Hazards in the Chemical Industry – Risk Management and Insurance

By J. M. Cowan
LONDON BUSINESS SCHOOL, SUSSEX PLACE, REGENTS PARK, LONDON NW1 4SA

1 Introduction

Risk Management involves the identification of potential causes of loss that are not strictly commercial, ascertaining the probability and size of such losses, and then attempting to reduce the impact of the losses on the business of the company, by reducing the likelihood of loss and by purchasing insurance.

Insurance is purchased to cover risks that are impossible to guard against completely, and to cover areas of suspected risk.

The risks of working in British industry are only marginally higher than the risks of staying at home. Society seems to accept deaths as long as they occur singly. According to the Department of the Environment, 6630 people were killed on the roads in 1977, but road deaths are reported in the national press only when there is a motorway 'pile-up', or when a school bus plunges over a precipice. Similarly, industrial deaths are reported only when several people are killed in one of the very few spectacular explosions that occur each year. However, in such cases, there is great public outcry, even though total industrial deaths in the first 9 months of 1977 were 282, and total chemical industrial deaths were 28.

The figures given in Table 1 show, in perspective, the risk to life of working in

Table 1 *Comparison of risk to life of a number of occupations and activities*

Activity or type of occupation	*FAFR*[a]
CHEMICAL INDUSTRY	3.5[b]
British Industry as a whole	4[b]
Coal mining	40[b]
Construction workers	67[b]
Jockeys (flat racing)	50 000[b]
Staying at home	3[c]
Travelling by car	57[b]
Travelling by air	240[b]
Motor cycling	660[b]

(*a*) Fatal accident frequency rates expressed in fatalities per 10^8 man-hours of exposure to the hazard, a period of time which is approximately equal to the number of hours in the total working lives of 1000 men; (*b*) figures from ref. 1; (*c*) figures from ref. 2.

[1] F. D. Sowby, in 'Proceedings of the Symposium on Transporting of Radioactive Materials', The Institute of Transport, London, 1964, p. 89.

[2] T. A. Kletz, in 'Hazard Analysis—A Quantitative Approach to Safety' (Symposium Series No. 34), The Institution of Chemical Engineers, London, 1971, p. 75.

the chemical industry. The number of accidents is declining each year, in spite of the construction and operation of increasingly complex equipment. Thus, the record of the chemical industry judged by any standard is good, although there will always be room for improvement. The FAFR for the chemical industry is an average; some operators persist in exhibiting a negligent attitude towards the safety of their employees, which increases the FAFR for the industry from the very low rates achieved by some of the more safety-conscious operators.

About half of reported accidents in the chemical industry are caused by slipping and falling, road accidents, *etc.*, which are in the category of 'background risk'. The other half are caused by explosions, gassings, chemical burns, *etc.* Thus, the erection of a guard rail or the introduction of a one-way system on a section of plant roadway may save just as many lives as the installation of an automatic fire extinguisher or a flashback arrester.

The danger to life, although most important, is not the only danger. If a chemical plant explodes, the shareholders lose some of their property and income, the directors lose part of their credibility, the plant management and workforce lose their jobs, and, should the explosion shower debris or emit toxic gases, the surrounding population may suffer damage to their property and health. It is thus in the interest of all to ensure that expenditure on risk management is efficient.

2 Law

There are six groups of laws which particularly affect safety in the chemical industry.

A. **The Factories Act, 1961.**—This act is still the most important of the laws and has 73 regulations. Among the more relevant ones are: the Chemical Works Regulations, 1922; Electricity Regulations, 1908; Carcinogenic Substances Regulations, 1967; and Asbestos Industry Regulations, 1969.

This body of law is being supplanted by the Health and Safety at Work Act, 1974.

B. **The Health and Safety at Work Act, 1974.**—This is a very comprehensive act that at present is not supplemented by detailed regulations. However, the act includes provisions for the speedy enactment of regulations and approved codes of practice, which is a great improvement over the scandalous fifteen-year delay in the preparation of the Highly Flammable Liquids Regulations. The procedure involves the circulation of documents outlining the intentions of the new regulations to interested parties for discussion and, on agreement in principle, the legal draft can be prepared.

C. **The Fire Precautions Act, 1971, and the Fire Precautions (Special Premises) Regulations, 1976.**—The 1976 regulations transfer responsibility for fire precautions at 'high risk' factories from the local authorities to the Health and Safety Executive. This applies to most large chemical plants.

D. The Town and Country Planning Acts, 1944—1971.—These include rules which new factories, and extensions to already extant ones, must obey. Planning authorities are increasingly concerned with the health, safety, and environmental implications of industrial developments. The Department of the Environment has advised planners to seek the opinion of Her Majesty's Factories Inspectorate (HMFI) on developments in the 'major hazard field' defined arbitrarily by the quantities of material stored on the premises, *e.g.*, 5 tonnes of phosgene, 100 tonnes of liquified petroleum gas (LPG).

E. Pollution.—The first act relating to pollution was The Alkali *etc.* Works Regulation Act, 1906, which controlled emissions from chimneys of plants to which it applied. Other acts which apply are: The Public Health (Smoke Abatement) Act, 1926; The Clean Air Act, 1956; The Public Health Act, 1961, which controls discharge of wastes into sewers; The Rivers, Prevention of Pollution Act, 1951; The Deposit of Poisonous Wastes Act, 1972; and The Noise Abatement Act, 1960.

The most recent act applying to pollution is The Control of Pollution Act, 1974, which has provided a framework for the planning and regulation of the disposal of waste on land and covers 'controlled waste' as defined under the act.

F. Petroleum Consolidation Act, 1928.—This covers the transportation, storage, and use of petroleum, petroleum mixtures, and various other substances described in numerous regulations and orders. Those involved with the handling of these materials must obtain a licence from the Petroleum Licensing Officer.

This act is under review because of its inadequacy as exposed rather forcefully during the Proceedings of the Court of Inquiry into the Flixborough disaster.[3] The Nypro plant had in store 433 850 gallons of highly flammable liquids on the day of the disaster, and yet only 8500 gallons were licensed under the act. The Court commented, 'We regard the present situation both as to storage and use of hazardous materials as unsatisfactory.'

G. Discussion of the Health and Safety at Work Act, 1974.—The Health and Safety Executive (H.S.E.) not only administers The Health and Safety at Work Act, 1974, but also The Factories Act, 1961, The Alkali *etc.* Works Regulation Act, 1906, The Petroleum Consolidation Act, 1928, and The Explosives Act, 1875.

The Health and Safety at Work Act, 1974, (HSW Act) differs from the Factories Act, 1961, in several important respects. In particular the sphere of responsibility of the employer toward his employees has been enlarged to include everyone in their employ, rather than only the workers on the factory floor. Furthermore employers are required to conduct their undertakings in such a way as to prevent, as far as is reasonably practicable, risks to the health and safety of employees, neighbours, and visitors; this includes the provision of a written safety policy. They should also appoint from amongst the employees at each

[3] Report of the Court of Enquiry into the Flixborough Disaster, Department of Employment, 1975.

plant safety representatives. The important, 'if not controlling' role to be played by employees in ensuring their safety is also included in this act.[4]

Of particular importance to the chemical industry is the fact that a manufacturer must ensure that his products are safe for the uses to which they shall be put and that relevant information and instructions reach the user. This is in contrast to the Factories Acts which made the user of the material responsible for safe working in its presence.

In the past, many products were sold under trade names without information regarding their properties, hazards, or even identity. By law the information supplied with petroleum products was more comprehensive; however, such information did not have to be supplied with equally flammable or more flammable non-petroleum substances.

A number of directives have been, or are in the process of being, issued specifying precisely what information should be included on the labels on the containers or tank vehicles from which the chemical will be drawn, and also the design of the labels and the symbols used on them. The information will include name of the chemical, the name, telephone number, and address of the producer, the symbol identifying the category of risk, and warning phrases, given in simple language comprehensible to laymen, that describe the risks and relevant safety precautions required.

The manufacturer must also ensure that he has carried out all the 'necessary' research to eliminate or minimize risks to health. The definition of 'necessary' research is rather a problem, but factors that would influence the decision concerning further research include the seriousness of the risk, the extent of use of the substance, the quantities used, and the cost of research. Long-term animal research is very expensive and facilities are limited, so selectivity is important. For substances already in use, Pittom[5] stresses the importance of the collation and assessment of available information rather than indiscriminate and unselective animal testing.

When a new compound is developed, it is difficult to know the extent of research necessary to discover any hazardous properties in order to ensure its safety. The HSE has promoted the idea of a notification scheme which requires essential toxicological information relating both to hazards to man in his working environment and in the general environment to be notified to an information pool. This will result in conformity with a scheme being discussed by the EEC. The requirements will be mandatory and it is expected that the Toxic Substances Advisory Committee being appointed by the Health and Safety Commission (HSC) will appoint a sub-committee to supply expert advice on the operation of the scheme and evaluation of the data to the HSE. The scheme will enable the HSE to advise users on the proper means of control necessary where the materials are in use.

[4] J. D. Rees, in 'Requirements of the Law in the Respect of Large Chemical Plant' (Advances in Chemistry Series: Safety in the Chemical Industry, Hazard Evaluation, and Plant protection), UMIST Institution of Chemical Engineers, London, 1976.
[5] A. Pittom, *Chem. in Britain*, 1977, **13**, 373.

The Act has a most beneficial effect on safety in all sectors of work and it encourages irresponsible employers and employees to take safety very seriously. It will also tend to promote the use of less hazardous materials and encourage firms to direct their research efforts towards improvement of safety. Quality of engineering and construction are covered by British Standards (Trade and Professional Association Codes of Standards) and Building Regulations. The British Standards Institute issues its specifications for a standard and all reputable operators follow it; however, they are often voluntary. Adherence to a British Standard permits the manufacturer to mark the B.S.I. emblem and the British Standard Number on his product.

H. Discussion of Pressure Vessel and Steam Boiler Legislation.—An important gap in legislation that has been recognised for many years, and emphasised by the Flixborough explosion, arises from the specific nature of the Boiler Acts of 1882 and 1890, and more recent legislation concerning steam boilers. Legislation exists to regulate steam boilers and air compressors, but this does not include other pressure systems. The Court of Inquiry examining the Flixborough disaster stated that, 'All pressure systems containing hazardous materials should be subject to inspection and test by a person recognised by the appropriate authority as competent, after any significant modification has been carried out and before the system is again brought into use'.[3]

The definition of 'pressure system', 'hazardous material', and 'significant modification' have been stumbling blocks, as has been the problem of who is an 'appropriate authority' and who should decide to recognize a person as 'competent'. The Report also states that, 'Existing regulations relating to modifications of steam boilers, which do not apply to pressure systems containing hazardous materials, should be extended so as to apply to such systems'. The main regulation applicable is the Examination of Steam Boilers Regulations, 1964, which states that, 'Where at any time there is carried out to any steam boiler a repair of a defect which in the opinion of a competent person will affect its safe working, that boiler shall be examined by a competent person in such a manner as will enable that person to satisfy himself that the repair has been properly carried out'. As far as can be ascertained, there have been no major problems in the operation of this regulation, even though the burden of responsibility is placed on the 'competent person', the extent of his competence remaining undefined. It is, therefore, hoped that the suggestions set out by the Court of Inquiry into the Flixborough disaster[3] will be complied with.

I. Functions and Structure of the Health and Safety Commission and the Health and Safety Executive.—The Health and Safety Commission was established to administer the Health and Safety at Work Act. It draws its members from employers, unions, and local authority associations. There are up to nine part-time members with a full-time chairman.

The Commission is aided by a number of advisory committees each composed of representatives of both sides of industry and other interested bodies, *e.g.* the medical profession. The committees provide expert advice on specific problems, help write regulations and codes of practice (which have a special legal status similar to that of the Highway Code), and act as forums for discussion.

The Health and Safety Executive calls itself 'the operating arm of the Commission'. It is the amalgamation of the Employment Medical Advisory Service with six inspectorates—those for factories, mines and quarries, nuclear installations, explosives, alkali and clean air, and agriculture—and is presided over by a Director (appointed by the Commission). The main tasks of the executive are enforcing legislation, providing information and advice, research, and the development of new initiatives for the consideration of the Commission. Problems of relevance to the chemical industry, which the HSE is studying, include toxic materials, flammable substances, dust, noise, offensive emissions, common accidents (studied by the Accident Prevention Unit), and major hazards (studied by a special branch of the executive which briefs the Advisory Committee on Major Hazards).

3 Hazards and Precautionary Measures

A. Classification of Hazards.—Liston (quoted by Fawcett and Wood[6]) classifies hazards as being of first or second degree.

First degree hazards provide the potential for trouble. These hazards include the presence of hazardous materials, heat, oxygen and ignition sources, the possibility of human error or mechanical failure, the movement of people and equipment, reduced visibility caused by vapour clouds, hazards from other processes, and *force majeure*.

Second degree hazards result from the first degree hazards and include fire and the spread of fire, explosion and secondary explosion, release of hazardous materials, collision and other impacts, and stumbling and falling.

Action to deal with first degree hazards is mainly associated with good engineering and design; however, in the case of plant failure, any resultant second degree hazards must be minimized.

B. Hazardous Materials.—Hazardous chemicals are those that are flammable, toxic, potentially explosive, corrosive, radioactive, oxidizing, compressed, or extremely hot or cold. The nature of the danger and its theoretical severity depend on the inherent hazards of the material modified by the conditions of storage and use. A full hazardous materials inventory must therefore be compiled including details of fire hazard, health hazards, stability, and other characteristics of each material.[7]

Further escalation of operational defects must be considered, and control of

[6] M. H. Fawcett and W. S. Wood, 'Safety and Accident Prevention in Chemical Operations', Interscience, New York, 1964.

[7] G. L. Wells, C. J. Seagrave, and R. M. C. Whiteway, 'Flowsheeting for Safety', Institution of Chemical Engineers, Rugby, 1977, p. 31.

damaging interactions is a key design factor.[8] Some of the main hazards are considered in the following sections.

Toxicity. This is an inherent property; the hazard to man, however, depends on exposure time, concentrations, and also on the physical form of the toxic material.

Fire Risk. Properties of a material that affect direct fire risk are dependent to a great extent on particle size, process conditions, method and rate of energy addition, *etc*. Before fire risk information can be used in designing a plant, careful checks must be made to ensure that the values, especially of explosion limits, are applicable to the conditions which will exist in the system contemplated.

Sources of Ignition. These include electricity, hot surfaces, exothermic reactions, spontaneous heating, friction, maintenance and process flames, static electricity, sun on glass, smoking, and careless actions which might activate one of the above.

Electricity. Electricity acts as a source of ignition either in the form of electrically heated surfaces or as sparks. Classification of electrical equipment for use in hazardous areas is determined in the UK according to the British Standards Code of Practice BS CP 1003, while flame proof and intrinsically safe equipment are defined by BS 229 and BS 1259, respectively.

Static electricity. Static electricity results when contact between dissimilar bodies causes a disturbance of the electrical charge at the interface. Consequent separation of the bodies may leave excess charge on each body, the charge being retained if one or both bodies is a poor conductor, or an insulated good conductor. A fire hazard will arise when the static charge accumulates until its potential is above the breakdown potential of the surrounding atmosphere. At this point, a spark may be generated by the discharge of energy. Static electricity is especially dangerous because it can develop almost anywhere, for example in liquid running through a pipe, in liquid splashing at the entrance of a vessel, in moving powder (depending on the physical nature), in dust particles in flammable vapour, and so on. Precautionary steps that can be taken are to avoid turbulent and rapid flows of liquid, the use of deflectors to prevent splashing and encouraging charge to leak away by changing the humidity, by bonding all containers, and by eliminating flammable atmospheres.

C. Release of Hazardous Materials.—Good design and operating methods will reduce the possibility of release of hazardous material; however, provision must be made for such an eventuality. Detection of leaks and their sources is achieved by analysers, meters, and gauges often linked to a central control room, so that

[8] Advisory Committee on Major Hazards, First Report, Health and Safety Commission, HMSO, London, 1976.

emergency shut off and isolation valves can be activated. Sometimes isolation valves operate automatically.

After a leak has occurred, it may be important to restrict its movement with the aid of dykes or ditches. Then the material that has leaked must be disposed of: therefore adequate drains or storage facilities are important. The passage and mixing of different substances in drains must be carefully regulated to prevent dangerous reactions, the build-up of dangerous vapour, or the accumulation of sludge restricting or preventing flow. It is vital that drains can cope with the maximum projected through-put in the event of a leak or of a storm, without bursting, flooding, or harming the environment in other ways.

D. Explosions.—'An explosion occurs in the atmosphere if energy is released over a sufficiently short time, and in a sufficiently small volume so as to generate a pressure wave that is audible and of finite amplitude travelling away from the source.'[9]

Four major explosions have been researched into by the Health and Safety Executive, and by a Court of Inquiry in the case of Flixborough. Brief details follow.

The Nypro, Flixborough Cyclohexane Explosion.[3] The Nypro (UK) Ltd., caprolactam plant at Flixborough sustained an explosion on June 1, 1974, and as a result 28 people lost their lives. The plant used cyclohexane as an intermediate for the production of caprolactam, the starting material for the manufacture of nylon. The cause of the explosion was the 'squirming' of the bellows (displacement of the two ends relative to each other) of a double bellows and 20-inch diameter dog-leg pipe arrangement which was constructed as a temporary connection between two reaction vessels. The squirming led to jack-knifing and thus to rupture of the bellows. This allowed the release of a large cloud of cyclohexane vapour which later ignited and exploded. This form of explosion is called an unconfined vapour cloud explosion, a type of environmental explosion: *i.e.*, it occurs in the open air.

The explosion led to an extreme example of the domino effect, a result which should be expected when unconfined vapour cloud explosions occur. Wells *et al.*[10] define the 'domino effect' as the way in which 'blasts and missiles from an explosion can affect the integrity of other plants containing flammable and toxic materials thereby causing the escalation of the disaster'.

In some other such incidents, no explosion has occurred. Instead, fire flashed back to the source of the leak and the vapour burned as a torch.

The Flixborough disaster occurred just before the passing of the Health and Safety at Work Act, 1974, and emphasised the need for it. The disaster had a profound effect on thinking in the field of chemical engineering, law, and the management of industrial risks, including insurance. Two important technical discoveries were made during the research into the causes of the explosion and

[9] Ref. 7, p. 34.
[10] Ref. 7, p. 35.

the consequent damage (which was enormous: 80% of the total plant, see also pp. 421, 423, 429 and 438). Professor Cottrell of Cambridge University and Dr. Swann of Imperial College, London, researched into zinc embrittlement of stainless steel. They found that very small quantities of zinc can cause embrittlement of stainless steel if it is allowed to gain access when the steel is heated to 800—900 °C and is under a stress of about 5.8 kg mm^{-2}. Under these specific conditions, failure of the steel will occur within a few seconds.

The second entirely new discovery was that a small fierce fire may produce, in a relatively short time, creep cavitation fractures in stainless steel piping.

These two discoveries have important implications. Zinc is widely used throughout chemical plants, for example on steel walkways for rust prevention and in galvanized wire and cladding, so that the hazard of zinc embrittlement is by no means remote. The possibility of creep cavitation means that even very small fires must be extinguished very rapidly; chemical companies are, therefore, re-evaluating their standards of fire fighting ability.

The Laporte, Ilford, Electrolytor Explosion.[11] On April 5, 1975, a Lurgi electrolytor at the Ilford site of Laporte Industries Ltd. exploded, showering the operator on duty with potassium hydroxide (caustic potash) electrolyte and burning him so severely that he later died. The process involved the electrolysis of potassium hydroxide in a 'Zdansky–Lonza Cell' with nickel-plated steel wire gauze electrodes which produced very pure hydrogen, with oxygen as a waste product.

Analysis of the gases produced and stored immediately before the explosion showed 'severe cross-contamination' of the hydrogen by oxygen and that the oxygen was 'grossly contaminated with hydrogen, probably within the flammable range'.[11] The mixture would have reached explosive proportions when the pure oxygen had been contaminated by 5% hydrogen.[12] The actual explosion occurred in the oxygen separator drum which ruptured, spilling the caustic solution over the operator.

This explosion was an internal explosion since it involved the detonation of the contents of a plant unit. Since the building had a roof deliberately lightly constructed in order to release the force of any blast upwards, a neighbouring school was not damaged, and neither were other neighbouring properties nor other parts of the plant.

The Dow, King's Lynn, Zoalene Explosion.[13] On June 27, 1976, some Zoalene detonated at the Dow Chemical Company's King's Lynn site. 'Zoalene' is the trade name for 2-methyl-3,5-dinitrobenzamide which is blended with wheat middlings to form 'Zoamix', a poultry feed additive.

The explosion occurred when some Zoalene in stock at the plant, which was

[11] Health and Safety Executive, 'The Explosion at Laporte Industries Ltd., Ilford, April 5, 1975', HMSO, London, 1976.

[12] H. F. Coward and T. W. Jones, quoted in Health and Safety Executive Report, 'Limits of Flammability of Gases and Vapours', US Bureau of Mines, Bulletin No. 503, 1976.

[13] Health and Safety Executive, 'The Explosion at Dow Chemical Company, King's Lynn, June 27, 1976', HMSO, London, 1976.

found to have been contaminated by water, was dried and then left in the drying vessel where it decomposed in adiabatic conditions heating up until it detonated.

One man was killed by the blast and extensive damage was caused to plant and buildings on the site. Furthermore, a few substantial metal fragments were hurled beyond the site boundary.

This explosion is also an example of an internal explosion, but the cause was decomposition of a material rather than a chemical reaction between two materials allowed accidentally to come into contact, as happened in the Laporte electrolytor explosion.

The Appleby-Frodingham, Scunthorpe Steelworks Explosion.[14] On November 4, 1975, an explosion occurred at the mouth of a torpedo ladle that had been filled with 175 tons of liquid iron from the Queen Victoria blast furnace at the Appleby-Frodingham works of the British Steel Corporation at Scunthorpe. Eleven out of 23 men working near and controlling the blast furnace and torpedo ladle died.

The wall of the blow pipe (point of entry of hot air into the blast furnace) of No. 3 tuyère was burnt through (this occurrence is called a 'burn down') allowing the hot air blast and debris from the furnace to spew out uncontrollably which caused a blazing fire. The hot debris poured onto a steel plug on No. 2 hearth cooler (the assembly supplying water to cool the blow pipe), and the plug was ejected. Cooling water gushed out and flowed down towards a torpedo ladle filled to within 30 cm of the top with liquid iron at 1500°C. After at least 400 gallons of water had entered the ladle, a locomotive driver was ordered to shunt it away to prevent the further entry of water. Three shocks were administered to the torpedo by the locomotive resulting in an explosion showering 90 tons of molten iron about the site.

The copper hearth cooler pipes supplied by the makers had holes facilitating both left and right hand installation. The unused holes were blocked with plugs. They should all have been made of brass rather than of steel, and of the other steel plugs (17% of total plugs) most were severely corroded. The brass plugs were also corroded by dezincification and no preventive maintenance studies had ever been undertaken to determine the lifetime of the plugs.

H.M. Nuclear Installation Inspectorate[15] explained the cause of the explosion as follows. In the torpedo ladle the metal was covered by a 2.5 cm layer of slag which, since it had been cooled by the water, had caused the evaporation of only about 10% of the water before the explosion; thus thermal equilibrium would have been attained. Rapid formation of steam and therefore pressure in the confined volume occurred only after the shocks induced by the locomotive had fractured the slag layer allowing hot metal to contact water. This led to more cracking of the slag layer and the mixing of water into the metal and the explosion occurred.

[14] Health and Safety Executive, 'Explosion at the Appleby–Frodingham Steelworks, Scunthorpe, November 4, 1975', HMSO, London, 1976.

[15] H.M Nuclear Installation Inspectorate, Health and Safety Executive, 'Explosion at the Appleby–Frodingham Steelworks, Scunthorpe, November 4, 1975', HMSO, London, 1976, appendix 1.

E. Some Precautionary Measures.—*Process Route.* There are, according to Speigelman[16] and the Advisory Committee on Major Hazards,[8] ten process routes that are particularly hazardous including processes subject to explosive reaction or detonation, processes subject to spontaneous polymerization or heating, *etc.* The Advisory Committee on Major Hazards to the Health and Safety Commission recommend that these process routes should be avoided if this can be achieved without incurring undue cost. If not, no materials used merely for the purpose of catalysis, mixing, heat transfer, *etc.*, should be added if they could compound the hazard.

A choice can sometimes be made between a batch process or a continuous process. The latter holds less material in the reaction vessels and pipes and involves fewer interruptions (which can be hazardous) to the steady movement of those materials. Automatic control is easier, and dangerous intermediates are processed without the need for storage. The vessels used for a batch process are easier to isolate and clean. Product purity is also more easily controlled.

Waste products must be processed and/or disposed of in a legal and safe manner.

Layout of the Site. Minimizing plant area is obviously economical in terms of land cost, rates, length of piping, roads, *etc.*; however, there are constraints. These are cost, ease of erection, and maintenance of plant *etc.*, operational convenience and safety (including emergency access) as well as the physical constraints of the site, topographical features, drainage, *etc.*, and legal and environmental constraints, *e.g.* planning permission and the appearance of the plant.

It is important when designing a plant to disperse the different units so as to minimize the spread of fire and to lessen the results of the domino effect. The domino effect has been studied especially carefully since the Flixborough disaster because the Nypro plant was generally regarded as well laid out. The management had based its safety plans on the assumption that the hazards would be those of escalating fire and explosions when, in fact, the domino effect resulted in near total conflagration. Within the constraints outlined above, no building should be any closer to a hazard area than it has to be, having regard to its functions.

Units containing mutually reactive materials should be segregated. Isolation by dykes, ditches, blast walls, or by enclosure in a building should be considered for particularly hazardous units, sensitive and vulnerable equipment, sources of ignition and noise, as well as key units used for safety or containing important business and technical information, and most especially the central control room.

At Nypro, the main office building, the laboratories, and the central control room were all destroyed. Drawings, plans, staff records and other documents were lost so that details of plant construction had to be obtained from the records held by manufacturers. An example of the loss of records which made the job of the Court of Inquiry difficult was the loss of data relating to the pressure

[16] A. Speigelman, 'Risk Evaluation of Chemical Plants', CEP Loss Prevention Manual, 1969, Vol. 6, p. 1.

and temperature of cyclohexane in the plant during the shift when the explosion occurred. Taylor states that a company should regard 'the entire control room as a repository of such valuable people and information that its resistance to fire and collapse should be significantly improved above today's standards wherever the hazard warrants this.'[17]

Units, for which the same or compatible fire-fighting equipment are required, can be conveniently grouped together. Other reasons for grouping of plant units include ease of operation, convenience of frequently visited items, and reduction in the amount of service area required.

4 Transport, Storage, Quality Control, and Theft

Risks to the flows of raw material to and products from the plant and the risks of theft and fraud must be considered as part of an overall risk management programme. In this Section they are dealt with briefly.

Transport.—The movement of chemicals may be effected by road, rail, sea, or air. Numerous laws, regulations, codes, and guides have been issued by Governments, international bodies, industrial associations, and professional institutions which attempt to cover an enormous number of different chemicals and the almost infinite number of combinations of these chemicals that may occur in mixed loads.

The regulations for all four forms of transport are intended to ensure safety during transit, so that, for example, the chemical cannot leak out and is kept at a temperature and pressure at which it will not ignite spontaneously, explode, decompose or change to an inconvenient state, or corrode its containers. Thus, refrigerated tanks are needed to store some gaseous materials in liquid form at much lower volume, and to prevent liquids from evaporating. When gases are cooled, some below their critical temperatures, no pressure need be applied to maintain them in liquid form, *e.g.* methane at 112 K and ethylene at 169K. Heated tanks are needed to prevent solidification of some liquids and to reduce their viscosity before pumping. Sometimes stainless steel containers are needed for very delicate or corrosive liquids, and sometimes other special materials must be used to line the containers to protect contents from contamination.

A voluntary safety aid widely used by road hauliers is the carrying of Transport Emergency Cards in the driver's cab. These cards inform the driver and the fire brigade as to the identity of the cargo, its properties, how to deal with a leak and how to extinguish it if it is burning or liable to catch fire.

Another voluntary system is HAZCHEM. Information similar to that contained in the transport emergency cards is painted partly in code form on the rear or side of the vehicle or on the barrels or on other containers. Hazchem, originally developed by the London Fire Brigade, is very popular among responsible hauliers, and it will probably become the official marking system.

The shipping of cargoes that react with sea, canal, or river water, or that are

[17] H. D. Taylor, 'Flixborough—The Implications for Management', Keith Shipton Developments Ltd., 1975, p. 12.

immiscible with water and spread rapidly to form a thin or unimolecular layer after spillage, *e.g.* benzene, are potentially hazardous operations. Ships carrying especially hazardous cargoes must often load and discharge at special berths. There are some chemicals which are only of value if absolutely pure, or which are liable to decomposition in the presence of the slightest impurity. These chemicals must be carried in specially constructed, sophisticated ships that are rigorously cleaned before each is loaded, and that have very few or no internal bulkheads which could harbour impurities. Such ships are now enormously costly to build, are expensive to maintain in the essential state of high efficiency, and require highly skilled officers to man them.

Storage. The storage of raw materials before they are used, and of products before they are sold, is normally the responsibiiity of the owner or the operator of rented storage. Loss by theft, fire, or some form of chemical change can be insured against. The size of the premium will depend on the inherent instability of the material, its quantity and its physical form, and the conditions of storage. Thus, careful storage will bring financial rewards as well as maintaining the integrity of the stocks.

Some of the rules that apply to storage in the open and in buildings are the same, such as keeping the storage area clean and free from litter and spillages of oil which are flammable and slippery. In the open, adequate drainage is necessary to prevent flooding. When toxic and/or flammable liquids are stored in tanks, each tank must be surrounded by a bund (a wall which forms a container capable of holding the entire contents of the tank) and tank farms should be surrounded by dykes to prevent the escape of liquids from it.

Inside buildings, adequate ventilation and protection against damp are necessary. Both inside and out, accessibility must be adequate so that men and vehicles moving stock do not collide with and displace neighbouring stock units and perhaps cause leaks or contamination of stock.

Another reason for dispersing stock units is to prevent the spread of fire and contaminating chemicals and the domino effect (see p. 426). Both inside and outside buildings, the installation of automatic fire extinguishing systems is essential in areas containing flammable materials. In many cases, this means the installation of water sprinklers. However, in situations where water would exacerbate the fire risk, *e.g.* burning oil, carbon dioxide, dry powder, or foam is used as the extinguishing medium.

Regular or continual sampling of the air around storage (and process) areas should be carried out in situations where the leakage of flammable or toxic volatile liquids, vapours, or gases is possible.

Quality Control. The supplier of a material is legally bound to supply the product specified in the contract of sale (unless the contract is frustrated, or both parties agree to void or change the contract). If the quality of the material supplied is incorrect, the supplier is liable for any damages caused to his customer. It is thus important for the supplier of a material to check it carefully before devising a sales specification, and if a specification already exists the material produced must conform to it, or it may become unsaleable.

The European Petro-chemical Association (EPCA) is endeavouring to form a committee to standardize methods of quality testing which have been the subject of insurance claims and other disputes in the past.

Failure of a Supplier to Supply Raw Materials or a Customer to Buy Products. If a process is heavily dependent on a raw material in short supply or with only one source, and the plant making it explodes, or some other severe disruption to supply occurs, the processor will probably be able to claim against his supplier for damages of material, profits, *etc.* This disruption could also adversely affect the reliability of the processor which may result in a loss of part of his share in his market, so it is in the interest of the processor to check on the safety standards and industrial relations of his suppliers.

Failure of a major customer can be even worse for the processor than failure of a supplier since the processor had added the cost of his process to the cost of the raw materials by manufacturing the product which then cannot be sold. It must either be stored or disposed of, both of which can be very costly, or the processor may be forced to sell it at a loss.

Loss of Proprietary Information and Theft of Property.—Theft can occur in many forms from the payment of inflated expenses claims submitted by employees and money stolen from petty cash, to pilfering of tools, stationery, and other artefacts useful in the home, the garden, or the car. Sensible management, control, and security can eliminate many of these petty crimes.The files containing the secrets of the company, such as its plans for the future, and its secret processes, are also valuable and are therefore the object of theft. Such theft is made especially simple for the burglar if the secrets are kept on computer tapes or discs.

On February 1, 1978, the first conviction in the world for stealing computer tapes and discs and demanding ransom money for their return was made. A total of 48 discs and 540 tapes, vital for the company's accounting procedures, were stolen from ICI's Rozenberg complex, as was the emergency copy from Rotterdam. The 'kidnappers', who had reduced their original ransom demand of £1 million to £275 000, were caught in Oxford Street in January, 1977, as they tried to snatch the money. The consequential losses due to loss of information stored in a computer or on computer tapes and discs can be insured against.

Perhaps the most worrying and fastest growing area of crime is the defrauding of a company with the aid of its computer. There are two types of such fraud: computerized and computer assisted. In computerized fraud the mechanism for defrauding the company is written into the programs used in the computer. Computer assisted fraud involves feeding the computer with data which will cause it to authorize the issue of money or property to the criminal.

5 Risk Analysis and Evaluation

A chemical plant operating company does not have a bottomless pit from which it may take money to spend on safety. It is therefore in the interest of both the company and its employees that money should be spent most efficiently.

In analysing risk, as it is imperative that nothing important is overlooked, systematic methods have been developed. Risk analysis of the flowsheet of an operation under consideration can be conducted systematically from two angles of approach. The 'analytical' approach involves discerning the inherent risks at each stage on the flowsheet. This is a thorough, but time-consuming process that will uncover numerous unimportant hazards as well as the really dangerous ones. The 'screening' approach involves examining the whole operation to discover whether certain anticipated hazards are present.

In practice, a combination of the two approaches is used. A stage-by-stage analysis of a general flowsheet will reveal areas of risk which can then be screened for greatest cost, social or environmental impact, or other important effects. The chosen areas can then be subjected to a more detailed analysis.

There are five methods widely used to evaluate hazards in chemical plants and, usually, several will be used together, these are:

(i) Operability studies.

(ii) Failure analysis and fault trees.

(iii) Hazard analysis.

(iv) The Dow Process Safety Guide.

(v) The ICI Rating plan for material damage insurance (described in Section 6).

A. Operability Studies.—Operability studies involve the study of a process flowsheet section by section. Various guide words are applied in turn to each section and these will generate deviations in conditions which may be hazardous. Factors which are kept in mind while applying the guide words are:

(i) Normal operations and foreseeable changes in normal operating conditions.

(ii) Start up and shut down conditions.

(iii) Suitability of equipment, instrumentation, and materials.

(iv) Provision for failure of services.

(v) Maintenance and safety.

This technique is often used as a prelude to hazard analysis, and the combination of these two methods is the most detailed and advanced method now in use.

B. Failure Analysis and Fault Trees.—Failure analysis is an analysis of the reliability (or resistance to failure) of a plant. The method is the opposite to operability studies in that it starts by listing various disasters, such as explosion, flooding, fire, *etc.*, and then proceeds to identify the events and groups of events which can lead up to them. A logic diagram of chains of such events is called a fault tree.

Most plant units incorporate protective devices designed to 'trip' (shut down) the system being protected when a certain deviation in the operating conditions occurs. The reliability of the plant is dependent both on the chances of failure of the system and on the chances that these failures will not activate the protective devices.

The 'hazard rate' of a system is the frequency of demands (occurrences which should activate the protective device) to which the protective system does not respond. The 'fractional dead time' of a protective device is the fraction of unit time during which the device will not operate either due to random failure or because the functioning of the device has been aborted to allow testing, and is thus a measure of the integrity of the device. There are two types of failure:

(i) 'Safe failures' which will spuriously activate the trip.

(ii) 'Dangerous failures' which occur if a demand is put on a trip and it does not operate as expected, possibly resulting in a disaster. In order to discover dangerous failures, the device is tested at regular intervals, the interval between tests being known as the 'proof test interval'. The limit to the reduction of the proof test interval is the cost of such frequent testing, and the increase in fractional dead time resulting from the tests, each of which could require the device to be aborted.

If θ = dangerous failure rate; T = proof test interval, and D = demand frequency, the conditions and $\theta T \ll 1$ and $DT \ll 1$ apply then:

$$\text{Hazard rate} = \text{Demand frequency} \times \text{Fractional dead time}$$

When $\theta T \ll 1$, which is the more important condition, the probability of system failure varies linearly with time.[18] These conditions are usually satisfied.

In order to understand the use of fault trees a hypothetical reactor in which a fuel is oxidized to yield a product is considered.[19] Figure 1 shows diagrammatically the layout of the reactor. An explosion is caused by the ignition of an explosive mixture of fuel and oxidant, which will be formed if the flow of fuel is too high or that of oxidant too low. These reductions in the flow will occur if one part of the protective system fails and the trip designed to shut down the reactor fails to operate.

The complete fault tree of the hypothetical reactor is shown in Figure 2. There are two types of logic gates used. The 'and' gate transmits an output event if all inputs occur simultaneously. The 'or' gate transmits an output event if one or more of the inputs occur. At an 'or' gate, all the failure frequencies or fractional dead times (FDT's) are added, dependent on whether the inputs are parts of a plant or protective devices. At an 'and' gate, the failure frequencies and the fractional dead times of all the inputs are multiplied. In this hypothetical example the rate of failure leading to explosion is 0.031 per year.

[18] B. C. Bullock, 'Terminology and General Principles of Reliability Engineering', appendix: 'Brief Review of the Theory Applicable to Protective Systems', ICI Ltd., Mond Division.

[19] 'Process Industry Hazards' (Symposium No. 47), Institution of Chemical Engineers, Rugby. 1976, pp. 141, 142.

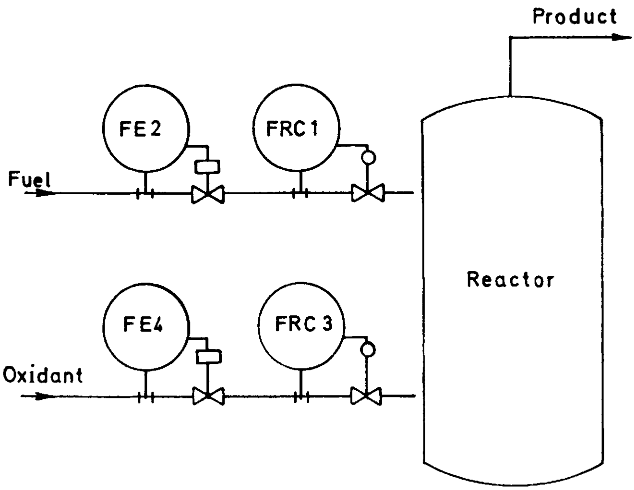

Figure 1 *Diagrammatic layout of a hypothetical reactor in which fuel is oxidized to yield a product*

Powers and Tompkins[20] have developed computer programs employing Boolean algebra to describe the plant unit models.

While operability studies are an example of the analytical approach to risk analysis and are very detailed and thorough, but time consuming, failure analysis and fault trees are an example of the screening approach which concentrates on the major problems and their causes.

C. Hazard Analysis.—This technique involves the comparison of fatal accident frequency rates (FAFR see Table 1, p. 419) with a target rate and the consequent allocation of resources so as to bring the FAFRs down to the target FAFR.

The process of hazard analysis was first developed by the United Kingdom Atomic Energy Authority to evaluate the likelihood of a reactor core melting and leading to a disaster. Reactors are designed to have a FAFR of 0.001, that is, one disaster in 10^7 years.

The FAFR for working in the chemical industry in the UK is 3.5.[1] ICI Petrochemicals Division has a target FAFR of 0.35 for each individual risk and ICI Mond Division has a target FAFR of 2.0 for all hazards to the man most at risk.

Recently there was a trend, in Holland for example, to insist that the maximum credible accident (MCA) frequency rate should be less than the 'safe' frequency defined by the authorities. This is often impossible to achieve, and this has been recognized. For example, in the case of a chlorine storage sphere, the MCA would arise if the bottom of the sphere fell out. In the case of an ethylene pipe-

[20] G. S. Powers and F. C. Tompkins, 'Synthesis Strategy for Fault Trees in Chemical Processing Systems', CEP Loss Prevention Manual, 1973, vol. 8, p. 91.

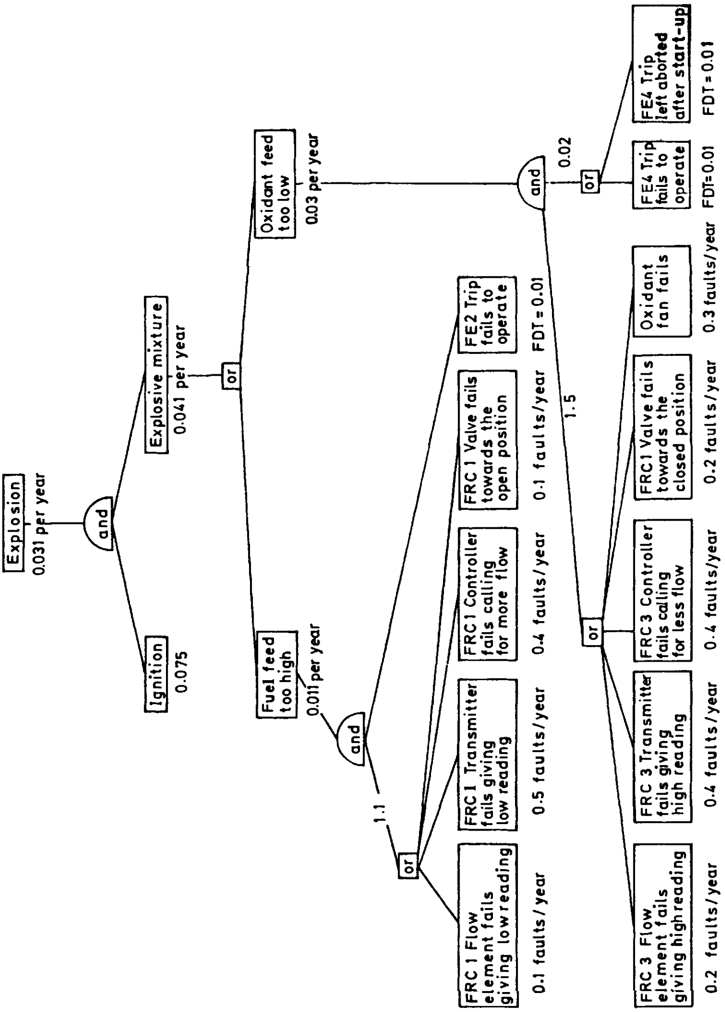

Figure 2 *Fault tree of the hypothetical reactor*

line, the MCA is fracture of the pipe. Both of these occurrences might result in appalling disasters; however, the possibility has to be accepted if plant incorporating such a unit is to be constructed in order to produce a useful product, and employ people in its production.

The plant is analysed using fault trees and failure analysis techniques and operability studies. The results aid decision, in the case of the possibility of purely financial loss, whether the cost of failure justifies the expenditure required to prevent it. In the case of danger to life, much more money will be spent—figures of up to £100 millions to prevent loss of one 'life' (calculated from FAFRs) were quoted to the author by ICI.

In deciding which method or combination of methods of risk analysis to use, the cost of gathering the required information must be taken into account especially in determining the amount of detail and the accuracy required.

D. Dow Process Safety Guide.—The Dow process safety guide[21] rates each unit in a plant numerically, the value being derived from a set of tables. The numbers are combined and analysed using a simple set of formulae to yield the Fire and Explosion Index for the whole plant. The tables are empirically based and rather crude; however, they provide a quick and simple method of obtaining an approximate result and they can be used by personnel untrained in science or technology, and thus are often used by insurance brokers and underwriters.

The guide is a useful tool for selecting, designing, and providing loss prevention and hazard protection systems for plants being designed and plants already extant. It applies primarily to process units, but it may also be applied to tank farms and warehouses.

The scale of the index is zero (safe) to 100 (extremely dangerous). The type of fire fighting and hazard prevention and control apparatus installed to combat the severity of the hazard is dependent on this severity, and some examples are mentioned by Ellis[22] in tabular form.

One limitation of the guide is that it does not consider personal safety equipment, structural requirements, corrosivity, or toxicity of materials handled, since these are all basic features which remain unaffected by variations in the fire and explosion hazards involved.

At present the guide does not cover release of toxic gas and hazards arising from reactions between conventional non-combustible materials.

6 Insurance

Risk is inherent in any human activity. By cautious behaviour, the risks of a particular action or series of actions can be progressively reduced. However, at any particular moment, there will still remain areas of risk which will be regarded as too serious, in terms of property, goods, or lives, to risk financial disaster.

[21] 'The Dow Process Safety Guide', CEP Reprint, American Institution of Chemical Engineers, The Dow Chemical Company, 1966.
[22] W. J. Ellis, 'Hazard Assessment in the Chemical Industry', ICI Ltd., Mond Division, p. 25.

This is the purpose of insurance; a method of transferring risk at a cost: the premium, and in effect, the cost of the risk is spread over a long time scale.

The insurance of chemical risks presents special problems. Many of the plants are unique and very new so that it will be unlikely that a disaster will have occurred previously at a similar plant. In such cases, there is no accurate actuarial method by which the premium can be reliably calculated. Some chemical risks are so colossal that, in a few cases, it has been impossible to insure them fully since the market does not have the capacity to sustain such losses. Some of the largest oil refineries and some North Sea Oil rigs (each covered for $600 million or more) fall into this category.[23]

The disaster at Flixborough marked a turning point. 'Prior to the disaster at Flixborough, the Nypro complex was regarded by insurers as a "perfectly average petrochemical plant". As an indication of confidence in the management and physical aspect of the operation, the leading office apparently accepted 20% of the material damage risk.'[17]

The Court of Inquiry described the plant as 'well designed and constructed'.[3] It was well dispersed and total loss was not regarded as a serious possibility. The insurance profession decided that the EML (estimated maximum loss)* was about 20% of the sum insured, and yet 80% of the plant was destroyed.[24]

It is because of this disaster, for which the insurance world has had to pay claims amounting to £50 millions,[25,26] and the United Kingdom balance of payments will lose over £100 millions due to the temporary need to import Caprolactam (Department of Trade officials), that premiums have been, and will be raised, often to levels that become almost prohibitive to the operator. The Flixborough losses could have been much higher. If the explosion had occurred during a period of economic expansion instead of recession, the business interruption losses would have been two to three times higher and the loss of life would have been much greater if the explosion had occurred on a weekday rather than on a Saturday.

There are three main types of insurance cover that should be arranged by the operator of a chemical plant: material danage, business interruption, and liability.

A. Material Damage Insurance.—The premium for material damage insurance for a chemical plant is calculated after consideration of (i) the hazard, (ii) loss prevention features, (iii) estimated maximum loss, and (iv) loss history. The fourth factor, loss history, is a combination of the loss record for the type of plant and the loss record of the company operating that particular plant. The information required to quantify the other three factors comes mainly from fire surveyors. They are usually heavily dependent on information supplied by plant personnel. If the plant engineer understands the function and information needs of the

*Sometimes referred to as PML (P = Probable or Possible) or NML (N = Normal).

[23] *The Daily Telegraph*, September 9, 1977, p. 21.

[24] C. J. Temple, 'Insurance, Safety and the Chemical Engineer', Institution of Chemical Engineers, London, paper 16 (Session 4) presented at the Eurochem Conference 1977.

[25] *European Chemical News*, November, 1975.

[26] *Schaden Spiegel*, Munich Re, 1976.

surveyor, he may be able to influence possibly a lower premium since the surveyor will always err on the safe (higher premium) side if he is not absolutely sure of the validity of the information presented, or if he is not presented with enough or the right kind of information.

Although surveyors have varying degrees of experience of chemical engineering problems, very few are qualified chemical engineers. A qualified chemical engineer is capable of making an independent assessment of the safety of the plant and is much more likely to be able to discover new dangers, whereas the experienced, but technically unqualified, man is limited by the boundaries of his experience. The ideal, at present, is to have a mixed team of older experienced men and young engineers, and the present imbalance is gradually being rectified by the recruitment of more chemical engineers as fire surveyors.

ICI has developed a rating plan for material damage insurance which attempts to quantify factors (i) to (iii) scientifically.

ICI Rating Plan for Material Damage Insurance.[27] The ICI rating plan applies only to plants with an EML of £1 million or more at 1975 values and these plants are called 'dominants'. (All other plants on an ICI site are grouped together and an average rate applied to their total value, which reflects their general characteristics and the general loss record of the particular ICI Division.)

The premiums for dominants are determined after consideration of three factors.

Inherent hazard classification—'C' factor. This is a 1 to 12 scale from low risk to high risk. It is based on the type of technology and the nature of the chemicals used. It includes reaction temperatures and pressures, types of chemicals used, corrosion hazards, and also the domino effect (see p. 426).

Estimated probable maximum loss—'P' factor. Methods of evaluation of the P factor vary, but generally they are an estimation of the worst possible catastrophe that could occur, taking into account hardware (see below) but ignoring water sprays *etc.*, since in the worst conceivable disaster these would fail or be inadequate.

Since Flixborough, it has been realized that especially in the case of an unconfined vapour cloud explosion, EML can equal total loss. Evaluation of the P factor has recently been further complicated by the increasing numbers of cases of arson and vandalism often politically motivated, as in Italy.

EML values are used by insurance companies primarily to assess the portion of a particular risk that a company (or Lloyd's syndicate) can carry—risks with small EML values will therefore be easier to insure. The EML may also affect the actual premium, especially in the case of excess of loss cover (see p. 444).

The adequacy of hardware, software, and firefighting facilities—the 'HSF' factor. Hardware comprises such factors as location, construction and layout, instru-

[27] D. F. Drewitt, 'Insurance of Chemical Plants', Institution of Chemical Engineers Continuing Education Course, Teeside Polytechnic, July 1975, Imperial Chemical Insurance Ltd., London, 1975.

mentation, emergency valves and other safety equipment, and emergency supplies, *e.g.* cooling water. Software comprises various management factors, such as maintenance, safety training, operating instructions, quality of labour, and management attitudes to safety, housekeeping, *etc.* The 'F' factor comprises works and municipal fire brigades, supplies, extinguishers, alarms, first aid, and fire fighting, *etc.*

The Rating Plan described above has been devised by ICI specifically in order to provide insurance ratings. Other hazard evaluation methods are also commonly used, such as the Dow method which is geared to the needs of designers and operators. Some insurance companies also use it since it is fairly simple and not too technical.

B. Consequential Loss and Business Interruption Insurance.—'A fire in a factory is not unlike a stone being dropped into a pool. The ripples spread out and gradually diminish, but it is hard to say just where they cease'. (Comment by a managing director of a diesel engine factory quoted by Taylor and Temple.[28])

The monthly statistics of the British Insurance Association quote losses that include only costs of material damage. However, business interruption losses can be between three and six times the material damage losses and thus are more important.

In the chemical industry, the most extreme vulnerabilities are those of unique or new processes, processes making high value products, and large scale single stream plants.

Very small fires and explosions, even if rapidly extinguished, can still lead to high losses due to the time taken in recommissioning and restarting the plant. This can cost well in excess of £100000 per day and take several weeks. Two examples from Schaden Spiegel[25] illustrate this factor. In 1971, after a series of explosions at a polyethylene plant the claim for material damage was £3.3 millions, whereas that for business interruption was £9.2 millions, a ratio of 1:2.8. At an ammonia plant where a fire damaged a crucial compressor in 1975, the material damage claim was £0.5 millions and that for business interruption £3.3 millions, a loss ratio of 1:6.6.

Another serious result of extended business interruption can be loss of market share, customers, and reputation, which may constitute a long term danger that could cripple a company. Inflation and shortages may also have profound implications when considering business interruption cover.[17]

Many companies operate an annual review system for their insurance cover. This is often inadequate owing to the rapidly decreasing value of money and the continually varying conditions that affect indemnity periods (as defined below). Continuous review is therefore desirable within the limits of cost effectiveness. Since business interruption losses are the most serious, adequate cover for them should take precedence over all other forms of insurance.

The indemnity period is the length of time required to re-establish the business.

[28] H. D. Taylor and C. J. Temple, 'The True Cost of Fire on Chemical Plant' (UMIST Symposium Sept. 1976) Institution of Chemical Engineers, Rugby, 1976.

Values for indemnity periods may often prove widely at variance with reality. This can be due to changing conditions of supply caused by variations in trading circumstances, such as under- or over-capacity, or changes in the activities of competitors.

Another problem is the difference between insurance methods and management accounting methods. It is not adequate for an accountant to add a certain percentage to the cost of the previous year's business interruption cover to budget for the changes discussed above. This usually means that the accountants and senior management of the company have not understood the intricacies of insurance cover and have not purchased insurance that is specifically designed for their organization.

Another source of business interruption is failure of a major supplier or a major customer, and such interruption of supply can be insured against. The necessity of continuing or increasing unprofitable production to retain a share in the market when the usual supply of raw materials has been interrupted can be insured against by an 'additional increased cost of working' clause in a business interruption policy. This 'additional increased cost of working' may be due to the need to use more expensive raw materials or components, or the need to buy in manufactured or semi-manufactured units or components.

C. Liability Insurance.—Loss must be 'fortuitous' for it to be covered by any insurance policy. Thus, acts in deliberate contravention of the law cannot be insured against. However, in cases such as the Flixborough disaster where the Court of Inquiry described the plant as 'well designed and constructed',[3] insurance claims would be settled for employer's and public liability and also contractor's and supplier's liability, if their workers or products were responsible for the disaster.

Employer's Liability. This is the liability of the employer to pay compensation to his employees (or their families) when death or injury occurs. Coward[29] has estimated that the value of a human life in the UK in August, 1973, was £50000. That value should be approximately doubled to bring it up to date. A death can be certified to have happened, but personal injury is harder to quantify, and awards have risen greatly in the past five years, even when inflation is taken into account. In 1972, the average employee's claim settlement for a serious injury based on loss of future earnings was £5000. By mid 1975, the figure had risen to £35000, which adjusted to 1972 values is about £20000.[30]

Public (or Third Party) Liability. The losses and damage resulting from a serious fire or explosion at a chemical plant can easily spread beyond the boundaries of the plant, as can the fire itself. At Flixborough, extensive damage was done to property and hundreds of people were injured outside the works boundaries. At a distance of half a mile from the plant, the pressure due to the explosion was

[29] S. K. D. Coward, 'The Economics of Accident Prevention—Explosions', Fire Research, 1973, Note 982.

[30] 'Industrial Injury Claims', Iron Trades Employers Insurance Association Ltd., 1975.

about 2 psi which is sufficient to damage roofs and break windows but not to demolish walls. Nearly 2000 houses were damaged as were 167 shops and factories. There were no serious injuries outside the plant, but the police recorded 53 minor casualties and hundreds were slightly injured. Crops were damaged, and in the case of a neighbouring field the entire wheat crop was sucked in towards the point of explosion by the partial vacuum following the blast.

Another example on a much smaller scale was the explosion at the Dow 'Clopidol' plant at King's Lynn in 1976 which hurled two substantial pieces of steel plate outside the works boundary. The explosion also broke numerous windows and caused two ceilings to collapse.

In the case of Flixborough such costs have been estimated at about £3.1 million.[28]

Nearly all claims in the past have been for physical damage and personal injury. However, in certain circumstances, claims could be made for loss of production at a neighbouring factory temporarily closed, for example, due to the emission of a massive quantity of toxic gases.

Liability of Contractors and Suppliers. If a catastrophe was caused by defective plant, faulty installation, or even a failure of a minor component due to a manufacturing defect, the supplier of the unit that failed could be faced with enormous claims from his customer, the general public, and in some cases even his customer's customers, and so on.

The employee or subcontractor (depending upon his contract) of a contractor or a supplier delivering to the site could, by one of his actions, cause a disaster while on the site. It is almost impossible for the contractor or supplier to evaluate his possible liability owing to such circumstances, and catastrophe insurance could easily be beyond his means, especially if he operates a small firm.

A prudent firm would, therefore, seek to limit its liability. This can occasionally be achieved by agreement with its customer (where there is a direct contractual relationship), although many firms will not accept disclaimers. A reasonable compromise might be for the supplier or contractor to accept a limited amount of liability for negligence, and in order to safeguard the purchaser the limit must be high (for example, £1 million). This form of liability can be more easily and cheaply insured against. The supplier or contractor would still be liable for damage and injury to persons not party to the contract.

The supplier of an 'off-the-shelf' component normally has little or no opportunity to limit liability by contract. The Society of British Aerospace Companies offer a catastrophe scheme to aircraft component manufacturers, and a similar scheme may be the answer, suggests Taylor,[17] to the liability problems of the supplier of 'off-the-shelf' components to the chemical industry.

D. Structure and Development of the Insurance of Chemical Risks.—The principle of insurance is the spread of risk so that the losses of the few are borne by the many. For most industrial fire and explosion risks, this is achieved by a combination of coinsurance and reinsurance.

Coinsurance is the direct participation by a group of insurers in a contract with their names and proportions of the risk covered appearing on the policy document.

Reinsurance is the spreading of risk by the coinsurers among other insurers throughout the world to limit to an acceptable level the amount of loss or aggregate of losses payable by the coinsurers. Reinsurers spread big risks still further by reinsuring amongst themselves.

The main factor which governs the extent of an insurer's participation in a policy is the assessment of the EML accepted by the leading company (the first company to cover a percentage of the risk, usually chosen for its expertise in that particular field by the broker on behalf of the insured). Most insurers have a Table of Limits on the value of risks they can accept, and depending on his opinion of the validity of the EML assessment and the quality of the risk, the insurer will calculate the 'line' (proportion of the risk) he wishes to retain. This net retention can be increased by the extent of any reinsurance facilities the insurer may have and wish to use, resulting in a gross acceptance of risk often several times the net line, and this gross acceptance will be the line he will write on the contract.

The traditional method of insurance of chemical risks was to place the risks with coïnsurers. They would base their premiums on a relative hazard scale which compared the fire and explosion risk of the plant in question with other plants and make slight adjustments for loss protection features (usually extinguishers).

Because insurers refused to reduce their minimum premium rate, clients and brokers attacked the level of premiums for high risk plants and forced them down to obtain an overall reduction in premium costs, which the excellent loss record of the chemical industry appeared to justify. This resulted in an unrealistic contraction of the rating scale with erosion in the rate differential between well protected and badly protected plants, which was the situation by the mid-sixties. When huge new petrochemical plants began to come on stream, as insurers had great faith (as did the chemical industry itself) in the ability of chemical engineers to design safe plants, the insurers did not make any changes in their rating system. Thus, during the late sixties and early seventies, many insurance companies suffered very severe losses. Insurers in the United States, prompted by such disasters as the Lake Charles oil refinery disaster, and also insurers in other countries, changed their rating systems. However, it was only after the enormous losses due to the explosion at Flixborough that insurers properly updated their rating systems in the UK.

Creswell[31] comments that 'The paths of hurricanes are little changed. What has changed is the subject matter: there are more constructions and belongings in the path of a storm. These are considerations for underwriters and there should be no surprise if the damage is greater each time.'

Cyclohexane always will explode and/or catch fire on ignition: what has

[31] J. N. Cresswell, 'Catastrophes', Chartered Insurance Institute, London, 1974.

changed is the quantity concentrated at one place. The explosion at Flixborough was so disastrous because of the massive size of the leak of cyclohexane and not because of any change in the properties of that material. There is now a surcharge on premiums for such risks which provides a more sensible loading for very large plants, and insurers no longer over-rate the capabilities of engineers and instead despatch their own surveyors to check plants to be insured.

In 1969, ICI introduced its own rating system as described previously (see p. 439), which is designed to generate a realistic evaluation of the risks for each plant. Since then, an ever increasing number of insurers have adopted either this or a similar system, and many reinsurers now insist on the use of such a system by the direct insurers. For the increasing number of very large risks, such methods are vital, although for small risks the older system is still suitable, especially as it is cheaper.

Thus for a large company, the expenditure on insurance risks valued in some tens or hundreds of thousands of pounds or less, merely in order to remove the relatively small variations in the published accounts that such losses would cause, should be carefully considered. Many operators will purchase excess of loss cover which insures them against losses over a minimum value up to a maximum value which, in effect, means that the operator leaves a proportion of his risk uninsured. An example is a division of a particularly large chemical company operating in Europe which insures against business interruption using an excess of loss cover. This covers the division for losses in excess of £0.6 millions up to a limit of £26.4 millions, the premium being approximately £0.5 million. By purchasing 'excess of loss' insurance rather than insuring against every loss, however small, as much as 30—40% of premiums may be saved.[23] Many companies combine excess of loss cover with a 'stop loss' cover which insures against the accumulation of small losses exceeding a value that is tolerable.

Direct access to the reinsurance market *via* a captive insurance company reduces the cost of such cover since the reinsurance market has much lower costs than the direct insurance market. Also the reinsurance market will cover more accurately according to the loss record of the reinsured company. A captive insurance company is one that is wholly owned by an essentially non-insurance enterprise. Examples are: Petroleum Insurance Co. Ltd., owned by Shell Petroleum; Tanker Insurance Co. Ltd., owned by British Petroleum, Ltd., and Imperial Chemical Insurance, Ltd., owned by Imperial Chemical Industries, Ltd. Oil Insurances, Ltd. is a mutual insurance company owned by a consortium of chemical companies, including Burmah–Castrol Co. Ltd., registered in Bermuda. There are between 200 and 300 captive insurance companies in the Cayman Islands and Bermuda registered there for tax reasons.

In contrast to the traditional method where prevention of loss would only affect future premiums (and then often only marginally), prevention of each loss by an enterprise which owns both the plant and its insurer will result in an immediate saving for that enterprise.

Local and international organizations exist specifically to manage and harness reinsurance facilities for captive insurance companies which join such organizations in the knowledge that all the members operate in the belief that 'prevention is better than cure', employing surveyors with a great degree of technical knowledge.

A self insurance fund created from premiums that would otherwise have been paid to an insurer will reflect, by its size, the effectiveness of loss prevention expenditure which, if desired, can be funded by it. Whereas insurance premiums paid are normally tax deductible, a self insurance fund carried over from one year to the next will be taxed. This can be partially overcome by establishing a captive insurance company since premiums paid to it by the non-insurance part of the enterprise will be deductible from the tax of that part of the enterprise.

Acknowledgements

I should like to thank the following for giving up their valuable time to assist me:

Prof. J. H. Burgoyne, of Dr. J. H. Burgoyne and Partners and the City University, and his librarian, Mrs. P. D. Dutton.

Mrs. B. Cowan, Mr. J. N. Creswell, and Mr. D. A. Roden, of Messrs. J. Besso, Roden and Co. Ltd.

Mr. H. Cowan, of Cowan Export Company.

Mr. M. Cardinal and Mr. LeCornu, of ICI Plastics Division.

Messrs. W. J. Ellis, J. Bunney, and D. Willoughby, of ICI Mond Division.

Mr. E. Stokoe, of De Pauuw–Stokoe, Antwerp.

Mr. P. Russell, of the University of Manchester Faculty of Law.

Mrs. J. Mortlock for typing the manuscript, Mr. I. N. Klein for drawing the diagrams, and Miss S. H. Cowan for help with the references and layout.