want it to do☆

Trevor Kletz

Department of Chemical Engineering, Loughborough University, Loughborough LE11 3TU, UK

Abstract

Able, well-meaning people are sometimes surprised to find that the equipment or instrumented system they have designed is unable to do what they want it to do, either because it defies the laws of science or has other unforeseen faults. Some examples are described.

Keywords: Accidents; Design; Equipment; Instrumentation; Safety; Unforeseen faults

1. Introduction

In the first few incidents the laws of science prevented equipment working in the way that the designer intended. Other failures were due to the designer's ignorance of the properties of materials or of a plant's features.

2. A level glass with a limited range

A level glass 1.2 m (4 ft) long was connected to vessel branches 0.6 m (2 ft) apart as shown in Fig. 1. The level glass will indicate the correct level only when the liquid in the vessel is between the two branches. If the liquid level is below the lower branch, the liquid in the level glass is isolated and its level cannot fall. If the liquid level is above the upper branch, vapor will be trapped in the upper part of the level glass. As the level rises, this vapor will be compressed. If there is any non-condensable gas present, the pressure in the level glass will rise but will be depressed below the level in the vessel.

☆ The incidents described in this article also appear in a forthcoming book, *Still Going Wrong*?—*Case Histories of Process Plant Disasters and How They Could have been Avoided*, to be published by Elsevier under the Butterworth-Heinemann/Gulf Professional imprint.

0304-3894/$ – see front matter
doi:10.1016/S0304-3894(03)00237-1

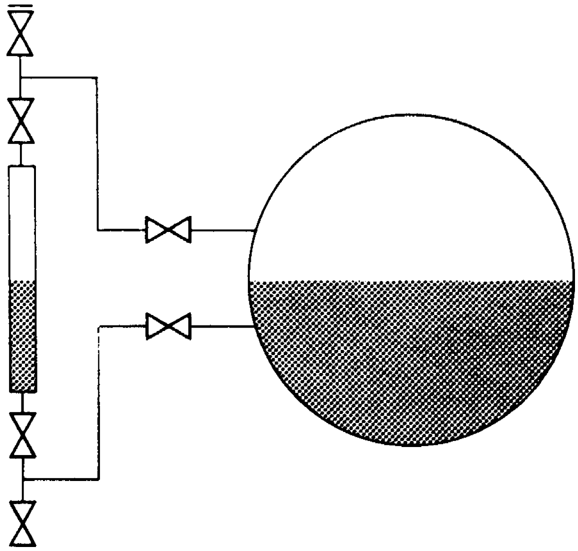

Fig. 1. This level glass has a limited range.

3. An explosion in a nitric acid plant

Ammonia was vaporized, mixed with air and passed over a catalyst. The ammonia and air flows were measured and a flow ratio controller was supposed to keep the ammonia concentration below the explosive limit (Fig. 2). The level controller on the vaporizer was out of order and the level of ammonia in it was on hand control. The level got too high and droplets of ammonia were carried forward. Flow measurements are inaccurate when spray

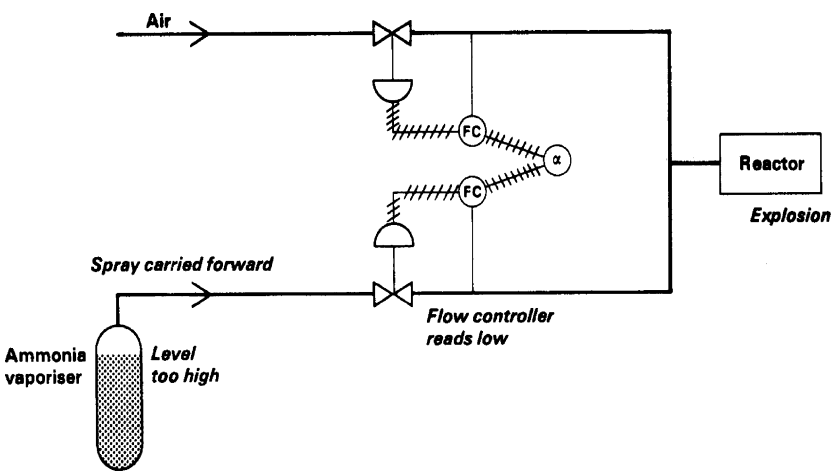

Fig. 2. Nitric acid plant explosion.

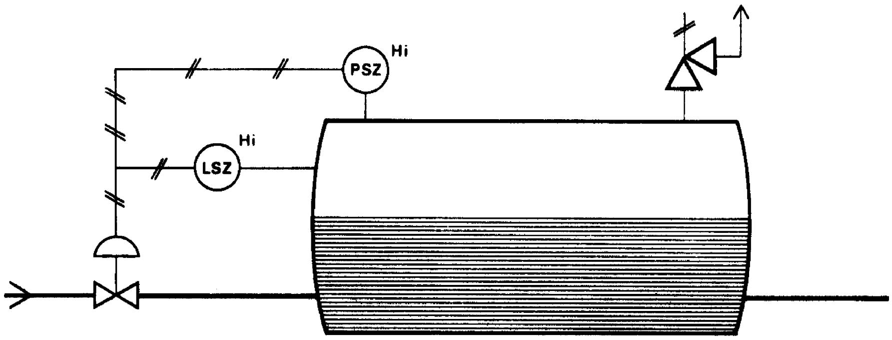

Fig. 3. Vapors and non-condensable gases were confused when this equipment was designed.

is present so the flow ratio controller did not detect the increased flow of ammonia and an explosion occurred. The size of the error in the flow measurement depends on the detailed design; if the spray increases the density of the gas by 50%, the flow of vapor and liquid could be 25% higher than the flowmeter reading.

4. Vapors and non-condensable gases confused

The following has been discovered more than once during hazard and operability studies. A vessel contains a liquefied gas such as LPG. It is fitted with a level controller (not shown) and in addition a high level trip to isolate the inlet line if the level gets too high (Fig. 3). The high level trip might fail; the relief valve will then lift and discharge liquid to atmosphere so a high-pressure trip is installed as well.

If the space above the liquid contains some nitrogen or other non-condensable gas, the system will work. As the level rises, the gas will be compressed and the pressure will gradually rise. But if there is no non-condensable gas present and the level rises slowly the system will not work. The vapor will condense and the pressure will not change until the vessel is completely full of liquid. The pressure will then rise too rapidly for the high-pressure trip to operate and the relief valve will lift.

Condensation takes a finite time. If the level rises rapidly the vapor may not have time to condense and the system will then work. The designer of the system probably did not understand the difference between a non-condensable gas, such as air or nitrogen, and a vapor.

5. Measuring the wrong parameter

The pressure of a water supply was normally high enough for it to be used for fire-fighting. If the supply pressure fell a low pressure alarm sounded and an alternative supply of water was then made available. Someone isolated the water supply in error. However, the trapped pressure in the line prevented the alarm from operating. The instrumentation could do what it was asked to do—detect a low pressure—but not what its designers wanted it to do, that is, detect that the supply was unavailable.

As often happens something else was wrong as well: the valve in the water line should have been locked open but was not. Valves that are locked open for safety reasons should be listed and checked periodically to make sure that they are still locked. They are part of a protective system.

6. A test that cannot always detect faults

Some hoses are strengthened by internal or embedded metal coils. If these hoses are used with flammable liquids the coils should be grounded by connection to the metallic end-pieces or they may become charged by induction. The usual way to check that they are grounded is to measure the resistance between the two end-pieces. However, some hoses contain two (or more) coils. If one them is not connected to both end-pieces, either by design or wear and tear, this will not be detected by the test [1].

7. An alarm that immediately reset itself

A rotameter was designed to measure a gas flow. If the flow stopped or decreased substantially the float dropped and interrupted a light beam. This triggered a low flow alarm.

The design had limitations. If the flow diminished only a little the light beam remained broken and the alarm light stayed on after the alarm bell was silenced. However, if the flow fell substantially or stopped completely, the float dropped, the light beam was restored and the alarm light went out (Fig. 4). One day when the flow actually failed, the operator cancelled the alarm, but with no light to remind him he was distracted by other problems and forgot that the gas flow had stopped. Several hours passed before this was discovered.

Afterwards the design was changed so that the light beam was broken when the flow was normal but fell on the light sensor if the flow changed. The alarm light then remained lit as long as the low flow continued. As a bonus it was also activated by a high flow.

Alternatively, the alarm could have been modified so that once it operated the light stayed on until reset by the operator.

8. A procedure that cannot do what we want it to do

If tests are being carried out on a vessel they are often made on the points of a grid. Lines of weakness, such as welds may then be missed. The grid should be tilted so that the test points are not all above or below each other (see Fig. 5).

9. What is meant by “similar”?

Some changes had to be made to a length of low pressure ventilation ductwork about 0.6 m (2 ft) diameter. To keep the rest of it in operation during the modification a by-pass was made round the affected section. To isolate this section the contractor was told to drill

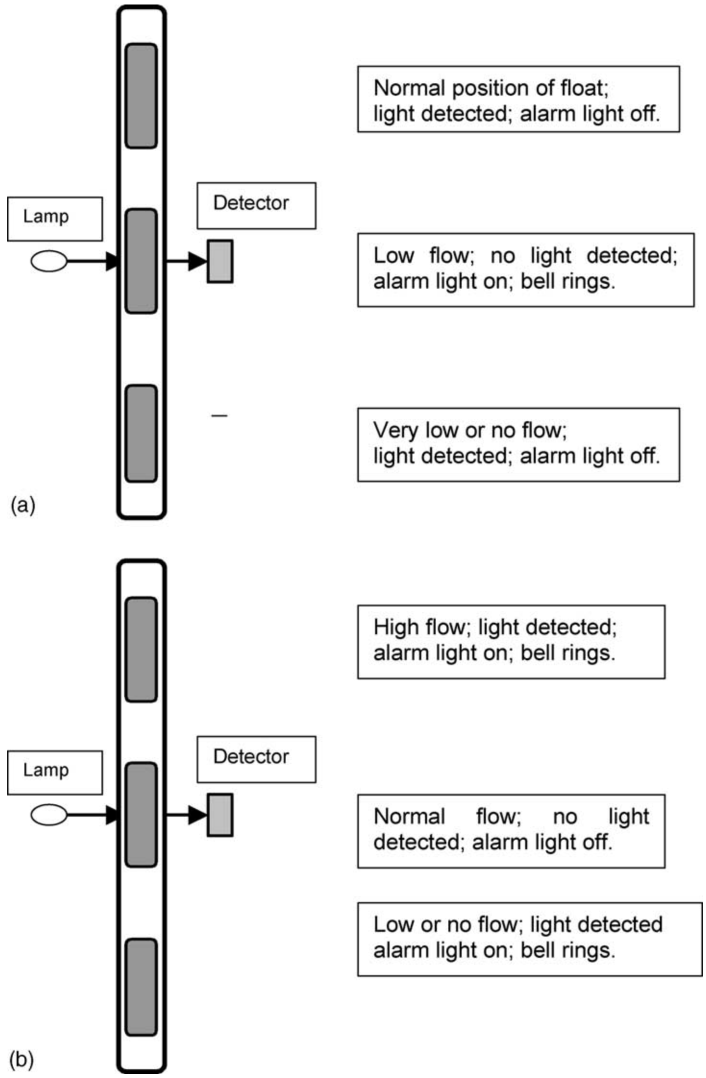

Fig. 4. (a) Original design of rotameter low flow alarm. (b) Revised design of rotameter low flow alarm.

a hole in the duct and push an inflatable rubber balloon through it. This is a standard item of equipment that had been used successfully on previous occasions. The drawing specified "[manufacturer's name] inflatable pipeline stopper or similar". This manufacturer's stopper is fitted with a rigid metal inflation tube that ensures that the balloon remains in position beneath the insertion hole. The contractor used instead a balloon fitted with a flexible tube. The inflated balloon moved a little way down the duct and blocked the by-pass line (see Fig. 6). Ventilation flow was stopped. The operators in the control room has been warned that

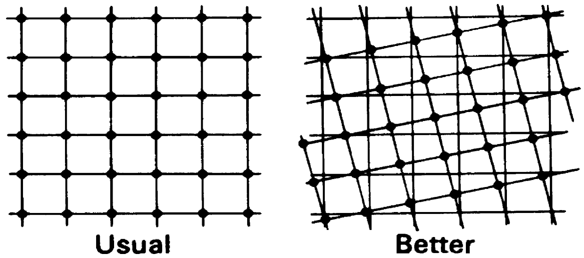

Fig. 5. Arrangement of test points on a grid. The “usual” method can miss lines of weakness such as welds.

changing over to the by-pass line might cause the low flow alarm to operate and therefore they ignored it. Some time elapsed before they realized what had happened.

The immediate cause of the incident was therefore the use of the word “similar”. What is similar to one person is dissimilar to another. (To some people bats are similar to birds; to

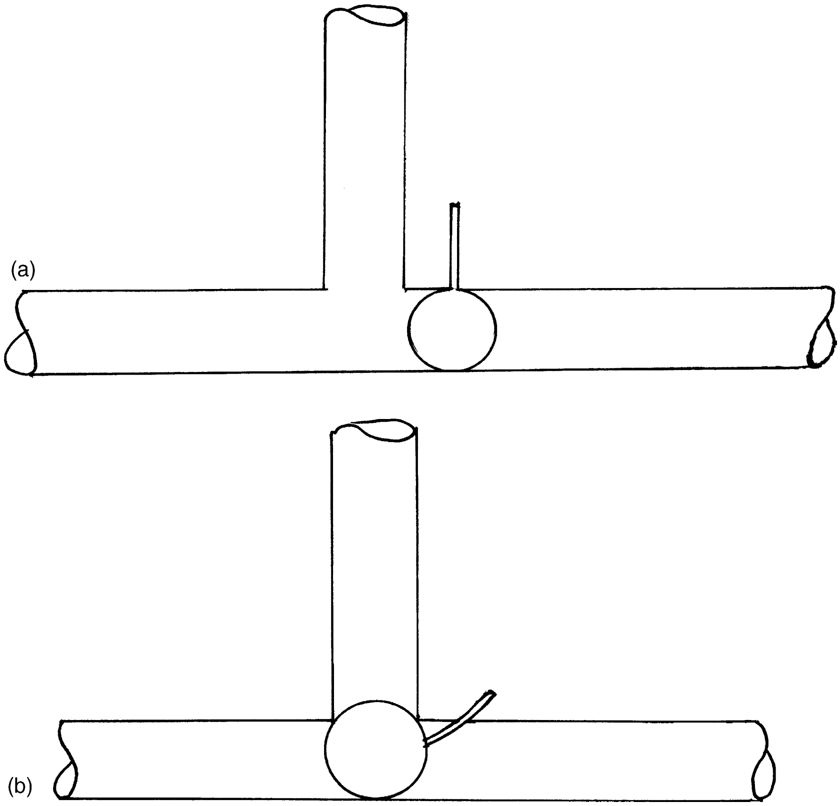

Fig. 6. (a) The intention: Inflatable stopper with rigid stem. (b) The result: Inflatable stopper with flexible stem.

others a bat—*Fledermaus* in German—is more like a mouse.) The word “similar” should never be used in specifications or instructions.

Another word that should not be used is “all”. Someone asked to remove all the blinds from a vessel does not know how many and may overlook one (or more).

10. An unsuitable material of construction

A former colleague of mine has described a New Year Ball that did not go exactly as planned [2].

We wished to make the New Year Ball particularly spectacular and had arranged for a couple of hundred brightly colored balloons to be released among the revelers from a net suspended from the ballroom ceiling. During the afternoon before the event we decided that manual inflation of the balloons was far too exhausting and I ordered a cylinder of compressed carbon dioxide to he sent up from the Analytical Lab. The balloons, all 200 of them, were inflated in no time at all and the clusters were hoisted to the ceiling in the releasable net. Imagine our chagrin and extreme embarrassment when arriving for the opening of the Ball a few hours later to find that every balloon had shrunk to the size of a small orange and on eventual release fell to the floor with sickening thuds. I had learned my lesson—India rubber is permeable to carbon dioxide!

When plastic water pipes are run through oil-soaked ground the water may become contaminated with oil.

In some combustible gas detectors the sample is drawn through a plastic tube to the measuring element. The plastics used absorb some flammable vapors. It is better to use detectors in which the element is at the end of a lead and can be located at the point of test, such as the inside of a vessel.

11. Draftmen’s delusions

Elliott [3] uses the term “draftsmen’s delusions” to describe problems that occur because the beliefs of the drawing office differ from the reality of the plant.

For example, a small solvent drying unit was designed to operate at a pressure of 2 bar gauge (30 psig). The drying chambers had to be emptied frequently for regeneration so a nitrogen connection was needed. The designer looked up the plant specifications and found that the nitrogen supply operated at a pressure of 5.5 bar gauge (80 psig). This was far above the operating pressure so the designer assumed there was no danger of the solvent entering the nitrogen main by reverse flow; he supplied a permanent connection. (He supplied a check valve in the line but these are not 100% effective. They would be more effective if they were regularly maintained but rarely are; we cannot expect equipment containing moving parts to work for ever without maintenance.)

If the designer had asked the operating staff they would have told him that the unit was to be located near the end of the nitrogen supply line and that its pressure fell below 2 bar gauge when other units were using a lot of nitrogen. If the designer had ever worked on a plant he would have known that it is by no means uncommon for nitrogen supply pressures to fall, especially when large units are being shutdown for maintenance or are being swept out ready for start-up.

On the drying unit some solvent, which was flammable, entered the nitrogen main by reverse flow and then entered another item of equipment where it exploded [4].

If the designer had known that the pressure in the nitrogen supply was liable to fall he would have fitted a low pressure alarm or isolated the nitrogen by double block and bleed valves or a breakable connection.

12. Thin bolted sheets are not leak tight

Air can leak into equipment made from thin bolted metal sheets. The nitrogen blanketed equipment in the last item was a thin metal cabinet containing sparking electrical equipment and located in a Division 2 area. The contaminated nitrogen brought solvent vapor into the cabinet. Later, the nitrogen supply failed entirely, air leaked in through the bolted joints and an explosion occurred, injuring the operator who was standing in front of the cabinet. The source of ignition was, of course, the sparking electrical equipment. Joints between non-machined surfaces should be welded.

A second incident occurred in a large blowdown system and led to an explosion, ignited by the flare. Again, the report recommended that joints between non-machined surfaces should be welded, that there should be a continuous flow of gas to sweep away any leaks that occurred and that the oxygen content in blowdown systems should be measured regularly.

Another incident occurred in the same plant 9 months later because these recommendations were not carried out on another unit. A small bolted duct conveyed gland leaks from compressors to a vent stack. Air leaked in and the mixture of hydrogen, carbon monoxide and air was ignited by lightning and exploded [5].

13. Tank dikes

Tank dikes are normally sized so that they will contain the contents of the largest tank. However, if a tank fails catastrophically, for example, as the result of brittle failure, the sudden rush of liquid may go over the top of the wall, especially if it has sloping sides. Such failures are infrequent but have occurred and there may be a case for increasing the height of the walls if vulnerable targets, such as public highways, are near them [6,7].

14. A trip that did not work under abnormal conditions

The by-product carbon dioxide from an ammonia plant was sent down a long (1000 m or 3300 ft) pipeline to another unit. The gas normally contained 2–3% hydrogen. At this concentration it cannot form an explosive mixture when mixed with air. If the hydrogen content reaches 8%, contamination by air could produce an explosive mixture. A trip was therefore installed to shut down the transfer if this figure was approached. The hydrogen level measurement was based on thermal conductivity.

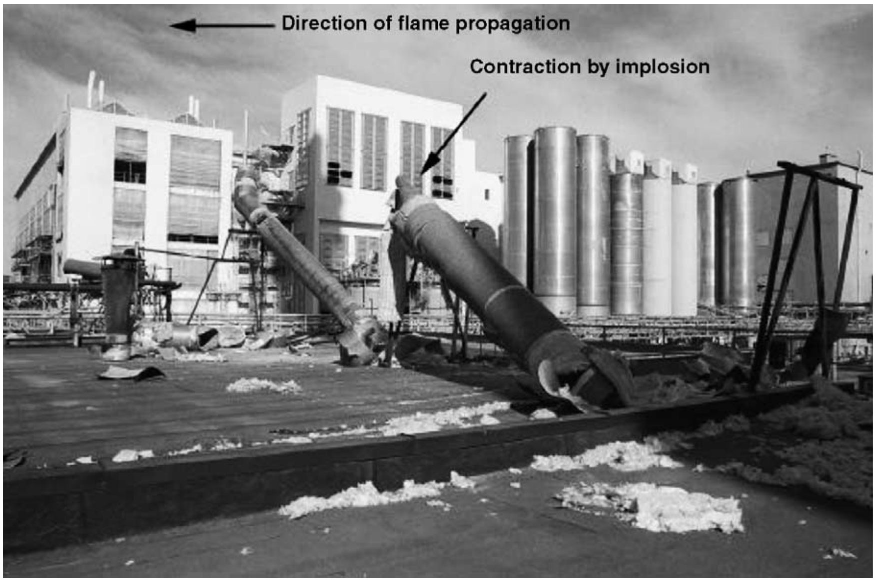

Fig. 7. The result of hydrogen and air entering a pipeline.

During shutdowns the ammonia plant was swept out with nitrogen. When the plant started up the initial hydrogen flow was therefore contaminated with nitrogen. It has twice the thermal conductivity of hydrogen so after a shutdown the trip was disabled until the nitrogen had been swept out. You've guessed what happened. Air got into the transfer line soon after a shutdown and an explosion occurred; 850 m (2800 ft) of the pipeline was destroyed (see Fig. 7).

The source of the air was never identified. Following an earlier incident different types of connector were used for compressed air and nitrogen hoses, so compressed air could not have been used instead of nitrogen for sweeping out the ammonia plant. The source of ignition may have been heat from cutting a bolt.

The report [8] comments, "Looking back it may seem unbelievable . . . . From management and down there had been a will to make safety a priority. During the previous 10 years, considerable money and resources had been spent. It was a painful surprise. With hindsight anyone can tell how the explosion could easily have been prevented." Afterwards the trip system was modified making use of a carbon dioxide measurement as well as the hydrogen measurement.

15. Protective equipment caused an explosion

A plastics manufacturing plant included a grinder to eliminate oversize particles. A stream of air removed the ground powder. There was an explosion suppression system to prevent a dust explosion: if a pressure sensor detected a rise in pressure chlorofluorocarbon (CFC) was released into the grinder and its associated piping to quench the explosion (Fig. 8).

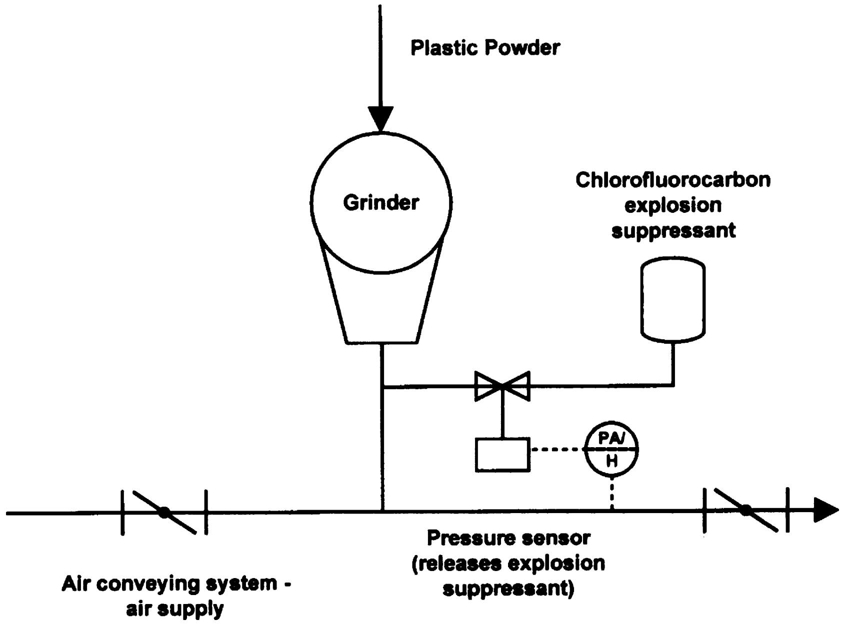

Fig. 8. Plastics grinder with explosion suppression system.

The system was in use for nearly 20 years but was never called upon to operate. Then the grinder exploded and the cause was the suppression system. An upset in another part of the unit allowed water to get into the grinding system and form a slurry with the powder. Some of the water or slurry worked its way into the branch leading to the pressure detector. This detector was very sensitive—a pressure of only a few inches water gauge was sufficient to activate it—so the suppression system operated and the CFC was released. The accumulation of slurry prevented the CFC flowing easily though the system and the door, weighing over 200 kg (about 500 lb), was blown off the grinder. It hit the wall of the room and bounced back. Fortunately no was injured but operators often stood in front of the grinder to inspect its operation through a window in its front. Many people were surprised that the release of CHCs could blow the door off but it was held by only four bolts and could withstand an internal pressure of only 1–1.4 bar gauge (15–20 psig).

It was certainly a physical explosion and not a chemical one as there was no soot or burnt material and the powder on the floor was still white [9].

The plant was designed before the days when Hazop was widely used. If the design had been Hazoped the possibility of water entering the system could have been recognized. Today explosion prevention systems often measure the rate of pressure rise and other materials are used as CFCs affect the ozone layer.

It is good practice when designing any equipment to ask, which part will give way if it is overpressured, and locate the equipment so that people are unlikely to be in the line of fire. We protect equipment from excessive pressure by relief valves or in other ways but all active protective systems are liable to fail.

16. Preventing similar errors

There is no simple way of preventing the errors described above. Hazard and operability studies will help but only if the teams, or at least some of their members, have a good understanding of what is scientifically possible and of the sort of errors that have occurred in the past. The more we discuss our designs with other people, including those who will have to operate the equipment, the more likely that someone will spot any weaknesses.

Figs. 1–3 and 7 are reproduced with the permission of the American Institute of Chemical Engineers. Thanks are also due to the authors of Ref. [8]. Fig. 8 is reproduced by permission of the *Loss Prevention Bulletin* of the Institution of Chemical Engineers and the authors of Ref. [9].

References

[1] T.H. Pratt, J.G. Atherton, Electrostatic ignition in everyday operations: three case histories, Process Safety Prog. 18 (4) (1999) 241–246.
[2] B. Whitefoot, Quoted by D. Claridge, Memories: Wilton Castle Club, ICI Chemicals and Plastics, Middlesbrough, UK, 2000, p. 69.
[3] P. Elliott, Overcome the challenge of corrosion, Chem. Eng. Prog. 94 (5) (1998) 33–42.
[4] T.A. Kletz, Learning from Accidents, 3rd ed., Butterworths/Heinemann, Oxford/Boston, 2001, Chapter 2.
[5] T.A. Kletz, What Went Wrong?—Case Histories of Process Plant Disasters, 4th ed., Gulf, Houston, Texas, 1998, Section 6.1.
[6] A.M. Thyer, I.L. Horst, S.F. Jagger, Bund overtopping—the consequence of catastrophic tank failure, J. Loss Prev. Process Ind. 15 (5) (2002) 357–364.
[7] Anon., Investigation Report 2001-05-1-DE: Refinery Incident, US Chemical Safety and Hazard Investigation Board, 2002, Section 3-2-3.
[8] J.O. Pande, J. Tonheim, Ammonia plant: explosion of hydrogen in a pipeline for CO_2, Process Safety Prog. 20 (1) (2001) 37–39.
[9] A.M. Dowell, D.C. Hendershot, G.L. Keeports, Explosion caused by explosion suppression system, Loss Prev. Bull. 146 (1999) 3–4.