

GREEN INTENTION, RED RESULT

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Abstract: Changes made to improve the environment have sometimes produced unforeseen and hazardous side-effects. Thus the confinement of flammable vapours in vent collection systems has caused a number of explosions, the replacement of CFCs in aerosols has led to a number of fires in plants and warehouses and enclosing compressor houses to reduce noise has made explosions more likely. These and some other similar changes are described.

Before changing designs or methods of operation we should try to foresee their effects, by Hazop or similar techniques, and we should balance the risks to the environment against the risks to people.

Keywords: modifications, environment, safety, vent collection, halogenated hydrocarbons, compressor houses

The way in which environmental controls are devised and applied is a matter of concern to the Health and Safety Executive. They must ensure compatibility with the way risks to employees from industrial processes are regulated. – D. Eves, HSE Deputy Director-General[1]

INTRODUCTION

Since the explosion at Flixborough in 1974 numerous publications[2,3,4,5] have drawn attention to the unforeseen effects of changes to plants and processes (and, more recently, organisation[6]). They have emphasised the need to examine proposed changes so that we can foresee, and thus avoid, unwanted and hazardous side-effects. The changes were often made to improve safety but had the opposite effect. This paper describes some changes made with the commendable purpose of improving the environment but which created hazards and also some new designs in which environmental considerations were put before safety ones. As far back as 1976 Bodurtha[7] wrote, "Explosions and fires are occurring with greater frequency with pollution control equipment" and gave some examples, including the following:

- Reducing the excess air in a furnace in order to reduce the formation of oxides of nitrogen can increase the chance of going fuel-rich. An explosion may then occur when air is added.
- Collecting dusts to reduce pollution, and collecting them dry to avoid water pollution, has led to dust explosions.

VENT COLLECTION SYSTEMS

During the last twenty years there has been increasing pressure to collect the discharges from tank and other vents instead of discharging them to atmosphere. The collected vapours are then burned or absorbed. Explosions are prevented, in theory, by keeping the concentration of vapour below the flammable limit or by inerting with nitrogen. However, the systems are inherently unsafe as the concentrations of vapour or nitrogen can easily change, as shown by the following incidents. References 8 and 9 describe others.

A fan collected flammable vapour and air from the vents on a number of tanks and distillation columns and fed the vapour/air mixture into a furnace as part of the combustion air. The system was designed to run at 10% of the lower explosion limit but when it was isolated from the furnace in error, the vapour concentration rose. When the flow was restored a plug of rich gas was fed into the furnace where it mixed with air and exploded; the flame propagated back up the vent collection system despite the presence of a flame arrester[10].

Vapours from another plant were sent via fans to water scrubbers and then to atmosphere. Following pressure to reduce emissions the scrubbers were replaced by an incinerator. Most of the equipment was blanketed with nitrogen; one vessel was not blanketed but there were arresters in the lines leading to the incinerator. The nitrogen concentration was not measured. During reactor charging the fan speed was increased to prevent vapour escaping through open manholes, more air was sucked in and there was an explosion. The flame arresters were fouled with a rubbery residue after only five days use[11].

Vent collection systems can allow an explosion in one vessel to spread to others. The fire that destroyed a bulk storage facility at Coode Island, Melbourne in August 1991 spread in this way. There were no flame arresters in the pipework. Whatever the cause of the initial fire or explosion the vent collection system provided a means of spreading the fire from one tank to another[12].

At one time it was difficult to prevent the spread of explosions through vent systems as flame arresters were effective only when they were located at the ends of pipes. Now effective inline detonation arresters are available[13]. However, like all flame arresters they need regular cleaning; this is often neglected.

When tanks have been overfilled, liquid has contaminated other tanks through common vent systems and this has led to runaway reactions.

When recovery systems for petrol vapour were installed in the San Diego area there were over twenty fires in four months. The petrol vapour, mixed with air, was drawn off by a fan and passed over a carbon bed; the carbon was then steamed to recover the gasoline which was then burnt. In time the problems were overcome but it seems that the recovery systems were introduced too quickly and without sufficient testing[14].

The carbon bed absorbers were probably the source of ignition as the heat of absorption can raise the temperature above the auto-ignition temperature of the vapour. These absorbers have certainly been responsible for many other ignitions[15,16,17]. In one case a fire burned for three days and 2000 people were evacuated from their homes[18]. According to Martin *et. al.*[19] carbon absorption and catalytic incineration are not suitable for air streams containing more than 25% (in some cases 40%) of the lower explosive limit. As we have seen, streams that normally contain less than this amount may contain a flammable concentration after a plant upset.

When the underground storage tanks at petrol filling stations are being filled the displaced vapour is now being returned to the tanker. Before the tanker is maintained it has to be gas freed. This is normally done by opening the manhole and sucking the gas out from the bottom of the tanker with an eductor driven by compressed air. With more petrol vapour in the tanker the flammable cloud is larger. In one incident it was ignited by a fired heater 5 m away. The flame flashed back and caused an explosion in the tanker. Subsequent calculations showed that the safe distance was 18 m[20]. When the vent recycle system was designed, did the team consider maintenance of the tanker?

Single vents as well as vent collection systems can cause problems. In 1984, at Abbeystead, Lancashire, water was pumped from one river to another through a tunnel. When pumping was stopped some water was allowed to drain out of the tunnel and leave a void. Methane seeping from the rocks below accumulated in the void. When pumping was restarted the methane was pushed through vent valves into an underground valvehouse where it exploded, killing 16 people. Most of them were local councillors who were visiting the plant.

If the operating staff had known that methane might be present, they could have prevented the explosion by keeping the tunnel full of water or by discharging the gas from the vent valves into the open air. In addition, they could have prohibited smoking, the probable source of ignition, in the pumping station (though they should not have relied on this alone). None of these things was done because they did not realise that methane might be present. The official report said that while references to the presence of dissolved methane in water supply systems had been traced in published literature they were not generally known to engineers concerned with water supply schemes[21].

Nevertheless it is surprising that a vent was routed into a pumphouse. It seems that this was done because the local authority objected in principle to any equipment that might spoil the view.

A small factory in a residential area recovered solvent by distillation. After giving trouble for several weeks the cooling water supply to the condenser finally failed and hot vapours were discharged from a vent inside a building. They exploded, killing one man, injuring another and seriously damaging the factory. Five drums landed outside the factory, one on a house[22].

There were no operating or emergency instructions, no indication of cooling water flow and drums were stored too near buildings but by far the most serious error was allowing the vent pipe to discharge inside the building. If it had discharged outside the vapour would have dispersed harmlessly or, at the worst, there would have been a small fire on the end of the vent pipe. Vent pipes are designed to vent so this was not an unforeseen leak. It seems that the vent pipe was placed indoors to try to minimise smells that had caused some complaints.

REPLACEMENTS FOR HALOGENATED HYDROCARBONS

When the chloroflurocarbons (CFCs) were introduced they were welcomed as non-flammable and non-toxic refrigerants, solvents and propellants for aerosols and foam-blowing. Their effects on the ozone layer were first recognised in 1974 and their manufacture is now restricted to developing countries where it is being reduced but will not stop until 2010. Existing stocks may still be used. One of the replacements is CHF_2Cl (HCFC22) which has only a twentieth of the effect on the ozone layer but is nevertheless due to be phased out in time. CF_3CH_2F (HFC134a) has no effect on ozone but is more expensive than the CFCs and has a greenhouse effect[23]. There has therefore been a move back to flammable refrigerants such as butane and propane and to ammonia which is toxic and also flammable though many users do not realise this[24]. The amount of refrigerant in domestic refrigerators and freezers is so small that hydrocarbons are not considered a hazard but there are substantial quantities in industrial and supermarket refrigeration systems. A news item in *The Chemical Engineer*, headed *Ice cream with a conscience*, praised Unilever for replacing CFC's in ice cream freezers with hydrocarbons but did not mention the flammability hazard[25].

A liquid chlorine tank was kept cool by a refrigeration system that used CFCs. In 1976 the local management decided to use ammonia instead. Some of the ammonia leaked into the chlorine and formed nitrogen trichloride which exploded in a pipeline supplied by the tank; six men were killed though the report does not say whether they were killed by the explosion or by the chlorine. Another explosion occurred while the contents of the tank were being drained into a pond filled with lime slurry[26]. The reaction between ammonia and chlorine has been well known for many years[27] but was not known to the plant management nor did they make any enquiries.

In aerosols CFCs were replaced by butane (or a butane/propane mixture) fairly rapidly as some manufacturers already used it and it was cheaper. The result was a number of fires and explosions, summarised in reference 28. Did the changeover have to be made so quickly and with so little consideration of the hazards of handling butane? After one fire the company was prosecuted for failing to train employees in the hazards of butane, in fire evacuation procedures and in emergency shutdown procedures. These actions were, of course, not necessary or less necessary, when CFCs were used. According to the report[29], "...employees did not realise the significance of the white mist flowing out of the filling room across the main factory floor". Following this fire HSE inspectors visited other aerosol factories and found much that could be improved. The manufacturers of the filling machines agreed to modify them so that they were suitable for handling butane. This, apparently, had not been considered before[30].

CFCs have also been widely used as cleaning solvents as they are non-flammable and their toxicity is low. Now flammable solvents are coming back into favour. A news item from a manufacturer described "a new ozone-friendly cleaning process for the electronics industry" which "uses a unique hydrocarbon alcohol formulation". It did not remind readers that the mixture is flammable and that they should check that their equipment and procedures were suitable.

Halons, especially Halon 1301 (CF_3Br), have been widely used for fire-fighting. They were considered wonder chemicals when they were introduced as they are cheap, stable, leave no residue and are outstandingly effective as fire-fighting and fire-suppressing agents. Halon 1301 has a low toxicity and is suitable for use in total flooding systems. Alternative, though less effective, materials, such as fluorinated hydrocarbons, have been reviewed in references 31, 32 and 33. Let us hope there will not be a return to the widespread use of carbon dioxide for flooding rooms containing electrical equipment. If the carbon dioxide is accidentally discharged while someone is in the room they will be asphyxiated. Accidental discharge of Halon 1301 will produce a concentration too low to cause harm in the short time needed for people to leave the room. Of course, procedures require the carbon dioxide supply to be isolated before anyone enters the room but these procedures have been known to break down. In 1998 the accidental discharge of carbon dioxide in a US government laboratory killed one worker and resulted in life-threatening injuries to others[34].

Halon 1301 has been chosen for use in the Channel Tunnel between England and France. It is so much more effective than any available alternative that its use is considered essential if coach and car passengers are to be allowed to remain in their vehicles inside the train. The tunnel was designed on the assumption that they will do so[35]. Halon 1301, of course, affects the ozone layer only when it is discharged (or leaks). This may be a price worth paying for its efficiency in saving life.

There is concern that flame retardants containing bromine will produce the bromine analogue of dioxin when burned. Little is known about its toxicity but the World Health Organisation has recommended that it should not be used where suitable alternatives are available. Let us hope that the lives saved by flame retardants will be taken into account in the debate[36].

The harm caused by the hasty replacement of CFCs is nothing compared with that caused by the banning of DDT, the cheapest and easiest way to kill malaria-carrying mosquitoes. The number of cases of malaria in Ceylon (now Sri Lanka) in successive years has often been quoted:

Cases	**Year**	**Comment**
2,800,000	1948	No DDT
31	1962	Large-scale DDT programme
17	1963	Large-scale DDT programme
150	1964	Spraying stopped
308	1965	
499	1966	
3466	1967	
1,000,000	1968	
2,500,000	1969	

Malaria kills two million people every year. The alternatives to DDT are too expensive for sub-Saharan counties. We are putting damage to the environment before the lives of people in these countries[37]. Rachel Carson's *Silent Spring*, which started the anti-DDT campaign, may have been responsible for more harm than any other book.

EXPLOSIONS IN COMPRESSOR HOUSES

A number of compressor houses and other buildings have been destroyed or seriously damaged, and the occupants killed, when leaks of flammable gas or vapour have exploded[38,39,40,41].

The ignition of a few tens of kilograms of flammable gas inside a building can destroy it, but if the gas is released out-of-doors several tonnes or tens of tonnes are needed. For this reason, during the 1960s and 1970s most new compressor houses and many other buildings that handle flammable liquids and gases were built without walls so that natural ventilation could disperse any leaks that occurred. The walls of many existing buildings were pulled down. Even on a still day natural ventilation is usually more effective than artificial ventilation, so the flammable zone round a leak will be smaller. If a leak should ignite, the pressure is not confined and damage is much less.

In recent years closed buildings have again been built in order to meet new noise regulations. The buildings are usually provided with forced ventilation but this is much less effective than natural ventilation and is usually designed for the comfort of the operators rather than the dispersion of leaks. In New Zealand in 1986 I saw two plants in which the most up-to-date safety features were installed, with one exception: both had completely enclosed compressor houses. The plants had to meet stringent noise regulations and enclosing the compressors was the simplest way of complying. One of the plants was out in the country, there was not a house in sight and it seemed that the regulations had been made for the benefit of the sheep.

I saw a similar compressor house in the UK in 1991. The safety features verged on the extravagant, but the compressor was totally enclosed as the local authority had asked for a noise level of 35 dBA or less in the nearest houses, a few isolated farms. Driving home after the visit I passed streets of houses alongside the motorway where the noise levels must have been far higher, at a level which many people would find intolerable. Regulators are not always consistent.

One leak started, soon after an overhaul, when the nuts holding a compressor valve cover in place failed as a result of overtightening. The escaping gas blew out the doors and windows of the compressor house and the leak was ignited by electrical equipment. The explosion killed one person and destroyed one wall of the building[42].

Note that the leaks that lead to explosions are often not from a compressor itself but from other equipment such as flanged joints. One leak occurred because a spiral wound gasket had been replaced by a compressed asbestos fibre one, probably as a temporary measure, seven years earlier. Once installed, the fibre gasket was replaced by a similar one during subsequent maintenance[43].

An alternative method of reducing the noise radiation from a compressor is to surround it by a housing made from noise insulating material, and purge the gap between the compressor and the housing with a continuous stream of compressed air[44].

SOME MISCELLANEOUS EXAMPLES

- The burning of waste products in furnaces to save fuel and reduce pollution has caused corrosion and tube failure.
- Shortening of pipe-runs to avoid heat losses and save fuel can result in congested plants. If a fire occurs the damage is increased, particularly if equipment is stacked above pipe-runs. There is no net gain if we save fuel bit-by-bit and then waste the saving in a big display of fireworks[45].
- A new method for the manufacture of ibuprofen produces less waste but requires the use of hydrogen fluoride as raw material and solvent[46].
- During the last 20-30 years, in many parts of Europe, open coal fires have given way to central heating, thus reducing smog, drafts and respiratory disease. Indoor ventilation has been further reduced by attempts to reduce draughts and thus save fuel. As a result indoor radon levels have increased. According to one estimate this has produced, in Sweden, an 8% increase in the chance of death from cancer[47].
- A newspaper report claimed that it was environmentally friendly to squeeze one's own orange juice. In fact, oranges cost seven times more to ship than concentrated juice and home squeezing recovers only 80% of the juice. In addition, juice firms recover oil from the peel[48]. We should consider the safety and environmental impacts of operations as a whole and not just those of isolated tasks.
- In recent years food which contains no additives has become increasingly popular. Would people buy it if instead of "Contains no artificial preservatives" the label said, "Contains nothing to prevent it going off" or if all the natural toxins were listed?
- Cycling saves fuel, reduces pollution and provides valuable exercise. However, the accident rate for cyclists is much higher than for drivers. Unless the route to school or work lies along quiet streets, we are safer travelling by car.

ARE NUMERICAL COMPARISONS POSSIBLE?

The HSE, in their well-known report on the tolerability of risk[49], have proposed an upper level of the risk to life from an industrial accident risk which should not be exceeded and a lower level which is "broadly acceptable". In between the risk should be made so low as reasonably practicable (ALARP), using cost-benefit analysis. For the upper level they suggest 10^{-3} per year for an employee and 10^{-4} for a member of the public (but 10^{-5} for nuclear risks); for the lower level they suggest 10^{-6}. Is a similar approach possible for environmental risks?

Similar principles to ALARP are used for the environment and the Department of the Environment have made a first attempt[50] to list events that could constitute major environmental accidents. The 13 listed include permanent or long-term damage to defined areas of land and water, damage (undefined) to an ancient monument, contamination of a water supply that would make it unfit to drink and affect more than 10 000 people, and death (or inability to reproduce) of 1 percent of any species. If these events are to be considered intolerable, we may well end up paying more to save the life of an animal than of a person. While loss of 1 percent of the world’s population of, say, chimpanzees, may well be a major accident, it is difficult to feel the same about 1 percent of, say, one of the 70 species of blue butterflies that inhabit the Andes mountains.

CONCLUSIONS

I am not, of course, opposed to attempts to reduce pollution and improve the environment. I do, however, suggest that before changing designs or methods of operation, for whatever reason, we try to foresee the results of those changes by using hazard and operability studies or other systematic methods such as those described in references 2, 3 and 5. In addition, we should never change or remove equipment or procedures unless we know why they were introduced.

We should be particularly cautious before we replace an inherently safe design by what that is inherently less safe, for example, before we replace a non-flammable and non-toxic substance by a flammable or toxic one. It is true that flammable and toxic substances can be handled safely but both people and equipment are liable to fail and the best achievable may not give a "broadly acceptable" level of risk.

We should also balance the risks to people against the risks to the environment and should not assume that the removal of risks to the environment must always come first. The two incidents in which vents were discharged inside buildings illustrate the results of such a policy.

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