NOMENCLATURE FOR HAZARD AND RISK ASSESSMENT IN THE PROCESS INDUSTRIES

David Jones

Second Edition

IChemE

The Editor

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FOREWORD

The Institution of Chemical Engineers is to be congratulated on the production of this most useful guide to terminology in the important field of hazard and risk assessment in relation to the operation of chemical process installations. In a field where constructive debate is an essential element of society's influence, a terminology which can be widely accepted is a necessary precursor to under- standing and progress.

It seems to me very worthwhile to attempt to establish a standard terminology in this particular field, even though such definition does not hold in a general sense because some of the terms defined here are used in rather different ways in some national legislation and European documents. It may well be that in the future the Institution's attention will be directed to these other aspects as well, but in the meantime this document serves a valuable function in the field to which it addresses itself.

Dr E.J. Cullen

Chairman, Health and Safety Commission

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PREFACE TO THE FIRST EDITION

Up until the early 1970s, discussion in the field of hazard and risk assessment was common only within a few specific sectors of industry. The terminology was fairly limited and well understood by those who used it. In the early 1970s the process industries began to realize that with new, higher intensity, higher inventory processes, the practice of learning by mistakes in the field of safety was no longer tenable. Much work was carried out to develop methods for the identification of what could go wrong and for assessing the likelihood of such undesired events. These techniques were developed primarily as aids to decision taking within a responsible organization, to help managers ensure that appropriate resources were applied in the areas where they would do the most good. To some extent they called on the terminology already existing in the field, but a considerable number of new terms were also introduced. Once again, the terminology was used within fairly small sectors of industry and, even though some of the expressions were somewhat inexact and the intended meaning did not always match the 'dictionary definition' of the word used, the sense was well understood by those who needed to use them.

By the mid 1970s there was already concern at national level over the inadequacy of the then current mechanism for the control of activities which had the potential for causing incidents which might have a major impact on the health, safety and property of the general public. Even at this stage the terminology was used by very few other than those actually using the associated techniques. However, the incident at Flixborough in June 1974 created such public awareness and attracted such media attention that quite suddenly the subject was on the lips of almost everyone.

It is possible that, without further incidents, interest would have waned. However, a number of factors continued to attract attention to the process industry and to encourage debate. These included:

- The reports of the Advisory Committee on Major Hazards which recommended UK legislation[1, 2, 19].
- The incident at Seveso in Italy which stimulated European legislation[12].
- Several other incidents around Europe which have stimulated local authorities to consider much more carefully the development and, in some cases, the control of operation of local industry. It is now common practice to seek expert advice when considering planning permission for development of, or near to, chemical or petroleum industry sites.
- The news value of fires, explosions or toxic releases with their high pictorial and headline impact has led to a style of reporting and, in some cases, initial exaggeration of incidents, which was not common before Flixborough.

- The planning inquiry concerning Canvey Island which led to the publication of quantitative risk assessments carried out by the Safety and Reliability Directorate of UKAEA for the Health and Safety Executive[3, 4].
- The European 'Green' movement which has continually focused attention on man's ability to do harm to himself by mechanisms other than war.

The result of these changes is that a somewhat ill-defined terminology designed and used by a small body of experts is now widely used, and often misused, in public debate, discussions with authorities and in the technical and popular press.

There is now concern that the lack of an agreed and widely understood terminology may be limiting the quality of debate and decision taking in this very important field. The Institution of Chemical Engineers (IChemE) therefore decided to set up a working party with the following terms of reference:

1. To establish a set of terminology in the field of hazard and risk assessment which will be widely acceptable throughout UK industry and authorities.
2. To produce clear definitions for the terms proposed in order to promote consistent usage by both expert and non-expert.

The working party was made up from practising engineers from industry, consultants, universities and the authorities, each contributing on a personal rather than a representative basis. The working party reported to the Engineering Practice Committee of the IChemE which has approved this report.

PREFACE TO THE SECOND EDITION

When the first edition was published, some relevant legislation was still at the drafting or consultative stage, and has now been implemented. Certain terms have been influenced by the final wording of the legislation and, consequently, these have become common terminology. This edition recognizes these changes and brings the definitions and references up to date.

CONTENTS

1. INTRODUCTION

The subject of hazard and risk assessment is very broad, covering the process industries, the nuclear industry, civil engineering and the field of insurance. Each of these areas has its own specialist terminology associated with hazard and risk and a comprehensive nomenclature was beyond the scope of the working party. It was therefore decided to narrow the remit to concentrate on the terminology appropriate to chemical hazards in the process industries. After careful consideration, the working party decided that it would not be sufficient to produce merely an alphabetically arranged list of terms after the manner of a dictionary. It was felt that such a procedure would not disclose fully the meaning of many of the terms and that they would be better understood if they were defined in their context.

It was decided, therefore, to set out the terms in the form of a narrative with explanations, and with the whole subject laid out in a systematic manner. Each word or term is presented in bold type on its first introduction in the narrative of the section in which it is defined, and printed in italics elsewhere in the main body of the report. It was accepted that readers would need an alphabetical list at some place in the report to help them to find any particular word and, therefore, an index to the report has been provided.

Another reason why it was considered that the dictionary approach would not be adequate was that, traditionally, dictionaries simply record usage; where a word has a number of meanings ascribed to it, they do not enter into judgement as to which meaning is to be preferred. In some cases, it was decided that it would be necessary to depart from normal dictionary practice and to recommend what seemed to be the best usage. This is particularly so where there are ambiguities or where literal interpretation of terms is not appropriate. In such cases the term has been marked by an asterisk in order to draw the reader's attention to the narrative for explanation. This seemed especially true in the case of those terms which have had their origin 'in-house' in one of the large organizations which pioneered the techniques of analysis covered in the report. However, when such organizations exchange experience in scientific conferences, confusion can arise because of differences in terminology. This is one of the areas where, in some instances, recommendations have been made for a single common usage.

Those terms which are marked with an asterisk (*) are considered by the working party to be potentially misleading and the attention of the reader is drawn to the narrative preceding the definition.

The working party had at its disposal a number of existing definitions such as those in BS 4778 Glossary of Terms Used in Quality Assurance[5], in the report of the Royal Society Study Group[6], and in the second report of the Advisory Committee on Major Hazards[2]. Although very few such definitions were found to be entirely satisfactory for the present purpose, where modified versions have been produced they are intended to be compatible with the essence of the definitions given in these sources. One area of difficulty found was where words are in both common and scientific use. This applied particularly to the key words, hazard and risk[18], where the difficulties are discussed at some length in the following section.

2. HAZARD AND RISK

Unlike many of the terms defined later, the words **hazard** and **risk** have the following characteristics:

- They are words in common use.
- In their ordinary dictionary meaning they are synonyms.
- There has been, and to some extent still is, sharp controversy as to the meaning to be assigned to them.
- They are terms of a very fundamental character which are to be found, either singly or in compound with other words, in virtually every text on the subject.

In consequence of this, it was decided to devote a more extensive and detailed narrative to these words and some of their derived expressions.

Though a decade ago it was common for one author to use *hazard* where another would use *risk* and vice versa[18], it seems true that in the UK there is a growing consensus as to the general sense in which the terms are to be used. This has arisen, at least in part, because authoritative bodies have seen the need in writing official or otherwise influential reports to include a glossary of the meanings of the terms used in the reports, though without necessarily seeking to impose these meanings on others. Of special significance here has been the publication by the Royal Society of its Study Group Report on 'risk assessment'[6] in which it has defined both *hazard* and *risk*. It is our intention in defining these terms in this glossary to ensure that the definitions provided should not be inconsistent with the definitions given in the Royal Society's Study Group Report. However, these were phrased in general terms and we have seen it appropriate to use definitions which are more specific to the field in question. The first term we shall define is *hazard*:

hazard a physical situation with a potential for human injury, damage to property, damage to the environment or some combination of these.

As so defined, *hazards* not only include process plant and associated materials, but also major structures, flying aircraft, and materials which release ionizing radiation. However, it is intended that this glossary should cover only the process industries and therefore the *hazards* discussed are **chemical hazards**, which may in turn be defined more narrowly as follows:

chemical hazard a *hazard* involving chemicals or processes which may realize its potential through agencies such as fire, explosion, toxic or corrosive effects.

Wherever the word *hazard* is used below, it has the meaning of *chemical hazard* as so defined.

The term **major hazard** has been used in the UK for many years; it was used in 1967 in the Annual Report of the Chief Inspector of Factories[8] and in 1972 in the Robens Report[7]. In addition, various documents have proposed definitions based on the quantity of materials stored on a given site. These include DoE Circular No. l /72 and 9/849, and the first and second reports of the Advisory Committee on Major Hazards[1, 2]. Perhaps it should be noted that subsequent legislation, namely the Notification of Installations Handling Hazardous Substances (NIHHS) Regulations 1982[10], and the Control of Industrial Major Accident Hazard (CIMAH) Regulations[11] and The Planning (Hazardous Substances Regulations 1992 (Consents Regulations)[25], which were derived from the earlier sources, do not use the term *major hazard*. The term may be defined as follows:

major hazard — an imprecise term for a large scale chemical *hazard*, especially one which may be realized through an *acute* event. Or, a popular term for an installation which has on its premises a quantity of a dangerous substance which exceeds the amount prescribed by the above references.

The term **major accident hazard** occurs in the title of the EEC Directive of 24 June 1982[12] and is synonymous with major hazard, but is legally defined in the CIMAH Regulations.

major accident hazard — a specific term defined in the CIMAH Regulations which means an occurrence resulting from uncontrolled developments in the course of an industrial activity leading to a serious danger to persons or the environment.

A substance constitutes a *hazard* by virtue of its intrinsic chemical properties or of its temperature and pressure, or some combination of these. For example, air and water may pose a *hazard* if compressed and heated, but neither would be classed as a **hazardous substance**, as their chemical properties alone do not constitute a *hazard*. The term *hazardous substance* may be defined generally as follows:

hazardous substance — a substance which, by virtue of its chemical properties, constitutes a *hazard*.

In the context of the NIHHS Regulations[10] and the Consents Regulations[25] the term *hazardous substance* has a more specific meaning, applying only to those substances listed in the regulations or meeting specified indicative criteria. Similarly, the term **dangerous substance** has a specific meaning under the CIMAH Regulations[11]. It is recommended that this term is used only with this specific meaning and that if a general term is required *hazardous substance* should be used.

dangerous substance* — a specific term defined in the CIMAH Regulations referring to listed substances and others meeting given criteria.

In assessing the threat posed by a *hazard*, the principal factors are the likelihood that it may be realized, and the likelihood and extent of the consequences, ie damage to people, property or the environment, in the event of its realization. The term which expresses likelihood in the present context is **risk**. Little controversy surrounds this point; the controversy around the use of *risk* is whether it may also be used to mean other, quite different, things - for example, whether it should also have the meaning attributed to *hazard* as defined above or a combination of the meaning of *hazard* with the meaning of likelihood. This practice of giving a number of meanings to *risk* is common where meanings are commercial rather than scientific and where meaning has to be deduced from the context. The working party recommends that the word *risk* should only be used to mean the likelihood of some specified undesired event. This would avoid the public confusion which arises when an installation is described using one meaning, as 'high risk', and using another as 'low risk'; it will encourage people to consider the 'risk of something happening'.

risk — the likelihood of a specified undesired event occurring within a specified period or in specified circumstances. It may be either a *frequency* (the number of specified events occurring in unit time) or a *probability* (the probability of a specified event following a prior event), depending on the circumstances

When considering the risk of harm to populations exposed to *hazards*, it is helpful to consider two derivatives of *risk*. In cases where the potential is large, many factors dictate the severity which might be realized, and there is a wide spectrum of possible harmful outcomes with associated likelihoods. This is known as the **societal risk**. In this case, the undesired event in our definition of risk is an accident which can affect a group of people. This is usually quantified as an *F-N curve*.

Individuals amongst the population who could be affected by such an accident will not usually be exposed equally. This distribution of the risk is illustrated by considering the likelihood of particular individuals being affected, known as the **individual risk**. In this case, the undesired event in our definition of *risk* is harm to a specific individual (or person living at a particular location). *Individual risk* can, of course, be used in the limiting case where only one individual could be affected in an accident.

societal risk — the relationship between frequency and the number of people suffering from a specified level of harm in a given population from the realization of specified *hazards*.

individual risk — the frequency at which an individual may be expected to sustain a given level of harm from the realization of specified *hazards*.

The usefulness and limitations of some of the above concepts can be illustrated by an example. One might assume that 10 tonnes of a toxic material poses a greater threat than 1 tonne.

However, whether any quantity actually poses a *hazard* depends upon the circumstances under which it is held. In the case of bulk storage, the larger quantity evidently has more potential for causing harm since, where *released* rapidly under the same conditions, harmful concentrations would extend to a greater distance. Although the larger quantity, in this case, could be said to pose a greater *hazard*, the magnitude of the effects resulting from an actual *release* depends on many other factors. There may be no people within this range of harmful effects and therefore no *risk* of injury. If there are people present, the number affected may vary depending on the wind direction, weather conditions and other factors, as well as the quantity *released*.

The likelihood of various sizes of detrimental effects to a population has been defined as the *societal risk*. The maximum number of people that could be harmed in an accident and the associated *probability* of occurrence is part of this concept. This maximum possible number affected in any one accident will usually be less than the total number of people who are within the range of possible harmful effects. *Societal risk* tells one nothing about its geographical distribution. People in the prevailing downwind direction from the storage would be more likely to be affected than those in the opposite direction. This will be reflected in the level of *individual risk* at such locations.

3. CONSEQUENCES

The process industries handle many *hazardous substances* which provide the potential for accidents leading to adverse consequences for people, property or the environment. There are three main categories of undesired events: *explosions, fires* and *toxic* or *corrosive releases*. *Hazardous substances* can cause adverse consequences under one or more of these categories.

3.1 EXPLOSIONS

3.1.1 DESCRIPTION OF EFFECTS

The term **explosion** is not a scientific one and it is used frequently in common parlance to describe incidents where there is just a loud noise. The working party recommends, however, that its use be confined to describing incidents where there is a rapid *release* of energy which causes a significant **blast wave** capable of causing damage. The Major Hazards Assessment Panel has addressed this topic in some depth and the Overpressure Monograph[23] will amplify the following text.

In a chemical explosion the gases, which form as a result of chemical reactions, expand rapidly due to a sudden increase in temperature, thereby increasing the pressure relative to the surrounding atmosphere (medium). A similar expansion can occur in a physical *explosion* when a gas under pressure is *released* suddenly into the atmosphere. These expansions initiate a *blast wave* which travels outwards, at first with a velocity comparable with that of the expanding gases. A *blast wave* consists of an initial positive pressure phase followed by a negative pressure phase. Where the pressure pulse formed by a *blast wave* creates a sharp discontinuity, this is usually termed a **shock wave**.

The damage which arises from an *explosion* may be caused, either by the effect of the *blast wave*, or by **missiles**. Part of the energy liberated in an *explosion* may be imparted to fragments or whole systems in the form of kinetic energy. These fragments, or *missiles*, may be projected outwards some considerable distance from the centre of an explosion.

DEFINITIONS

explosion	a *release* of energy which causes a pressure discontinuity or *blast wave*.
blast wave	a pressure pulse formed by an *explosion*.
shock wave	a pressure pulse formed by an *explosion* in which a sharp discontinuity in pressure is created as the wave travels through a fluid medium at greater than sonic velocity.
missiles	fragments or whole systems which are projected by a *release* of energy.

3.1.2 TYPES OF EXPLOSIONS

If the *explosion* is caused by a chemical reaction then there are two basic terms which are used to describe the mechanism or type of *explosion*, namely a **deflagration** or **detonation**.

A *deflagration* occurs when the reaction front advances at less than sonic velocity into the unreacted material. For a rapid *deflagration* of a flammable vapour-air mixture, the flame front moves at a velocity of a few tens to several hundred metres per second. A *deflagration* may have varying degrees of violence, ranging from cases with negligible blast damage effects (cf *flash fire*), to cases in which a distinct *blast wave* with potential for serious damage is present.

The conditions cannot be specified as yet, under which the *flame front* may accelerate sufficiently to create a *deflagration* with significant blast damage effects rather than a *flash fire*. A *detonation*, on the other hand, is where the chemical reaction is extremely rapid and the reaction front advances into the unreacted material at greater than sonic velocity.

In the case of *explosions* of vapour or *gas clouds*, a number of terms are used to describe the circumstances of an *explosion*. The principal two are **confined explosion** which describes an explosion of a flammable vapour-air mixture inside a closed system (eg vessel or building) and **unconfined vapour cloud explosion** (often shortened to UVCE) which relates to an *explosion* of a flammable vapour-air mixture in the open air. The latter term was very widely used, but is imprecise as, in practice, a *UVCE* will nearly always be partially confined due to the presence of buildings, structures, trees, etc. It was included in this listing due to its previous widespread use, but the term **vapour cloud explosion** is preferred and is now more commonly used.

There are many other terms used which fall into the category of describing the characteristics of an *explosion*. Most of these are self-explanatory, eg dust *explosion*, mist or aerosol *explosion*. The term dense phase *explosion* relates to an *explosion* caused by the chemical reaction of a solid or liquid material, such as TNT (trinitrotoluene).

A *blast wave* may be created by other means than evolution of gases from a chemical reaction. For example, the term **pressure burst** relates to the rupture of a pressurized system and subsequent formation of a *blast wave*. Similarly, when a material rapidly changes its state a *blast wave* may be formed. For example, the sudden release of pressure and subsequent flashing of a liquefied gas may contribute to the *blast wave* created by the *pressure burst*. Where the change of state is a result of a significant temperature difference between two or more substances as they come into contact, then the term **rapid phase transition** is used usually to describe this event which may produce a *blast wave*; for example, the instantaneous vaporization of water to steam on contact with molten metal. In the case of these *explosions*, there is no combustion process, only a release of physical, rather than chemical, energy.

The term **BLEVE (boiling liquid expanding vapour explosion)** is similar, to the extent that the limited blast involved arises only from physical energy. The acronym *BLEVE* is now used widely and is abused. It was introduced originally in the USA to describe a specific sequence of events commencing with the sudden rupture due to fire impingement of a vessel/system under pressure containing liquefied flammable gas. The *release* of energy from the *pressure burst* and the flashing of the liquid to vapour (*flash fraction*) creates a localized blast wave, this being in no way due to the flammability of the material. However, immediate ignition of the expanding fuel-air mixture leads to intense combustion, creating a *fireball* which rises away from the ground due to buoyancy.

This is the principal hazard, together with the missile effects of the ruptured containment system. In recent times, attempts have been made to widen the usage of the term *BLEVE* to include any sudden failure of a system containing any liquefied gas under pressure. It is felt that, to avoid confusion, the name *BLEVE* should be avoided wherever possible and terms such as *pressure burst*, flashing and *fireball* should be used to describe the particular scenario. If the term *BLEVE* is to be used then it is recommended that it should only be used in its original sense as described above.

DEFINITIONS

deflagration	the chemical reaction of a substance in which the reaction front advances into the unreacted substance at less than sonic velocity. Where a *blast wave* is produced which has the potential to cause damage, the term explosive *deflagration* is usually used.
detonation	an *explosion* caused by the extremely rapid chemical reaction of a substance in which the reaction front advances into the unreacted substance at greater than sonic velocity.
confined explosion	an *explosion* of a fuel-oxidant mixture inside a closed system (eg vessel or building).
vapour cloud explosion (VCE)	the preferred term for an *explosion* in the open air of a cloud made up of a mixture of a flammable vapour or gas with air
Unconfined vapour cloud explosion (UVCE)*	an imprecise term originally used as defined for *VCE* above, but not commonly used now.

pressure burst the rupture of a system under pressure, resulting in the formation of a *blast wave* and *missiles* which may have the potential to cause damage.

rapid phase transition the rapid change of state of a substance which may produce a *blast wave* and *missiles*.

BLEVE*† used to describe the sudden rupture due to fire impingement of a vessel/system containing liquefied flammable gas under pressure. The *pressure burst* and the flashing of the liquid to vapour creates a *blast wave* and potential *missile* damage, and immediate ignition of the expanding fuel-air mixture leads to intense combustion creating a *fireball*.

† (boiling liquid expanding vapour explosion)

3.1.3 COMMON TECHNICAL TERMS USED IN QUANTIFYING THE EFFECTS

There are numerous detailed technical terms relating to quantifying the effects of *explosions*. Below are terms which are used frequently and for which definitions are provided.

DEFINITIONS

overpressure for a pressure pulse (*blast wave*), the pressure developed above atmospheric pressure at any stage or location is called the *overpressure*. *Overpressure* is sometimes used to describe exposure of equipment to pressures in excess of the design pressure, but the term overpressurization is preferred for this purpose.

peak positive overpressure the maximum *overpressure* generated is called the *peak positive overpressure*.

duration the time taken for the pressure pulse to decline to zero is known as the positive phase duration, usually shortened to *duration*.

side-on overpressure if a pressure-sensitive device which offered no obstruction to the passage of the *blast wave* was placed in its path (ie one which was facing sideways in relation to its advance), the device would record *side-on overpressure*.

reflected overpressure if a 'rigid' object was perpendicular to the advance of the *blast wave* (ie facing), the object would reflect and diffract the wave. Due to this reflection, the object will experience an effective *overpressure*, usually called the reflected *overpressure*, of at least twice the *side-on overpressure*.

epicentre — the ground location beneath the inferred centre of a *vapour cloud explosion.*

explosion 'efficiency' — the ratio of the energy in the *blast wave* to the energy theoretically available from the heat of combustion, usually expressed as a percentage.

TNT equivalent — the amount of TNT (trinitrotoluene) which would produce the same damage effects as those of the *explosion* under consideration. For non-dense phase *explosions* the equivalence has meaning only at a considerable distance where the nature of the *blast wave* arising is comparable with that of TNT.

3.2 FIRES

When a material burns, **thermal radiation** is emitted. This form of heat transfer other than by conduction or convection can cause harm or damage to people and objects. The amount and rate of energy emission depends on a number of factors, the first of which is the type of **fire**. A **pool fire** may result from the ignition of flammable vapour from a spill of liquid which has collected on the ground or in a container. The linear rate of evaporation of liquid from a *pool fire* is usually termed the **burning rate**. This term is also used to describe the mass burning rate of other types of fires. If the ignition takes place when material is emerging from the release point under pressure, a **jet flame** can be produced. If, however, the *release* produces a cloud of gas which is then ignited, the **flame front** usually moves through the cloud in a **flash fire**, ultimately consuming at least those portions of the cloud in which the concentration is above or below the **lower** and **upper flammable limits** respectively. Portions of the cloud which are at concentrations above the *upper flammable limit* will not burn until further diluted with air. The *lower and upper flammable limits* are not constant and depend on a number of factors. On occasions, a cloud *fire* can induce sufficient buoyancy to rise in the air, burning as a **fireball**.

An adequate supply of oxygen is necessary to sustain combustion of the material and, therefore, a *fire* will draw air into the combustion zone. In the case of extremely large *fires* (over several kilometres square) caused by large scale wartime bombing, this inrush of air reached hurricane force. This phenomenon is known as a **fire storm**. However, the relevance of *fire storms* to chemical plant *hazards* is very doubtful.

For each type of *fire*, the radiation emitted depends, among other things, on how fast the burning material is consumed. Calculations of the rate of energy received at a target are based on the behaviour of black body radiators. The extent to which the source approaches the emissive power of a black body at the same temperature is known as the **emissivity**. This can be used to predict the **surface flux** of a flame. To estimate the proportion of this flux received at any specified 'target', it is necessary to know the **view factor**, which depends on the spatial configuration of source and target, and the **transmissivity** of the intervening medium which allows for the attenuation of radiation passing through that medium. The **absorptivity** of the target material determines what fraction of the incident energy will go towards raising the target's temperature. More details on these aspects can be found in the Thermal Radiation Monograph[24].

Fire, in the sense discussed above, refers to the combustion of materials in air. However, there are reactions in which air is not involved but which produce similar *hazards*, eg the burning of military propellants or the burning of iron in a chlorine atmosphere. No attempt has been made to produce definitions for such specialized areas.

Safety measures associated with *fire* fall into two broad categories: **fire prevention** measures are those intended to reduce the likelihood of a *fire* occurring; **fire protection** measures are those which seek to minimize the extent of damage from *fire* should it occur. *Fire protection* systems may detect, extinguish, contain, or allow persons or property to tolerate a *fire*.

DEFINITIONS

thermal radiation	the propagation of energy in the infra-red region of the electromagnetic spectrum, commonly 'heat'.
fire	a process of combustion characterized by heat or smoke or flame or any combination of these.
pool fire	the combustion of material evaporating from a layer of liquid at the base of the *fire*.
burning rate	the linear rate of evaporation of material from a liquid pool during a *fire*, or the mass rate of combustion of a gas or solid. The context in which the term is used should be specified.
jet flame	the combustion of material emerging with significant momentum from an orifice.
flame front	the boundary between the burning and unburnt portions of a flammable vapour and air mixture, or other combusting system.
flash fire	the combustion of a flammable vapour and air mixture in which flame passes through that mixture at less than sonic velocity, such that negligible damaging *overpressure* is generated.
Lower flammable limit (LFL)	that concentration in air of a flammable material below which combustion will not propagate.
Upper flammable limit (UFL)	that concentration in air of a flammable material above which combustion will not propagate.

fireball	a *fire*, burning sufficiently rapidly for the burning mass to rise into the air as a cloud or ball.
fire storm*	an extremely large area *fire* resulting in a tremendous inrush of air which may reach hurricane force.
emissivity	the ratio of the radiation emitted by any surface or substance to that emitted by a black body at the same temperature.
surface flux	the radiant power emanating from unit area of a flame or other source, also known as surface emissive power (SEP).
view factor	the solid angle subtended by the source at the target, as a proportion of the solid angle of a hemisphere.
transmissivity	the fraction of incident *thermal radiation* passing unabsorbed through a path of unit length of a medium.
absorptivity	the ratio of the radiant energy absorbed by any surface or substance, to that absorbed under the same conditions by a black body.
fire prevention	measures taken to prevent outbreaks of *fire* at a given location.
fire protection	design features, systems or equipment which are intended to reduce the damage from a *fire* at a given location.

3.3 TOXIC SUBSTANCES

Everyone is exposed to a great variety of chemical substances in the normal course of their life, both at work and away from work. Most of these substances do not present a *hazard* under normal circumstances, but have the potential for being injurious at some sufficiently high concentration and level of **exposure**. **Toxic** substances, or **poisons**, are those materials which can have an injurious effect when introduced into, or absorbed by, a living organism. In this same context, **corrosive** materials are included because they may damage or destroy living tissues.

The terms **acute** and **chronic** are used frequently in connection with both *toxic exposure* and *toxic effects*. Although used in their normal sense, care is necessary in the use of these terms. *Acute* implies short duration, while *chronic* implies a prolonged or recurrent nature. Short term accidental *exposures* would therefore be termed *acute*, while daily *exposures* to background concentrations in the workplace would be termed *chronic*. To avoid confusion, it is recommended that the terms *acute* and *chronic* should not be used to infer high and low concentrations of *toxic* materials. Their meaning should be restricted to describe time rather than severity, in line with the medical profession in their description of disease.

Some effects do not arise immediately after *exposure* and are termed 'delayed' or 'latent'. These terms are obviously relative and confusion can arise between *exposure* to a **carcinogen**, where the induction period before the appearance of harm (if it does arise) may be many years, and *exposure* to *toxic* agents, where a person may appear to survive a lethal *exposure* only to die after a day or two.

For some substances, a very small quantity may cause considerable harm, whereas for others, a much larger quantity may be required to have a harmful effect. It is this relative power of a *toxic* material to cause harm that is termed **toxicity**. It is important to distinguish *toxic* and *corrosive* materials from those which are purely narcotic or **irritant**. The latter may cause pain and discomfort through immediate or prolonged contact with the skin, but they do not themselves harm or destroy living tissues. Similarly, narcotic substances dull the senses and impair reactions without necessarily causing permanent damage.

Materials which are not *toxic*, *irritant* or *corrosive* may still endanger life if present in high enough concentrations in the atmosphere, by reducing the oxygen content and thus may lead to **asphyxiation**.

Two types of occupational *exposure* limit are now in use: **maximum exposure limits (MEL)**, which should not normally be exceeded, and **occupational exposure standard (OES)** which are considered to represent good practice[15]. For each type of limit, two types of *exposure* are considered: the **long term exposure limit** is concerned with reducing the *risk* from total intake, day after day, over long periods; the **short term exposure limit** is aimed primarily at avoiding *acute* effects from brief exposures or peaks in *exposure*. Both *long* and *short term exposure limits* are expressed as time weighted average concentrations; the *long term exposure limit* is normally averaged over eight hour periods, and the *short term exposure limit* over a ten minute period. Some of the *short term exposure limits* were formerly expressed as ceiling values which should not be exceeded even instantaneously, but this could not be monitored in practice since all samples need to be taken over a finite period. Ten minutes is considered to be the shortest practical time over which most personal samples can be taken at the levels of the *exposure limits*, due to the limitations of available sampling and analytical techniques.

Presently, *MEL* are only specified for a small number of hazardous substances. It should be noted that further action to reduce *exposure* below the limits may be necessary to fulfil legal requirements, particularly in the case of substances for which there is no apparent threshold below which adverse effects do not occur. The limits should not be used as an index of relative *hazard* to *toxicity* and do not represent a sharp dividing line between 'safe' and 'dangerous' concentrations.

Until recently the term threshold limit value (TLV) was used to describe *exposure* limits, but has been superseded by the above. TLVs have traditionally been quoted in three forms. The **time weighted average (TLV - TWA)** has been used to cover long term effects, the **short term exposure limit (TLV - STEL)** has been used to cover *acute* effects from a few minutes' *exposure*, and the term **ceiling (TLV - C)** has been used to cover situations where even the briefest of *exposure* is likely to cause harm.

Many attempts have been made to categorize *toxic* materials according to the health hazards that may result from single high level *exposures*. The majority of these 'classifications' are based on the **lethal dose** administered, or **lethal concentration** inhaled over a period of 4 hours, that results in the death of 50% of a test group within 14 days. This is the concept of the terms **LD_{50}** and **LC_{50}** respectively. Percentages other than 50 may be quoted. It should be noted that the term LC_{50} is often used loosely for *exposure* durations of other than four hours, in which case the exposure period should be stated. Another term used in the UK for assessment of risks to people is that defined by the Health and Safety Executive of **dangerous dose**[20] (or dangerous toxic load[21]). This is designed to be a suitable means of assessment for the wide range of susceptibility of the general public.

A further concept used in categorizing actual health *hazards* is that of conditions which are **immediately dangerous to life or health (IDLH)**. This term originated in the USA and was developed with reference to escape from highly *toxic* atmospheres. It can be confusing since the definition also refers to conditions which could have cumulative or delayed effects on health.

DEFINITIONS

exposure — amount of a *toxic* substance to which an individual is exposed. This may represent the amount ingested, absorbed or inhaled, or it may refer to the integral of concentration with time in the immediate environment. Where ambiguity may arise the basis used to define the *exposure* should be specified.

dose — used as a synonym with *exposure*.

toxic — the property of substances which, when introduced into or absorbed by a living organism, destroy life or injure health.

poison* — common term for a *toxic* substance.

corrosive — in the context of *toxic* substances a corrosive substance is one which may, on contact with living tissues, destroy them.

acute — immediate, short term. Relating to *exposure:* conditions which develop rapidly and may cause harm within a short time. Relating to effects: effects which appear promptly after *exposure*.

chronic — persistent, prolonged and repeated. Relating to *exposure*: frequent, or repeated, or continuous *exposure* to substances. Relating to effects: when physiological effects appear slowly and persist for a long period or with frequent recurrences.

carcinogen — a substance which produces cancer.

dangerous dose — a dose of *toxic* gas, *thermal radiation* or *explosion overpressure* which gives all of the following effects:

- severe distress to almost everyone;
- a substantial fraction requires medical attention;
- some people are seriously injured, requiring prolonged treatment;
- any highly susceptible person might be killed.

toxicity — the relative power of a toxic material to cause harm

irritant — a *non-corrosive* material which may cause pain, discomfort or minor injury, through immediate prolonged or repeated contact with the skin or mucous membrane. Such reactions may appear as a precursor to more serious injury.

asphyxiation — endangering life by causing a deficiency of oxygen.

maximum exposure limit (MEL) — an occupational *exposure* limit which should not normally be exceeded. (Previously referred to as **control limit**)

occupational exposure standard (OES) — an occupational *exposure* limit which is considered to represent good practice and a realistic criterion for the control of *exposure*, plant design, engineering controls and the selection and use of personal protective equipment. (Previously referred to as **recommended limit**).

long term exposure limit — a time weighted average concentration, usually averaged over 8 hours, which is appropriate for protecting against the effects of long term *exposure*.

short term exposure limit — a time weighted average concentration, usually averaged over 10 minutes, aimed at avoiding *acute* effects.

threshold limit value – time weighted average (TLV – TWA)*	the time weighted average concentration for a normal eight hour work day or 40 hour work week to which nearly all workers may be exposed, day after day, without adverse effect. (Superseded by the term *maximum exposure limit*)
threshold limit value – short term exposure limit (TLV – STEL)*	the maximum concentration to which workers can be exposed for a period of up to 15 minutes continuously without suffering from (1) intolerable irritation, (2) *chronic* or irreversible tissue change, or (3) narcosis of sufficient degree to increase accident proneness, impair self-rescue or materially reduce work efficiency; provided that the daily *MEL* also is not exceeded.
threshold limit value – ceiling (TLV – C)*	the concentration which should not be exceeded even instantaneously.
lethal dose (LD_{50})	the quantity of material administered orally or by skin absorption which results in the death of 50% of the test group within a 14 day observation period.
lethal concentration (LC_{50})	the concentration of airborne material, the four-hour inhalation of which results in the death of 50% of the test group within a 14 day observation period.
immediately dangerous to life or health (IDLH)*	conditions such that an *acute* exposure will lead to *acute* or *chronic* effects.

4. RELEASE AND DISPERSION

4.1 MECHANISMS OF RELEASES

The potential of many *hazardous substances* to cause harm can only be realized via a **release** of energy or of the substance to the surrounding environment. This can arise from failure of the **containment system** designed to hold the substance in a safe condition. *Releases* fall in a spectrum from deliberate and controlled discharges necessary for the operation of a process, to inadvertent and uncontrolled escapes. The possible effects of all such *releases* should be considered, but it is particularly important to identify *initiating events* which may cause inadvertent containment failure leading to an uncontrolled *release*.

Initiating events fall into two general categories, those internal and those external to a system. Internal causes may be subdivided broadly as those arising from departures from design conditions during operation (eg overheating), failure of equipment operating within design conditions (eg due to defective or incorrect materials of construction) or from human error in operation. External causes can be similarly subdivided, examples being failure from mechanical damage, 'natural hazards', external corrosion, and domino effects (ie events arising at one plant affecting another).

Releases from containment systems range from slow discharge through a small pinhole failure to rapid discharge resulting from a major break. Various mechanisms, such as fatigue, creep, or stress corrosion, may cause cracks or defects to grow, possibly leading to a through-wall failure and, therefore, a release. If the defect exceeds certain critical proportions, which depend on a number of factors, a propagating **fracture** may rapidly result in a major failure. For example, perforation of an underground pipeline could result from a third party activity, such as digging with a pneumatic drill. Such **punctures** may lead to a propagating *fracture* under certain conditions. The type of *fracture* may be described as brittle or ductile. A complete failure of pipework resulting in discharge from two open ends of pipe is often described as a **guillotine** failure, a term which is usually used in the description of hypothetical failure cases.

A sudden and severe failure of equipment, possibly with division into a few or many pieces and resulting in a rapid release of the contents, is often referred to as a **catastrophic failure**. However, a catastrophe as such, is not necessarily the outcome in terms of damage, other than that suffered by the equipment itself. It is useful to have such a term to describe a variety of very serious equipment failures, but because of the subjective and possibly misleading interpretations which may be derived from the term 'catastrophic' it is recommended that it is only used in conjunction with the term 'failure' and with specific reference to the equipment concerned. Another term encountered is 'disruptive', which also implies breaking open of equipment, and which is often used synonymously in this context.

DEFINITIONS

release	the discharge of energy or of a *hazardous substance* from its *containment system.*
containment system	the process and storage equipment in which a *hazardous substance* is kept.
fracture	the breaking open of a *containment system* by the propagation of a crack.
puncture	a perforation or hole in a *containment system* as a result of impact.
guillotine	complete severance of piping.
catastrophic failure (of containment)*	the sudden opening up of a specified part of a *containment system* resulting in a rapid loss of contents.

4.2 BEHAVIOUR OF RELEASES

The type of release depends on the manner in which the *containment system* fails, the physical properties of the material involved and the storage conditions.

Some *initiating events* lead to such a rapid *release* of inventory that they are termed **instantaneous releases**. Others produce discharge over a prolonged period and are termed **continuous releases**. Quantification of the rate of *release* is achieved using fluid mechanics principles applied to single or two phase flow.

Gases held under pressure as liquids form an important category of *hazardous substances*. On depressurization a proportion of such materials vaporize with a resulting decrease in temperature. This can result in two phase flow in the leak path, for example, if a liquid off-take pipe is severed at a point some distance away from a vessel. This is known as **flashing flow**. In many cases the driving pressure is sufficiently high for this flow to become choked and so the substance is still under pressure on *release* to the atmosphere, where further flashing occurs. Once depressurization to atmospheric pressure is complete the temperature of the material will have fallen to its normal boiling point. The proportion which would be vaporized if the entire depressurization were carried out adiabatically is known as the **flash fraction**. It provides an estimate of the maximum proportion of a superheated liquid emission which promptly vaporizes on release to the atmosphere. Rapid depressurization is a violent process and such a *pressure burst* may be hazardous in its own right and much of the remaining liquid fraction may be atomized. **Momentum turbulence** will entrain the surrounding fluid and a proportion of these droplets may 'rain-out' and subsequently vaporize. Heat transfer between the surrounding medium, usually the atmosphere, and the suspended liquid droplets may also lead to further vaporization. These factors tend to increase the vapour fraction beyond the theoretical *flash fraction*.

Pools, formed by spills of materials which are normally liquids at atmospheric temperature and pressure, evaporate by atmospheric convection and solar heating. Pools, formed by gases which have been liquefied by low temperature, also vaporize by taking heat from their surroundings, in this case mainly from the sub-medium. The rate of these processes is characterized by the **regression rate** of the liquid pool. This rate is enhanced significantly if the vapour is flammable and is ignited, in which case the term linear *burning rate* is usually used.

The quantity of released material made airborne, its form, composition, and temperature, can therefore depend on many factors. The description of the *release* required as input to consequence models, particularly dispersion calculations, is known as the **source term**.

DEFINITIONS

instantaneous release	the escape of a specified quantity of a *hazardous substance* over a short time span, typically a few seconds.
continuous release	the escape of a *hazardous substance* at a flow rate which is sustained for a prolonged period.
flashing flow	two phase flow in the leak path of a *release* of superheated liquid.
flash fraction	the fraction of a superheated liquid that will vaporize under adiabatic conditions on depressurization to atmospheric pressure.
momentum turbulence	turbulence induced by the speed with which the material is injected into the surrounding fluid.
regression rate	the rate of decrease in depth of a liquid pool.
source term	the quantitative description of a *release* required as input to a consequence model, ie quantity or rate, concentration, temperature, density, etc.

4.3 DISPERSION

When a *hazardous substance* is released it may explode or burn at the point of *release*, or it may travel away from the source. During such travel it becomes progressively diluted with the surrounding fluid. This is the process of **dispersion**. A **gas** or vapour may mix with air and form a **gas cloud** which drifts downwind; a liquid may mix with water and disperse along any currents present.

If *dispersion* proceeds for a long enough time the concentration of *hazardous substance* will fall below that required to cause harm. For a flammable substance, the concentration will eventually fall below the *lower flammable limit*; for a toxic substance, the level will fall below the threshold of significant *toxicity*. The progress of dispersion to such levels may be estimated quantitatively using a *dispersion* model which predicts mean or **peak concentration** at a point of interest, or **isopleths** showing the extent of the effects of a *gas cloud*. Great care is necessary in interpreting the results of model calculations, particularly with the definition of mean or *peak concentration*. *Dispersion* is a stochastic phenomenon, since it is determined by turbulence. In principle, concentration should be defined in statistical terms, taking specific account of: frequency and duration of sampling, number of samples, volume of samples, duration of event. In practice, for toxic substances a time-averaged mean concentration or integrated *dose* is used, so statistical details are neglected. For flammable substances, real difficulties can arise, since the *instantaneous* concentration determines whether ignition is possible.

The *dispersion* behaviour of a *gas cloud* is determined by its intrinsic properties as well as local external conditions. Differences arise between **dense**, **neutral density** and **buoyant gas clouds**. A *dense gas cloud* may be formed from a **dense gas** or because it is associated with a cold vapour *release*. Such *gas clouds*, which may also be called heavy or non-buoyant, tend to slump towards the ground in the early stages of *dispersion*. A *buoyant gas cloud*, often associated with combustion, tends to rise. A *neutral density gas cloud* has the same density as the atmosphere so it follows the turbulence pattern of the atmosphere. This is known as **passive dispersion**. The external conditions affecting *dispersion* include **wind speed**, **surface roughness** and the stability of the atmospheric boundary layer, which is characterized by **weather category**.

A gas cloud may behave as a discrete **puff** from a brief instantaneous *release*, or a **plume** may form during a *continuous release*. The time-averaged shape of a *plume* is a cigar-shape downwind, but an instantaneous picture may show a complex shape. Time-averaged *plume* dimensions are usually of most interest for *toxic* materials, but instantaneous dimensions are of interest for flammables (see above).

DEFINITIONS

dispersion	the process of dilution of a *hazardous substance* by the surrounding fluid.
gas	adequately understood and used in common parlance. Vapour is sometimes used instead, particularly for the evaporation of a spill of liquid.
gas cloud	the mass of gas/air mixture within a particular envelope of concentration limit.
peak concentration	the highest concentration predicted at a point by a *dispersion* model.

isopleth	a surface joining points of equal concentration, ie a three- dimensional 'contour', in a *gas cloud*.
dense gas cloud	a *gas cloud* which is heavier than the surrounding air immediately after the *release* process, because either the gas is a *dense* gas, or the mixture has a temperature sufficiently below ambient.
neutral density gas cloud	a *gas cloud* which has a density equal to that of the surrounding air.
buoyant gas cloud	a *gas cloud* which is lighter than the surrounding air.
dense gas	a *gas* whose density exceeds that of air at the same temperature.
passive dispersion	a *dispersion* process dependent only on atmospheric conditions in which the properties of the dispersing material do not affect the local turbulence.
wind speed	the mean speed of the air past a stationary point at a specified height, eg 10m.
surface roughness	a measure related to that component of the turbulence of the atmosphere which is aided by the departure of the ground profile from perfect smoothness.
weather category	a measure related to that component of the intrinsic turbulence of the atmosphere which is specifically determined by thermal stability.
puff	the *gas cloud* resulting from an *instantaneous release*.
plume	the *gas cloud* resulting from a *continuous release*.

5. ASSESSMENT TECHNIQUES

5.1 GENERAL TERMINOLOGY

Loss prevention is a general term used to describe a range of activities carried out in order to minimize any form of accidental loss, such as damage to people, property or the environment or purely financial loss due to plant outage. It includes the various techniques and approaches that have been developed for the assessment and control of *risk*. Some terms are used to describe the general objective of an activity, others are more specific and imply use of a particular technique. The extent and detail of an assessment depends on the particular problem, but the main stages are:

1. Identification of undesired events.
2. Analysis of the mechanisms by which undesired events could occur.
3. Consideration of the extent of any harmful effects.
4. Consideration of the likelihood of the undesired events and the likelihood of specific detrimental outcomes. Likelihood may be expressed as *probability* or *frequency*.
5. Judgements about the significance of the identified *hazards* and estimated *risks*.
6. Making and implementing decisions on courses of action, including ways of reducing the likelihood or consequences of undesired events.

Various combinations of terms such as '*hazard*', '*risk*' and 'safety' with 'analysis', 'assessment' and 'evaluation' are in use to describe all or part of these activities, often loosely being used as synonyms. The term **hazard analysis** has become established and is now widely used to describe the systematic approach to *hazard identification* of stages 1 and 2 above followed by, where the severity of the *hazards* concerned justify it, the subsequent consideration of likelihood and consequences involved in stages 3 and 4. This consideration usually involves quantitative estimation to a greater or lesser degree. Where it does, that part of the process is sometimes referred to as **risk analysis**. Use of the term *risk* necessarily implies consideration of the likelihood of events and outcomes and, to this extent, the working party considers the term 'probabilistic risk analysis' to be tautologous. An advantage of using the terms hazard or safety to describe such studies is that discrimination can be made between publications on diverse subject matters, such as financial decision making and chemical plant safety, which give different meanings to the term *risk*.

The Royal Society Study Group[6] use the term '*risk* estimation' for stages 1 to 4, '*risk* evaluation' for stage 5 and '*risk* management' for stage 6, giving a general definition for the term **risk assessment** which covers stages 1 to 5 in this context. These terms do not encompass the very common situation where none or only some of the aspects are treated quantitatively and therefore the *risk* is not explicitly estimated. Because there are a number of factors which influence the degree to which the consideration of likelihood and consequences merit, or allow, quantitative estimation, the working party have found it useful to draw only a limited distinction between *hazard analysis* and *risk analysis*. The definition adopted for *hazard analysis* includes the identification stages 1 and 2 and the subsequent stages 3 and 4, so far as they are relevant in a particular case. It is recommended that the term *risk* should only be used, in describing a study or assessment, where an estimate of likelihood is involved. The use of the term 'assessment' rather than 'analysis' implies taking judgements about significance rather than estimation alone, and so a definition for *risk assessment* covering stages 1 to 5 has been adopted.

The term **hazard survey** is used to describe the application of *loss prevention* techniques in the assessment of the hazards from an installation and the means of controlling them. The scope of a hazard survey depends on the hazards and other features of the particular installation. It necessarily involves a consideration of possible accidents, and may include a *risk assessment*. It includes consideration of all features important to safety, ie design, management, operation, maintenance, protective equipment, emergency procedures and training. By identification and examination of the critical features, it should consider whether any justifiable improvements to reduce *risk* can be introduced.

However, even when this whole process is complete, it is very rare that the risk can be reduced to zero. The remaining element of assessed *risk* is known as the **residual risk** and it is usually this which is compared with the chosen criteria.

The presentation of a justification for the safety of an installation, based, for example, on a *hazard survey*, is known as a **safety report**. This term is used in connection with the CIMAH Regulations[11] and will therefore have a quasi-legal use for the particular type of installation concerned. Similarly, **safety evaluation** is used to describe the analysis of *risk* required by the Pipelines Inspectorate.

It is important to ensure that the standard of all features vital to safety are monitored and updated. The **safety audit** is a review process carried out with this objective. Features of the process and design, management policy and attitudes, training, operating procedures, emergency plans, personnel protection, accident reporting and so on, may be examined by appropriately qualified personnel, usually including safety professionals independent of production management, to disclose strengths and weaknesses and recommend necessary actions.

DEFINITIONS

loss prevention — a systematic approach to preventing accidents or minimizing their effects. The activities may be associated with financial loss or safety issues and will often include many of the techniques defined in this report.

hazard analysis	the identification of undesired events that lead to the materialization of a hazard, the analysis of the mechanisms by which these undesired events could occur and usually the estimation of the extent, magnitude and likelihood of any harmful effects.
risk analysis*	an imprecise term which infers the quantified calculation of *probabilities* and *risks* without taking any judgements about their relevance. A term equivalent to risk estimation in Royal Society terms[6].
risk assessment	the quantitative evaluation of the likelihood of undesired events and the likelihood of harm or damage being caused together with the value judgements made concerning the significance of the results.
hazard survey	the total effort involved in an assessment of the hazards from an installation and their means of control.
residual risk	is the remaining *risk* after all proposed improvements to the facility under study have been made.
safety report	the presentation of a justification for the safety of an installation. (NB use in connection with CIMAH Regulations.) Previously known as Safety Case.
safety evaluation*	an alternative term for *safety report* used, in particular, for the assessment of pipelines
safety audit	a critical examination of all, or part, of a total operating system with relevance to safety.

5.2 HAZARD IDENTIFICATION METHODS

There are two categories of *hazard* identification techniques: fundamental and comparative methods. Fundamental methods are based on a systematic consideration of deviations from the design intent. The most powerful method is a form of *hazard* study which uses **guidewords** applied to process stages or functions. **Failure mode and effects analysis (FMEA)** is the other widely used fundamental method. A primary objective of these techniques is to identify the **initiating events** which may lead to dangerous situations.

Hazard studies may be carried out at various stages as a design evolves. Early in a project, a limited study may be carried out to identify the most serious *hazards*, which may require consideration of fundamental design changes. Such a study will often be accompanied by some preliminary *risk assessment*. Later studies will be more detailed, with the objective of discovering all significant hazardous situations; they may also identify operability problems which may lead to lost production. This involves application of *guidewords* on a line by line basis to plant diagrams and procedures and is known as a **hazard and operability (hazop) study**.

Hazard and operability studies can be applied to existing plants — in particular when modifications are being considered — but are most effective when carried out at a design stage where a wide range of possible actions still exist. The *guidewords* used must be relevant to the stage of the design and must be sufficiently comprehensive to be capable of identifying the *hazards* involved. A general set of guidewords with a broad range of application has been published by the IChemE[13]. Many specialist lists have also been developed for particular applications.

Experience has shown that this technique is most effective when carried out by a team of designers, operators, safety advisors independent of the design functions, and other specialists as appropriate, at a series of study meetings. The outcome of a study meeting is a list of actions to be pursued outside the meetings, eg design changes for consideration, cases identified for more detailed study and analytical quantification and items which will require further consideration at a later stage in the design.

Failure mode and effects analysis involves consideration of the possible outcomes from all known failure modes or deviations within a system, identifying which lead to undesirable situations. There is no formal method but results are usually summarized in tables. *FMEA* is most useful where there is a limited number of failure modes known to be of interest. When, within this process, the chance of failures and the seriousness of their consequences are ranked to identify the most critical features, the process is known as Failure Modes Effects and Criticality Analysis (FMECA).

Hazard identification procedures also provide information on the mechanisms by which the identified *hazards* can be produced and as such, the distinction between these techniques and the complementary analytical techniques described in Section 5.3, which can also be used for *hazard* identification, is somewhat artificial. The main difference is that the *hazard* identification techniques do not provide a framework for setting down mechanisms, while the analytical techniques must start from an event which has been identified by some method.

Comparative methods use **checklists** based on in-house or industry- wide experience and may derive from Codes of Practice or fundamental studies on similar plants. This may be adequate where the plant design is relatively standard and sufficient experience exists for the principal *hazards* to be well known. **Hazard indices** provide identification via *checklists*, although they also provide a preliminary ranking order for the degree of *hazard*. The best known and most widely used are the Dow Fire and Explosion Index and the Mond Index[16, 17].

DEFINITIONS

guidewords	a list of words applied to system items or functions in a *hazard* study to identify undesired deviations.
failure mode and effects analysis	a process for *hazard* identification where all known *failure modes* of components or features of a system are considered in turn and undesired outcomes are noted.
initiating event	a postulated occurrence capable of leading to the realization of a *hazard*.
hazard and operability study (hazop)	a study carried out by application of *guidewords* to identify all deviations from design intent with undesirable effects for safety or operability.
checklist	a method for *hazard* identification by comparison with experience in the form of a list of *failure modes* and hazardous situations.
hazard indices	a *checklist* method of *hazard* identification which provides a comparative ranking of the degree of *hazard* posed by particular design conditions

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5.3 ANALYTICAL TECHNIQUES

The main technique for analysis of the mechanisms, or failure logic, leading to hazardous events is the use of **logic diagrams**. They can be classified as 'top down' or 'bottom up' depending upon whether they trace outcomes back to causes or follow causes through to possible outcomes. They provide a powerful method for displaying qualitative information, but also provide a model for quantification. The main techniques, although there are other variations, are **fault tree analysis**, **event tree analysis**, and **cause-consequence analysis**.

Fault tree analysis works back from an undesired event, known as the **top event**, to the sub-events which are immediate precursors of the *top event*, then to the precursors of those sub-events and so on. Combinations of events are illustrated by **gates**, which, when the logical combination of the input conditions is satisfied, produce a specified output which is propagated. A *fault tree* models system states but can only show sequences of events with difficulty. There is a considerable amount of terminology specific to *fault trees* for which the reader should refer to a specialized text.

Event tree analysis follows a cause through to the possible outcomes, branching at each point where there is more than one possible result from the precursor event, until the final outcomes of interest are reached. The outcomes are conditional on the occurrence of the precursor events and so event sequences and time dependence can be readily displayed.

Cause-consequence analysis also follows through causes to events, but allows for the use of *gates* to show logical combinations of events or stages while retaining the ability to show sequences and, therefore, time delays. Although potentially very useful where these factors are important, it is necessarily more complicated than *fault tree* and *event tree analysis* and is not used widely.

DEFINITIONS

logic diagram	a representation of the logical combination or sequence of events leading to or from a specified state.
fault tree analysis	a method for representing the logical combinations of various system states which lead to a particular outcome (*top event*).
event tree analysis	a method for illustrating the intermediate and final outcomes which may arise after the occurrence of a selected initial event.
cause-consequence analysis	a method for illustrating the possible outcomes arising from the logical combination of selected input events or states.
top event	the selected outcome whose possible causes are analysed in a *fault tree*.
gate	a symbol in a logic diagram which specifies the logical combination of inputs required for an output to be propagated.

5.4 QUANTIFICATION OF EVENT FREQUENCY

The likelihood of an event occurring is normally expressed as a **frequency** of occurrence over a time period of interest (usually a year). This can be related to the number of occurrences over a sufficiently long period or a **probability** that the event will occur within a shorter period or in specific circumstances, eg a plant lifetime or **on demand**.

An event *frequency* may be estimated by the following methods:

- direct use of statistical data on the occurrence of similar events, requiring the number of events that have occurred and the total amount of experience to be known. This is sometimes called the historical approach;
- synthesis from the *frequencies* and *probabilities* of sub-events, eg component failures, by quantification of *logic diagrams*;
- a combination of the above approaches.

Availability of relevant data is often an important factor in selecting the approach to be adopted. The mathematical model for quantification of event mechanisms which include logic combinations is derived by use of Boolean algebra. The quantification process usually involves application of **reliability** engineering techniques. There is a wide range of terms specific to this field for which reference should be made to an appropriate source[5, 14].

If there are protective systems which provide safeguards against particular hazardous events, the *frequency* of the hazardous event depends on the *frequency* of *demands* on the protective system and the *probability* of the protective system being in a failed state *on demand*. The average *probability* for a protective system being unavailable is known as the **fractional dead time**. This utilizes a knowledge of the distribution of the failures, the test interval and repair times to obtain the fraction of time for which the system is unavailable for any reason.

Failure modes are often classified as fail-to-danger or fail-safe. In protective systems a **fail-to-danger fault** would make the protective action less likely in the event of a *demand*, while a **fail-safe fault** would usually result in spurious operation of the protective system, often causing an unnecessary shutdown. These terms can cause difficulties and it is often clearer to use more specific terms such as 'fail to closed position', 'fail to open circuit', etc.

Failures may also be referred to as 'revealed' or 'unrevealed', depending on whether their effects are immediately apparent. *Fail-to-danger faults* in passive protection systems are likely to be unrevealed in normal operation.

Where high reliability of engineered safety features is required, consideration may need to be given to building in **redundancy** and **diversity**. The analysis of failure *probability* for these types of systems must give attention to the possibility of failures of more than one component or system due to the same cause. Power failure or external events such as lightning or earthquake are examples of such **common cause failures**. Where this causes different items to fail in the same manner, the resultant failures are known as **common mode failures**. This commonality is only of interest if it results in items being in a failed state at the same time.

DEFINITIONS

frequency the number of occurrences per unit of time.

probability a number in a scale from 0 to 1 which expresses the likelihood that one event will succeed another.

reliability the probability that an item is able to perform a required function under stated conditions for a stated period of time or for a stated *demand*

.

demand	a condition which requires a protective system to operate.
fractional dead time	the mean fraction of time in which a component or system is unable to operate on *demand*.
failure mode	the manner in which a component fails.
fail-to-danger fault*	a fault which moves a plant towards a dangerous condition or limits the ability of a protective system to respond to a dangerous condition.
fail-safe fault*	a fault which results in no deterioration of safety.
redundancy	the performance of the same function by a number of identical but independent means.
diversity	the performance of the same function by a number of independent and different means.
common cause failure	the failure of more than one component, item or system due to the same cause.
common mode failure	the failure of components in the same manner

5.5 QUANTIFICATION OF EVENT CONSEQUENCES

There are three stages in the quantification of the possible consequences of a hazardous event. The first stage requires a model for the attenuation of the damage causing effect (eg *toxic* concentration, *explosion overpressure* or *thermal radiation*) over time and distance. The second stage utilizes knowledge of the critical levels of *exposure* (eg a dose-effect relationship) to obtain a relationship between degree of damage and distance, often known as the **hazard range**. This may be a maximum distance for a particular level of damage (eg fatal injury) or may be a relationship between distance and *probability* or degree of damage or injury. **Vulnerability model** is a term used to describe the mathematical models adopted to combine these two stages of the quantification of event consequences.

There may be different outcomes from a hazardous event depending on the prevailing circumstances. In the third stage of consequence quantification, the results of the *vulnerability* model are applied to the particular case under consideration (eg plant layout, personnel or population distribution) with probabilities allocated to variable factors such as wind direction, weather conditions and occupancy. The result is a relationship between *probability* (conditional on the occurrence of the hazardous event) and the extent of detriment, usually expressed as the number of people suffering a specified degree of harm.

The product of the event *frequencies* and the conditional *probabilities* gives the *frequency* at which numbers of people would be harmed by the event. Summation of the *frequencies* for particular numbers of people over all events gives the overall relationship between the number of people affected and the *frequency*, ie the *societal risk*. This is often expressed as an **F-N curve** showing the cumulative frequency at which N or more people are affected.

This presentation is adopted as it is not particularly useful to state the chance of killing exactly 10 people rather than 9 or 11. Besides giving a misleading impression of the accuracy of such a calculation, it is actually the chance of all accidents larger than certain sizes which is usually of interest.

The *frequency* at which an individual at a particular location would be harmed by an event, is obtained from the product of the event *frequency* and the conditional *probability* for the specified degree of harm at that location. Where more than one event has the potential to harm the individual, the *individual risk* is obtained by summation over all such events.

DEFINITIONS

hazard range	the relationship between distance from the source of *hazard* and detriment.
vulnerability model	the mathematical models applied in the estimation of *hazard range*.
F-N curve	a plot showing, for a specified *hazard*, the *frequency* of all events causing a stated degree of harm to N or more people, against N.

6. CRITERIA

In assessing the performance of any plant, works, site or industry, it is essential that we have a measure against which to judge its adequacy. The general term for such a measure is **criterion** (plural **criteria**).

Criteria may be used either in the predictive mode, that is to assess the need for action against some predicted *risk*, or in the historical mode to assess actual recorded performance. They are generally quantitative statements expressed as the *frequency* of a specified undesired event. In setting *criteria*, it is essential that the units chosen are consistent with available techniques for prediction or measurement, and that the chosen value is within the limits of credible use of those techniques, otherwise no valid comparison can be made. In the field of *hazard* and *risk* assessment, *criteria* are set as standards of safety performance which may be used to indicate situations where expenditure or procedural changes are necessary. An organization may set *criteria* for itself or be guided by some external body.

Criteria based on *risk* alone can only provide general guidelines. The accuracy of assessments is generally only to an order of magnitude precision and so *criteria* cannot be applied rigidly. The law in the UK requires adoption of 'reasonably practicable' measures to prevent accidents, which means implementing such measures unless the reduction in *risk* is insignificant in relation to the sacrifice necessary to achieve it. Although this can involve emotive issues, implicitly or explicitly putting a value on human life and suffering, cost-benefit aspects are an important element in taking decisions. However, it is useful to set *risk* targets for designers in order to encourage development of economical ways of limiting risk. Several ways of including these concepts in *risk criteria* have been proposed. One approach involves setting a limiting *risk criterion* which must be achieved; costs, *risks* and benefits are considered only once this target has been met. A second, insignificant level of *risk* may also be set as a very stringent target beyond which further reduction in *risk* would be unlikely to be justifiable. This type of compound *risk criterion* is known as a **two boundary criterion**.

The most common criteria used in hazard and risk assessment are those associated with fatal accidents. These can relate to major incidents where multiple fatalities could occur or to those incidents where the possible consequences are limited. In the case of multiple fatalities, these are often expressed as **societal risk criteria** to give an indication of the impact on the local population of a catastrophic event. Because of the difficulty of accurately predicting the number of fatalities in any particular event, it is sometimes convenient to consider **major incident criteria** instead. In this case, a number of categories of incident are defined with a range of consequences in each category. The categories are chosen to be consistent with the discriminating power of the assessment technique. *Frequency criteria* can then be ascribed to each category.

The use of 'fatal accident *criteria*' is sometimes seen as being over-precise, especially when the relative susceptibility of different members of the general public would make a difference to the assessment. In this respect the Health and Safety Executive have published risk criteria for use in relation to land use planning decisions[20]. These Criteria are specifically related to the assessment of a *dangerous dose* which allows for the variations in susceptibility of the general population. Further advice on the use of *risk assessment* in relation to decision making is given in another HSE publication[22].

Individual risk criteria are used where it is necessary to consider the distribution of *risk*. *Individual risk criteria* may be expressed either as peak values, to indicate where the *risk* is concentrated on one or very few individuals, or as average values where the *risk* is shared fairly evenly amongst the exposed population. Both peak and average values have their advantages. **Average individual risks** can be compared directly with statistics for other man-made and natural *risks* to achieve a good perspective on the size of the problem, while **peak individual risks** will indicate situations where a small sector of the local population carries a disproportionate amount of the total *risk*.

An example of such a *criterion* is the **fatal accident rate (FAR)** which is usually used in assessing *risk* to an exposed workforce rather than to a population outside a works. *FAR* is sometimes applied in the predictive mode to quantify the *risk* faced by an individual in a particular job. In this case, it is defined as the predicted number of fatal accidents per 10^8 hours of exposure to the *hazards* involved in that job. (10^8 hours is approximately equal to the working lifetime of a thousand people.)

Only rarely will any one of these *criteria* convey the whole picture alone and a thorough assessment will usually examine the situation against a number of them.

Terms which have been widely used in the past are acceptable *risk* and criterion of acceptability. At first sight, these seem attractive concepts because they suggest an absolute level of performance which, if achieved, would be acceptable and therefore would avoid much emotional debate. However, the word 'acceptable' immediately begs the question 'acceptable to whom?', and the debate in this area is no less emotional. The true value of quantitative assessment and *criteria* is not in trying to prove that a given situation is acceptable, but in improving decision taking by helping to put problems in perspective.

Acceptability is a much wider issue involving not just the quantitative assessment and *criteria*, but also the **perceived risk** as seen by those concerned. *Perceived risk* is the phenomenon of an individual interpreting the magnitude of a *risk* against the background of his own understanding. This background may be the result of extrapolation of his own experience or may be influenced by 'popular belief' as expressed in the media or by other interested parties. Thus the *perceived risk* may either exceed or fall short of the result of a quantitative assessment.

Perceived risk cannot be predicted and is often linked only loosely to measures taken to reduce the true *risk*. It will generally be influenced most directly by education or propaganda.

Thus, acceptability is most unlikely to be determined specifically by *hazard* and *risk assessment* and it is, therefore, strongly recommended that terms in the field of *criteria* which use the word 'acceptable' should be avoided.

DEFINITIONS

criterion	is a standard of performance with which assessed performance may be compared.
two boundary criterion	is a compound *criterion* with a lower standard which must be achieved and an upper standard as an ultimate goal.
societal risk criteria	*criteria* relating to the likelihood of a number of people suffering a specified level of harm in a given population from the realization of specified *hazards*.
major incident criterion	*criterion* (expressed as a *frequency*) for incidents falling within a defined category of consequences.
individual risk criteria	*criteria* relating to the likelihood with which an individual may be expected to sustain a given level of harm from the realization of specified *hazards*.
average individual risk	is the average chance of any individual in a defined population sustaining a given level of harm from incidents which are considered to be limited to that population.
peak individual risk	is the highest individual *risk* for any person in the exposed population.
fatal accident rate (FAR)	(previously known as FAFR) is the number of deaths that have occurred or are predicted to occur in a defined group, in a given environment, during 10^8 hours of total exposure.
perceived risk	is that *risk* thought by an individual or group to be present in a given situation

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INDEX

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