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Invited Viewpoint

Major hazards in the process industries: Achievements and challenges in loss prevention*

H.J. Pasman

TNO Prins Maurits Laboratory, Netherlands Organization for Applied Scientific Research, P.O. Box 45, 2280 AA Rijswijk (Netherlands)

H.A. Duxbury

ICI Engineering, Brunner House, P.O. Box 7, Winnington Northwich, Cheshire CW8 4D3, and Department of Chemical Engineering, Loughborough University, Loughborough, Leicestershire LE11 3TU (Great Britain)

and

E.N. Bjordal

Norsk Hydro Research Center, P.O. Box 2560, 3901 Porsgrunn (Norway)

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Abstract

In 1991 it is twenty years since the European Federation of Chemical Engineering (EFCE) Working Party (WP) on Loss Prevention (LP) in the Process Industries, of which the authors are all members, was initiated. It is therefore worthwhile to look back and also to look forward to what we can expect to come. For this paper we were asked to focus on the evolution of process safety, particularly as it occurred in the U.K. and The Netherlands.

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1. Process industry, hazards, risks, safety and loss prevention

Spills and mishaps with hazardous materials as a result of accidents at industrial facilities do occur, sometimes leading to incidents such as large fires, explosions (Fig. 1), generation of toxic smoke, dispersion of toxic vapours, and

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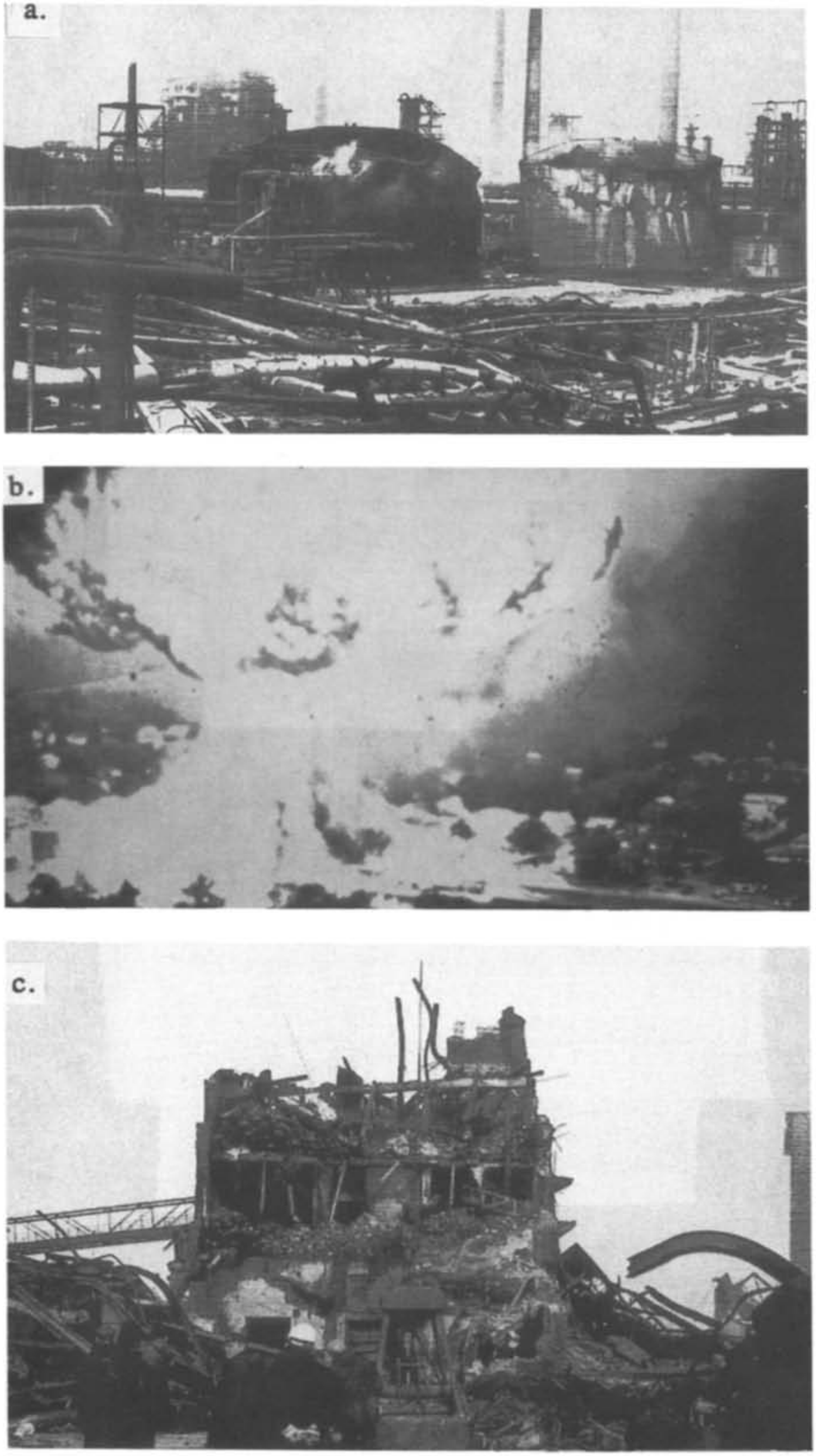

Fig. 1. Pictures of industrial explosion damage. (a) Pernis, The Netherlands, 1968, VCE of hydrocarbons from slops tank, roughly 40 ton TNT eq., (b) Crescent City, USA 1970, BLEVE of propane tank cars, and (c) dust explosion Roland-Mühle, Bremen, 1979.

ecological impact. Industrial facilities here includes processing plant, storage facilities, and the transportation system (vessel/barge/harbour sites, railway yards, road tankers, pipe lines).

We may handle materials with properties presenting hazards. In a situation in which actions occur their presence may become a danger. When by some cause containment is lost, integrity of life, health, equipment or the environment may be threatened. So, we create *risks* in producing and bringing these materials together in (large) quantities. Risk contains the elements *extent of damage* and *probability of realization*. The latter refers both to the probability of the causing event and to that of the damage.

Safety is the complex of human actions intended to prevent the unwanted events from happening. Perfect safe operation is part of the ultimate in skill or craftsmanship. The avoidance of exposure of humans to risks has ethical and legal grounds. In addition there are strong economic reasons.

Loss Prevention, originally an American expression, is concerned with the unwanted event and the damage if it should happen. Quoting the former Secretary of the Working Party, Dr. Bond [1], Loss Prevention is thus a pro-active, systematic approach to preventing accidents and their consequences to people, equipment and environment, and incorporates safety, occupational health and environmental issues. He also formulated three Laws of Loss Prevention:

1. *"He who ignores the past is condemned to repeat it"* or in plain Dutch: Even a donkey does not hit itself twice on the same stone,

2. *"Success in preventing loss is in anticipating the future"*, so think before you start, and finally:

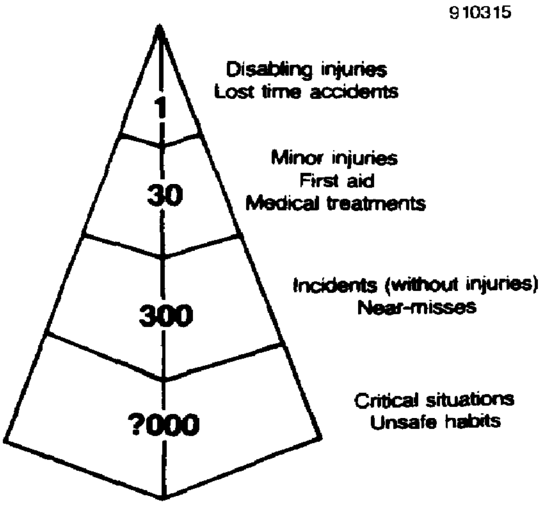

Fig. 2. Accident/incident pyramid of ratio's serious to minor events [1].

3. "You are not in control if a loss has to occur before you measure it" with a clear reference to quantification.

For every one large accident, numerous minor ones occur, and even more unintended events which do not cause injury (near misses); still more unsafe practices may exist (Fig. 2). Large accidents are often the result of a coincidence of factors, also frequently preceded by minor defects not necessarily relevant to the main event, but distracting and at the crucial moment confusing the picture. Sometimes seemingly improbable accidents are repeated.

Typical fields of application of Loss Prevention (LP), which has both hardware and software aspects, are shown below:

- Hazards research (physics and chemistry)
- Risk analysis and assessment, cost-benefit considerations
- Safe design and engineering, plant modification, repair and demolition
- Safe operation, management, organization and communication
- Training, education and emergency planning
- Legislation and insurance aspects.

There is a relation between LP and Total Quality Management, but they are not identical.

2. Evolution of Loss Prevention over the past decades

We have witnessed large expansion and scale-up of industrial activities. At the same time with the expanding economy growing awareness and concern has developed. In Europe this really commenced in the second half of the sixties. Several disasters occurred at this time. New phenomena were recognized, for which new words had to be introduced: Vapour Cloud Explosion or VCE, Boiling Liquid Expanding Vapour Explosion or BLEVE, and Thermal Runaway of chemical reactors. Governmental authorities responded e.g.:

- UK: Robens Committee Report 1972, founding of Health & Safety Executive,
- The Netherlands (NL): Committee for Prevention of Industrial Disasters, 1964.

Then after the thermal runaway of the reactor at the ICMESA plant at Seveso, Italy, in 1976, the subsequent dispersion of the hyper-poison TCDD (tetrachloro-di-benzo-*p*-dioxin) and the evacuation of the surrounding population, which caused worldwide attention, the European Community (EC) reacted in 1982 with the post-Seveso Directive [2]. This Directive required the reporting of serious accidents and introduced a requirement for notification and the drafting of a safety report on industrial installations containing over certain threshold quantities of hazardous materials. Meanwhile it has been amended twice and extended and also nationally implemented (Germany Störfallverordnung 1980; UK Notification of Installations handling Hazardous Substances Regulations NIHHS 1982 and Control of Industrial Major Accident Hazards Regulations CIMAH 1984; NL Besluit Risico's Zware Ongevallen 1988).

The world of chemical engineers in Europe unified to exchange experiences and views to avoid future mistakes, at first only nationally. The series of symposia on this subject in the UK, Hazards I, II etc., started in 1960; this year Hazards XI took place. In The Netherlands there were symposia on safety matters in 1963 and 1969, the latter with foreign lecturers. In 1978/79 in Germany DECHEMA investigated the Fachausschuss "Gas- und Flammen-reaktionen" to split off the Fachausschuss "Sicherheitstechnik in Chemieanlagen", presently under chairmanship of Dr. V. Pilz. An interesting account of 90 years of German industrial safety and technical surveillance is given by him in [3].

In 1971 the first symposium of international stature was organized by the Institution of Chemical Engineers in Newcastle, UK. An excellent symposium [4], the proceedings are worth rereading. There a small group of LP-engineers joined together under the leadership of T.A. Kantyka. Under the aegis of EFCE this became the present Working Party. Every three years an international symposium has been organized (Table 1). The programme has always given priority to case histories and in general to exchange of information based on facts rather than academic considerations.

In the second half of the seventies the Risk Analysis debate started: In the beginning a Babylonic language confusion. Later a heated discussion focussed on what quantification is worth with definite pro's and con's. The concept of Quantified Risk Analysis (QRA) was taken from the nuclear energy industry: The Rasmussen report [5]. The Three Mile Island reactor accident in 1979 in the U.S. led to increased discussion and some voices at the Basel symposium in 1980, claiming the concept to be impractical, because of the Human Factor, were strong. In the years that followed, the EFCE Working Party (WP) had a Study Group working on the subject and in various countries pilot studies were done like the Dutch COVO study [6], the English Canvey Island report [7] etc. Surprisingly, in the Scandinavian countries there was much support for the idea from the start. In the Netherlands Quantified Risk Analysis became the basis for the External Safety Report [8].

TABLE 1

EFCE Working Party on Loss Prevention first committee meeting late 1971, at Symposium in Newcastle, UK

Symposia			
Delft	1974	Cannes	1986
Heidelberg	1977	Oslo	1989
Basel	1980	Taormina, Sicily	1992
Harrogate	1983		

In the U.S. the American Institute of Chemical Engineers (AIChE) started to organize the Loss Prevention Symposia about 1960. (The EFCE WP LP has always liaised with AIChE through two common members.) Also the Chemical Manufacturers' Association was active early on. In the seventies the Department of Transportation and the Department of energy became involved by initiatives of the U.S. Coast Guard to study the safety of transportation and storage of Liquid Natural Gas, ammonia and other bulk chemical shipments to U.S. ports. Vapour cloud dispersion and explosion experiments and studies were undertaken. Large oil companies like Exxon and Shell stepped in, while universities performed modelling research. However, the thrust died away and it was only after the Bhopal methyl-isocyanate disaster in India in 1984 with a death toll of 2500 that the U.S. Congress and Environmental Protection Agency came into action, and AIChE with the support of the industry founded the Center for Chemical Process Safety (CCPS) in New York in 1986. With only a small permanent staff CCPS organizes symposia and courses, and issues guidelines. The guidelines are usually prepared by expert organizations under contract. This work is monitored by project committees, of which the members are drawn from the subscribing companies. Some valuable guidelines are available, others are in the pipeline.

Worldwide interest in Loss Prevention has continued to grow. In the past industry had already cooperated in safety matters like the ammonia and fertilizer industry (EFMA or European Fertilizer Manufacturers' Association, successor to ISMA/APEIA), the Chlorine Institute, and after the U.K. Flixborough explosion in 1974 the Hydrocarbons Oxidation Study Group, later expanded into the International Process Safety Group. Also the International Section of the ISSA (International Social Security Association) for the Prevention of Risks in the Chemical Industry had organized conferences, while over the years much had been going on in hazardous materials transport safety issues. However, after the Mexico City LPG accident and Bhopal, bodies like the Organisation for Economic Cooperation and Development (OECD), the United Nations organisations UNEP and UNIDO, the World Bank and the International Union of Pure and Applied Chemistry (IUPAC) became active in sponsoring meetings, the latter with a special focus on developing countries. In Australia, Singapore and Japan Loss Prevention groups are being formed.

Meanwhile in Europe and elsewhere safety consultant firms are fast proliferating. Apart from this sign that the field is becoming mature there are such phenomena as the appearance of monographs on Accident Investigation [9] and the establishment of specialized journals. The Institution of Chemical Engineers (IChemE) has issued the Loss Prevention Bulletin since 1975. This is basically a case history information exchange scheme. From later date are the professional journals like the Journal of Hazardous Materials (September 1975) and the safety issues of Plant/Operations Progress. Recently there is the Journal of Loss Prevention in the Process Industry, the French Préventique, prévention et gestion du risque, and from the Institution of Chemical Engineers, the IChemE Environmental Protection Bulletin and "Process Safety and Environmental Protection - Trans IChemE, Part B". IChemE also issues training

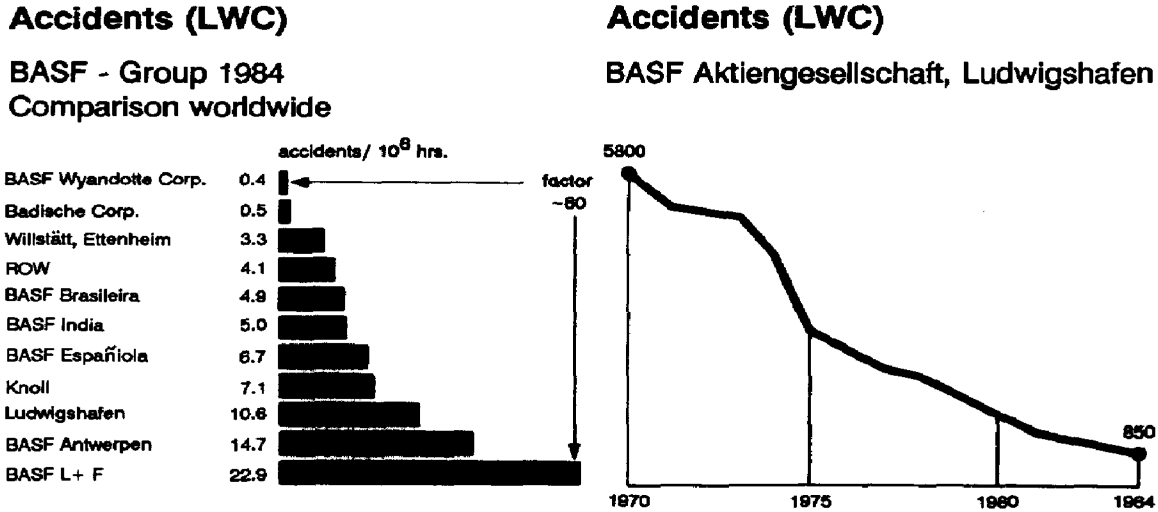

Fig. 3. International accident statistics comparison and annual downward trend [10]; differences between countries should be considered with some reservation, since the unit (LWC = Lost Workday Case) is subject to local influences.

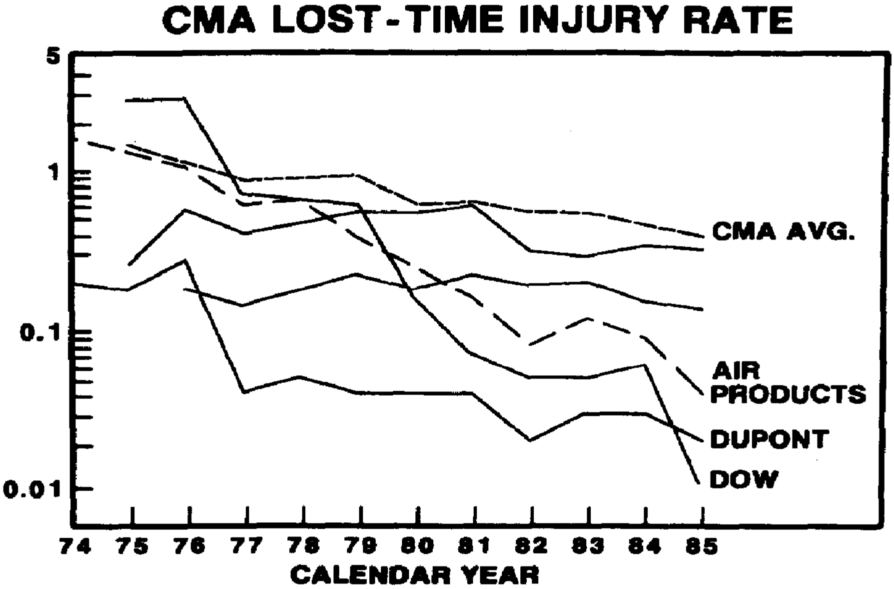

Fig. 4. Trends in American chemical process industry accidents statistics [11]; Lost-time injury rate is the percentage of workers in the corporation who suffered in a given year an injury so severe that it caused the worker to miss some workdays (CMA = Chemical Manufacturers' Association).

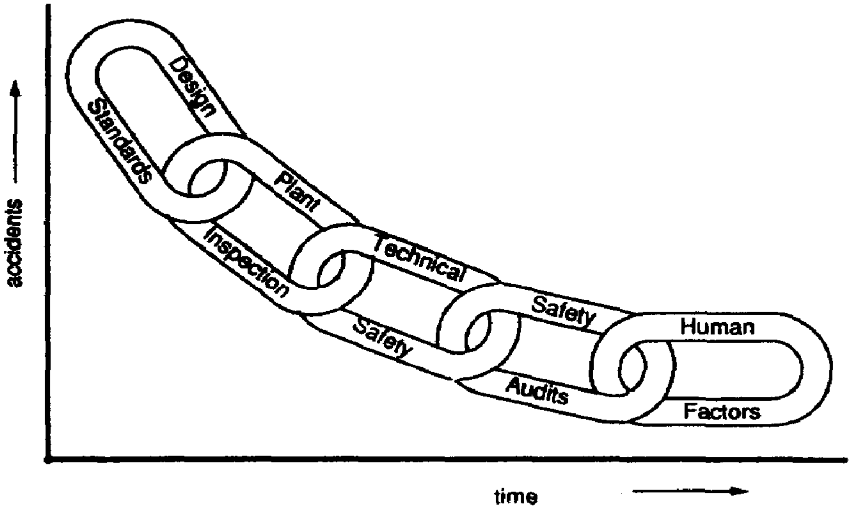

Fig. 5. History of aspects sequentially emphasized to improve safety, after Bond [1].

packages of interactive training using video, computer-based, slide and open-learning techniques [60]. Subjects include Handling Emergencies, Safer Piping, Work Permit Systems, Human Error, Safe Handling of LPG, Controlling Electrostatic Hazards, etc.

Accident statistics for the process industry show a continuously downward trend. For a long time there has been discussion on why the safest U.S. companies have roughly an order of magnitude less Lost Time Accidents than European ones. Even U.S. subsidiaries in Europe or European subsidiaries in the U.S. have been shown to be better, e.g. according to Joschek's welcome address to the Working Party's 5th Symposium [10], Fig. 3. Earlier recognition by management of the importance of safety is certainly a contributing factor. As can be seen from more recent data [11] as a whole there is steady improvement with figures approaching zero, Fig. 4; see also Fig. 5 which elucidates the trend.

There are new challenges: Modernization of process and plant with new materials, new components, new unknowns: Tougher physical conditions in some instances and in any case tougher financial constraints, more automation in control: How to efficiently transfer experience to new generations of engineers. Outside the plant the public, the media and the Government have ever-increasing expectations with respect to the environmental impact of chemical plants, e.g. smells and waste disposal. They also expect possible accident scenarios to have been considered and emergency plans drawn up.

3. Achievements in Loss Prevention

3.1 General

Safety engineering has become a full grown discipline of its own, with sub-specialisms, risk analysis methodology, standards and codes of practice.

Major research programmes have been undertaken and continue to be carried out: In the U.S. in the seventies the U.S. Coast Guard undertook major programs. An international Industry initiative started in 1976 led to the formation in 1978 of the AIChE Design Institute for Emergency Relief Systems (DIERS), which was cooperatively funded by companies, and which between 1978 and 1985 developed methods to design vents for chemical reactors. Users clubs are still active. After 1985 CCPS had initiated research and coordinated efforts, e.g. CCPS (AIChE's Center for Chemical Process Safety) administers the International Vapour Cloud Research Committee for the exchange of information in this field.

In Europe the Council of the European Community funded through DG XII common research programmes like the one on Major Technological Hazards in STEP (Science and Technology for Environmental Protection). The well known Thorney Island heavy gas dispersion trials cosponsored by Industry and managed by the U.K. Health and Safety Executive were carried out. There has also been the national and multinational research on dust explosions, vapour clouds, human factors, etc.

In the following a condensed survey of the state-of-the-art will be given.

3.2 Hazards research

3.2.1 Material properties and test methods

In particular condensed materials are considered here. Progress has been steady. This is reflected by the UN schemes as in Fig. 6 for classifying hazardous material [12]. The methods are far from perfect but taken together they provide a picture so that surprises like a soap constituent being as detonable as TNT or an organic peroxide deflagrating faster than a porous propellant, no longer go by undetected. The limits, however, are still hard to establish: What is the effect of confinement and of venting, and what is the critical diameter below which no reaction is possible, and therefore what containment is adequate or what packaged size can be allowed? What is the effect of grain size and porosity, what of ageing or of moisture and oxygen? Liquids show their own specific characteristics. Hence, for a quantitative prediction more has to be learned. This is also true for thermal reaction hazards in storage, in layers of residues, or settled dust, with contaminants playing an important role.

3.2.2 Spills and vapour clouds

In the last 10 to 15 years at universities, institutes and companies a tremendous amount of work has been carried out to model free jet and two phase flow, liquid pool spreading, evaporation of volatile, sometimes cryogenic liquids from soil and water surfaces and heavy gas cloud formation. Besides a long list of hydrocarbons there are chlorine, ammonia and hydrofluoric acid, the latter with quite complicated thermo-dynamics [13]. So, it is a matter of (highly)

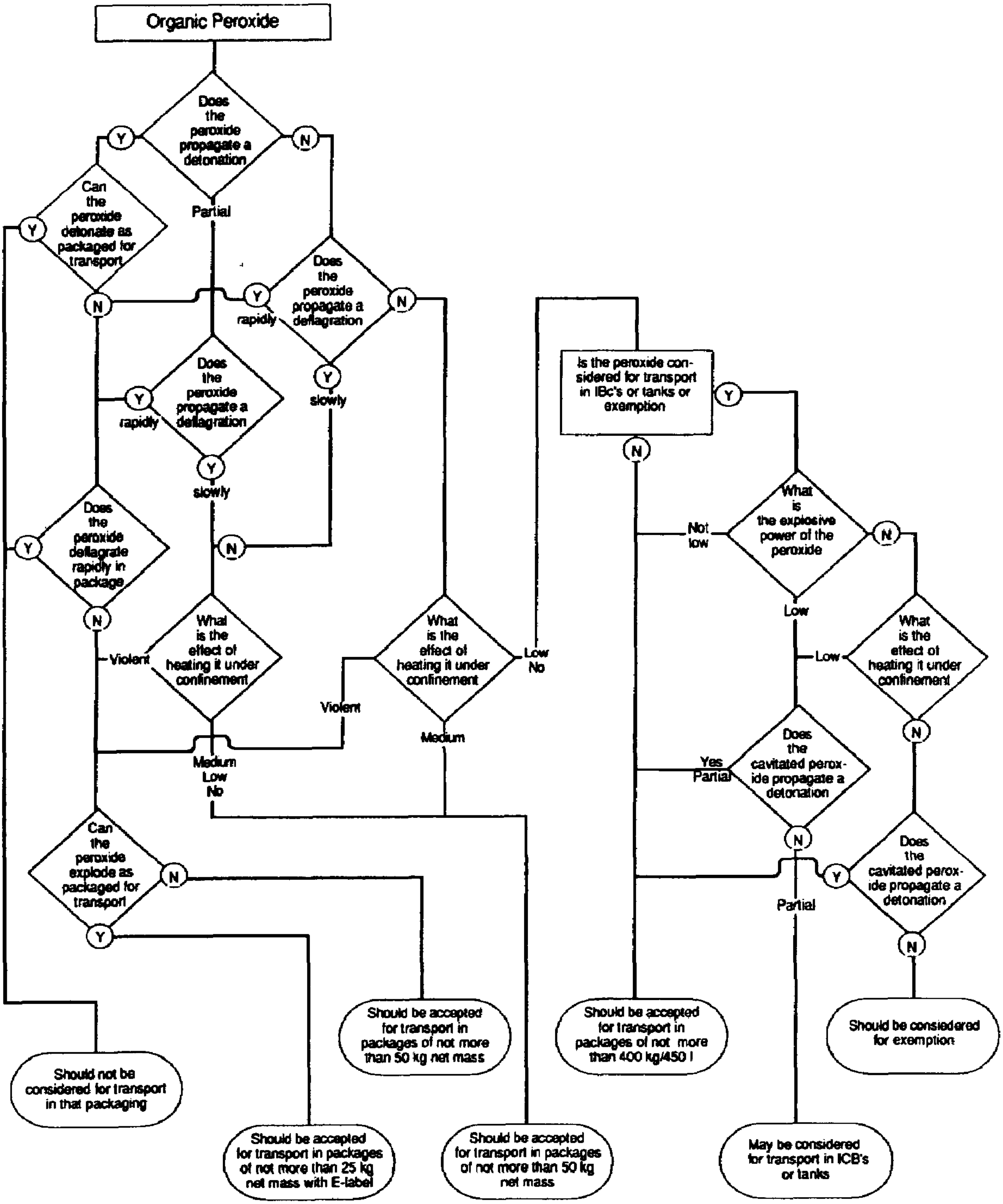

Fig. 6. UN Hazardous materials Classification flow-chart for organic peroxydes [12].

dynamic processes of dispersion from a source that is neither instantaneous nor continuous.

The Dutch, so-called "Yellow Book" [14] was in the forefront, when it was compiled by TNO in 1978. Since then many improvements have been made. Both in the U.S. and in Europe vapour cloud dispersion field trials have been organized. When it comes to normal meteorological conditions and flat terrain

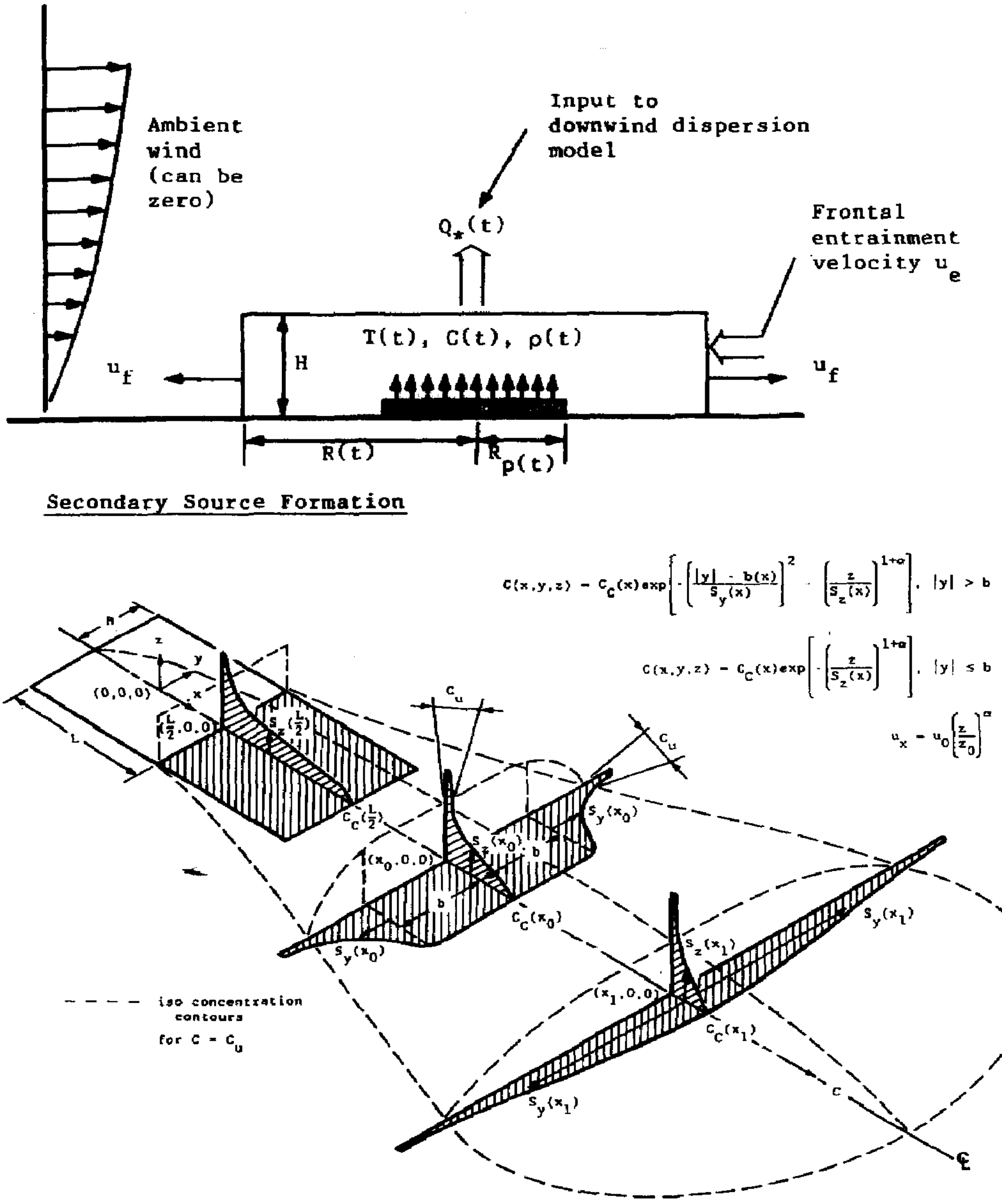

Fig. 7. Schematic diagram of DEGADIS denser-than-air gas dispersion model, after Spicer and Havens [15].

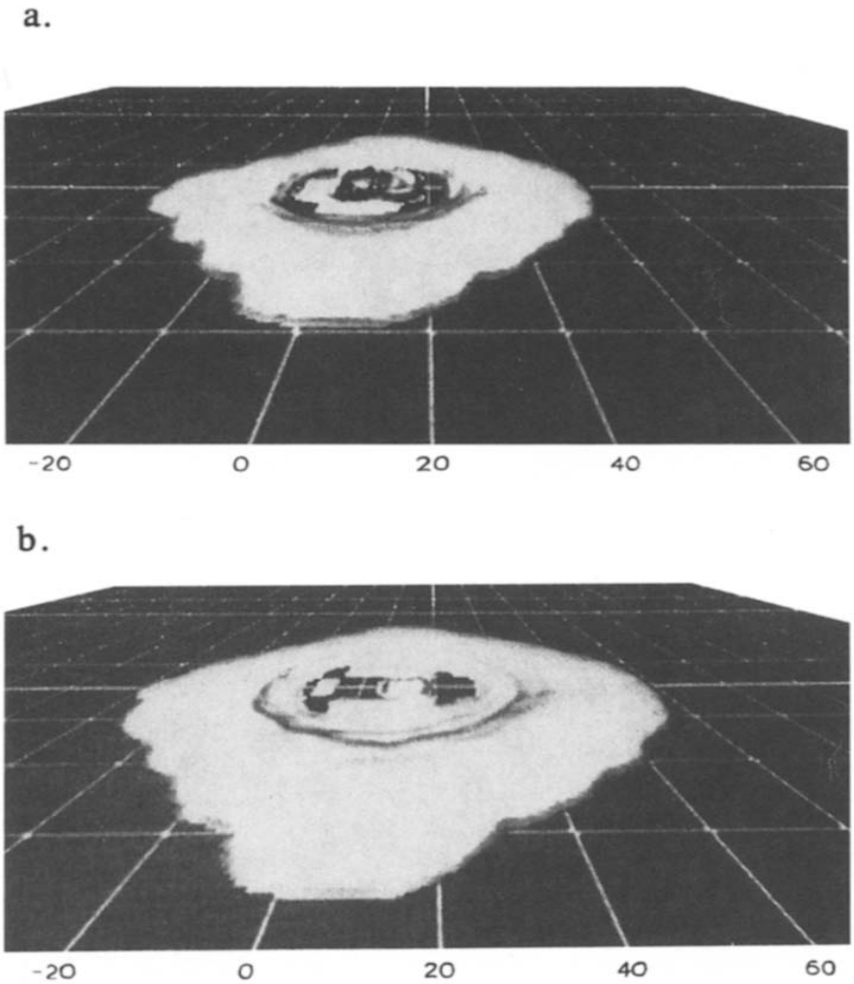

Fig. 8. Pictorial views of the 1% concentration cloud surface for Thorney Island Trial No. 9 as calculated with the three-dimensional computer model FEM3, after Chan et al. [15]. (a) Time = 20 s, and (b) time = 30 s.

without buildings, tree lines and such like, then in the case of a-well defined source the cloud contours and mean concentration profiles can be predicted reasonably well with "calibrated" semi-empirical models (see [15], and Figs. 7 and 8). However, for more reliable near-field effect calculations in case of an explosion, or the far field effects of highly toxic vapours, when concentration fluctuations and meandering are important, more powerful means are necessary.

The capability of more realistic modelling of the so called source terms e.g. of the breaking of a free jet against near-by objects, seems a high pay-off area. Turbulence modelling, and flow around obstacles and on slopes are other challenges. One can expect therefore that for the future all possibilities of computational fluid dynamics with 3-D models will be utilized to make further progress. A better insight might help to improve practices of operation, to prevent damage by better lay-out of plant, better design of control rooms and more effective mitigation/dispersal techniques.

3.2.3 Vapour cloud, gas and dust explosions

Although often brought under one heading, the research on the notorious explosions of vapour clouds (VCE) in the open air has been by an approach, that differed completely from that of flammable gas and dust explosions inside equipment.

The starting point for the VCE-work to estimate the effects was to assume a detonation of a hemispherical cloud. This leads to exaggeration. In practice mostly a flashfire occurs without significant blast, although there are cases with awesome blast effects and a very few cases in which a detonation may have occurred. (Port Hudson, Franklin County, MO, U.S.A., Dec. 1970: Liquid Propane Pipeline fracture. Similarly but on much larger scale, 2–3 kton TNT eq.: Ufa, Ural, U.S.S.R., June 1989, 575 killed.)

The first five years of experiments with balloons far out in the desert re-

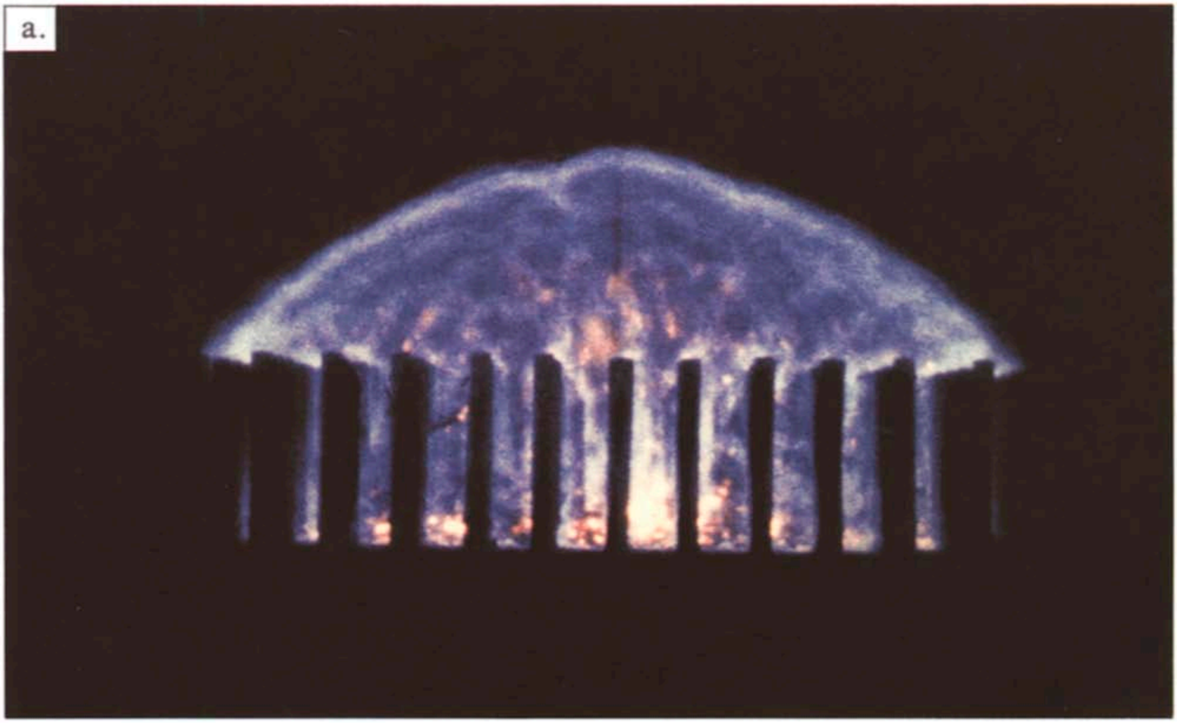

Fig. 9. Vapour cloud explosion experiments at various scales. (a) Side-view of a flame propagating over a ground plane with vertical obstacles (obstacle diam. 0.018 m) [16], 1980; (b) intermediate scale; horizontal obstacle (diam. 0.1 m) [16], 1983; (c) vertical obstacles diam. 0.08 m, in hemi-circular array, semi confined; top view [56], 1987; (d) field trial set up with vertical obstacles (diam. 0.5 m), geometry as in (c) [57], 1990; (e) field trial in semi confined, vertical obstacles (diam. 1 m), rectangular array [16], 1982.

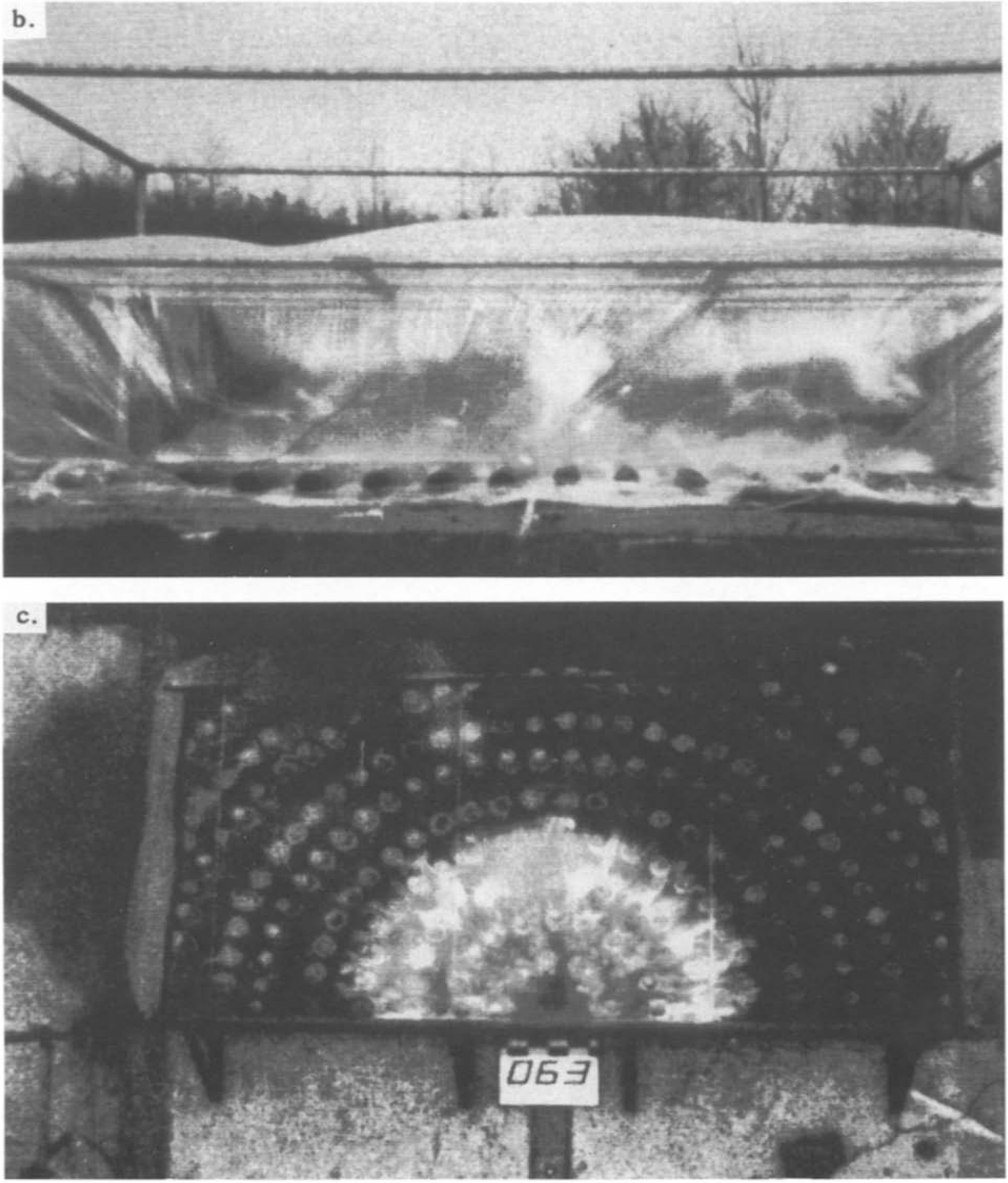

Fig. 9. (Continued).

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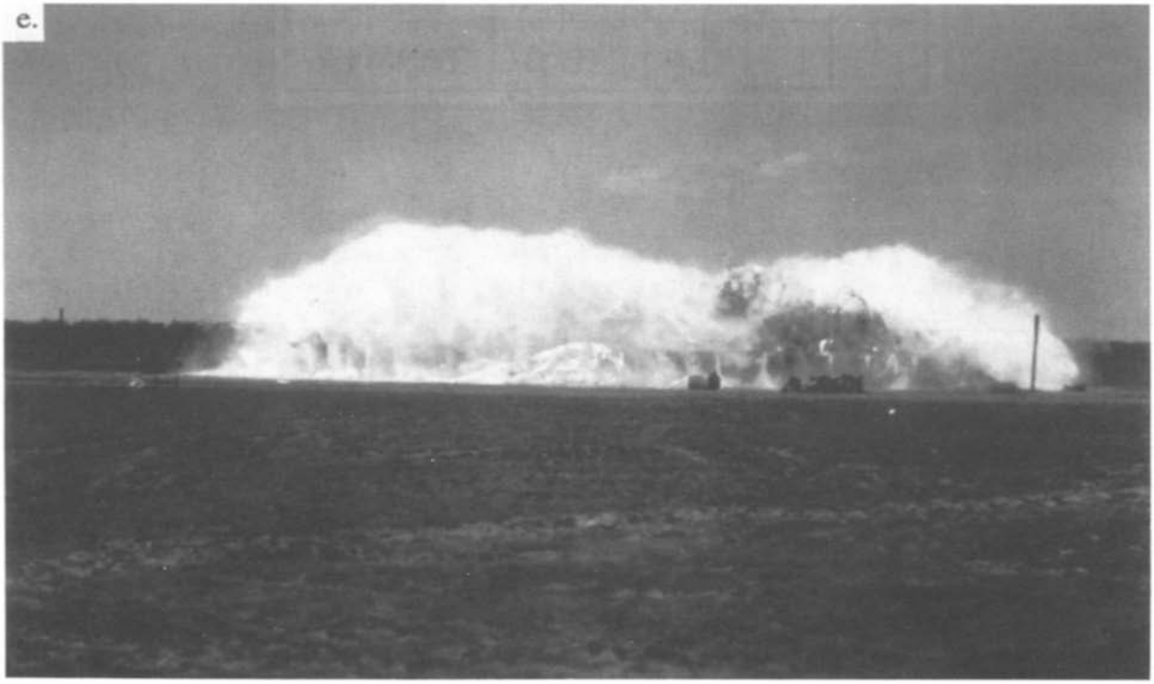


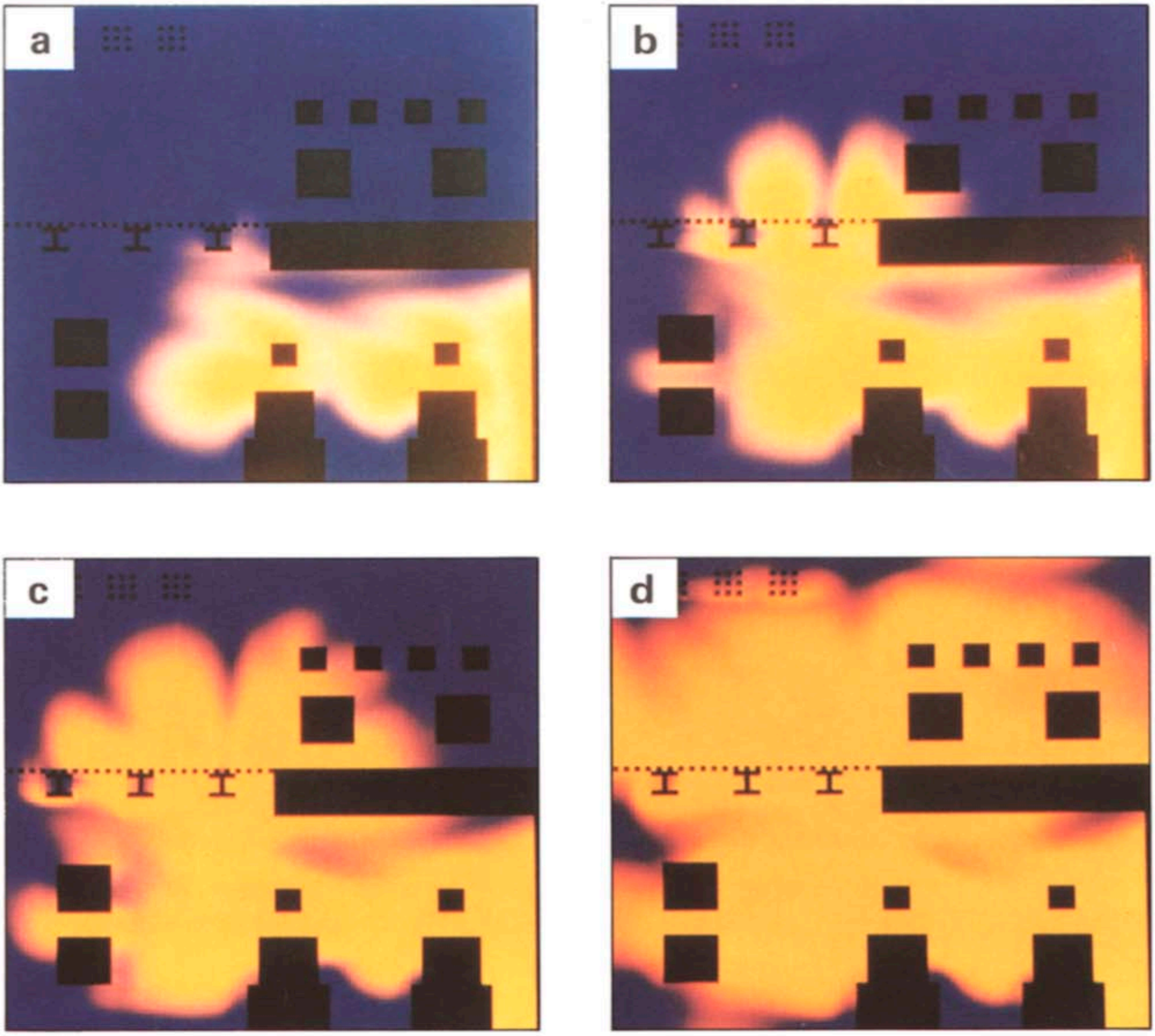
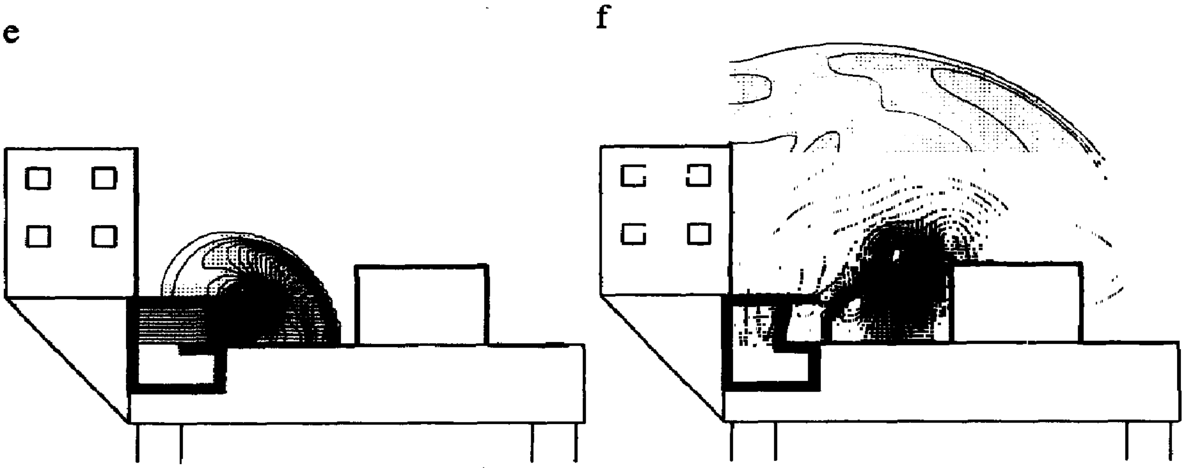


Fig. 10. (a) to (f): Based on experiments TNO developed a 3-D reactive gas dynamics code REAGAS and a 3-D BLAST code. Shown are examples of 2-D computations of flame propagation in a two-floor cubicle type building e.g. simulating a compressor module on an off-shore platform with tanks, pipe racks and a partially grated floor. Ignition of a stoechiometric mix is at time=0 s in the lower right corner. The flame contours at 0.18, 0.19, 0.195 and 0.20 s are shown in (a)-(d). Note the rapid growth of the flame after a slow start. (e) and (f): The upper right wall of the compressor module fails after which a blast wave moves outwards and reflects against deck-houses (e,f). The pressure-time profiles of calculated blasts have been experimentally validated. (e) Time=0.0232 s, blast rate 556 m/s; and (f) time=0.0941 s, blast rate 404 m/s.

vealed that when the gas was ignited by a spark or a flame no blast was produced. It was only with initiation by high explosive that blast was generated. On the other hand theoretical models indicated that the build-up of a shock wave ahead of the flame depended strongly on the flame propagation velocity.



It was known and confirmed that flame acceleration is induced by turbulence in the gas ahead of the flame. This turbulence can be generated by the flame itself when it pushes unburnt gas through (congested plant) areas with obstacles to the flow (Figs. 9a–e). There appeared to be the possibility of scaling the phenomena at least for the initial stages from laboratory size to conditions in practice [16]. Also reactivity could be scaled on the basis of laminar flame velocity. The crude TNT blast equivalency model can now be replaced by a model such as the Multi-Energy Method [17], which is able to estimate the blast profile more realistically from contributions of violently exploding parts of the cloud (A guideline for the rating of violence and estimating the corresponding cloud volume will be derived in a near future project). For an even more refined picture as e.g. for detailed design work 3-D computational fluid dynamics models become available for calculation of gas dispersion, flame propagation and blast (Figs. 10a–f).

Gas and dust explosions inside vessels have been studied here in Germany and elsewhere. A famous name is Bartknecht [18]. By hard, thorough work based on the cubic law which relates the rate of pressure rise to the cube root of the volume of a vessel:

$$(\mathrm{d}p/\mathrm{d}t)_{\max}\sqrt[3]{V}=K,$$

and hazard classification in fixed ranges of K-values, a wealth of empirical knowledge has been created. Subsequent work in the U.K., sponsored by Industry and the Health & Safety Executive, and carried out by the British Materials Handling Board (BMHB), has led to much improved advice on the effect of duct length and layout. Design advice based on this and on the work by Bartknecht and others has been published by the Institution of Chemical Engineers [19–21]. Further work by the BMHB on "pressure piling", the self-"pumping" of connected vessels caused by precompression when the flame passes from one vessel to the other, leading to a more vigorous explosion by

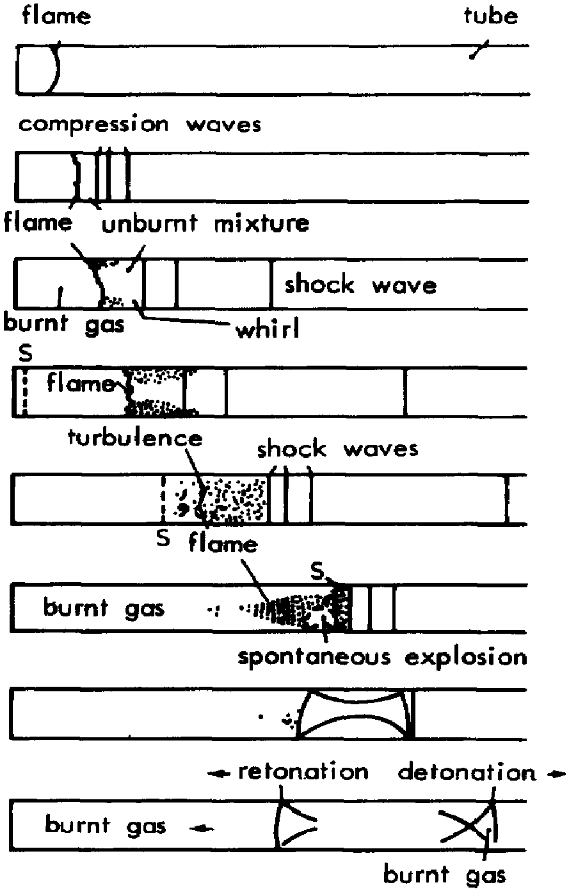


Fig. 11. Sequence (schematically) of running up to detonation of a flame propagating in a fuel/air mixture in a pipe closed at one end and ignited near the closure [22]. The rougher the tube wall the earlier the transition.

both flame jet ignition and a higher final pressure is in hand. Particular effects such as the self-strengthening effect of dust explosions when the flame whirls up settled dust, the explosions of aerosols, the effect of coupling and feeding of a flame at a tube wall covered with a combustible material, and the acoustic and Taylor instabilities during explosion venting causing pressure spikes, have been recognized. Work has also been done on the running up to detonation in e.g. a pipe (Fig. 11) for which e.g. the work of Wagner and co-workers can be quoted [22].

The determination of the relative reactivity of fuels and dusts has been developed in terms of ignition sensitivity and combustion pressure in a closed vessel. (The one cubic metre vessel or the 20-litre sphere). This stimulated work on static electricity, in particular with a view on pneumatic transport and silo storage.

A long list of preventive and protective countermeasures has been established: flame traps, quenching, compartmentization, isolation by rotary valves, venting, pressure tight equipment, inerting. Also VDI- and ISO-norms were developed (guideline ignition sensitivity dust/air [23], and ISO 6184/3 Explosion Protection Systems, 1st ed. 1985). However, much of the work has been empirical. Now is the time to step back and with the tools available do some more fundamental work. More refined designs, taking account of location and strength of ignition, geometry of equipment, turbulence conditions etc. could be made.

3.2.4 Thermal runaway of reactors

The self heating process that could lead to overpressurization and failure of a reactor is reasonably understood. Undue delay in start of reaction by too cold a mixture, stratification, a sudden lack of cooling, or faulty control of temperature may cause runaway. After the relief device opens the generation of bubbles within the liquid (by flashing, or as non-condensable gas) causes the liquid level to rise ("swell"), usually to the top of the reactor so that two-phase flow occurs in the vent. Methods for assessing whether this will happen, and for determining the required size of relief system have been developed by DIERS (referred to in Section 3.1; for the Users Group see [24]). It is very important to measure the heat generation rate in truly adiabatic test equipment, and apparatus like the Vent Sizing Package [25] is available for this. For vent sizing it is necessary to distinguish between systems in which the pressure is simply the vapour pressure, those which generate non-condensable gas, and hybrids [26]. New methods for calculating two-phase flashing choked flows have also been proposed [27].

It should be borne in mind that due to the temperature increase a change in reaction pattern to an even more exothermic and violent (e.g. decomposition) reaction may occur; an example leading to a deflagration is shown in Fig. 12. An overview of characteristic safety values for chemical processes was recently given [28]. Calorimeters to carry out reactions under programmed temperature control and simultaneous measurement of the heat effect have been successfully marketed.

Because of the difficulties in handling the relieved material, attention is now moving to means of separating the vented liquid from the gas or quenching the relieved reacting mixture, as well as to alternatives to relief. The latter include dumping the reactor contents into a quench vessel, injecting reaction stoppers into the reactor, and providing sufficiently reliable control systems to prevent the event from happening.

There is space for refinements, dealing with scaling effects and early detection of runaway. The deflagration of reactive liquid deserves more study. Generally speaking however much knowledge about process hazards has been gained and an inherently safe design has often become possible.

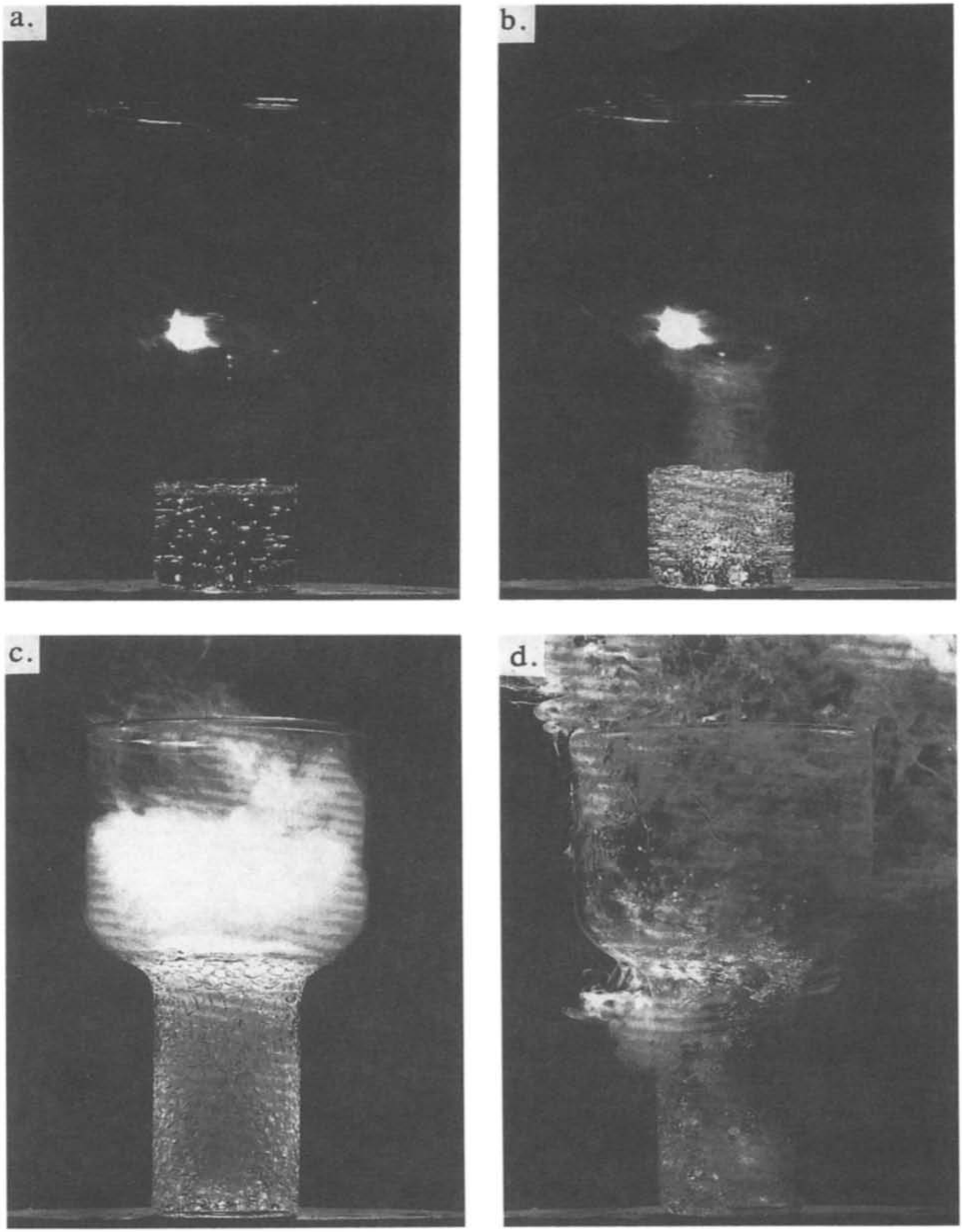


Fig. 12. Runaway and turbulent deflagration of *tert*-butylperoxybenzoate when heated in a glass beaker on a hot plate [54].

3.2.5 Toxicity issues

In accident situations acute toxicity effects are of concern rather than chronic ones, since people will be exposed suddenly and usually only for a short duration. Also the mechanism will be by inhalation, rather than orally or via the skin. Various criteria are in use. Toxic concentration and dose (TC, TD) are threshold values. Lethal concentration and dose (LC, LD) are usually the values for 50% chance of dying. The Emergency Population Exposure Limit (EPEL) would be a useful one, but there is insufficient information. The Short Term Exposure Limit (STEL) is a maximum concentration over 15 minutes which must not be exceeded. The Risk Index (RI) is proportional to the quotient of volatility and STEL. Finally the IDLH is a value that is Immediately Dangerous to Life and Health.

It is obvious that there is room here for standardization. Because of lack of data, however, one has to resort usually to LC_{50}-values derived from animal experiments. When doing this a new difficulty appears, namely how to extrapolate from rat or mouse to a human being. The approach depends on the way the toxic material affects the body: Locally or systemically. Locally acting substances cause direct damage to the lungs. Differences between animals and humans are e.g. the surface area of the lungs and the respiratory volume in time. Systemically acting substances spread via the blood over the body as a whole. For both cases body weight is used as a measure for extrapolation. Since the matter is extremely complex in detail, safety factors have to be added, causing much discussion.

Finally a conversion can be made into a Probit function. Probit is a transformation that linearizes the cumulative normal distribution (Fig. 13). The function takes the form:

$$Pr = a + b \ln c^n t,$$

in which c is the exposure concentration and t time. On the basis of the available information the values of a, b, and n are estimated. The recent Dutch "Green Book" [29] summarizes these values for 22 important chemicals. A sample is given in Table 2.

3.3 Hazard identification and risk analysis

3.3.1 Avenues of approach

The methodology of Risk Analysis has grown rapidly to what some will call a multi-headed monster. However, it became known in the late seventies from a so called fish bone chart (Fig. 14). This presented the sub-methods and the subsequent steps in an analysis for existing installations. An EFCE Study Group on RA published a report in 1985 [30].

For the design of a new process or a new plant ICI developed a sequence of

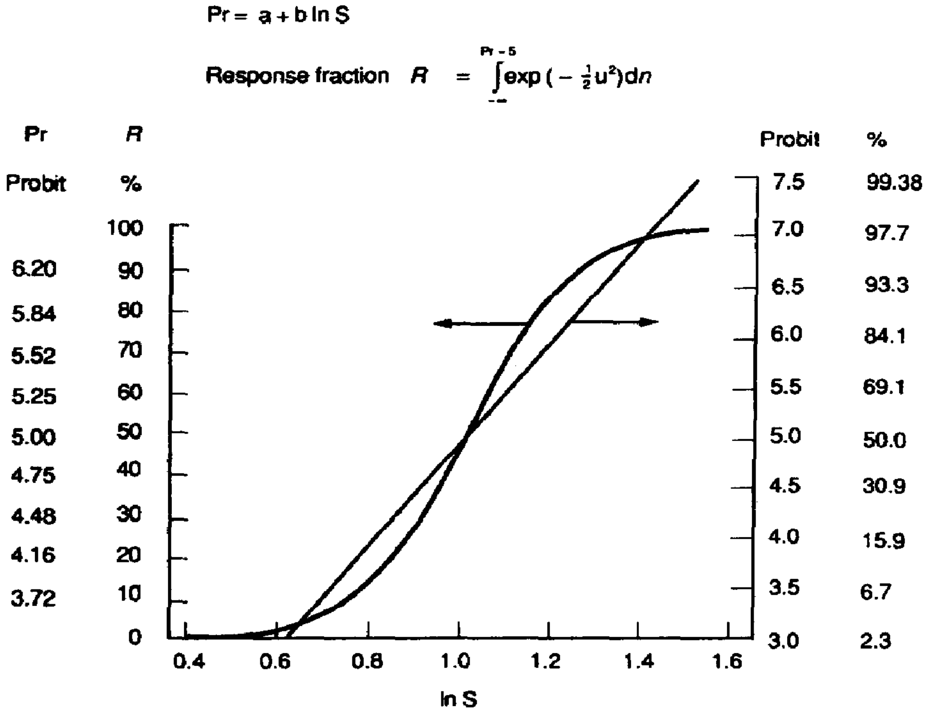


Fig. 13. Probit transformation of a normally distributed variable [29].

TABLE 2

Parameter values for acute toxicity prohibit function from [29]

Chemical	LC_{50} (30 min) (mg/m^3)	n	b	a
Ammonia	6164	2	1	−15.8
Bromine	1075	2	1	−12.4
Phosgene	14	0.9	1	−0.8
Methyl-isocyanate	57	0.7	1	−1.2
Nitrogen dioxide	235	3.7	1	−18.6
Hydrogen fluoride	802	1.5	1	−8.4
Sulphur dioxide	5784	2.4	1	−19.2

six Hazard Studies [31]. The two lines of thought will be treated below in parallel.

3.3.2 Identification of an unwanted event

The imaginative capability of a person for something that he has never experienced before, is rather limited. So we need techniques to stimulate the human mind. This can be done by a number of types of study. The different types need different data, and have different advantages. When a project is

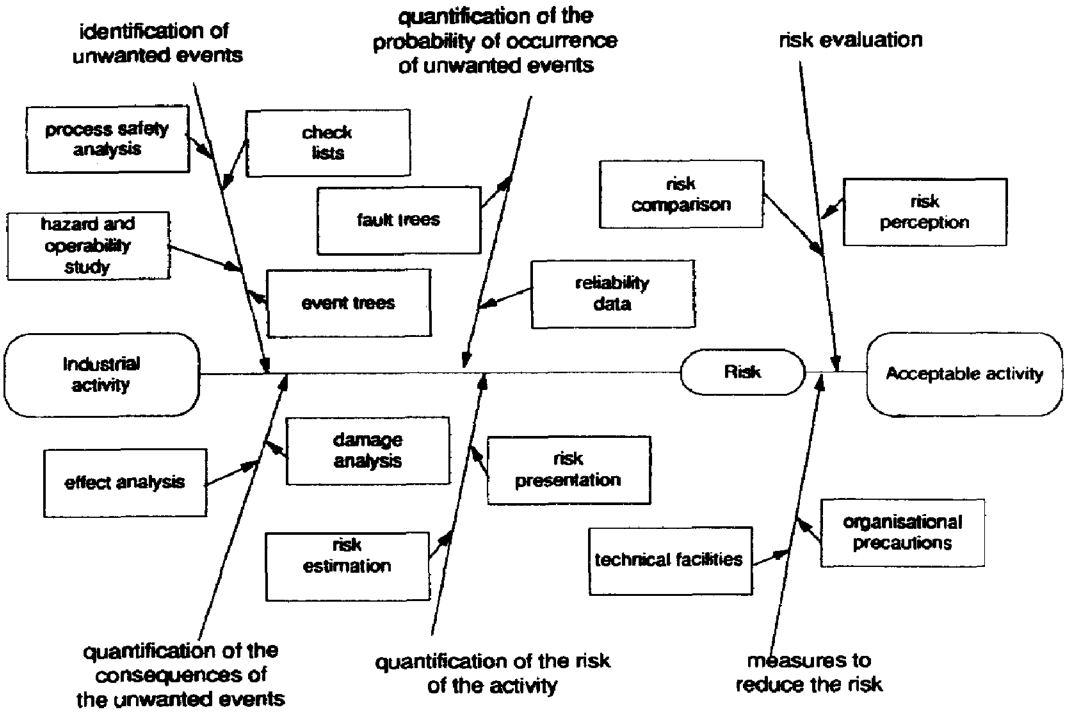


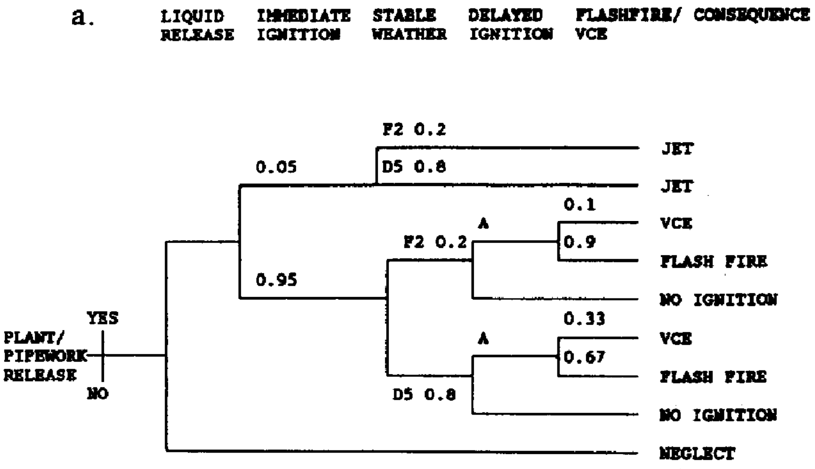
Fig. 14. Fish bone chart representing the Risk Assessment process.

first envisaged, "Hazard Study No. 1" can be done at the *exploration* stage. This makes an inventory of the hazardous properties of all materials involved and possible interactions and hence of the constraints on the project by nearby plant or population.

A process safety study supported by experiments if need be, can help to avoid risky process routes or hazardous chemical intermediates and by-products. Event data banks on accidents like the TNO FACTS [32], its Dbase III Plus PC version and SRD's MHIDAS, may be consulted. A logic diagram approach using an Event Tree (Fig. 15a) to identify possible hazard effects branching out from an "Initiating Event" may be used.

When designing a new process, a "Hazard Study No. 2", may be done at the *process and project specification* stage as soon as a process flowsheet is available, to identify significant hazards and their causes, and make any necessary design changes. For the consideration of significant hazards a logic diagram approach of a Fault Tree is recommended (see below Section 3.3.4).

When a detailed line diagram and full operating instructions are available, (i.e. at the *detail design* stage) a "Hazard Study No. 3", may be done. This study is sometimes called "HAZOP" (Hazard and Operability Study). The method, which originated in ICI [33], is known in Germany as PAAG [34]. On the basis of an engineering line diagram a team of engineers preferably of different backgrounds and led by an experienced chairman, checks systemat-



A:

Hole Size	Delayed Ignition Probability Low	Medium	High
13 mm	0.04	0.14	0.24
25 mm	0.05	0.25	0.45
50 mm	.4	.6	.8

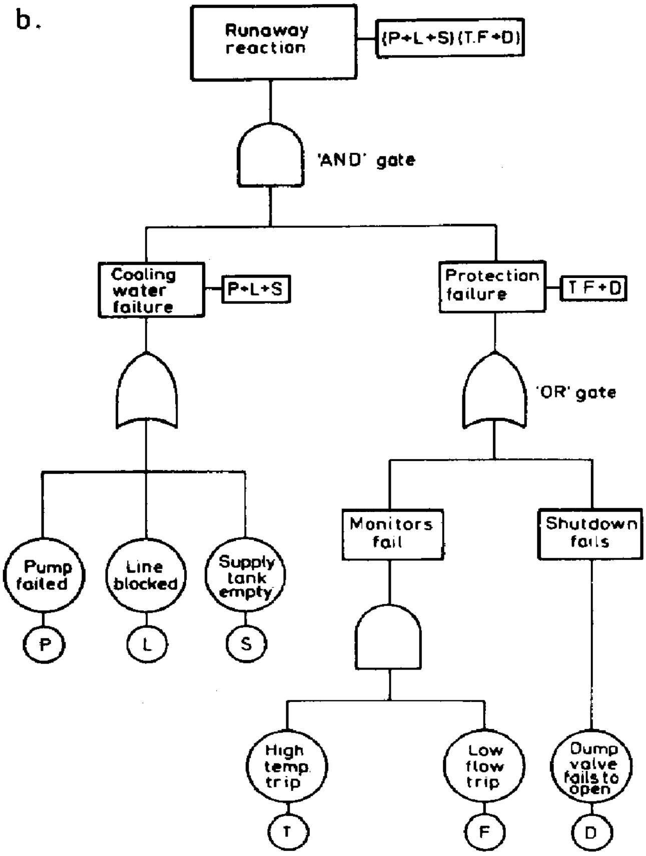


Fig. 15. (a) Plant/Pipework Event Tree in case of LPG spill, after Crosswaithe et al. [55]; the numbers refer to probabilities, Table A provides probability data for delayed ignition at various conditions of assumed hole size, F2 and D5 to weather conditions. (b) Example fault tree of reactor runaway [30]; P, L, S, T, F, D refer to probabilities of basic fault events.

ically the effect of deviations from the design conditions. This is done by using guidewords like "No", "More", "Less", "Reverse" etc. and considering the possible effects.

It is an effective check that all hazards have been identified, but as it is done at a late stage in design it is difficult to make design changes to eliminate problems, rather than add on extrinsic safety features. However, if the previous Hazard Studies have been done, little need for such changes should arise.

Other identification techniques that have been tried, are Rapid Ranking, Index methods [35,36], Cause–Consequence Analysis [37], Failure Mode and Effect Analysis [38].

When the first three Hazard Studies have been completed, it is still necessary to ensure that all the actions are done, that aspects of safety like machine guarding, access, etc. have been addressed, and finally that actual plant design and operation, after commissioning, is consistent with the design basis. This work can be formalised into "Hazard Studies Nos. 4, 5 and 6", at the *construction* and *commissioning* stages, and after *operation* has been established.

3.3.3 Consequence analysis

(This can be required as part of Hazard Study No. 2 described above.) It consists of two stages: *Effects* and *damage*. Spill, dispersion, heat radiation by fire or blast by explosion are calculated first [14] and give input to the estimation of damage in the environment e.g. on the basis of Probit functions [29,39]. In this field the concepts are quite well developed, however the advent of modern computational techniques promises further progress towards Computer Aided Design work to optimize layout and construction of installations, and provide escape routes for personnel.

3.3.4 Event probability

(This can also be required as part of Hazard Study No. 2 referred to above.) The problem is to obtain reliable information on failure probabilities and to achieve something useful within constraints of time and funds. Fault Tree Analysis (FTA) as developed for Reliability Engineering [40] helps to estimate the frequency of an unwanted "Top Event" from a logic model of failure mechanisms of a system (e.g. Fig. 15b), but does not resolve all uncertainty. In chemical processes often delays occur as in a reaction runaway, which is not simple to handle in FTA. Also there are dependent failures. Further there is the so called Human Factor, which could provide an element of great uncertainty. It is treated below.

Chemical plants are complicated, there are many components. Although data banks like the one operated by Systems Reliability Service (SRS) of the U.K. Atomic Energy Authority (UKAEA), provide information taking into account type of component and (corrosive) environment, there is still an element of judgment coming in. A number of companies have set up their own information gathering system with a view to improving inspection and maintenance schemes. Certainly in case of installment of process computers and high integrity protective control systems with redundancy and diversity, reliability considerations are essential.

In the Dutch Safety Report studies for which often a quantified risk analysis (QRA) is required, one concentrates on pipes and tanks, potentially producing the largest spills and applies generally accepted failure rate data, unless there is other evidence.

3.3.5 Human Factor

Around 1980 the "Human Factor" was claimed as a *Deus ex Machina* to prove that QRA was meaningless. In 1985 EFCE installed a Study Group under the Chairmanship of Prof. Burkardt from the Goethe University of Frankfurt. The report of the study is in print [41]. It looked at Human Factors in accidents often also appearing in incidents and analyzed these. (E.g. the technique developed in the U.S. for accident investigation MORT or Management Oversight and Risk Tree [42] can be used. Its aim is to seek problems, defects and oversights which could trigger the event or prevent its early identification. It is, however, rather time consuming.) It concludes that three classes of accidents could lead to an incident: Those where the operator tries to stay within the specified range without using controls and this proves to be too difficult; the system is sensitive to internal or external disturbances; and the operator tries to implement to a "cost" a given production schedule.

The report subsequently describes models of behaviour and how errors can arise by lack of experience, wrong learning, improper motivation and wrong attitude. It deals with ergonomics in control room design on the basis of the abilities of a human operator. An operator works only sequentially; he needs repeated information updates and can make predictions; he can compensate for an increase in difficulty by increasing his work load; he looks at the system only through an internal, mental model; and he is incapable of estimating the risks in a given situation. (An operator is no robot and also no superman.) The report derives rules of design as e.g. provide only useful info, which is not difficult to interpret and is usable for prediction; provide alarms that cannot go unnoticed; reduce the number of control actions and facilitate devising tactics and strategies; where things get difficult or hazardous to perform automate; mode and direction of action of controls should be clear and the number limited; facilitate operator-system dialogue. It further emphasizes the use of training simulators and analyses the vigilance problem. A simulator should create a realistic situation of time pressure, confusion, and emergency schedules unfolding.

The report provides techniques for *improving human behaviour* with respect to Loss Prevention (motivation, social climate and environment, personnel management, instructions (not too lengthy) and procedures (clear), avoiding stress and alcohol or drugs, adequate training, quality of provided information, discipline, checking performance). Then there is a five-step method for short term behaviour modification:

(1) Find accident concentrations
(2) Revise safety rules and working procedures
(3) Develop a plan of action
(4) Realize the plan
(5) Install efficiency controls.

Finally there are the long term solutions and the integration into overall safety efforts with an emphasis on management, communication, safety auditing and planning and training for emergencies. As regards the latter, there is nowadays PC-software available with good graphics of e.g. dispersing clouds over a plant area.

Attention of *management* to safety matters has proved to be of utmost importance and it is a major achievement of the past ten years that in many companies this has been understood. It should be no less important than production, quality, cost and personnel [10]. The Center for Chemical Process Safety of the American Institute of Chemical Engineers CCPS has published a guideline on technical management [43]. It stresses clear objectives and goals, good organization with clear limits of authority, explicit assignments of func-

Fig. 16. Individual risk contours (y^{-1}) around an installation.

tions and responsibilities. There should be a safety plan and budget with time constraints within which certain tasks have to be accomplished. Internal reviews to control and monitor progress should follow. Another key point is a good reporting system on near misses. Audits should be held regularly to see that safety procedures are being followed and that all equipment is fit for its purpose. External consultancy may be of assistance here.

Application of a computer expert system is sometimes considered to assist the operator, in particular now that smelling and direct eye contact with the installation from a somewhat remote control room are no longer possible, and for decision making time pressure can become high. Devising an expert system is, however, no sinecure.

3.3.6 *Risk presentation and perception*

Risk studies contain many uncertainties. To be clear at least about the effects on people often only lethal injuries are considered. So, the results are usually expressed in contours (isopleths) of annual probability of fatal acci-

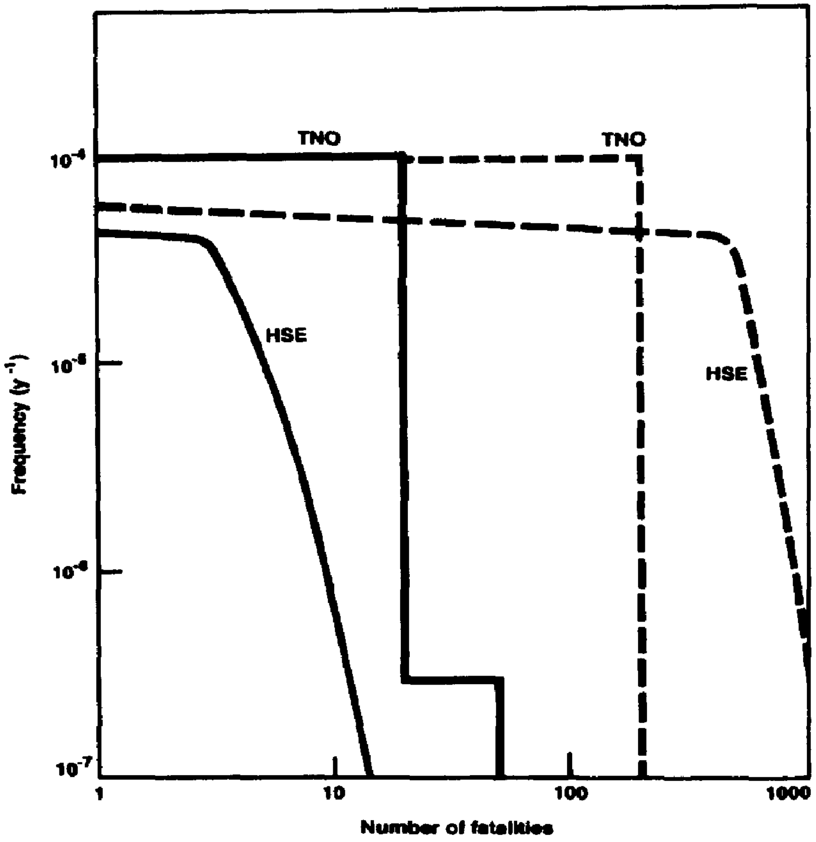


Fig. 17. Societal risk curve as the result of calculation. Example was chosen of a LPG storage tank having been subject of study first by TNO and some years later by HSE, after [55]. (—) Industrial, and (----) urban environment.

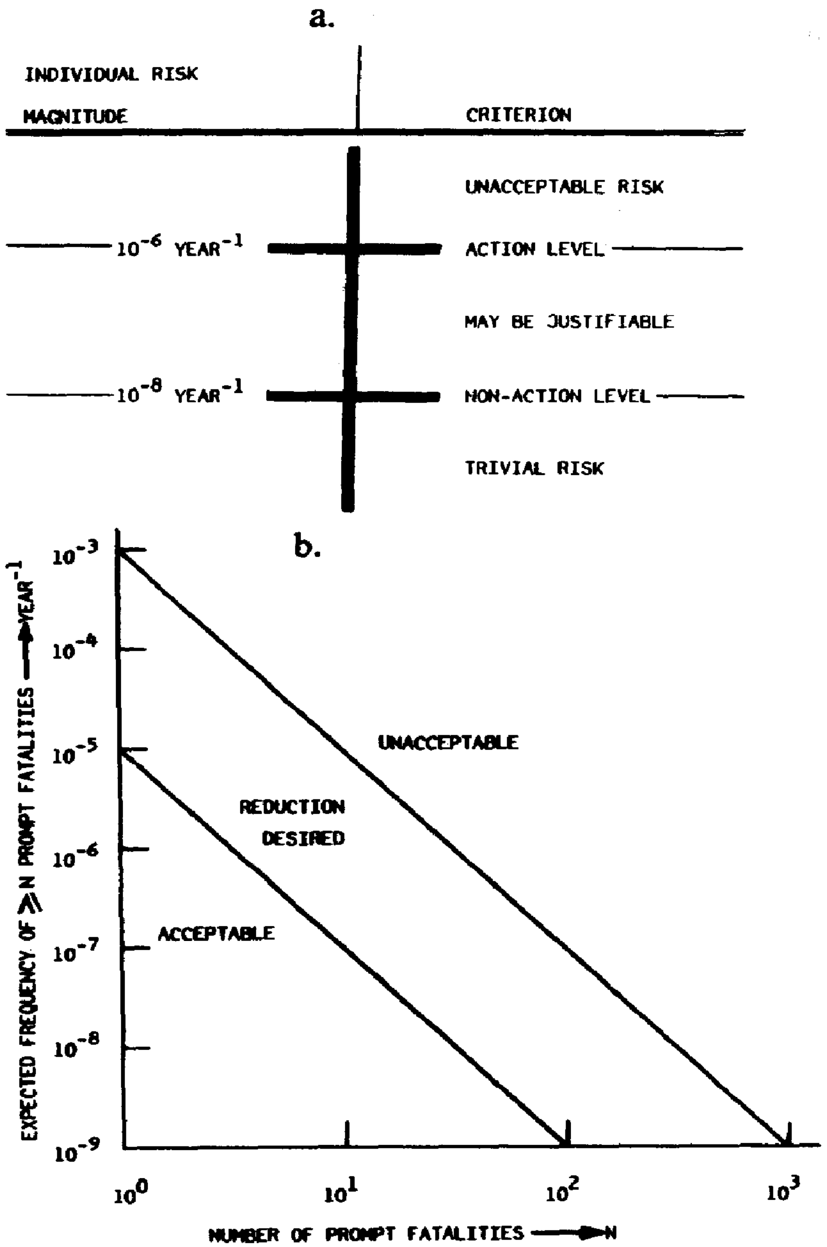


Fig. 18. Provisional risk criteria according to Dutch law after Ale [8]. (a) Individual risk criteria, and (b) societal risk criteria.

dent to an individual around the threatening installation (Fig. 16). These are called *individual risk* curves. Further the frequency (y^{-1}) distribution of accidents with more than *N* prompt fatalities can be derived producing the *group* or *social risk* curve (Fig. 17). The significance of the latter has to do with the fact that a large accident with say 10 victims is perceived as disproportionally more serious than 10 accidents with one fatality each.

Because of the uncertainty in reliability data for rare events and the uncertainties in risk modelling, the overall risk predictions may be no more accurate than two orders of magnitude.

Several psychologists made studies of how the general public perceives the "threat" posed to them by industrial activities, e.g. [44]. Generalisation of conclusions does not seem easily possible, although the extent people believe one is in control is important.

3.3.7 Law and regulation

The chemical engineer does not have only the laws of physics and chemistry as his boundary conditions, but also a package of regulations. Certainly in Europe much new regulation has been passed. We cannot say it is uniform [45]. In "Safety Standards and Regulations for Chemical Plant in Europe, a Comparison" [46] an overview is given. It contains four parts: The basic elements, the process of licensing, standards for pressure vessels and standards for explosion proof equipment.

The Dutch law has the reputation of being the most quantified with criteria for the risk to be accepted by the general public. This amounts basically to 1% of the natural death risk run by the population group of age 10–14, which is 10^{-4} per year. The maximum acceptable individual risk is thus 10^{-6} per year [8]. The whole picture is given in Figs. 18(a) and (b). Although there were tough discussions beforehand, after implementation parties seem rather relaxed. These criteria hold for the external safety report only. In case of the occupational safety report an indexing method is applied based on quantities and hazard properties of the materials present. If a certain index value is passed a HAZOP study and the collection of data on unwanted events is required. Only if no experience is available will a risk and effect study be considered [47].

3.3.8 Emergency planning

Emergency planning has one main goal, namely to minimize the consequences of an accident. In order to optimize energy planning in an industrial project it should start at a stage in the design before the plant layout is decided. It follows the same pattern as risk assessment of the plant itself. In addition the planner has to deal with two important aspects:

- the emergency organisation in acute operation has to cope with a non-steady activity with rapid and unforeseen changes,
- cooperation with the surrounding society is vital during many major accidents including demanding tasks of providing adequate information.

Many accidents in the past have shown the need for very detailed planning based on knowledge such as:

- how fast can an emergency shut down valve function,
- how much cooling water is needed per square meter in order to cool a tank.

Such knowledge gives input to:

- choice of and size of fire fighting and other equipment,
- calculations about size of the fire brigade,
- time between the start of the fire and the brigade coming into action.

Establishing safe escape ways and safe havens are major parts of the emergency planning in a project. Calculations on the maximum conceivable accident and maximum development speed of an accident which the emergency organisation should be able to handle, are necessary at the plant design stage. Training and retraining the operational personnel also follows systematic plans. The way of tackling such different tasks systematically is to establish some acceptance criteria, to run emergency risk analyses, and to verify the results by e.g. an emergency planning "HAZOP".

A modern emergency center of an industrial complex may be computerized. Source and size of fires and gas releases are fed into the computer, which foresees the development of the accident and gives advice how to cope with the coming situation. The development of good emergency plans is necessary for the business; it is also required to meet pressure from society and authorities since information from the industry about the risks to the environment will be more and more open in the future.

4. Some challenges to loss prevention

4.1 Organization and consolidation of information

The present information avalanche has to be digested and to be passed on to younger generations in a comprehensive and effective manner. Repeating the message can be crucial. Besides it is in the interest of all, that smaller companies, universities and others, who do not have the specialist Loss Prevention resources at their disposal like the large international companies, should be able to find their way to appropriate information. The Working Party on Loss Prevention by organizing symposia tried to fulfill the need. However, more effort is required.

At present with the support of CEFIC (Conseil Europeèn des Federations de l'Industrie Chimique) we are seeking industry sponsorship for founding a *European Process Safety Center*. Such a centre should reinforce as a technical focus the work of the WP and keep in touch with other centres of expertise. It will perform the following functions:

(a) Provide advice on how to access safety knowledge, whom to consult, what data bases exist and what information is available,
(b) Collect R&D needs, see below in Section 4.5,
(c) Provide technical and scientific background information with respect to safety legislation,

(d) Provide a single source of information on training materials for teaching and courses.

It is proposed that it will initially consist of just a technical manager, a skilled communicator and a part-time secretary.

4.2 Safe plant design

Methods developed to date have largely been for evaluating the safety of some proposed design. In the future we expect to see a greater emphasis on the use of our knowledge to synthesise a safe plant design in the first place.

The value of *Inherent Safety* is recognized, but there is room for better awareness and practice. The concept, described in [48,49], puts emphasis on the substitution of hazardous materials by those of lesser hazard or, where this is not feasible, by inventory reduction or the use of less extreme process conditions. For future plants an equivalent concept of inherent environmental friendliness and inherent hygiene needs to be established [30].

4.3 Computers and automation

In the design field the use of computer programs as computational aids has, from the 1960's onwards, led to an ever-increasing assurance that standard safety-related design calculations are being carried out correctly, e.g. in relief system sizing. This is a very real contribution to safety.

More recently attention has been given to expert systems to help handle logical problems, and there can be no doubt that this will be an area of growth in the next ten years. A reasonable capability exists already for preparing expert systems to enable individuals to carry out design applications. Much more difficult [50,51] is their application to design problems handled by teams, e.g. hazard and operability studies aimed at identifying hazards. Much study is going on in this field, but there is a long way to go yet. The rewards will be high in terms of both assurance of safe design and saved effort.

The use of computers for process control has become commonplace. Computer controlled plants can fail in new ways — e.g. many valves may be opened simultaneously. This must be taken into account when identifying the hazards which the safety systems need to handle.

The use of computers for critical safety applications is a matter of discussion, because of concerns about the reliability of both hardware and software. The widespread availability of programmable electronic systems (PES's) has increased this concern. Some Companies insist on "hard-wired" systems for critical safety applications. The U.K. Health and Safety Executive has issued guidelines on the use of PES's [52].

How to achieve reliability in control/protection software is a pressing problem, and will receive much attention in the next decade.

4.4 Control of damage to the environment

The huge and complex industrial plants represent a threat in many people's feelings. Some major accidents have strengthened these feelings (Mexico City, Seveso, Bhopal, Basle), The answers from the process industry have been the emphasis on high quality in design and operation of plants and information to the public. The goal is plants without impact to the environment at all.

In the future the industry has to be able to show with historical statistics a further substantial fall in the number of mishaps per year all over the world. The systematic approaches to identifying hazards and quantifying risk where appropriate, already developed for safety, should also be applied for the protection of the environment.

Unforeseen long term consequences of industrial activity is another type of problem (loss of power production, death of forests, etc.). Such problems are challenges.

4.5 Coordination of research

Research includes work of an experimental nature and the development and review of models, techniques and software.

AIChE's CCPS is quite active in the United States in keeping track of research needs. Recently Mr. Carmody, its director, for instance, published a list of topics on mitigation, protection and analysis topics [53].

Also, in Europe a more systematic effort has been undertaken in the realm of EC's STEP. Last year an initiative was taken for a Safety Management and Hazard Assessment Research Cooperation in Europe, with the well found acronym SHARE. The aim is to maximise benefits and harmonize national and European programmes.

If a European Process Safety Centre can indeed be established[1], as pointed out before, its tasks will include collecting the needs, informing the members accordingly, acting as a catalyst and providing independent advice on priorities.

5. Acronyms

AIChE	American Institute of Chemical Engineers
BLEVE	Boiling Liquid Expanding Vapour Explosion
BMHB	British Materials Handling Board
CCPS	Center for Chemical Process Safety (AIChE)
CEFIC	Conseil Europeèn des Federations de l'Industrie Chimique
CMA	Chemical Manufacturers Association
COVO	Commissie Veiligheid Omgeving (Committee for the Safety of the Population at Large)
DECHEMA	Deutsche Gesellschaft für Chemisches Apparatewesen, Chemische Technik und Biotechnologie e.V.
DIERS	Design Institute for Emergency Relief Systems (AIChE)

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[1] Meanwhile (November 1991) a sufficient number of companies offered to sponsor the Centre. Hopefully it will be in operation from late Spring 1992 onwards.

EC	European Community
EFCE	European Federation of Chemical Engineering
EFMA	European Fertilizer Manufacturers Association
EPEL	Emergency Population Exposure Limit
FACTS	Failure and Accidents Technical Information System
FTA	Fault Tree Analysis
HAZOP	Hazard and Operability Study
HSE	U.K. Health and Safety Executive
IChemE	Institution of Chemical Engineers
IDLH	Immediately Dangerous to Life and Health
IUPAC	International Union of Pure and Applied Chemistry
ISO	International Organization for Standardization
ISSA	International Social Security Association
LC	Lethal Concentration
LD	Lethal Dose
LP	Loss Prevention
LPG	Liquefied Petroleum Gas
LWC	Lost Workday Case
MHIDAS	Major Hazard Incident Data Service
OECD	Organisation for Economical Cooperation and Development
PAAG	Prognose von Störungen, Auffinden der Ursachen, Abschätzen der Auswirkungen, Gegenmassnahmen
QRA	Quantified Risk Analysis
RI	Risk Index
RA	Risk Analysis
SHARE	Safety Management and Hazard Assessment Research Cooperation in Europe
SRD	Safety and Reliability Directorate
SRS	Systems Reliability Service
STEL	Short Term Exposure Limit
STEP	Science and Technology for Environmental Protection
TNO	Toegepast Natuurwetenschappelijk Onderzoek (Applied Scientific Research)
TNT	2,4,6-Trinitrotoluene (trotyl)
TC	Toxic Concentration
TCDD	Tetrachloro-dibenzo-*p*-dioxin
TD	Toxic Dose
UKAEA	United Kingdom Atomic Energy Authority
UN	United Nations
UNEP (IEO)	United Nations Environment Programme (Industry and Environment Office)
UNIDO	United Nations Industrial Development
VCE	Vapour Cloud Explosion

VDI	Verein Deutscher Ingenieure
WP	Working Party

References

1 J. Bond, Loss Prevention: An important part of total quality management, Quality Forum, 16(4) (1990) 179–184.

2 European Communities, Council Directive on the major-accident hazards of certain industrial activities, 82/501/EEC, Official Journal of the European Communities, No. L230/1-18, 05.08.1982.

3 In Zentrales Ingenierswesen, ATÜ Anlagensicherheit und Technische Überwachung, Kolloquium zum 90jährigen Bestehen des Fachbereiches Technische Überwachung und zum 60jährigen Bestehen des Fachbereiches Werkstofftechnik, Bayer, Leberkussen, 1988.

4 Major Loss Prevention in the Process Industries, 106th Event EFCE, IChemE Symp. Series No. 34, London, 1971.

5 U.S.A.E.C.: "Reactor Safety Study - An assessment of accident risk in U.S. commercial nuclear power plants"; Draft report, WASH 1400 (the Rasmussen report), NTIS, Dept. of Commerce, Springfield, VA 22151, Aug. 1974.

6 Risk Analysis of Six Potentially Hazardous Industrial Objects in the Rijnmond Area: A Pilot Study, D. Reidel, Dordrecht, 1982.

7 Canvey: An Investigation, Health and Safety Executive, HMSO, London, 1978. Canvey: A Second Report, Health and Safety Executive, HMSO, London, 1981.

8 B.J.M. Ale, Risk Analysis and Risk Policy in the Netherlands and the EEC", J. Loss Prev. Process Ind., 4 (1991) 58–64; See also M.F. Versteeg, External safety policy in the Netherlands: An approach to risk management, J. Hazardous Mater., 17 (1988) 215–222.

9 T.S. Ferry, Modern Accident Investigation, 2nd ed. Wiley, New York, NY, 1988.

10 H.-J. Joschek, Welcome Address 2, Proc. 5th Int. Symp. Loss Prev. Safety Prom. in the Process Ind., Cannes, Soc. Chim. Ind., 28 r.St-Dominique, F75007 Paris, Vol. III, 1986, pp. 9–30.

11 P.L. Thibaut Brian, Managing Safety in the Chemical Industry, EFCE Event No. 377, Preventing Major Chemical and Related Process Accidents, London, I ChemE Symp. Series No. 110, EFCE Publ. No. 70, 1988, pp. 615–619.

12 Recommendations on the Transport of Dangerous Goods, 2nd ed. U.N. St/SG/AC 10/11/ Rev. 1, New York, NY, 1990 (ISSN 1014-7160).

13 Int. Conf. on Vapor Cloud Modeling, J. Woodward (Ed.), Boston Marriott Cambridge, Cambridge, MA, Nov. 2–4, 1987, AIChE, 345 East 47th St., New York, NY 10017, pp. 1–180.

14 Methods for the calculation of the physical effects of the escape of dangerous materials (liquids and gases), 1st edn. 1979, Parts I and II, Report of the Committee for the Prevention of Disasters, Dir. Gen. of Labour, Min. Social Affairs, Balen van Andelplein 2, 2273 KH Voorburg (The Netherlands).

15 Heavy Gas Dispersion Trials at Thorney island -2, J. McQuaid Ed., J. Hazardous Mater. 16, (1987), Special Issue: T.O. Spicer and J.A. Havens, Field test validation of the DEGADIS model, 231–245, and S.T. Chan, D.L. Ermak and L.K. Morris, FEM3 Model simulations of selected Thorney Island Phase I Trails, 267–292.

16 C.J.M. van Wingerden, On the scaling of vapour cloud explosion experiments, Chem. Eng. Res. Des, 67 (1989) 339–347.

17 A.C. van den Berg, The Multi-Energy method: A framework for the vapour cloud explosion blast prediction, J. Hazardous Mater., 12 (1985) 1–10.

18 W. Bartknecht, Explosionen, Ablauf und Schutzmassnahmen, Springer-Verlag, Berlin, 1978.

19 C. Schofield, Guide to dust explosion prevention and protection. Part 1 – Venting, IChemE, Rugby CV21 3HQ (UK), 1984.

20 C. Schofield and J.A. Abbott, Guide to dust explosion prevention and protection. Part 2 – Ignition prevention, containment, inerting, suppression, and isolation, IChemE, Rugby, 1988.

21 G.A. Lunn, Guide to dust explosion prevention and protection. Part 3 – Venting of weak explosions and the effect of vent ducts, IChemE, Rugby CV21 3HQ (UK), 1988.

22 D. Pawel, Untersuchungen über den Anlauf von Gasdetonationen über Detonations-grenzen, Dissertation Univ. Göttingen, 1971.

23 W. Berthold, Bestimmung der Mindestzündenergie von Staub/Luft Gemischen, VDI Fortschrittberichte, Reihe 3, nr. 134, 1987, Verlag VDI, Düsseldorf.

24 H.G. Fisher, The DIERS users group: A forum for development/dissemination of emergency relief system design technology, Plant/Operations Prog., 8(2) (1989) 70–72.

25 J.C. Leung, A.C. Buckland, A.R. Jones and L.D. Pesce, Emergency Relief Requirements for Reactive Chemical Storage Tanks, EFCE Event No. 377, Preventing Major Chemical and Related Process Accidents, London, IChemE Symp. Series No. 110, EFCE Publ. No. 70, 1988, pp. 169–184.

26 H.A. Duxbury and A.J. Wilday, The Design of Reactor Relief Systems, IChemE Hazards X Symp., Manchester, April 18-20, 1989, IChemE Symp. Series No. 115, 1989, p. 125.

27 First, K.E. and Huff, J.E., Design Charts for Two-phase Flashing Flow in Emergency Pressure Relief, March 7-9, 1989, Systems, Int. Symp. on Runaway Reactions, Boston Marriott Cambridge, Cambridge, MA, Sponsored by CCPS, AIChE, IChemE 1989, pp. 681–721.

28 T. Grewer, H. Klusacek, U. Löffler, R.L. Rogers and J. Steinbach, Determination and assessment of the characteristic values for the evaluation of the thermal safety of chemical processes, J. Loss Prev. Process Ind. 2 (1989) 215–223.

29 Methoden voor het bepalen van mogelijke schade (Methods for the determination of possible damage), Ministry of Housing, Physical Planning and Environment, CPR 16, 1st edn. 1990, (ISSN 0921-9633); translation in preparation.

30 Risk Analysis in the Process Industries, A.P. Cox, (secr.), EFCE Publ. Series No. 45, IChemE, Rugby, 1985.

31 R.D. Turney, Designing plants for 1990 and beyond: Procedures for the control of safety, health, and environmental hazards in the design of chemical plant, Trans. IChemE, 68B (1990) 12–16.

32 L.J.B. Koehorst, An analysis of accidents with casualties in the chemical industry based on historical facts, In: Ms. V. Colombari (Ed.),6th EuReData Conf. on Reliability Data Collection and Use in Risk and Availability Assessment, Siena, Italy, 15–17 March 1989, TNO-ref. no. 88-340; also FACTS A database for industrial safety, Eurocourse, Ispra, Italy, 8–12 Oct. 1990.

33 H.G. Lawley, Operability studies and hazard analysis, Chem. Eng. Prog. 8(5) (1973) 105–116.

34 PAAG-Verfahren (HAZOP), Prognose von Störungen, Auffinden der Ursachen, Abschätzen der Auswirkungen, Gegenmassnahmen, ISSA Prevention Series No. 2002, Gaisbergstrasse 11, D-6900 Heidelberg (ISSN 1015-8022).

35 Fire and Explosion Index, Hazard Classification Guide, 4th edn., Dow Chemical Company, Midland, MI, 1976.

36 D.J. Lewis, The Mond Fire, Explosion and Toxicity Index, AIChE Loss Prevention Symp., Houston, TX, April 1-5, AIChE, 345 East 47th St., New York, NY, 10017, pp. 20–26. 1979.

37 D.S. Nielsen, The Cause/Consequence Diagram Method as a Basis for Quantitative Accident Analysis, Danish AEC Report RISØ-M-1374, Roskilde, 1971.

38 Procedures for performing a Failure Mode and Effect Analysis, Dept. of Navy, Washington, DC 20362, MIL-STD-1629A, 1977.

39 R.F. Griffiths, The use of probit expressions in the assessment of acute population impact of toxic releases, J. Loss Prev. Process Ind., (1991) 49–57.

40 D.F. Haasl, Fault Tree Handbook, USNRC NUREG-0492; see also Guidelines for Chemical Process Quantitative Risk Analysis, Center for Chemical Process Safety (AIChE), 345 East 47th Street, New York, NY 10017, 1989.

41 Human Factors, A Report of the Human Factors Study Group to the Loss Prevention Working Party of EFCE, obtainable from IChemE, Geo Davis Bldg. 165–171 Railway Terrace, Rugby CV21 3HQ (UK).

42 W.G. Johnson, MORT Safety Assurance Systems, Marcel Dekker, New York, NY, 1980, pp. 55–73.

43 Guidelines for Technical Management of Chemical Process Safety, Center for Chemical Process Safety (AIChE), 345 East 47th Street, New York, NY 10017, 1989.

44 P.J. Stallen and A. Tomas, De belevenis van industriële veiligheid in Rijnmond, Ph.D. Thesis, University of Nijmegen, 1986.

45 V. Pilz, Safety-related Regulations for Chemical Plant in Various European Countries, 6th Int. Symp. Loss Prev. and Safety Prom. in the Process Ind., Oslo, Norway, Vol. II, 1989, pp. 67-1/67-10.

46 Safety Standards and Regulations for Chemical Plant in Europe, A Comparison, 1988, DECHEMA Praxis der Sicherheitstechnik Vol. 2, D-6000 Frankfurt am Main.

47 Dutch Labour Inspectorate, Occupational Safety Report, Guideline for compilation, P-172-2E, UDC 614.8(047), The Hague, 1990, p. 10.

48 T.A. Kletz, Cheaper, Safer Plants, IChemE, Rugby CV21 3HQ (UK), 1984.

49 J.L. Hawksley, Risk Assessment and Project Development, Royal Society of Chemistry Symposium, Edinburgh, 1985.

50 A.G. Rushton, The Integration of Safety Considerations, IChemE Symp. Series No. 114 Computer Integrated Process Engineering, 1989, pp. 27–34.

51 A.R. Bunn and F.P. Lees, Expert design of plant handling hazardous materials: Design expertise and computer-aided design methods with illustrative examples, Chem. Eng. Res. Dev. 66 (1988) 419–444.

52 Programmable Electronic Systems in Safety Related Applications – Parts 1 and 2, Part 2 General Technical Guidelines, HMSO, London, 1987. Other references: Dependability of Critical Computer System 1, 2 and 3 - Techniques Directory, 1988, 1989 and 1990, Elsevier, London.

53 Th.W. Carmody, Current research, developments and future needs, Plant/Operations Prog. 9(3) (1990) 204–205.

54 J. Verhoeff, Experimental Study of the Thermal Explosion of Liquids. Ph.D. Thesis, Delft, University of Technology, Delft, 1983.

55 P.J. Crosswaithe, R.D. Fitzpatrick and N.W. Hurst, Risk Assessment for the siting of developments near LPG installations, EFCE Event No. 377 Preventing Major Chemical and Related Process Accidents, London, IChemE Symp. Series No. 110, EFCE Publ. No. 70, 1988, pp. 373–400.

56 C.J.M. van Wingerden, Experimental Investigation into the Strength of Blast Waves Generated by Vapour Cloud Explosions in Congested Areas, Proc. 6th Int. Symp. Loss Prev. and Saf. Prom. in the Process Ind. Oslo, Norway, June 19–22, Norwegian Society of Chatered Engineers, Oslo, 1989, Vol. 1, Lecture 26, pp. 1–16.

57 C.J.M. van Wingerden, 1991, to be presented at the 7th Int. Symp. Loss Prev. and Saf. Prom. in the Process Ind., Taormina, Sicily, 4–7 May 1992.

Additional reading

58 F.P. Lees, Loss Prevention in the Process Industries, Vol. 1 and 2, Butterworth, London, 1980.

59 Dutch National Environmental Policy Plan, Premises for Risk Management, risk limits in the context of environmental policy, Second Chamber of the States General, Session 1988-1989, 21 137, No. 5, VROM 90312/6-89, Voorburg, The Netherlands, 1989.

60 B.M. Hancock, Loss Prevention Bulletin and LP Training modules, IChemE, Geo Davis Building 165-171, Railway Terrace, Rugby CV21 3HQ, (UK)