UNEP – INDUSTRY & ENVIRONMENT GUIDELINES SERIES

GUIDELINES ON RISK MANAGEMENT AND ACCIDENT PREVENTION IN THE CHEMICAL INDUSTRY

UNITED NATIONS ENVIRONMENT PROGRAMME

UNEP - Industry & Environment Guidelines Series

Guidelines on Risk Management and Accident Prevention in the Chemical Industry

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Industry & Environment Office
UNITED NATIONS ENVIRONMENT PROGRAMME

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First edition 1982

ISBN 92 807 1058 3

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FOREWORD

In the review of the Chemical Industry and the Environment, the issue of risk management and accident prevention was identified as one of the major areas on which attention should be focused and at the UNEP Workshop on Environmental Aspects of the Chemical Industry, held in Geneva from 22 to 25 May 1979, one of the Workgroups addressed this issue. The Workshop endorsed the need for concise and pragmatic advice on the measures needed to manage risk and reduce/prevent accidents in the manufacture of chemicals.

Furthermore, one of UNEP's goals is to prepare guidelines on reducing the adverse environmental impact of specific industries and it is within this framework that the Guidelines in Risk Management and Accident Prevention in the Chemical Industry have been drafted.

The Guidelines are primarily on the industrial and technological process aspects of the chemical industry. They identify the major issues which need consideration when formulating strategies and policies and therefore endeavour to act as a catalyst for further detailed institutional, administrative and technical measures needed for the effective management of risk and prevention of accidents in the manufacture of chemicals.

ACKNOWLEDGEMENT

The Guidelines on Risk Management and Accident Prevention in the Chemical Industry were drafted for UNEP by Cremer and Warner Limited under the general direction of Professor Sir Frederick Warner, FRS, and co-ordinated by Mr. D.G. Blackburn.

The following persons provided valuable advice and comments:-

Mr. Y.J. Ahmad, Director for Special Assignments, Assistant to the Executive Director, UNEP, Kenya

Mr. H.J. Dunster, Deputy Director General, Health and Safety Executive, U.K.

Mr. Fong Seok Phoy, Anti-Pollution Unit, Prime Minister's Office, Republic of Singapore

Mr. E. Hellen, Chief, Occupational Safety and Health Branch, Working Conditions and Environment Department, International Labour Office, Switzerland

Mr. C. Henry, Laboratoire d'économétrie de l'Ecole Polytechnique, France

Dr. M.W. Holdgate, CB, Chief Scientist and Deputy Secretary, Departments of the Environment and Transport, U.K.

Mr. S. Garry Howell, Industrial Environmental Research Laboratory, United States Environmental Protection Agency, U.S.A.

Dr. F.L. Kafka, ICI Holland BV, The Netherlands

Mr. D. Larré, Director, UNEP Industry and Environment Office, France

Dr. E. Meinsma, Shell Nederland Chemie BV, The Netherlands

Mr. D. Schmidt, Special Assistant to the Executive Director, UNEP, Kenya

Mr. M.H. Sokkar, Planning and Projects Manager, Al Nasr Company for Manufacturing Coke and Chemicals, Arab Republic of Egypt

Mr. J.I. Waddington, Director, Promotion of Environmental Health, World Health Organization, Regional Office for Europe, Denmark

The Project Officer was Mr. Nay Htun, UNEP Senior Programme Officer

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1. INTRODUCTION

This document provides guidelines on the important principles and factors which can aid judgement and management in order to contribute to the prevention of accidents in the manufacture of industrial chemicals.

Industrial chemicals in this context include organic and inorganic chemicals, medicinal and pharmaceutical products, dyes, tanning and colouring materials, essential oils, toilet, polishing and cleaning preparations, fertilizers, explosives and pyrotechnics synthetic resins and plastics, cellulose derivatives, and pesticides. This classification is that generally adopted by the United Nations and it excludes radioactive materials which require more specialised treatment.

The policy makers and decision-makers in these fields will be those whose responsibility is to prevent accidents. This objective is often achieved by voluntary measures which include the seeking and provision of advice and the training of personnel. Although a regulatory base is needed, a well-run factory should not be faced with high risk situations.

Accidents occur everywhere, not only in industry, and by their very nature, will never be completely prevented or eliminated. The reduction of the incidence of accidents and the limitation of their consequences is a more realistic goal. An accident in this context is a departure from normal designed operating conditions, the results of which can lead to injury, loss of life or the expectation of life or of its enjoyment, or waste of material resources and impacts on the environment. The decision-maker will be called on to exercise management judgement in deciding how best to implement both legislation and professional and technical recommendations, with the objective of obtaining the best standards of safety and of accident avoidance. This exercise of management skill, discretion and authority is defined as risk management.

These guidelines are confined to fundamental principles. Detail is eliminated as far as possible. Those who have to take binding decisions on matters of policy and whose responsibility is to ensure effective implementation of that policy will be advised by experts in a wide variety of specialist disciplines. The availability of competent technical advice is essential to a manager when he takes ultimate responsibility for the effective use of resources in reducing risk.

The avoidance of accidents requires, as a first step, an appreciation of the circumstances under which accidents can occur. This involves the complete listing of the hazards which can exist in the manufacture of chemical products, their storage, containment and distribution to the point of bulk usage. Once identified, the potential consequence of the hazard must be evaluated and the probability of such an occurrence estimated. This combination of consequences and probability will allow the hazards to be ranked in a logical fashion to indicate the zones of important risk. Thus, management and the regulatory authority, in discussion with other interested groups, including the workforce, can decide at what point special measures become unnecessary.

One of the most important and difficult areas of decision is the definition of the criteria by which the quantified level of risk may be considered acceptable and how far those in authority are justified in exacting standards of safety which may well call for very high levels of capital investment, operating cost and social inconvenience. Indeed, it can be unequivocally stated that the complete elimination of accidents and the postulation of zero risk implies no activity at all. Against this must be weighed the advantages which chemical manufacture confers on society, particularly its contribution to employment, improved living standards, enhanced life expectation, health, enjoyment and happiness of the community. It is also true that reluctance to take small calculated risks in one sector of an activity may introduce greater risks elsewhere.

Another problem in the assessment of risk from the point of view of its acceptability is the decision on the social significance of the consequences of a single fatality or a small number of deaths compared with the impact of an accident involving numerous fatalities. The probabilities are usually inverse functions of the number of fatalities. Emotively, the catastrophe has a far greater effect on community decisions than the steady erosion of life which numerous minor accidents can generate. While the theory and statistics of such events are well elaborated, the derived decisions are based more on subjective opinion than on quantitative evaluation.

Although there are limitations to the absolute quantitative evaluation of risk and to numerical precision in the definition of acceptability, there is no doubt about the usefulness of the technology and method in locating and defining in a relative manner those areas of significantly enhanced risk. This allows the manager to deploy his facilities in a manner which allows him to optimise his resources to obtain the best possible reduction of risk. Optimisation of resources will include a debate between manager and staff which may lead to agreed procedures, whether of a regulatory or training kind, that will themselves be beneficial both in reducing risk and in promoting confidence.

The disposition of limited resources in achieving this objective of reducing accidents raises the question of how such resources can be most effectively applied to obtain the best result. Here the policy question is not one of acceptability but of optimisation. The reduction of accidents which cause loss of life or injury is not amenable to precise quantitative or mathematical treatment. The improvement in social well-being may be widely disseminated as to place, time and degree and by its very nature, extremely difficult, if not impossible to quantify. Even if a risk meets a criterion of acceptability, however arbitrary and imprecisely defined, the question of how much effort is justified in its further reduction remains a problem for management and, increasingly, for society. Although individual lay members of society may perceive risk in a subjective manner, it is important that their elected and specialist representatives must judge the cost/benefit of further risk reduction as objectively and knowledgeably as possible.

The foregoing discussion has been confined to the question of the value judgement of the consequences of an accident. In the assessment of potential material and property losses and the justifiable steps which may be taken to prevent them, the problem is relatively simple in that cost effectiveness techniques can be rigorously applied so that the financial return for a given expenditure can be quantified, and optimised, both with reference to the capital value of plant and property and with respect to the losses associated with production shortfalls during equipment replacement. The entrepreneur can also quantify and cover much potential loss by appropriate insurance but, of course, the community as a whole may suffer by such accidental losses even if adequate compensation has been provided.

The public tolerance of industry depends on the feeling that people will not suffer. Even where there is insurance, loss of life as a result of an industrial accident provokes a hostile reaction. There is, therefore, a strong requirement on the manager, in his own interest, to prevent accidents since strict profit and loss accounting may conceal wider issues.

The general methods of risk management and their application are reviewed in more detail below. But the absence of absolute, invariant values for what is acceptable, and what is not, clearly shows that while the manager may be assisted by quantitative evaluations, he is left to arbitrate on matters in which his judgement must play a very important part. Society, however, will also tend to participate through its specialist representatives.

2. GENERAL PRINCIPLES AND DEFINITIONS

While the principles outlined below are of general application, the chemical industry, to which they are here applied, is defined as that of the movement and processing of industrial inorganic and organic chemicals. This may involve their change of state or composition, or both, their storage, loading and offloading, transport and delivery to the point of bulk usage and the treatment and elimination of by-products in the form of gaseous or liquid effluents, or solid discharges.

The terms in risk management and accident prevention are often loosely used and it is important that they are defined with precision so that there can be no confusion about their meanings and the implications derived from their discussion. The following definitions are assumed in these guidelines:-

Safety:	The freedom from unacceptable risks of personal harm, injury, or loss of material resources.
Accident:	An unintentional departure from normal operating conditions, usually with a propensity to reduce safety.
Hazard:	A set of conditions in the operation of a product or system with the potential for initiating an accident sequence.

Hazard Analysis:	The identification and specification of hazards, the determination of probabilities of accidents and of their consequences.
Risk:	The combined effect of the probability of occurrence of an undesirable event, and the magnitude of the event.
Risk Assessment:	The integrated analysis of risk and its quantification.
Risk Evaluation:	Comparison of the results of risk assessment with other existing risks with a view to determining their acceptability.
Risk Management:	That aspect of risk assessment which combines the probability of the occurrence of an injurious event with its consequences and uses the resultant parameters as an aid in the optimisation of the use of resources to reduce the probability of injury, loss of life, or waste of physical or material sources.
Safety Management:	The application of organisation and management principles to achieve the reduction of risk.

3. IDENTIFICATION OF POTENTIALLY HAZARDOUS SITUATIONS

Hazards can exist almost anywhere and the avoidance of accidents and their injurious consequences can only be achieved by firstly identifying potential hazards, estimating their significance and, if the circumstances justify it, in taking steps to improve the situation. These studies are most advantageously begun in the very early stages of project design when the intrinsic safety of the chemical manufacturing process and its proposed method of operation, are studied from the point of view of safety and the containment of materials. The methods by which potential dangers can be identified range from very simple check lists to extremely complex procedures in which branched chains of sequential events are examined in great detail to ensure that every aspect of the engineering design where an accidental failure could occur has been thoroughly reviewed and the cause, effect and consequence evaluated. These studies are supported by growing collections of data on the performance of materials, artefacts and structures which allow estimates of rates of failure to be made with an increasingly high degree of precision.

The identification of potential hazards and assessment of plant safety should be undertaken at all stages of a project, that is, from conceptual design right through to plant operation. Different hazard identification techniques are appropriate at each stage and examples of these are listed in Table I. A useful list of references describing these techniques is given in LEES (1980), while a good example, and now well established method for identifying potential hazards throughout a project, has been developed by ICI (GIBSON, 1975).

TABLE 1

SAFETY AUDIT AND HAZARD IDENTIFICATION TECHNIQUES

1. Review data, for all materials, on toxicology, flammability, reactivity.

2. Application of hazard indices.

3. Check process design of process, operations, equipment, instrumentation.

4. Review process stability under departures from normal conditions.

5. Qualitative failure studies.

6. Quantitative development of failure studies.

7. Risk reduction by changes to process or design.

8. Application of safety audits and quality assurance programmes during construction, commissioning, operation and maintenance including:

   materials and equipment inspection
   non-destructive testing
   corrosion and condition monitoring
   operator task analysis and operating procedures
   emergency planning

While the manager's role will not require his participation in these detailed studies, it will be incumbent on him to be satisfied that they have been competently carried out by experts in the field who will supplement and independently judge the work of the chemical engineering design team and that of the many specialists who have contributed to the estimation of risk factors in the proposals.

The principles on which the identification and location of potential hazards in a chemical manufacturing unit are based may be summarised as follows.

3.1 Preliminary Hazard Survey

A detailed knowledge of intrinsic and extensive properties of the materials handled is desirable to provide information on the potential danger from the effects of failure of the containment system of the chemical plant. To this end, more and more notification schemes have come into existence in recent years, both nationally and internationally, for the tighter screening of potentially hazardous substances. Truly comprehensive information, however, will seldom be available and frequently there will never be enough information for watertight judgement. Commonly, the manager simply has to observe the standards required of him by the community and assume that compliance with these will be regarded as an adequate performance.

Release of material may cause death or injury by chemical or thermal burning or scalding, blast, asphyxiation, toxicity or freezing. Such dangers may increase very rapidly if the leakage itself is augmented by further weakening of the fabric of the plant by the action of heat, blast, cold, corrosion, or chemical attack. For most industrial chemicals and their progenitors there is a wide body of literature giving details of hazardous properties of materials, both in their ability to release energy and generate fires and explosions but also in their effects on human health and well being. Examples of some useful compilations of hazardous material properties are given in NFPA (1975), SAX (1975) and BRETHERICK (1975). Information about the chemicals should include not only a complete schedule of possible reactions but also full information about the effect of contaminants and special hazards caused by the physical form of the material. Danger can be enhanced by extension of active surfaces produced by grinding and the presence of dusts and other finely divided materials. Reactivity of raw materials and products to common ambient substances such as water and air can also be dangerous.

Certain types of chemical reaction, usually of an exothermic nature, can cause a runaway generation of energy which once initiated increases very rapidly, often exponentially, with time. The resultant high temperatures create pressures which can be explosive. They may generate vapours which can be highly flammable even to the point of detonation on mixing with air or oxidising materials. Vapours can easily diffuse and cause toxic, narcotic, burning or explosive effects over a wide area.

Both the immediate effect of an accidental large release and the long-term delayed damage caused by a relatively small discharge of a poisonous or toxicologically active material must be considered. These can occur either as a small discrete release due to an accident, or to the consequences of minor deviations in process operation which, although apparently minuscule in their magnitude, can continue for a very long time.

The problem can be particularly difficult in the case of new processes and products where the amount of background information is limited. This is especially important in the estimation of the toxicological effects of the chemicals involved. Indeed, in the history of the chemical industry many chemicals have been found to have long-term effects in much smaller concentrations than were first thought safe.

Animal experiments and medical monitoring of humans have been used in efforts to quantify the relationship between cause and effect, and these together with industrial experience form the basis of Threshold Limit Values (TLV). These represent conditions under which it is believed that the majority of workers may be exposed day after day without adverse effects.

Other occupational criteria used in the assessment of the noxious effect of discharges are Emergency Exposure Limits (EEL) concentrations which can be tolerated without adversely affecting health, but not necessarily without causing temporary acute discomfort or other evidence of irritation or intoxication. These can be tolerated in the short term by those associated with the operation, if this is necessary to ensure the avoidance of a more serious accident. They vary with the time of exposure.

Similar but more rigorous standards are applied to public or community exposure. These are expressed as Short Term Public Limits (STP) or Public Emergency Limits (PEL). Time of exposure is, of course, very important in the application of these criteria.

Check lists can be used to identify hazards and they may also help to determine appropriate action. They may take the form of questions or keywords. Although such check lists are useful to convey information to personnel who are unskilled in hazard studies, and do assist in identifying faults, they suffer from the disadvantage that items not included on the list are not checked. There is a tendency, therefore, for the list to be extended until it becomes so long, and contains so many items irrelevant to a particular case, that it becomes burdensome and is discarded.

However, for relatively low hazard plants, checklisting may be all that is required. A list of references covering such checklists is given in LEES (1980), and a useful general checklist for plant siting and design by BALEMANS (1974). It is important to emphasise that checklists should only be used as a final check and not as a primary tool for hazard identification.

The UK Health and Safety Commission in its proposal for so-called notifiable installations (HSC 1976) has drafted a simple check list which allows immediate assessment and warning on some plants where the possibility of a serious danger exists. The checklist is based on the quantities of material stored or processed on the plant. The list is useful, but not of course exhaustive. If the quantities stated are exceeded by a factor of ten, then it is necessary for the organisation operating the notifiable installation to submit a hazard survey to the Health and Safety Executive. Such a survey is intended to give information on the inventory of the chemicals involved, the population exposed, on the process, and on the management system. A more detailed hazard assessment may be necessary and this is described in fuller detail in the U.K. Advisory Committee on Major Hazards, First and Second Reports of HSC, 1976, 1979.

Another procedure to identify hazardous areas in manufacturing plant, particularly those involving new technology, is to use various hazard indices. The most widely used hazard index is that produced by the Dow Company (1976) and provides a guide to assess the need for protection against fire and explosion.

With the potential hazards identified, it is possible and desirable with major hazard installations, to undertake preliminary risk assessments at the preliminary or conceptual design stage to ensure that the siting of the plant and internal plant layout is acceptable. These risk assessments cannot be refined until the project develops and more detail becomes available. This approach is discussed further in Sections 5 and 6 and in reference CREMER AND WARNER (1978).

In summary, the compilation of the properties of the chemicals to be used should allow identification of all major hazards and inherent process risks early in the process development stage. If particularly hazardous chemicals, reactions, severe operating conditions and large inventories of chemicals can be eliminated, or significantly reduced, the need for extensive protection of the final plant is avoided. Attention should be given at this stage to whether the selection of a different process route, operating conditions, or other design options, is desirable on the grounds of safety.

3.2 Review of Process Engineering

Implicit in the development of the design of the chemical plant will be the production of a range of documents consisting of: process flow diagrams, piping and instrument diagrams (P&ID's - sometimes called engineering line diagrams or engineering flowsheets), specifications for the various items of equipment, layout drawings, and specifications and codes relating to the manner in which the plant is to be built. In the later stages of the project the operating manual will be prepared by the plant designer. This will provide details of the method of plant operation, including procedures for the safe shutting down of the plant in the event of a malfunction and how to deal with emergencies. These documents will require detailed critical review by process specialists during their development to identify potential hazards and to ensure that operating procedures are inherently safe such that the consequences of possible operator error are minimised as far as possible.

The P&I diagrams should be subjected to a methodical review in which the effects of deviations from the designed operating conditions are examined. The object of this review is to ensure that in the event of an assumed deviation in a plant sub-system that one or more instruments will function correctly to counteract the deviation, or to react such that deviations are not transmitted downstream, for example, by initiating the closure of a valve. This may require the provision of a pressure relief valve to protect the system from overpressure. Reference would be made to the flow diagram and to equipment specifications to establish the effects on equipment and that materials of construction are satisfactory for the deviated process conditions. Common mode failures must also be identified. These may be the result of a loss of essential services, such as instrument air or power supplies.

Effectively, the review would consider the effect of the following on the plant:

- Loss of cooling water
- Loss of electrical power
- Loss of instrument air
- Blocked-in sub-system
- Failure of control valve, fully open or closed
- Fire

It must be established that pressure relief valves, alarms and trip actions have been provided to ensure containment of materials in the plant. Relieved vapours or gases must be collected and disposed of safely either via a closed flare system or a treatment system, according to the nature of these materials.

Experience has shown that the dangers of malfunction and accident tend to concentrate in certain operations. Start-up and shutdown, loading or unloading, or indeed any discontinuous repeated process operations require more care in examining details in their safety studies than those in which smooth continuous steady conditions are maintained.

A methodical and systematic procedure, known as the Hazard and Operability Study, has been developed for the study of the detailed process engineering for a plant (BCISC, 1977). The method is a very powerful tool for two reasons. Firstly, the reviewers are obliged to examine all parts of the design and not merely those which they believe to be important. Secondly, each hazard is almost certain to be encountered more than once when a different variable is considered.

The P&I diagram of the process is examined line by line. Guide words are applied to each state of the process (for example, pressure, temperature, flow, concentration) thereby generating deviations. The deviations in turn lead to consequences with respect to hazard. A consequence will require action to alter the plant design depending on its seriousness and the frequency with which it could occur.

The hazard and operability study involves the use of experienced people with detailed knowledge both of the process and of hazard analysis. It is also tedious and time consuming.

One of the most unpredictable causes of accidents is operator error. Even a competent and well trained operator can suffer momentary lapses which may be caused by fatigue, boredom, stress, illness or unexplained inattention. The usual remedy to minimise accidents which arise from this cause is to fit automatic control or other safety devices which prevent operator mistakes from being dangerous. However, these devices can fail even though the likelihood is greatly reduced by effective design, adequate maintenance and regular checking. Multiplication of safety devices and fail safe mechanisms brings in its train its own problems in that they can require more complicated procedures in stopping and starting plant operations. In order to analyse whether the frequency of failure of some of these complex systems is sufficiently low, it is necessary to undertake detailed studies concentrating on the particularly sensitive area of plant or equipment. These studies often involve "fault tree" or "event tree" analysis, which are used not only to identify and portray the logical development of particular failures but also to assess quantitatively the probability of failure (see section 5.0).

3.3 Plant Layout

In plant layouts, the absence of good roadways and impediments to freedom of movement of traffic are dangerous. Adequate spacing of the structures can reduce the domino effect of a hazardous incident in one of them. Destruction of a critical structure such as a control room could be disastrous and this may indicate the necessity for special reinforcement to give blast and fire protection in such critical zones. Lack of adequate fire resistance in materials of construction, poor ventilation and the presence of sources of ignition are some of the many hazards easily identified by preliminary inspection of draft proposals. Secondary containment, blast walls, refuges and the isolation of drains and conduits from ingress of dangerous material must be provided.

The search for potential hazards on a proposed plant site cannot be confined to the plant boundaries. The dangers from natural phenomena need to be considered together with the possibilities of destructive effects from accidents or unwanted impacts from adjacent manufacturing units. These include undesired sources of ignition, corrosive, reactive or harmful emissions and even a possibility that an accident in the locality of the installation might have a dangerous impact on the proposed new project.

3.4 Transportation

The ancillary operations of the movement of raw materials and the loading of the chemical product into containers and its transport to the point of use are important areas in which danger may occur. Apart from the normal safety review of the operations, such as that given to other parts of the process plant, there are special risks here which must be investigated and minimised. For example, the likelihood of spillages of materials due to errors in coupling hoses to vessels, and the over-filling of vessels. Clear identification of containers and their contents is important and legends should be supplemented by pictorial representation to avoid language difficulties.

Contamination of products can cause reactions of explosive violence and the repetitive discontinuous nature of the loading and unloading operations makes them more than normally liable to operator error. In addition, the transport of containers carried on public highways, seaways or railroads are subject to the possibilities of traffic accidents outside the responsibiliy and control of the chemical manufacturer. For this reason it may be necessary to specify more than normal margins of safety since the probability of traffic or transport accidents can include a greater degree of uncertainty in the estimation of risk.

3.5 Conclusion

In summary, hazard identification requires an imaginative and comprehensive appreciation of what might happen in the chemical plant based on intimate knowledge of the materials to be processed, the plant and machinery, the method by which it will be worked, the possibility of external impact on the operations, and the approximate consequences due to a mishap in any of these areas.

The procedures of hazard identification are applied to the initial design stage. If they are implemented effectively at each subsequent stage of the design, right up to the final construction and inspection of the finished plant as it is handed over to the operators, most hazards will either have been eliminated or they will have been reduced to acceptable levels in probabilities of damaging accidents.

The process of a safety review must be a continuous one in that as the project develops from the design to the construction stage, changes in technology are sometimes made, as knowledge increases. These changes can arise from improvements in process, or from cheaper or more efficient mechanical or civil design or construction. It is most important that the safety aspect of such changes are monitored as efficiently as the preliminary studies. The latter statement applies also to any modification made for whatever reason after the plant has been built. Furthermore, it will be necessary to monitor the safety awareness of the operations team and management when the plant is operational. The use of safety audits, independently applied, can be of particular value to achieve this task (see 'SAFETY AUDITS', BCISC, 1973).

4. ASSESSMENT OF HAZARD AND CONSEQUENCE

The potential release of material or energy must be quantitatively evaluated to determine its impact and consequence. This involves an estimate of the appropriate inventory and calculation of the rate of release and of dispersion behaviour. Such calculations are based on simplifying assumptions incorporated in mathematical models which take account of the type of release, the physical properties of the material and weather or other conditions which affect the rate at which the release is diluted in the atmosphere. A good guide to some assessment techniques can be found in LEES (1980).

4.1 Flammable Materials

The release of flammable material and its subsequent ignition can cause a wide variety of thermal and explosive effects. The simplest case is that of a steady state fire caused by ignition at the point of leakage which burns at a constant rate until the flow of fuel is interrupted or the fire is extinguished. The chief damage occurs by thermal radiation whereby the heat generated may damage the environment and health. However, if a vessel is surrounded by a fire, it is possible for the strength of the vessel wall to be weakened due to the high temperatures. Vessels have failed catastrophically for this reason. In such circumstances, flammable material is expelled violently and a fireball effect of explosive intensity is produced by the ignition of the boiling liquid as it expands into vapour. This produces very intense and dangerous thermal radiation. Account should be taken of the effect of fire on essential services, since damage to power and instrumentation supplies is likely to cause escalation of the incident.

Flammable gas or vapour which is released from a plant fracture and not ignited at source produces a different and often a very much greater hazard. Whereas immediate local fires and explosions can cause casualties among employees, the number of such people in the immediate locality is usually relatively small. If the flammable gas or vapour is not ignited at source it may, depending on composition, physical characteristics, conditions of release and weather conditions, travel airborne for considerable distances from the point of release in the form of a large cloud. Such a cloud passing over a densely populated centre creates a very great danger as a chance source of ignition can ignite the whole cloud with the possibility of very destructive blast and intense heat radiation. In such circumstances the dispersion and dilution of the cloud, and the probability of it being ignited by an adjacent plant, workshop, domestic premises or road traffic, has to be considered.

4.2 Toxic Materials

While the visible effect of accidental poisonous emissions is less spectacular, the effect may be devastating and the toxic material may be carried for considerable distances by air or water and subsequently ingested by humans. An example was the release of an ultra-toxic chemical at Seveso in 1976, which caused severe and prolonged pollution. Also, the discharge of mercury catalyst into Minimata Bay, Japan.

4.3 Assessment Method

The basis on which the magnitude of such hazards is assessed is derived from a combination of empirical data and theoretical concepts. Following the identification of a potential hazard and data collection, the first steps in the assessment process are the modelling and precise specification of the incident generating the release, calculation of the rate and duration of release and its dispersion pattern. Then the potential effects of the release such as fire, blast, asphyxiation or poisoning are derived from model simulations of the behaviour of the release during its effective life, coupled with data on sources of ignition, effects of dilution on flammability, toxicity, and thermal radiation intensity.

This representation of the harmful effects of the release, as it changes with time and distance, is then applied to a population distribution so that the effect in terms of fatalities can be evaluated.

Obviously such calculations can be complex. Indeed, many would be impossible without the use of computers and sophisticated mathematical models when attempts are made to analyse the sensitivity of changes to certain parameters, for example, meteorological conditions. The lack of data and of completely satisfactory mathematical treatment make the results approximate at best, though improvements in the collection of data and its treatment are taking place continuously.

The outcome of the calculations is a figure for the number of the casualties which might be caused by an accident on the plant. It is usual to assess this separately for employees and others within factory limits, and for the population outside this area in the surrounding community.

Having completed the assessment of hazardous consequences in this way, the next step in the chain of safety assessment procedure is to estimate the probabilities of such occurrences as is described in the next chapter.

5. CALCULATION OF PROBABILITY: QUANTIFICATION

The assessment of the magnitude of potential fatal consequences, discussed in the previous section, must as far as possible be complemented by calculating its probability of occurrence. Management will be guided by the fact that, as far as risk is concerned, a potential accident of sensational proportions and damaging effect may have no significance if its probability is sufficiently small. Similarly, minute consequences of appreciable probability contribute very little to overall risk. The next step in the assessment of the safety or otherwise of the plant is the assignment of probabilities to the potential consequences which have been revealed both in nature and possible magnitude by the study of the factors discussed in the previous sections. Those in authority will then use the results as a basis for a cost/benefit evaluation, however crude or difficult to carry out, to decide on the acceptability or otherwise of the risk.

An accident in the chemical industry usually occurs when a piece of equipment fails to function in its intended duty, or an operator makes an error, or some external factor prevents or impairs designed performance. An integral and vital part of hazard assessment is the estimation of the likelihood of such events. The prediction of the frequencies of these occurrences is a complex task and the results are often only approximate, particularly when the incidence of such events is rare and when there is little historical information to guide the assessor.

After the identification and precise specification of the potential accidents, or failures in the expected performance of the chemical production, storage and transport system, there are two main approaches to the assignment of probabilities.

One method uses historical data and collected experience on plant failures to predict large-scale events without analysing in detail the initiating causes. Much detailed information is available in long-term records of failures, and their causes, in pipelines and associated ancillaries, pressure vessels and control systems. This is often based on world-wide experience and it can be used, appropriately modified, to estimate the probability of failure of the components of most types of chemical manufacturing plant. The comprehensive approach is to break down each element of the plant into its components and to consider each mode of failure together with the contributing factors and to assign to them reliability data based on published statistics. This is the "fault tree" approach for synthesising the risks and consequences of failure of the whole plant. It is of special value in calculations of complex cases in which several different modes of failure are possible and when no comprehensive data are available to cover the system in its entirety.

Fault tree analysis has been widely used in the aerospace and nuclear industries and its use is being rapidly extended to the chemical industry. However, the technique is laborious, time consuming and expensive in its employment. Its use is therefore justified only in the examination of those critical sections of a chemical plant where, for instance, the integrity of containment depends on the reliability of a complex control system. For simple systems, or single components, the direct use of historical data for the probability of failure in the component itself is preferable and more convenient. The data are, however, by no means complete and an important part of the safety assessment process is the compilation and manipulation of data on equipment failure based on actual plant operating records.

The probability of failure is only part of the probability of a given level of loss being sustained. In fact, a given failure may be associated with a variety of ultimate damage levels. In a release of a flammable vapour or a toxic vapour, factors such as operator intervention, wind direction, time of day and population distribution will all influence the number of people likely to be exposed to the vapour. The presence of ignition sources must be added to the list of factors in the calculation of consequences when a flammable vapour is involved. Each of these factors has an associated probability, so that the analysis must be carried out on all permutations of possible situations. The resultant extensive sets of quantified damage and probability pairs, calculated for each accident scenario, forms the basic output of a detailed and comprehensive hazard analysis.

The calculations are approximate because both the data and the models used in the processing of the figures are themselves subject to over-simplification and statistical error margins. For example, component failure rates based on recorded experience may be in error by an order of magnitude or worse. For this reason the risk of an important accident cannot be precisely estimated and the numerical results must be regarded cautiously as indicative only. However, data and models are improving with experience and predictions are becoming more accurate. Most importantly, the estimates, however approximate, are much better than no information at all, and the exercise of carrying out the risk analysis is very likely to indicate possible improvements.

The uncertainties, however, cannot be ignored. If calculations and decisions are based on worst case assumptions, the conclusions have the merit that they err on the safe side. However, in a chain of calculations, each element of which has its own independent source of uncertainty, the use of worst case assumptions in all the steps will give an overall result which is extremely pessimistic. While each worst case assumption may be plausible in itself, their simultaneous multiple conjunction could be regarded as unrealistic.

Where there are few sensitive parameters and the number of steps is small, worst case assumptions may be acceptable. Where there are multiple uncertainties the best approach is to aim for the most likely values of parameters and then to evaluate the effect of uncertainty on the overall conclusions. This will give a span of risks which can then be ranked as to likelihood. The estimated uncertainties can then be helpful in the judgement of the importance of the risks.

Graphical representation of risk areas, such as contour maps of risk values, are most useful in presenting the assessor with a concise and easily assimilated representation of the overall risk and the effect on population centres.

6. CRITERIA

The criteria of risk are the standards by which risk is judged as to its acceptability by the community. Probably the simplest starting point is the desirability that the construction and operation of a chemical enterprise should introduce no greater risk to the external community than previously existed before its inception. However, this is equivalent to the statement of a "no risk" objective. Existing risks do not justify additional risks, but only provide a basis for comparison.

As background, one may consider those natural phenomena over which man has no control. They include lightning, storms, tidal waves, earth movement and volcanic eruption. Statistically, an average individual has a chance of being killed by such catastrophes once in a million years (1 in 1,000,000) or more, though obviously, there will be a variation around this figure depending on location and its environment. Such a risk is about the smallest hazard to which human beings are subjected and the inevitability of the cause is often described as an "Act of God", in that it transcends most human effort of avoidance or reduction. The risk is fatalistically accepted by many communities but sometimes they have decided to move to a less sensitive place.

At approximately ten times this risk, namely the single chance of being killed in a hundred thousand years (1 in 100,000) from causes like fire, drowning, poisoning, or a firearms accident, the only action generally taken by the community consists of warnings to "take care" and a very small, almost negligible, investment in safety measures.

When the personal risk increases to a probable mortality of once in ten thousand years (1 in 10,000) from a given cause, delegated authorities in the industrialised countries may sanction funds for remedies. In general, a proposal for an activity which gives a chance of a member of the community being killed once in a thousand years (1 in 1,000) is almost certain to cause protest and calls for immediate improvement at almost any cost, or a complete ban on the operation may be proposed.

But there is no apparent logic in community reaction. Very large groups of people will voluntarily accept a high likelihood of death in fifty years (1 in 50) as motor cyclists, and in about two hundred years (1 in 200) as moderate smokers. There are many other relatively dangerous activities which are accepted without question largely, it is said, because they are chosen freely by the participants, or the latter have taken a "calculated risk" or perceive a benefit. It is doubtful, however, whether much analytical thinking is devoted by the individual or groups involved to the consequences or probabilities associated with their choices. It would seem that there is a need for increased understanding of the risk-benefit relationships pertaining to the chemical industry.

More precise criteria are available for some industrial activities and the chemical industry has a good record in improvement of safety and presently enjoys a relatively high freedom from fatal accidents, though this is not to say that there is no scope for further progress. The parameters used for reporting industrial mortality differ from those used for risks in the wider fields of community life and, therefore, a direct comparison cannot be made without conversion.

One measure of risk (Kletz, 1971) is the Fatal Accident Rate (FAR), which is the number of fatalities which one might expect in one hundred million hours of exposure, that is, corresponding to a group of 1000 workers during their working lives. In round figures, an employee spends about two thousand hours a year at his place of employment, so that a FAR figure of unity corresponds to an expectation of fatality once in fifty thousand calendar years (1 in 50,000). The U.K. and Dutch chemical industries have an overall FAR of four, corresponding to a once in twelve and a half thousand years (1 in 12,500) mortality expectation and the figure of four compares favourably with metal manufacturing and shipbuilding (8), agriculture (46), coal mining (10-12), and construction erectors (67). Industrial figures tend to be somewhat over-optimistic in that they usually include all workers in the enterprise, some of whom, in offices and non-manufacturing locations, are well separated from zones of factory hazards. Nevertheless, the employee figure for the chemical industry, with a specific individual employee risk of death of one in twelve and a half thousand calendar years, does not cause significant protest. It will, however, be appreciated that such risks are additive to other everyday risks.

The community standards, that is to say, the acceptable risks to which people outside the plant boundaries are subjected, are more exacting and it is becoming common to use the criterion that the proposed undertaking should introduce no significantly greater risk to the community as a whole than existed previously, even though the risk to employees may be very much greater. This reduces the community risk to the "Act of God" category, namely, the expected once in a million year fatality for an ordinary person living in the locality and not working at the plant.

As has been mentioned in the introduction, a concentration of fatality as a disaster causing multiple casualties is much less acceptable to the community than the same statistical incidence spread out over a long period. This is understandable in view of the dramatic nature of the event and its very high emotional impact, and the possible social disruption of a community such as occurred at Aberfan, Wales, in 1966, when one hundred and forty four people were killed including a very high proportion of children. There is good evidence that the probability is an inverse function of the number of casualties, the function being dependent on the type of enterprise. Positive conclusions are difficult to draw and the only guidance that can be given is that where there is a possibility of a concentration of fatalities, even with low probability, very serious consideration must be given to the location of the factory in relation to population centres, to the dispersion of the population (which can result in higher transportation risks) and to the limitation of quantities of dangerous materials.

So far, the discussion of criteria has been confined to the two different classes of individuals, namely the general community in the outer zone and those who work within the factory confines. It is usually postulated that those in the outer zone should enjoy a higher standard of safety than that of the workers, on the grounds that the workers have freedom of choice in their employment and are financially compensated for the risks they take. Both these postulates are over simplifications.

In the first place, mobility of labour and choice of employment are not as fluid as the assumption implies. Constraints on workers seeking gainful occupation are often very rigid indeed, particularly in times of unemployment and housing shortages, and there can be the additional deprivation of community life for those who wish to seek employment far from their homes and families. Secondly, the financial rewards for taking increased risks to life and limb in industry are often disproportionate in various sectors of the chemical industry itself. And, of course, they are widely different in the whole field of general industry. Further, implicit in the postulate, even if it were valid, is the assumption that a given chance of sudden death can be equated with a unique value expressed in monetary terms.

The increased bargaining power, and increased environmental and health awareness of workers, will undoubtedly put pressure on chemical manufacturers to improve their standards of safety and increase the financial compensation for the acceptance of risk. So it appears that this, combined with public awareness of the statistics of risk in the industry, will generate increasing pressure for improvement of standards in the future. Thus, policy decisions may be needed to initiate action to achieve this now, thereby avoiding excessive future expenditure in upgrading installations to achieve new and improved standards of safety which may well, in the course of time, become obligatory.

The discussion of criteria, as far as numbers are concerned, has of necessity been confined to fatalities. It will be appreciated that these numbers have margins of error which are bounded by ranges within probability distributions. And, of course, the numbers deal only with fatalities, because they can most easily be handled quantitatively.

There have been attempts to extend this numerical approach to cover risks other than those of fatalities. In these, injury is related to fatality in that so many injuries of a given gravity count as one fatality. This gives the appearance of extending the statistics of fatal accident incidence to a wider field with a common numerator. The limitations are obvious. It could well be argued that because of some severe injury, or long-term disease resulting from an accident, the victim would require indefinite support and would no longer be a productive member of society.

To sum up, the manager can be guided by numerical criteria on risk applying separately to the community and the chemical factory employees. These are subject to an appreciable margin of error. The possibility of single incidents with multiple fatalities requires special value judgement. The probabilities of accidental injury, disease or physiological damage are not easily estimated, though in many cases measures introduced to effect a reduction in the probability of fatality will reduce the incidents. Reductions in risk should always be sought if they can be achieved with a reasonable deployment of resources.

Both management and community authorities can be guided by quantitative risk assessments and numerical expressions of what may be criteria of risk acceptability. However, they should base their acceptance of a proposed activity on their own experienced judgement after carefully weighing the technical, economic and political aspects.

7. ENGINEERING STANDARDS AND CODES OF PRACTICE

An important part of the body of published guidelines which can assist in the prevention of accidents is provided by standards and codes of practice. Local, national and international standards are drawn up by official bodies after a careful review of the important factors in the reliability, design, fabrication and testing of plant and equipment with the object of ensuring their integrity, including an adequate margin of safety, under the proposed operating conditions. While some of their provisions have the force of law, this is not usually the case.

Codes of practice and standard specifications also cover testing principles and practice, certification, identification and approved marking of the equipment, and, very often, of its material of construction, where samples are reserved as proof of integrity, special treatments such as stress relieving, operating limits, inspection, and maintenance schedules. There is a very wide range of international bodies which produce such documents. There is a need for unification and simplification in the multiplicity of existing codes. As well as national and international bodies, sources include technical institutions, trade associations and individual manufacturers. An important contribution is made by insurance organisations, in whose interest the reduction of accidents is commercially important.

Such codes have a very valuable and almost universal usefulness in that they are particularly comprehensive in summarising knowledge and experience of best practices in the design and operation of standard equipment in the chemical plant. However, the use of such approved specifications requires a careful study of their limitations, since the calculation procedures in some international codes may differ, for example, in the design stresses and safety factors employed.

Departure from the standard or code requires rigorous justification. A disadvantage of the standard or code is that it can never be entirely up-to-date and the use of new materials, methods of design and fabrication, testing and operation call for special study of the relevance of the officially published specifications to the proposed operating conditions of new advanced, and sometimes untried, plant and process.

8. SOME MANAGEMENT ASPECTS

Management is concerned with the effective implementation of policy and the planning of routes and procedures by which control can be maintained. At the inception of the project it is essential that the safety principles are outlined in a formal document, prepared by the plant designers and approved in detail by those charged with safety assessment. Interaction between the two will produce the operation safety document by stages outlined diagrammatically in Figure 1.

The procedures by which safety is assessed, as discussed in Sections 3-6 of this guideline are then carried out in collaboration with the design team but with the complete independence from commercial and emotional involvement by the safety assessment body, so that risks are either quantified or, where this is not possible, specified in as much detail as practicable. This will allow the decision to be taken as to whether the proposals are acceptable or not in the light of the approved safety principles. Design will, of course, include operating instructions which must form an integral part of the design package. A design contractor will normally produce an operating manual to cover procedures for the safe startup, normal operation, shutting down, and for dealing with foreseen emergencies on the plant. These instructions may be adequate for the transfer of information to the plant owner, but they do not contain sufficiently detailed instructions necessary for the day-to-day management and operation of the plant. Management must arrange in good time, therefore, to produce their own detailed operating manuals for use in the instruction and training of operators before the initial plant startup.

It is essential at all stages of the safety assessment work, that formal and precise records of assumptions, methods, procedures and calculations are kept and independently checked, and that they are updated promptly as and when modifications are made. The maintenance of impeccable records is a tedious and time consuming procedure, but is essential if the integrity of the safety assessment and the decisions derived from it are to be assured.

A very significant element in the execution of a good safety policy is the high and responsible involvement of all levels of employees and the impartiality and independence of that part of management functionally responsible for safety. Once the norms of safety policy have been established and agreed by management, no commercial pressure must be allowed to increase risk by taking expedient measures which may ephemerally increase profitability, product quality or market satisfaction at the expense of increased hazard. Not only would such action be socially unacceptable, it could also have a delayed adverse effect on viability. Industrial experience has shown that accidents, even without injurious consequences to people or equipment, can vitiate the smooth running of an operation which is essential for efficiency and economical production.

The principle must also be implemented in the terms of reference and job specification of the safety officer whose responsibility must be clearly and unequivocally defined as the delegated executive of the management in implementing safety principles throughout the organisation.

The education and training of all employees will be necessary in an endeavour to obtain general acceptance of the important principle that safety is the concern and responsibility of all workers in the organisation from top management to the most junior employee.

Consideration should be given to a policy for incentive bonus payments to employees related to accident-free plant operation. It will also be necessary to encourage and commend individual effort and good safety performance so that an enthusiastic "esprit de corps" is created in the organisation with the common objective of avoiding accidents.

The steps which are necessary to achieve this start with the very careful selection of those who are involved with plant operation in all its aspects. Such selection must include an examination of the physical and mental capacity of the candidate employee, suitability for training, and reliability, particularly under sudden stress. After training, the quality of the working cadre must be maintained by constant refreshment of the awareness of the sensibility to safety principles by frequent retraining and practice.

The necessity to enforce strict and rigid safety discipline will be obvious, though the development of individual self-discipline cannot be overemphasised. This will include formal written procedures, authorised by qualified personnel, covering the starting up and shutting down of plant, and access to it. Repair, maintenance and alteration procedure will require special authorisation. Inspection and approval of the completed work and formal permission to recommission units will be obligatory under carefully controlled conditions. The need for all plant alterations to be subjected to a full review and approval by engineering and safety specialists, both with respect to design and intallation, is essential (Flixborough explosion, England, 1974, PARKER, 1975). Abbreviated procedures, which should be foreseen, will obviously be necessary in emergencies. Particularly rigorous control is necessary to cover the movements and activities of personnel from outside organisations such as contractor staff and visitors who are often less easily supervised than the inhouse employees who are usually better disciplined and controlled by management.

Many chemical manufacturing operations are implemented on a contractual basis by major engineering houses as turnkey projects. It should be an essential part of the know-how package that detailed attention is given to safety aspects of the operation and that a full and comprehensive dossier is prepared on the potential hazards of the proposed activity. There are sometimes objections to this on grounds of confidentiality or secrecy. They must be overcome.

In the day-to-day operation of a chemical plant an accidental occurrence of considerable hazard potential may happen but which, in fact, does not result in serious damage or casualties. This is the so-called "near miss", which may arise from a process deviation, and should be reported to management so that steps may be taken to improve safety. Any process deviation, however, should be really serious, and well above any high alarm setting and potentially hazardous, before being classed as a "near miss". Otherwise, many trifling deviations are likely to be reported. Another example of a "near miss" is a large spill of volatile liquid, but without serious damage or casualties. Rigorous retrospective examination of the circumstances of such events are essential.

Preoccupation with hazards specific to a chemical plant operation must not detract from the careful examination of all those normal hazards which are met with in ordinary activity, such as falling or tripping, strain in lifting, rotating or other dangerous machinery, sharp edges, poor illumination, blind corners, dangerous lifts and cranes, and the consequences of their failure.

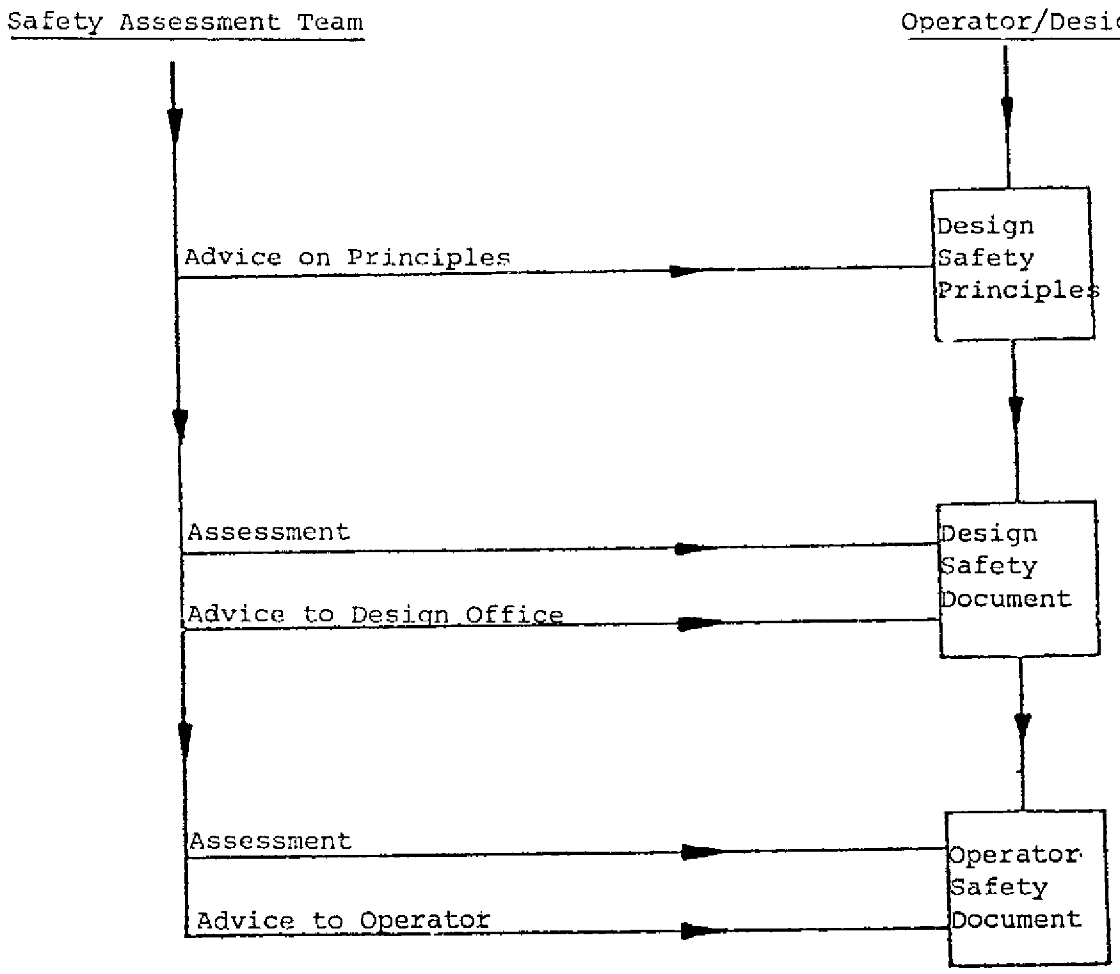

FIGURE 1: FUNCTIONAL RELATIONSHIPS IN THE FORMULATION OF DESIGN AND OPERATIONAL DOCUMENTS

9. EMERGENCY PLANNING

Effective preplanning of emergency action, in collaboration with local and national authorities which may be required in the event of a serious accident, is an obvious necessity. Such services include hospitals, first aid, fire services, specialist decontamination units and other sources of expertise, accommodation for disaster relief centres, police and even military and civil defence forces. It is essential that information on the chemical and toxicological properties of chemicals, whether feedstocks, intermediates or products, and the methods for their neutralisation and detoxificiation are notified to all the emergency services as a matter of routine. Most useful in the preparation of such emergency plans is a thorough review of previous accidents and an appreciation of the problems which have arisen in similar incidents. But serious accidents are seldom duplicated precisely, because appropriate preventive measures will usually have been taken. So historical records must be interpreted imaginatively to find out what could have happened as well as what actually occurred.

Not only must the plans be drafted with precision and be well co-ordinated in their different spheres of application, but their exercise must be rehearsed and practised frequently and at regular intervals to ensure smooth and effective implementation. A well publicised chain of command, with understudies for key roles, is essential and adequate provision must be made for secure means of communication. These arrangements, of course, must be effective both at night and in the daytime, and in holidays or shutdown periods, as well as during normal operation.

Emergency services and facilities for rapid connection of firefighting equipment, water and power supplies must be compatible in their connections and supply characteristics with those alternatives which may have to be used in times of crisis.

Rescue equipment, breathing apparatus and protective wear must be available in adequate quantities and accessible in several locations. It would be desirable also to train medical and paramedical personnel in treating cases of exposure to the chemicals likely to be encountered. This would require the treatment procedures to be determined as part of the overall planning programme.

Good traffic control is essential in disaster situations and measures will be necessary to avoid impediments to essential movements of rescue and auxiliary services. These can easily be blocked and rendered inoperative by non-essential traffic and spectator curiosity.

The effectiveness of such programmes must be assessed regularly and procedures appropriately modified as a result. The necessity to modify and update such activities as a result of simulated practical experience is often overlooked.

10. CONCLUSIONS AND SUMMARY

Broad principles of risk management and accident prevention have been defined and outlined. Management must employ expert advice and imaginative interrogation to see that hazards have been comprehensively catalogued and, where possible, quantified both as to effect or consequence and probability, using the potential incidence of fatality as the criterion. There are no hard and fast rules. Application of the techniques described will improve effectiveness in the employment of resources in achieving accident reduction. Quantification of risk can be an aid to the value judgements which management must make under the influence of the social climate of the moment. Some important management aspects are outlined and the essentials of emergency planning reviewed.

The guidelines have placed some emphasis on the identification of hazardous situations. This emphasis is intentional. Provided such situations can be recognized, measures may be taken in design or procedures to reduce their hazardous potential. This is the basic function of risk management and should always be practiced even though circumstances, due to lack of data or techniqes, may not allow a reliable quantification of risk.

The stages and chains of events involved in hazard assessment are placed in perspective in Figure 2.

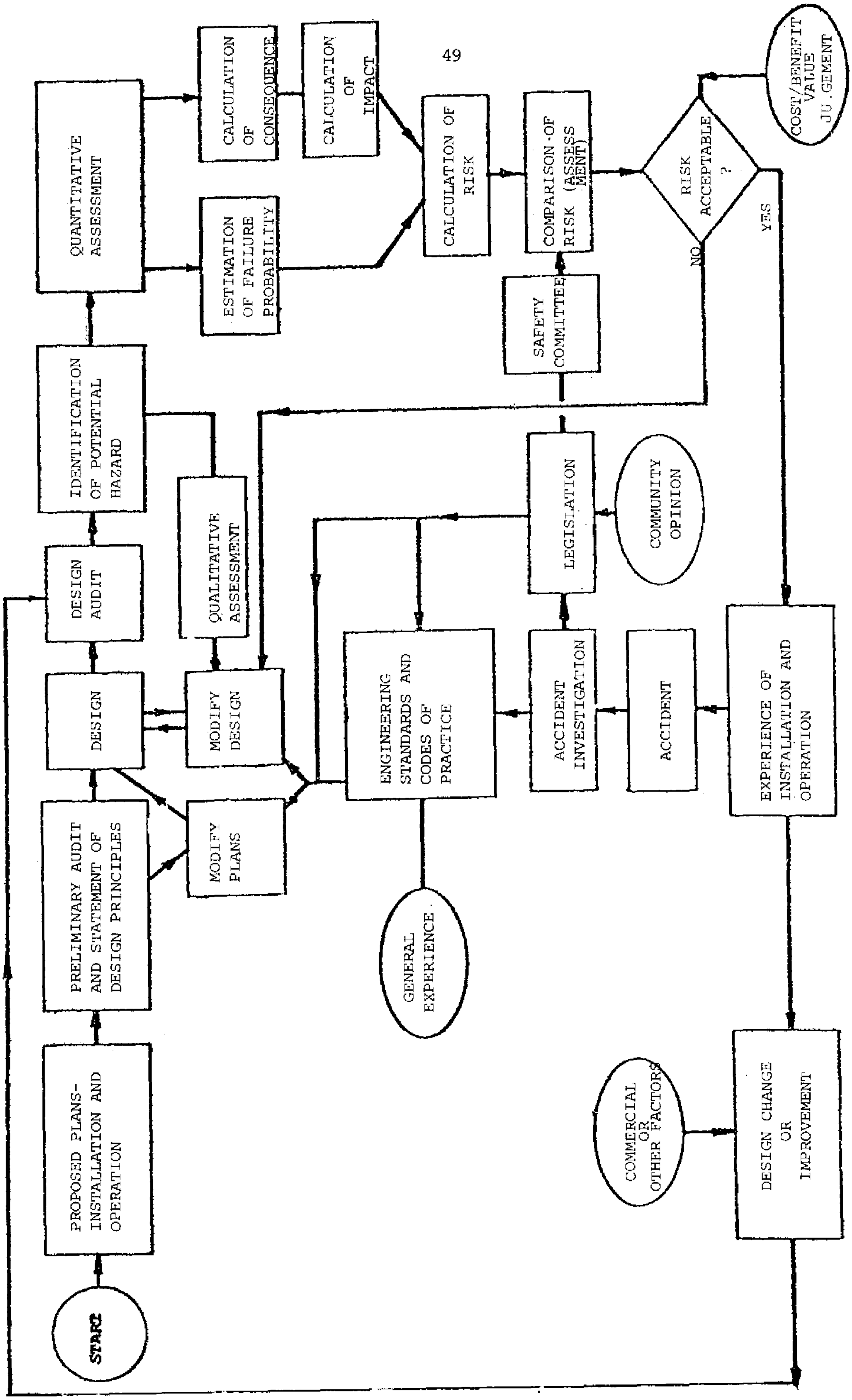

FIGURE 2 : HAZARD ASSESSMENT IN PERSPECTIVE

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