INHERENTLY SAFER PLANTS - RECENT PROGRESS

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In an inherently safer plant, instead of *adding on* protective equipment to control the hazards, we *avoid* them by using less of the hazardous material or safer alternatives or by eliminating hazardous equipment or operations. Though the chemical industry has been slow to adopt such designs, there has been some progress. Some recent work is reviewed and the reasons why progress has not been more rapid are discussed. (Inherently safer design; safety; process intensification; substituition; elimination; passive safety.)

INTRODUCTION

The usual procedure in plant design has been to identify the hazards and operating problems, originally by waiting until an incident occurred, more recently by using a technique such as hazard and operability studies, and then add on protective equipment to control them. In an inherently safer design we try to avoid the hazards and operating problems by a change in design: by using less of the hazardous material (intensification), by using a safer material instead (substitution), by using the hazardous material in a less hazardous form (attenuation) or by eliminating hazardous equipment or operations. Alternatively we ask if we can limit the effects of hazards, not by adding something on but by changing reaction conditions or by limiting the amount of energy available.

Some chemical engineers have always been conscious of the need to avoid hazards rather than control them but the subject was not studied systematically until after the explosion at Flixborough in 1974 (Parker(1), Kletz (2) and Lees (3)). This vapour cloud explosion, one of the worst that has ever occurred, was the result of a leak from a cyclohexane oxidation plant and drew attention to the fact that many oxidation plants contain large inventories of hot, flammable liquids under pressure above their normal boiling points. If there is a leak the escaping liquid turns to vapour and spray. The inventory in the plant is large as conversion is low, most of the raw material has to be repeatedly recycled and it gets a series of 'free rides'; the processes are inefficient as well as hazardous.

Ten years later the leak of a toxic intermediate, methyl isocyanate, at Bhopal drew attention to the fact that we carry stocks of many materials which it is convenient but not essential to store. After Bhopal many companies drastically reduced their stocks of MIC and other hazardous intermediates (Wade *et al* (4)).

This paper outlines some recent developments in inherently safer design and discusses the reasons why progress has not been more rapid than it has been. It also discusses the related subject of passive design and the public acceptability of inherently safer designs. It supplements Kletz (5), which reviews the whole field, and Kletz (6).

While this paper is concerned with industrial safety the principles apply equally to the prevention of pollution, the elimination of waste and the prevention of industrial disease. However, I know of no systematic review of the application of inherently safer design in these fields.

None of the suggestions made in this paper can applied in every case. They are aims, not panaceas. But we may find that they can be applied more often than we think.

Collecting examples of "inherently safer design" is rather hit and miss as this phrase is not widely used as a keyword or indexing term. A computer search for "inherently safer design" produced few references, mainly my own papers! A search for "inherent safety" produced numerous references to the nuclear industry. A search for "intensification" produced numerous references to image intensification and some Russian papers on intensification of heat transfer in the steel industry but only one to the sort of intensification discussed in this paper. A search for papers in which "intensification" and "safety" both appeared reduced the number of references to four but three still referred to image intensification. "Process intensification" produced a number of Russian papers (mainly in the *Journal of Applied Chemistry in the USSR*) on heat transfer, absorption, milling, magnetic treatment and compacting powdered mixtures as well as references to some of Ramshaw's papers. This seems to be the most promising indexing term.

"Substitution" is, of course, widely used by chemists in a different sense to that discussed here but a search for papers including both "substitution" and "safety" did produce a few references to fuel substitution.

In general, indexers often miss abstract concepts. If a change to a pump caused a fire, "pump" and "fire" will be indexed but "modification" may not be and anyone looking for reports of accidents caused by modifications will not find it.

INTENSIFICATION

The underlying principle is that what you don't have, can't leak. The best way of preventing a leak of hazardous material is to use so little that it hardly matters if it all leaks out.

Intensification produces reductions in cost as well as increases in safety as smaller inventories need smaller equipment. Much of the progress in intensification has come from the need to reduce costs, for example, the Higee distillation/absorption system (Ramshaw (7)) and its development, the de-aerator described by Balasundaram *et al* (8). Inherently safer design is not just an isolated but desirable improvement but part of a package of improvements that the chemical industry needs to make for the years ahead.

Reaction provides more scope for intensification than any other unit operation as many reactions are slow processes that require a long residence time. Improved mixing [for example, in a pump (Butcher (9))] can often improve conversion but if it *cannot, and a long residence time is essential, a long thin* tube may be an alternative to a pot reactor. Its integrity is high, the leak rate is limited by the cross-section of the tube and leaks can be stopped by closing a valve. In theory, if 20,000 tonnes/year is required it can pass through a line of 5 cm (2 in) bore; if 1000 tonnes/year is required it can pass through a line of 1 cm (0.4 in) bore (Middleton and Revill (10)). Pressure drop may prevent the use of long tubes but tubes up to 90 m long, though 18 cm (7 in), in diameter have been used in the brewing industry for handling an unpromising material described as "thick porridge" (Shore (11)).

Almost any unit operation can be intensified. An intensified plate heat exchanger has very narrow spaces (fractions of a millimeter) between the plates. The liquid flow passages are etched into the plates by techniques similar to those used in making printed circuits (Cross and Ramshaw (12)). A number of the exchangers are now in use (Anon (13)).

SUBSTITUTION

Less hazardous materials or reactions can often be used in place of hazardous ones. For example:

- Ultraviolet or electron beam radiation can be used to cure coatings and adhesives applied as solids. Flammable or toxic solvents are no longer needed. The solids used are less irritant to the skin than those used when the technique was first developed in the 1970s (Anon (14)).

- Carbon dioxide can be used instead of sulphuric acid to control the pH of drinking water. The water cannot be overdosed as if too much carbon dioxide is injected the excess will not dissolve, an example of inherently safe control. The sulphuric acid is not only harmful if spilt but corrodes equipment (Boniface (15)).

- Combustion is a reaction that can easily get out of control and produce undesirable by-products. Toxic waste can now be oxidised to water electrochemically at low temperatures (70-96°C). The off-gas is said to contain no harmful residues (Steele *et al* (16)).

- A new insecticide for the control of the malaria mosquito is safer and simpler to use than alternatives. Much *smaller doses are needed - a few boxes are equivalent to a* truckload of DDT - so it is easier (and safer) to transport to remote areas (McDonald (17)).

- Helium is purified by passing it over a carbon bed cooled to -196°C by boiling liquid nitrogen. If the helium is contaminated with more oxygen than nitrogen the oxygen (boiling point -183°C) is preferentially absorbed and the carbon-oxygen mixture can explode. If silica gel, less efficient but non-combustible, is used instead of carbon, an explosion cannot occur (Hempseed and Ormsby (18)).

ELIMINATION OF (HAZARDOUS) EQUIPMENT OR OPERATIONS

I have put brackets round 'hazardous' as all unnecessary equipment and procedures should be eliminated. Unnecessary complication means that there are more opportunities for human error, more equipment to fail or corrode and more equipment to be constructed and maintained (many accidents occur during construction and maintenance). There are many examples in reference 5. Here are some more:

- Storage tanks for nonflammable liquids can be made from translucent plastics. There may be no need for a level indicator and the operator always knows the level in the tank. He does not have to rely on instrumentation that may be out-of-order.

- A pair of self-supporting pipes can be used instead of a pipebridge to take pipes over a road.

- The overhead vapour line on a distillation column can be replaced by an an internal dephlegmator or an air cooler mounted on top of the column.

- It may be possible to generate gas under pressure instead of generating it at low pressure and then compressing it. Compressors are often sources of leak.

Here are some obviously hazardous operations that have been or could be eliminated:

- Until the 1870s, in the early days of the Solvay process for the manufacture of sodium carbonate, an manhole at the top of each batch distillation column had to be opened and solid lime tipped in, every time it was charged. This was hazardous as ammonia vapour could escape. Ludwig Mond (the founder, with John Brunner, of Brunner Mond, one of the forerunners of ICI) suggested that milk of lime should be pumped into the columns instead (Anon (19)).

- Two valves were on different floors so two men were needed to operate them. By moving one valve near the other possibilities for misunderstanding were removed.

- The immediate cause of the failure of the Challenger space shuttle was failure of an O-ring between two sections of the body. The design of the O-ring has been improved but must the body be made in sections?

PASSIVE SAFETY

Passive safety is not the same as inherent safety. Water spray is an active safety measure as someone or something has to turn it on and even if they do the valves may not open. Fire insulation is passive, as it does not have to be commissioned, but it is not inherently safe as it can fall off or be removed for maintenance and not replaced. The inherently safer solution is to use a non-flammable material, if we can, and remove the possibility of fire.

A recent report (Forsberg *et al* (20)) describes many passive safety features suggested for water-cooled nuclear reactors. Some have not yet been tried out and may, of course, in the event not be practicable. Some of the suggestions may have possible applications elswhere and one is described below.

If circulation is lost a gas cooled nuclear reactor can be cooled by convection but most water-cooled reactors need pumped cooling to prevent overheating. Hence the proliferation of emergency cooling systems characteristic of this design. A weakness of the Three Mile Island design, not mentioned in most descriptions, is that the design actually prevented convection cooling. The heat source (the core) was only a little below the heat sink (the steam generator) and there were siphon loops in the water circulation lines which filled with steam and formed vapour locks (Figure 1). In recent designs better layout can give convection cooling equal to 25 percent of full load, enough to remove the residual heat produced after a shutdown by radioactive decay, usually about 6 percent of full load (Figure 2).

Passive safety in this instance requires an instinctive understanding of what (heat and fluid) will move where without being pumped, an understanding that the Three Mile Island designers seem to have lacked. How many chemical engineers have this understanding? Safety apart, there may be money to be saved if convection can assist pumped flow; 25 percent of pumping costs may be worth having. It is easy to draw a pump on a line diagram; it is much harder to jiggle layouts and pipe configurations to maximise convection.

A new plant was a carbon copy of an original one, except for one minor change: the floors were 10 feet apart instead of 8 feet. The increase was just enough to prevent convective flow and efficiency was lost (Crowl (21)).

WHY HAS PROGRESS NOT BEEN FASTER?

Although there has been real progress towards inherently safer designs in the oil and chemical industries since Flixborough, and especially since Bhopal, progress has been slower than many people hoped. As an example of the reasons, consider the Higee method, already mentioned, for intensifying distillation and other liquid-vapour contacting processes by carrying out the operations in compact rotating equipment.

Though Higee has been shown to work satisfactorily, very few of the units are in use, even in the company in which it was invented, and most of the applications have been for stripping liquids with gases or for treating gases with liquids, not for distillation. Why is this?

One reason is that operating managers are not convinced that rotating equipment is reliable although Higee operates at the speed of a centrifuge, a reliable and well-proven item of equipment.

Another reason is that although Higee can halve the capital cost of distillation equipment, as a proportion of the total capital cost of a project this is small. Project engineers and business managers are understandably reluctant to use new technology for a small percentage saving in cost in case there are unforeseen difficulties which prevent or delay the achievement of design output. [Similarly, in the nuclear industry, at a conference two speakers thought that a small, inherently safer, pressurised water reactor would not attract utility companies. "They would want known systems with improved features rather than new concepts (Covan (22))."]

Nevertheless, the major oil and chemical companies spend large sums every year on distillation equipment. The potential advantages of Higee to them, in cost savings and increased safety, are large. It is surprising that they have not invested in one or two Higee units each, just to gain experience of them, any unexpected costs or delays being underwritten by the company as whole rather than by specific projects or businesses. Unfortunately, one of the results of the movement towards business-centered rather than functional organisation is that there may be no central department that can recommend or fund such an investment. This provides a good example of the effects of organisation on technology.

The advantages of Higee are so great that ultimately it will surely succeed. In the short term it seems most likely to be used for gas-liquid applications other than distillation, especially when expensive materials of construction have to be used, so that the savings are greater than usual, when space is scarce, as on off-shore oil platforms, and when there are height limitations.

PUBLIC ACCEPTABILITY

The public, not without reason, doubt the ability of the chemical industry to keep hazardous materials under control. Inherently safer designs should re-assure them. Otway and Haastrup (23)) doubt this. They write, "...reducing risks by changes in design philosophies and physical plant are unlikely to have a large enough effect on public attitudes to create a climate for the acceptance of technologies previously rejected". However, even the public should be able to realise that what you don't have, can't leak. Otway and Haastrup's reservations apply more to the nuclear industry where the inherently safer designs now under development inevitably still produce radioative by-products.

It must also be remembered that inherently safer designs are not a recipe for absolute and complete safety. Higee has more moving parts than the equipment it replaces; ultraviolet light and electron beams can be hazardous in the wrong place; but on balance Higee and radiation curing will bring about a significant increase in safety.

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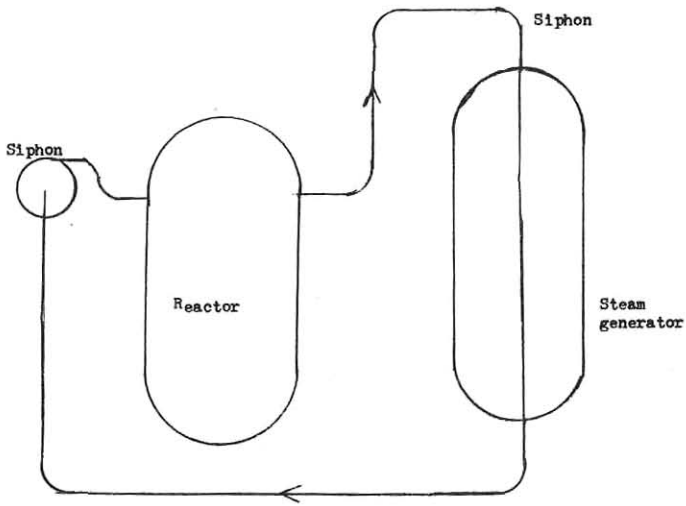

Figure 1 In the Three Mile Island design small differences in height and siphons prevent convective circulation.

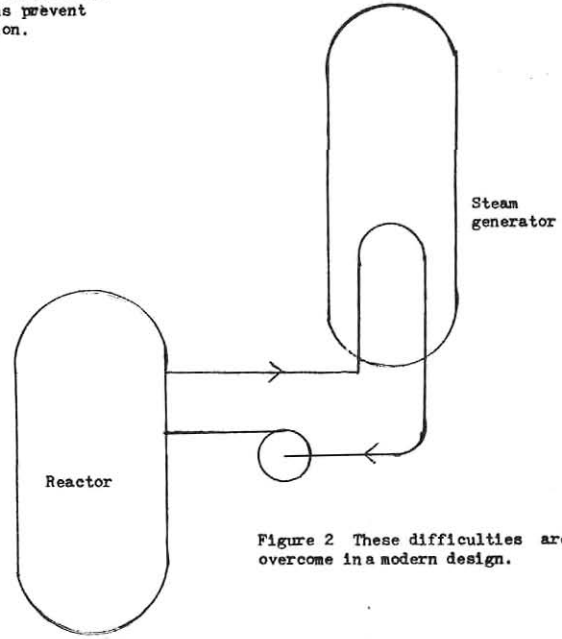

Figure 2 These difficulties are overcome in a modern design.