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Risk Assessment - Recommended Practices for Municipalities and Industry

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Foreword

This document was originally prepared by the Risk Assessment Expert Committee of the former Major Industrial Accidents Council of Canada (MIACC). However, it was not published prior to the dissolution of MIACC in 1999, but was transferred to the Canadian Society for Chemical Engineering (CSChE) as part of the work plan of the CSChE's newly-formed Process Safety Management division under which the Risk Assessment Expert Committee now operates. It is sincerely hoped that the information in this document, which provides introductory guidelines for users to consider and not standards or procedures that must be followed, will lead to consistent applications of risk analysis and assessment techniques across Canada.

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1. INTRODUCTION

1.1 BACKGROUND AND OBJECTIVE

The development of this guide took place under the auspices of the former Major Industrial Accidents Council of Canada (MIACC) before MIACC's dissolution in November 1999. The project was then transferred to the newly-formed Process Safety Management division of the Canadian Society for Chemical Engineering (CSChE). The information below describes the development of the guide in the context of other work taking place under MIACC. The documents referred are now available either through the Canadian Association of Fire Chiefs' *Partnerships Toward Safer Communities* initiative or the CSChE.

During 1988-1992, the MIACC Working Group 1 (then Risk Assessment Expert Committee) developed a simplified *risk analysis* methodology (referred to as Version 1 below), which formed the basis of the 1994 *MiniGuide for Hazardous Materials Risk Assessment for Municipalities and Industry* (MIACC, 1994)[1]. The full supporting documentation for the Version 1 methodology explaining its scientific basis, and also providing basic information on the risk management process, has been published as *Risk Assessment Guide for Municipalities and Industry* (MIACC, 1997). The focus of these documents was to provide guidance in land-use planning and siting decisions.

The 1994 MiniGuide covers both the risk *analysis* and risk *evaluation* components of risk *assessment*:

1. The simplified risk *analysis* component of the 1994 MiniGuide is based on:
   - Use of the MIACC hazardous substances list for *hazard identification*, assuming that all hazardous events that can occur at a simple hazardous installation can be represented by two types of events (*large* and *small* releases);
   - The Dutch Guide (1988) enclosures for *consequence analysis*;
   - Assumed representative incident frequencies for *frequency analysis*; and
   - A two-point approximation of the individual risk profile (risk versus distance from risk source) for *risk estimation*.
2. The risk *evaluation* component is based on allowable individual risk levels for different levels of population density (implied by land use; see Figure 1.1).

The 1994 MiniGuide furthermore provides results of applying the Version 1 methodology to simple installations, in terms of tables of “exclusion” and “no restriction” distances for land use around such installations.

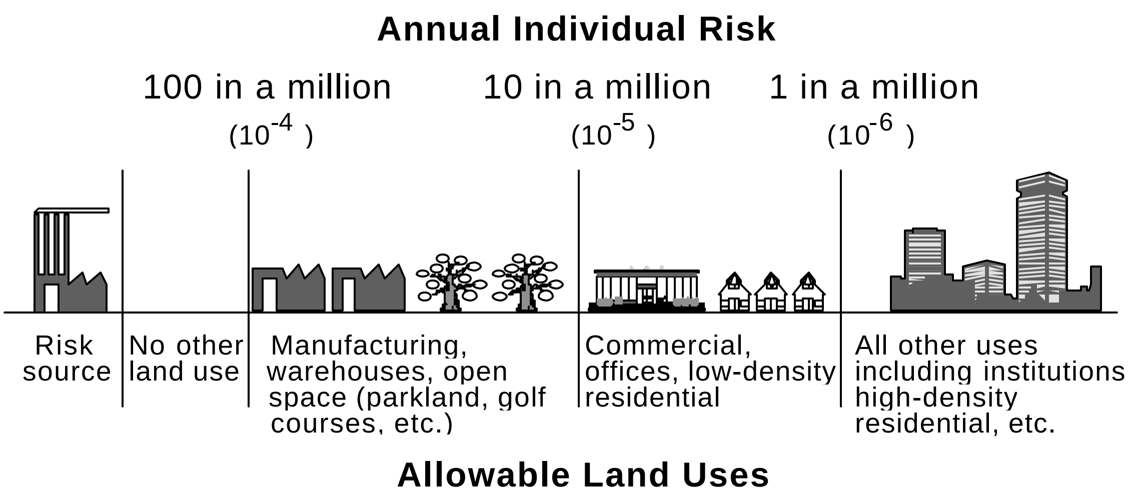
The Version 1 simplified risk *estimation* method (i.e., the method of combining hazardous event frequency and consequence information to quantify risk) is not well suited for some hazards such as explosions and BLEVEs (Boiling Liquid Expanding Vapour Explosions), as well as for non-point risk

[1] Full references are given in Section 9 at the end of this document

sources such as dangerous goods transportation corridors and pipelines. Furthermore, the consequence analysis techniques (based on the 1988 Dutch publication) have become out-of-date.

The objective of the present document is to describe a more advanced methodology for *risk analysis* that will be applicable to a much broader class of hazards and risk sources. Its focus is still to provide guidance in land-use planning and siting decisions, although many of the techniques discussed can also be used in a range of other applications such as design of hazardous installations and emergency response planning.

Figure 1.1 MIACC's Risk Acceptability Criteria



The present document hence provides guidance on the techniques for analyzing major accident risks from hazardous substances. As such it is analogous to the *Risk Assessment Guide for Municipalities and Industry,* which described the scientific basis of Version 1 methodology. All the limitations identified for Version 1 have been addressed in this version. The updating of the MiniGuide using this advanced methodology has not yet been undertaken, due to resource availability for this heavily modelling-oriented task. **The *risk evaluation* component (i.e., the risk acceptability guidelines shown in Figure 1.1) remains the same as in Version 1.** (Note that the intent of the MiniGuide is for use as a screening tool for facilities with a single hazardous material that might impact the public.)

This guideline establishes a scientifically defensible and self-consistent risk analysis methodology, applicable to point as well as line sources of risk. The end point of the analysis is estimation of an appropriate risk measure (i.e., "individual risk" - see below) to be used in conjunction with the risk acceptability guidelines (Figure 1.1) for risk evaluation.

However, it should be borne in mind that the process of going through the risk analysis is probably just as important as, or perhaps more important than the calculated end point. The application of the process provides much insight to the factors contributing to the overall risk of a hazardous facility, and thus points to effective risk control measures. The intermediate steps in the analysis can be used for identifying and prioritizing risks, and thus develop risk reduction measures, without the need to carry the quantitative analysis to its end point.

1.2 INTENDED USE OF THIS DOCUMENT

This document is intended to guide municipalities and industry in *conducting* or *evaluating* the technical risk analysis portion of risk assessments. With reference to Section 2, the General Risk Management Framework, the stakeholder participation/risk communication component, which plays a crucial role in risk evaluation, is not covered by this guide.

For experienced risk analysts this is a working document or tool. For the layperson this document is a reference work and should enhance the ability of a layperson to judge when to enlist the advice of an experienced risk analyst. For example, a proponent would use the techniques recommended here for preparing a risk assessment for a proposed development. The decision-maker, often a layperson in technical risk analysis matters, would evaluate the *applicability* of the assessment by comparing the techniques used in the assessment against the techniques recommended here. Evaluation of the *quality* of the assessment should be done by an experienced risk analyst.

These risk assessments (or individual components of a risk assessment, such as consequence analysis) might be undertaken to assist decision-making in:

- Land use and route planning, e.g.,
  - Hazardous facility siting or expansion,
  - Hazardous material pipeline or transportation route planning,
  - Approval of land developments near existing hazardous installations,
- Facility safety management, e.g.,
  - Technology changes,
  - Facilities improvement, or
- Incident management, e.g.,
  - Emergency preparedness,
  - Emergency response.

This document thus forms the basis of a national guideline to promote consistent application of risk assessment techniques across different industrial sectors and regions across Canada.

It should be borne in mind that quantitative estimates of risk carry with them large uncertainties, depending on the quality and detail in the analysis. It is the responsibility of the risk analysts to select the approaches appropriate to their situation and defend their work. The present document provides minimum requirements in conducting risk assessments to ensure a level of consistency in accuracy of risk estimates. Thus, when used with the risk acceptability guidelines, the set of risk analysis methods (hazard identification, frequency and consequence analysis, as well as risk estimation methods) recommended here form a complete and self-consistent set.

This document is *not* intended to replace the accepted practices of process safety management as described in other documents such as those published by the Canadian Society for Chemical

Engineering, Canadian Chemical Producers' Association, American Petroleum Institute and Center for Chemical Process Safety.

The intent of the document is to provide guidance for quantitative estimation of the appropriate parameters characterizing risk of hazardous substance accidents to human populations.

Also, it should be understood that the MIACC risk acceptability criteria are not intended to replace any commonly used land-use practices (such as adequate emergency egress, fire hydrant density, road allowance, parks and open space, noise, and other environmental considerations). They should be applied as an additional consideration, to take into account the special hazards of a given facility.

1.3 SCOPE

This document provides recommended practices on how to analyze risks of hazardous installations. It describes qualitative, semi-quantitative and quantitative methods of risk analysis and evaluation.

There are many different types of risk, such as individual versus societal risk, acute (safety) versus chronic (health) risk, and from a receptor perspective, such as risk to human receptors, other environmental receptors, equipment, or property. One can also consider risk in terms of financial impacts.

This document focuses on:

- Individual risk as the calculation end-point (see the previous section and Section 2.1), although societal risk considerations are built into the risk assessment methodology through the risk acceptability guidelines (see Section 2.2), and the methods recommended here can be readily extended to estimation of societal risk (see Appendix A4),
- Acute risk of fatality from hazardous material accidents in terms of their immediate safety impact on human populations, as opposed to:
  - injury or long-term impacts of such accidents, or
  - long-term health impacts of routine hazardous materials releases into the environment,
  - immediate or long-term impacts on environmental receptors or property (although many of the techniques presented are equally applicable or readily extendible to characterizing acute risks to property or the environment), or
  - property damage/business interruption.

For consistency with the intent of the risk acceptability guidelines, risk is estimated for a receptor that could be exposed to the hazards of the accident at the time that it occurs; probability of existence of that receptor at the time of the accident is not included in the calculation. This consideration is built into the definition of individual risk in Section 2.1. Thus, in health risk assessment terminology, the present methodology focuses on the estimation of the source, pathway, and vulnerability aspects of risk and not on exposure probability in terms of whether a receptor is present or not at the time of the accident.

The techniques described in this guide are generally applicable to point and line sources of risk. Point sources of risk include chemical plants, distribution terminals, storage facilities. Line sources of risk include transportation corridors for pipelines, rail, truck, air, and marine tanker routes.

The terminology used in the document is consistent with existing Canadian standards in the field of risk assessment and management (CAN/CSA-Q634, CAN/CSA-Q850).

2. THE GENERAL RISK MANAGEMENT FRAMEWORK

2.1 DEFINING AND CALCULATING RISK

Risk is defined as a measure of frequency <u>*and*</u> *severity of harm due to a hazard.* The hazard in our context is the presence of hazardous materials having toxic, explosive, and/or flammable characteristics with the potential to cause harm to humans (and property or the environment if a broader context is considered). In the context of public safety, risk is commonly characterized by fatalities (and injury) to members of the public.

Safety is relative; it is a judgement of the acceptability of risk: an activity is considered safe if its risks are considered acceptable. This definition of safety emphasizes the decision-making process. It recognizes that there is no such thing as "zero risk" because no matter what precautionary steps are taken, there is always some chance of an accidental release of a hazardous substance and a chance that someone will be adversely affected. The objective of risk management is to prevent or reduce the illness, injury or loss of life (or damage to property or the environment) due to the operation of facilities, such as chemical plants, which handle hazardous materials, or transportation corridors with dangerous goods traffic.

Risk, by definition, includes a consideration of both the likelihood and severity of an event. However, in dealing with sources of risk, discussion very often focuses only on the consequences of a major event such as a catastrophic release from a rail tanker, ignoring the frequency of the event. Although the consequences of a worst-case event may be high, the chance of this event happening must not be excluded from the decision making process.

The common and convenient measure of risk due to a specific hazardous event is calculated by:

$$\text{Event Risk} = \text{Event Frequency} \times \text{Event Consequence}$$

There are many possible hazardous events for any facility, which depend on the quantity and nature of chemicals present, the type of vessels, piping, and valving, and loading/unloading operations, etc. Each possible hazardous event contributes its share to the overall "facility risk", which is calculated by summing the risks of all possible events that could occur in the facility. In order to simplify the risk analysis, events with similar consequences are usually considered in groups.

Public risk can be considered from an individual and a societal perspective.

Individual risk of fatality is the chance (in any year) that a person near a hazardous facility might die due to potential accidents in that facility. This person is usually assumed to remain at the same unsheltered location for purposes of analysis and comparison against the risk acceptability guidelines of Figure 1.1. Hence, individual risk is also sometimes referred to as geographical or positional risk. Since the severity of impact of accidents usually decreases with distance from the risk source, the individual risk (of fatality) will decrease with distance. The variation of individual risk around a facility is usually presented on a map in terms of constant risk lines or contours. Other factors, depending on the nature of the accident, such as wind direction, topography, climatic conditions, all affect the risk zones and hence the risk lines.

The MIACC risk acceptability guidelines use individual risk of fatality as the basic risk measure. Societal risk is also used in some jurisdictions. A description of this parameter is provided here as general background information for Canadian readers.

Societal (event) risk is the annual expected number of fatalities for the event (the product of event frequency and consequences in terms of the number of potential fatalities if that event occurs). Societal facility risk is the total expected number of fatalities in a year due to a hazardous facility and is estimated from all possible events that could take place at the facility.

Whereas individual risk <u>is not</u> generally dependent on the actual number of people living in the area, societal risk <u>is</u> a function of population density, i.e., societal risk will increase with increasing number of people exposed to the risk source.

Societal risk can also be thought of as the number of people exposed to given levels of individual risk (i.e., the number of people within the individual risk contours). Societal risk information is sometimes presented graphically showing the relation between event frequencies and the number of people that could be affected by each event. These graphs are called "FN Curves", where N is the number of fatalities and F is the cumulative frequency of events with N or more fatalities. These graphs show the range of multi-fatality accidents possible.

2.2 EVALUATION OF RISK ACCEPTABILITY

Acceptability of risk depends on the nature of the risk and on those who may bear it. Broadly, there are levels of risk that people will accept, and other levels that they will not. Every person faces risk in every aspect of their life, some voluntarily, some imposed. *Voluntary risks* are those we assume due to some perceived benefit, e.g., smoking, sky-diving. *Involuntary risks* are imposed on people by decisions made by others or by natural occurrence, e.g., second-hand smoke, violent storms. Generally, individuals will adjust behaviour or activities to reduce voluntary risks to an acceptable level, but for imposed risks they may have no degree of control or influence. Therefore, acceptable levels for involuntary risks are usually lower than voluntary risks.

Adjusting risk levels often implies costs (of risk reduction activities) that may be borne by persons other than those who bear the risk. As well, benefits (of reduced risk) are often attributed to persons other than those who bear the costs. The levels of costs and benefits as well as who bears or receives them will affect the acceptability of risk.

The judgement of risks means that "acceptable" risk levels will vary with the benefits and costs no matter how they are calculated and by whom. “Acceptable” risk levels include levels of risk which are considered “negligible” as well as those which are considered “tolerable.” Generally, risks considered to be negligible do not require control measures. Tolerable risk levels are higher than negligible risk levels, but are accepted only if all reasonable and practicable (cost-effective as judged by stakeholders) control measures are implemented to reduce risk.

Risk acceptability criteria are often based on the premise that the risk being evaluated should not make a substantial addition to existing risk of everyday life. An increase of 1% in the individual risk of death due to a specific hazardous activity is the basis of many criteria of not-acceptable or intolerable risk. Acceptable or tolerable risk criteria are factors of 10 to 100 less than for not-acceptable risk. Between “not-acceptable” and “tolerable” risk levels, risk reduction is *required*. Between the "tolerable" and "negligible" risk thresholds, risk reduction is desirable and should be implemented if deemed cost-effective by the stakeholders. The reduction in risk levels is achieved by taking risk control measures (see below).

Individual risk is often expressed in terms of an annual probability of death for the exposed person. An annual probability (or chance) of death of one in a million is often taken as an acceptable level—this value is generally written as 10^{-6} per year. A commonly used level for unacceptable annual probability of death is one in 10,000 (or 100 in a million)—which is written as 10^{-4} per year. Some jurisdictions have also developed acceptability criteria for societal risk. These are commonly based on the use of FN curves.

In Canada, the Major Industrial Accidents Council of Canada (MIACC) developed the risk acceptability criteria presented in Figure 1.1. These criteria are specified in terms of allowable land-uses for specified levels of individual risk. Existence of adequate emergency response plans and ease of evacuation should be considered in addition to these guidelines. Note that this approach also implicitly provides a guideline for allowable societal risk in one simple statement, and does not require the use of separate societal risk acceptability guidelines using FN curves.

The MIACC criteria do not have any regulatory status and can be used as guidelines only. As such, it is important to involve the stakeholders who are risk receptors for a given hazardous installation in land-use decisions around that risk source (see the discussion below on Risk Management Process).

According to the MIACC criteria, no other land use other than the risk source (i.e., facility, pipeline, corridor) should be allowed within the 100-in-a-million (10^{-4}) annual individual risk zone. By implication, for on-site personnel, higher risks are acceptable. Between 100-in-a-million (10^{-4}) and 10-in-a-million (10^{-5}), uses involving continuous access and the presence of limited numbers of people but easy evacuation, e.g., manufacturing facilities, warehouses and open spaces, are allowed. Between 10-in-a-million (10^{-5}) and 1-in-a-million (10^{-6}), uses involving continuous access but easy evacuation, e.g., commercial uses, offices, and low-density residential areas, are permitted. Below 1-in-a-million (10^{-6}), development is not restricted in any way, including institutional uses and high-density residential areas.

In order to put these numbers into perspective with respect to everyday experience, information on some common risks is provided in Appendix A1.

It is understood that all these neighbourhoods should be designed in accordance with all the common land-use planning practices in terms of emergency egress, fire hydrant density, road allowance, parks and open space, noise, and other environmental considerations. MIACC criteria are not intended to replace any of these practices, but to be applied as an additional consideration.

2.3 THE RISK MANAGEMENT PROCESS

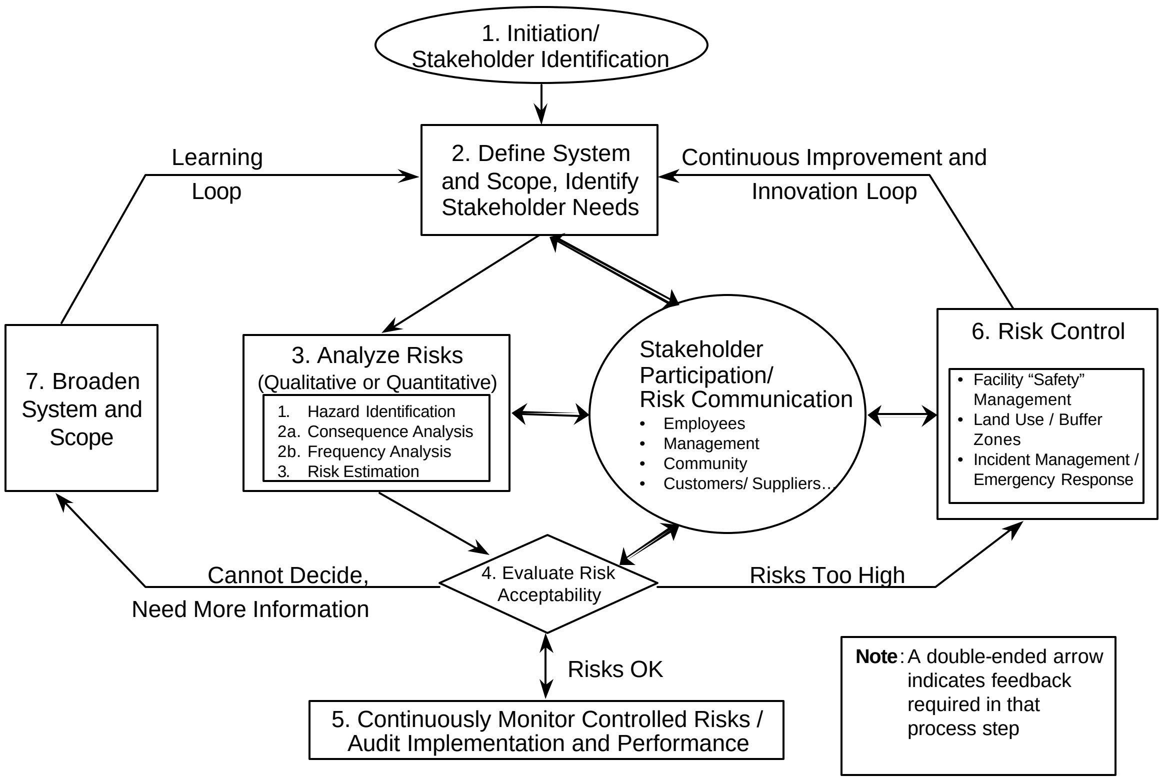
The process of estimating the risks of a facility, judging its safety, and developing risk control measures if required, comprise the risk management process. The steps in the risk management process are shown in flow chart form in Figure 2.1.

System description consists of understanding the components of the facility and how it operates, establishing an inventory of hazardous substances used, transported, and manufactured, and being familiar with the surrounding area that might be affected by hazardous events in the facility, in terms of population, land-use, and climate, etc. Examples of hazardous facilities are chemical plants, refineries, and transportation corridors such as rail corridors, pipelines or waterways where dangerous goods are transported.

Other important components of the *system* that must be understood by the risk assessors and decision-makers include the applicable health, safety, and environmental laws and regulations, and the values of the stakeholders. The latter can only be accomplished by early involvement of the stakeholders in the decision-making process.

Hazard identification answers the question: *What can go wrong?* Potentially hazardous events are identified and defined in this step. For example, the realization that one can get hit by a car while crossing a street, and that one could die or become injured as a result of this accident, constitutes the hazard identification step.

Figure 2.1 The Risk Management Process



Before risk can be managed, it must be understood. *Risk analysis* helps to understand the risk of a hazardous facility and the reductions in risk achievable given certain risk control measures. It answers the following questions for the identified events: *How often is the event expected to occur?* (frequency analysis) and, if it occurs, *What are the consequences of the event?* (consequence analysis).

Frequency analysis makes use of *historical data* in similar facilities. Fault and event trees are also commonly used in frequency analysis to assist in keeping track of cause-effect relationships, and system and material behaviour characteristics.

Consequence analysis consists of modelling the behaviour of releases of hazardous substances, and their impact on critical receptors making use of *dose/response (vulnerability) data* and models.

Risk estimation is the process by which the frequencies and consequences of events are combined to quantify risk. The results of risk analysis are used extensively in risk management decisions throughout the world.

The uncertainties in estimating the likelihood of rare events, and in projecting the effects on human populations, are considerable. However, high uncertainty does not mean high risk. Typically, conservative assumptions are made to avoid underestimation of risk. Estimation of uncertainties in risk estimates is currently an area of active research.

Risk evaluation answers the questions: *Is the risk judged by the stakeholders to be acceptable?*, and, *Do we need to do anything about it?* Whether we judge a risk to be small or large, acceptable or unacceptable depends on many factors. A hazardous facility is often seen as posing an involuntary risk to someone living nearby (especially if the facility is built after the person starts living there) but it might be seen as a voluntary risk if someone chooses to live near an existing facility provided that the person is aware of the risks before moving there. The MIACC risk acceptability criteria are designed for cases of involuntary risk resulting from hazardous facilities. They are intended to be used as public safety guidelines.

The combined process of risk analysis and risk evaluation is usually called *risk assessment*.

If the risks are judged to be acceptable, then further risk control measures, or system changes, will not be required. However, it is then essential to develop programs to *monitor* the situation so that it does not deteriorate over a period of time. *Safety audits* are among the tools used for this purpose.

If it is judged that further safety improvements are required, risk control options introducing system modifications need to be examined.

Risk control answers the question: *What can be done to reduce the risks if we need to?* Risk can be reduced by decreasing the likelihood and/or consequences of hazardous events. Risk control measures can be broadly classified into:

- Safety management of the hazardous facility; this includes process safety management practices, such as technological measures (e.g., design changes and inventory reduction), risk elimination (avoidance), risk transfer (insurance), and management measures (e.g., auditing, inspection, maintenance, training and work practices),
- Incident management, such as emergency response, emergency response plans and exercises, and
- Land-use restrictions.

The "facility safety management" type of risk control measures can generally only be taken by the company operating the hazardous facility. In our context of major industrial accidents, process safety management is probably the most important component of “facility safety management”. Incident management issues are generally addressed by municipal fire departments or hazardous materials teams in co-operation with the operators of the facility. The third type of risk control measures are addressed by municipal planners, often in consultation with all stakeholders, including operators of the hazardous facilities. (More detailed guidance on various risk control measures is beyond our present scope and can be found in other MIACC publications).

Risk control measures will have certain costs associated with them. By estimating the risk reduction possible for each option, it is possible to assess the costs and benefits for each option, and informed decisions on which option should be selected can be made on this basis.

Risk management is the process by which the risks associated with hazardous activities are estimated, evaluated for acceptability, and, if required, reduced using risk control measures. The importance of *stakeholder participation/ risk communication* in the risk management process cannot be overemphasized. Identification of the stakeholders in any given situation, communication of the risks to employees, the public, and other stakeholders exposed to these risks and their participation in understanding the risks and commenting on risk control measures, are essential to ensure buy-in from the stakeholders regarding the acceptability of the risks and risk control measures that would be implemented.

Industrial operators and developers are strongly encouraged to learn more about risk communications and its role in the risk management process. Project acceptability will depend as greatly on stakeholder analysis/ involvement as the technical analysis.

More detailed guidance on how to identify the relevant stakeholders, understand their needs, and how to ensure their participation in the decision-making process is beyond the scope of this technical guidance document which focuses on the risk analysis component of the process. The MIACC Safer Communities initiative[2] is aimed at developing a forum for this purpose.

At the MIACC Annual General Meeting in October 1997, the membership supported the launching of the "Partnerships Toward Safer Communities" initiative. A Safer Community is one where all stakeholders within a community are working together in partnership to continuously reduce the risk form major industrial accidents involving hazardous substances. This is achieved through facilitating co-operative efforts by all partners towards the delivery of joint industry-community programs for public safety, plant safety, and environmental protection at the community level.

The goal of the Partnerships Toward Safer Communities Initiative is to establish Joint Coordinating Committees (JCCs) in MIACC List 1 communities to implement major hazard measures, and to instil sound Process Safety Management practices in these sites. The MIACC publication "Guiding Principles on Joint Community and Industry Emergency Preparedness" provides guidance on establishing a JCC within a community.

2.4 UNCERTAINTY IN RISK ESTIMATES

Risk analysis results are derived from the processing of large quantities of information obtained from numerous scientific fields. Some of these can be highly subjective, incorporating numerous assumptions. In addition, they are based on limited and "imperfect" data. There are many uncertainties in the process. These can be described as:

- Uncertainties due to inherent variabilities in the physical systems that we study
- Modelling uncertainties
- Input data uncertainties

[2] now the Partnerships Toward Safer Communities initiative of the Canadian Association of Fire Chiefs – see the website www.ptsc-program.org for current information on this initiative and related activities.

- Uncertainties pertaining to the degree of detail – more detail requires more effort and therefore greater cost
- Uncertainties pertaining to the analyst(s)' lack of experience or lack of knowledge in one or more areas of the risk analysis

Typically, conservative assumptions are made to reduce the level of effort required and to err on the safe side (i.e., have confidence that risk is overestimated). However, if uncertainties are too large, the results of the analysis may be meaningless. The best risk analyses are those that yield results from which meaningful conclusions can be drawn, but completed for the lowest possible cost. These studies require a comprehensive understanding of the factors that affect the results and the strategic use of realistically conservative assumptions.

3. HAZARD IDENTIFICATION - "What can go wrong?"

3.1 INTRODUCTION

The process of **Hazard Identification** answers the fundamental question, "What can go wrong?". Hazard Identification is the first of several elements in the process of **risk analysis**. Its prime purpose is to identify hazardous events which can lead to undesirable consequences.

The output of the Hazard Identification phase of a risk analysis should be a list of unique accident scenarios for which both scenario frequency and scenario consequences can be estimated. Each scenario will represent a range of conditions. The "finer" the analysis, the more accident scenarios that will be identified. This will reduce the uncertainties but increase the cost.

When selecting the hazardous events for quantifying risks, it is important to include a range of scenarios, from a worst possible case to more realistic scenarios. The significance of these scenarios within the risk context is then put into perspective by analyzing the frequency of these events.

In order to identify hazardous events it is necessary to:

- Establish the undesirable consequences of interest, and
- Identify the material, system, process and facility characteristics that can produce these undesirable consequences.

Undesirable consequences may include human, environmental and economic impacts. One must consider not only the potential for hazardous events to occur but also the existence and location of receptors.

For the purposes of this guideline, the undesirable consequences are defined in terms of fatality of a member(s) of the public from hazardous events such as fires, explosions and toxic gas clouds.

Using fatalities as the measured consequence provides a consistent basis for:

- Analysis, and
- Comparison against the MIACC risk acceptability criteria, which are stated in terms of annual chance of fatality due to potential hazardous events in a nearby facility.

In addition to the consequence of public death, hazardous events could have wider ranging consequences. These could include human impacts other than public fatality (such as public or on-site personnel injuries) and impacts associated with environmental (such as contaminated drinking water resulting in long term health effects, e.g., cancer) and economic factors (such as lost production, equipment damage, loss of resource use).

Although the main focus of this guide is public safety, many of the techniques described here are generally applicable to these broader risks.

3.2 IDENTIFICATION OF MATERIAL, SYSTEM, PROCESS AND FACILITY CHARACTERISTICS THAT CAN PRODUCE THE CONSEQUENCES OF CONCERN

Once the undesirable consequences of interest are established, the next stage of the Hazard Identification process is to identify the material, system, process and facility characteristics that could produce these undesirable consequences.

A three-step process is recommended for this purpose:

Step One - Identify the hazardous substances (and their location)

Step Two - Gather hazardous substance information

Step Three - Identify specific events which can lead to hazardous substance release

Step One - Identify hazardous substances

MIACC has developed a list of hazardous substances and threshold quantities at, or above which, a risk assessment is recommended as a matter of priority (MIACC, 1994)[3]. The list was developed from the collective experience of a MIACC Technical Working Group focused upon the release of hazardous substances which could endanger the public.

As described in the MIACC Lists, the presence of a substance at an industrial site in a greater quantity than its stated threshold quantity does not necessarily indicate the existence of an unacceptable risk to the public. It simply signifies that the presence of the given quantity of the substance merits an assessment to estimate the risk. Equally, the identification of a site with a substance (or substances) below the threshold quantity does not indicate that the site necessarily presents an acceptable risk; it indicates that under typical circumstances the assessment of such sites can be a lower priority than sites with more than the threshold quantity, unless there is some other factor that would suggest an earlier risk assessment should be done (e.g., a history of releases, spills or accidents at the site).

The MIACC Lists are categorized into Priority Hazardous Substances, Hazardous Substances and Environmentally Hazardous Substances. The listing of these substances and their threshold quantities is intended to help local authorities and industry identify sites which represent the greatest potential risk to the community. This will provide a basis for the prioritization of accident prevention activities and emergency response planning. It is recommended therefore that, in order to efficiently identify the highest risks, the MIACC Lists be used in the following priority:

Priority One: Sites at which substances of MIACC List 1 (Priority Hazardous Substances) exist in quantities at, or exceeding, the threshold quantities shown therein.

Priority Two: Sites at which substances of MIACC List 2 (Hazardous Substances) exist in quantities at, or exceeding, the threshold quantities shown therein.

[3] the lists developed by MIACC are being currently revised and incorporated into regulation under section 200 of the Canadian Environmental Protection Act 1999 – for more information see the website www.ec.gc.ca/CEPARegistry/

Priority Three: Sites at which substances of MIACC List 2 (Hazardous Substances) exist in any other quantities.

Priority Four: Sites at which substances of MIACC List 3 (Environmentally Hazardous Substances) exist in quantities at, or exceeding, the threshold quantities shown therein.

Priority Five: All other sites at which potentially hazardous substances are handled.

Though such a list is not comprehensive, nor could it ever be, it should provide an initial guide to those seeking locations of hazardous substances which present a potential risk.

Step Two - Gather hazardous substance information

Once the hazardous substance and the location have been identified, all information relevant to the materials, systems, process and facility characteristics should be gathered. The typical information required includes:

- Material properties
- Quantities
- Operating conditions
- Storage, transportation and processing facility design details (including mechanical features, metallurgy, etc., which could lead to failure, and special safety features which could reduce the risks associated with the facility)
- Operating and maintenance instructions and procedures

It is strongly recommended that all of this data be collected and documented before analysis of the material, system and facility release characteristics begins.

Material Properties. Material properties consist of physical, thermodynamic, and health effects properties of materials. The are required to characterize the release, atmospheric transport/combustion, and health effects. The information should include the usual physical state of the substance (solid, molten, liquid, gaseous or liquefied gas), and hazardous properties such as autoignition temperature, exposure limits, etc. The MIACC Lists contain some of this information and references to other sources. The Material Safety Data Sheets (MSDS) required by the Workplace Hazardous Materials Information System (WHMIS) regulations will also provide a source of material data.

Quantities. The capacity to store and process hazardous substances is determined by assessing the physical characteristics of the storage, transportation and processing facilities. The quantities of hazardous substances therein are determined by operating conditions and practices. It should be recognized that in assessing risk, the potential to have greater than normal operating quantities during upset conditions should be identified. The data may be obtained from visiting the site, reviewing storage and transportation records, and reviewing the physical facility design characteristics.

Operating Conditions. The operating conditions must be known in order to characterize the release. Age of the facility is an important characteristic to consider at this stage, since it may influence frequency of releases. Operating conditions of pressure and temperature (and phase), in combination with the fundamental physical material properties, will influence the release and dispersion characteristics of the substance. For continuous production and transportation (e.g. pipelines), transfer rates should also be documented.

For manufacturing and processing facilities, the quantities and operating conditions may be obtained from the process flow diagrams, material balance sheets, and operating manuals/ procedures.

Facility and transportation system design details. This data is required to analyze the mechanical, electrical, structural, control and other physical characteristics which can lead to a release. For processing facilities, such as chemical plants or oil refineries, much of this data may be found on the Piping & Instrumentation Drawings (P&ID's). This type of drawing may also provide information on the normal process flows and operating conditions.

The quantity and nature of design information required will be influenced by the technique selected to identify specific release events (see step four). For example, if it is determined that a Hazard and Operability (HAZOP) technique is to be used, then P&ID's will be mandatory. If, however, a Checklist technique is to be used, P&ID's may not be required.

The data pertaining to the design of storage, transportation, and processing facilities will help in the analysis and identification of the physical characteristics which can lead to a hazardous substance release.

Operating, testing and maintenance instructions and procedures. The data identified above places emphasis upon the physical conditions which can lead to a release. However, consideration must also be given to the human aspects of operations and maintenance. Historical data, supported by research, indicates that the root causes of many releases are founded upon human errors. It must also be recognized that releases can have multiple causes.

Systemic influences, such as management systems and safety culture, can manifest themselves in operating, testing and maintenance procedures and practices and thus significantly influence the frequency of hazardous substance releases. In order to establish the influence of these factors upon the potential for a hazardous substance release, it is essential that documented operating and maintenance practices be reviewed, in conjunction with an assessment of the manner in which these practices are implemented on a routine basis through interviews with operating and maintenance staff. There may also be value in reviewing management audits.

Step Three - Identify specific events which can lead to a hazardous substance release

After identification, location, and data gathering of hazardous substances, the final step is to identify the specific events which can lead to the release of a hazardous substance. This is the last analysis required to answer the question "What can go wrong". There are a number of well established techniques that can be applied to systems, processes, and facilities in order to identify specific events which could lead to the release of a hazardous substance. The following techniques are the most common:

- Safety Reviews
- Checklist Analysis
- What-if Analysis

- Failure Modes and Effects Analysis (FMEA)
- Hazard and Operability Analysis (HAZOP)

These methods are described in more detail in numerous references (e.g., CCPS, 1992). Each method has characteristics which make it more, or less, appropriate to specific hazard circumstances. After consideration of the specific hazardous substances and the nature of the facilities, the most appropriate technique should be selected. The various techniques with an evaluation of their advantages and disadvantages as hazard identification tools are reviewed in the following pages.

It should be noted that fault and event trees (without quantification of frequency or probability of each branch) could also be used as detailed hazard identification techniques. Specifically, fault trees are used for understanding possible causes of a release, and event trees are used for developing possible hazard outcomes following a release. Since their use is more commonly associated with frequency analysis, they will be covered as part of that topic later in this document.

Safety Review

The purpose of a Safety Review is to identify facility conditions or operating practices or procedures that could lead to an accident. It is the simplest of the hazard evaluation techniques and has historically been the first used. It has also been referred to as a Process Safety Review, Design Review, or Loss Prevention Review. The scope of a Safety Review may vary from an individual, informal walk-through of a facility to a formalized, team examination. Reviews may be applied to both existing facilities and proposed new facilities. Reviews should be conducted by skilled and experienced personnel.

The technique can be readily adapted to identify specific events which can lead to the release of hazardous substances. The typical review includes interviews with staff functions, including operations, maintenance, engineering and management.

Safety Reviews

Advantages	Limitations	Applicability to Hazard Identification
- Easy to use	- Limited by team experience	- High level review
- Flexible to needs	- Lack of rigor	- Identification of obvious hazards
- Resources as needed	- Minimum level of hazard identification	
- Can include staff from various functional areas	- Generally only identifies major risks	

Checklist Analysis

A checklist analysis uses a pre-defined documented list of items or questions to assess the integrity of systems, processes, procedures, or facilities. The checklist questions are typically answered yes or no. Using checklists is a very prescriptive technique which is frequently applied to test for compliance with standards or regulations.

Checklists provide an opportunity to effectively take advantage of previous experience. Questions may be structured based on previous incident data to seek out the potential for specific events which can lead to a release of hazardous substances. The corollary to this is that the questions are only formulated based upon previous experience. Checklists are therefore limited by their author's experience and knowledge. The technique is not particularly effective in identifying new, or previously unrecognized, events which can lead to a release. Also, checklists may not apply to new or unique facilities or processes.

The rigor and thoroughness of checklists is directly proportional to their length. Unfortunately, the longer the checklist, the more tedious is its application.

Checklists by their very nature tend toward being facility- or process-specific. They do, however, have the advantage that they can be prepared by experienced staff but implemented by those with less experience, providing the user understands the technical basis of the checklist. They can be customized to specific industries, processes, or companies. A specific example of this would be the development of a checklist relating to the use of chemicals, particularly chlorine, in the treatment of water for swimming pools.

Within the limitations described above, particularly the potential to miss new hazards, Checklists can be a powerful, cost effective hazard identification technique[4].

Checklist Analysis

Advantages	Limitations	Applicability to Hazard Identification
- Easy to use	- Still somewhat limited by team experience	- Custom checklists for specific industries, processes and companies
- Can be quick	- Repetition may lead to errors	
- May be customized	- Minimum level of hazard identification	
- Cost effective		
- Less experienced but	May not identify new hazards	- Best applied to processes

[4] a good example of such a checklist can be found in CCPS (1992) Appendix B.

still knowledgeable users	where hazards are well understood

What-If Analysis

The What-If analysis is appropriate to apply to new and unusual circumstances as well as existing operations. It is essentially a brainstorming approach in which the participants review the process or facility and repeatedly ask the question "what-if?". Through their imagination and experience, and through asking questions of themselves and voicing concerns to their peers, the participants identify events which may lead to undesirable consequences. It is preferable that the participants are both experienced with, and knowledgeable of, processes or facilities at least similar to those under review.

As a hazard evaluation technique, the strength of a What-If analysis is its ability to identify hazards, particularly those in new or unusual circumstances. It may be used to specifically target the consequences defined in the scope of this guide, that is, releases of hazardous substances which can lead to the death of a member of the public.

What-If analysis can therefore be a powerful procedure for identifying specific events which can lead to hazardous substance releases. It is, however, an analysis technique which is constrained by the knowledge, capability, and experience of the participants. If the participants do not have the appropriate knowledge or experience, they may not have the ability to identify events which have not yet occurred.

A What-If analysis is less structured than other techniques. The lead analyst may open the session with a few generic questions, however, other questions will be developed and new scenarios explored as the brainstorming progresses. The What-If approach works well for evaluating procedures.

What-If Analysis

Advantages	Limitations	Applicability to Hazard Identification
- Easy to use	- Limited by participant experience & capability	- Works well for evaluating procedures
- Adaptable to specific scenarios	- Unstructured, challenging to retain focus	- Works well for new & unusual circumstances
- Works well for new & unusual scenarios		

Failure Modes and Effects Analysis (FMEA)

A Failure Modes and Effects analysis (FMEA) is more structured than a What-If analysis. The technique provides for a rigorous analysis of equipment to identify single failure modes which can lead to an effect or incident. The Failure Mode provides a description of how the equipment failed (e.g., open, closed, stopped, running, on, off). The Effects provide a description of the undesired consequence or incident. As a hazard evaluation technique it may also be used to relatively rank the criticality of each effect.

This technique is adaptable to identify the undesirable consequences within the scope of this guide. That is, an analysis can be undertaken on equipment pertinent to hazardous substances. The effects analyzed can be limited to releases which will lead to potential for fires fuelled by flammable liquids and flammable liquefied gases, the release of toxic liquefied gases, and the evaporation of volatile toxic liquids.

The technique focuses upon single failures of equipment. Its weakness is that it does not recognize multiple failures or multiple causes of incidents. It is also inadequate to identify failures resulting from human error or procedural weaknesses.

Failure Modes and Effects Analysis (FMEA)

Advantages	Limitations	Applicability to Hazard Identification
- Structured & rigorous	- Limited to identification of single failures - Does not recognize multiple causes - Does not examine human factor or procedural causes	- Works well for evaluating specific items of equipment for physical integrity

Hazard and Operability Study (HAZOP)

The hazard and operability study (HAZOP) uses rigorous analytical methods to identify deviations from the design intent through a detailed analysis of the facility design. A multi-disciplined team, lead by a risk specialist, rigorously analyzes the design, normally using Piping & Instrumentation Diagrams (P&ID's). The analysis is structured around a systematic review of the design using "guidewords" applied to pre-selected system nodes. The "guidewords" (no, more, less, as well as, part of, reverse, other than) are applied to parameters such as flow, level, or pressure at the specific design nodes. The "guidewords" provide structure to ensure a systematic approach. The HAZOP technique can be viewed as a structured brainstorming session.

Since the original "guideword" HAZOP technique was developed, some companies have developed the "knowledge-based" HAZOP technique. It relies on the knowledge of team members to identify hazards with the design or operation of the facility, and as such can be considered more of safety review/checklist technique. We shall focus on the "guideword" technique in the remainder of this document.

The outcome of a HAZOP study includes the identification of hazards and operability problems. A study may lead to recommendations to change the design or operating procedures or identify the need for further information and study. It is important to note that the prime purpose of the study is to identify hazards, not to redesign the process and develop solutions.

Although originally conceived as a process for identifying hazards and operability problems in new, untested designs, HAZOP has been shown to be an effective method to review existing operations. It should be recognized that a HAZOP study is a rigorous review of detailed design, and, as such, requires extensive resources, both manpower and time. A typical study team may comprise five to seven multi-disciplined specialists for a number of weeks.

Hazard and Operability Analysis (HAZOP)

Advantages	Limitations	Applicability to Hazard Identification
- Structured brainstorming	- Time consuming and has large manpower needs	- Works well for multi-discipline evaluation of detail design and procedures
- Applicable to existing & especially novel or untested designs	- Normally assumes initial design intent was correct (the team could also identify that the design intent was incorrect)	
- Addresses design & procedures in multi-disciplined manner	- Potential to be tedious, may lead to errors	

3.3 SELECTION OF TECHNIQUES FOR HAZARD IDENTIFICATION

All of the hazard identification techniques including Safety reviews, Checklist analysis, What-If analysis, FMEA and HAZOP can be adapted to identify hazards within the scope of the MIACC guide. All are recognized and accepted techniques for which reference texts, papers, and training are available. Checklist analysis, What-If analysis, FMEA and HAZOP are recognized in the United States as techniques which meet legislated OSHA needs. Computer software to support and document all of these analysis techniques is available commercially. These include:

- PHA-PRO (Dyadem International)
- PHA Works (Primatech)
- HAZSEC (DNV Technica)

The selection of a specific technique will be primarily driven by four criteria:

- What is the subject of the analysis?
- What resources are available?
- What are the expected outcomes?
- At what stage of a project is the analysis being applied?

The nature of the subject will have a large influence upon which technique is selected. For example, if the process or facility is well understood and standards and regulations are well established, a Checklist technique may be chosen. If the process is new with many unknowns, one of the brainstorming techniques, such as What-If or HAZOP, may be chosen. If the subject of analysis is essentially physical in nature and limited to specific items of equipment the FMEA technique may be the most appropriate. If, on the other hand, the subject is procedural, the What-If technique could be used. If the scope of the analysis includes both equipment and procedures, then a HAZOP study could be used. HAZOP or FMEA will be the most appropriate for detailed design reviews.

The second criteria, the availability of resources, will also influence the selection of a specific technique. It is important, however, to ensure that due diligence is demonstrated. The most appropriate technique must be selected without the selection being unduly constrained by the availability of resources.

There is significant flexibility with respect to the resources required to undertake What-If analysis and Safety reviews. For these techniques the resources are essentially determined by the pre-defined scope of the analysis. Because of the brainstorming nature of What-If analysis experienced, knowledgeable staff are required.

For a Checklist analysis, once a Checklist has been established, the technique may be executed by less experienced, but still knowledgeable staff. Under such circumstances, potential for overlooking significant issues must be borne in mind. Under certain circumstances, a Checklist analysis may be undertaken by only one person; in general however, the resources required will vary with the depth of evaluation expected.

An FMEA analysis may be undertaken by one experienced specialist, however, the analyses should be reviewed by others to ensure completeness. For larger and more complex analyses, several multi-disciplined team members may be used.

The HAZOP process is a rigorous detailed approach which requires a multi-disciplined team of typically five to seven members. The duration will vary with the complexity of the study. For large process plants, studies lasting several weeks are not unusual.

The next criteria for the selection, the expected outcome, will be influenced by the scope of the analysis. It should be emphasized that the prime purpose for utilizing any of the techniques is to identify and document specific events which can lead to a hazardous substance release, although some of these techniques also lend themselves to identifying operability issues.

If the expectation is to provide a high level view of major areas of risk, a Safety Review or What-If analysis may be the most appropriate. For example, to identify “worst case” scenarios, these simpler techniques will be more appropriate. If the expectation is to identify risks associated with deviations from known standards and regulations for well understood operations, the Checklist analysis would be the most appropriate. For identification of risk exposure resulting from single failures of individual components within specific equipment, an FMEA analysis would be appropriate. If the expected outcome is a rigorous analysis of all aspects of both design and operating procedures then a HAZOP study should be undertaken.

At the conceptual design stages of a project, a knowledge-based HAZOP would be suitable. At detailed design stages and for existing facilities, guideword HAZOP or What If/Checklist techniques would be suitable.

In addition to the formal methods identified above, the benefit of utilizing the existing knowledge and experience base of operating and engineering staff cannot be overemphasized. The success of any of the methods is to a large extent a function of the knowledge and experience of the participants. Caution, however, must be always exhibited when utilizing existing knowledge and experience. Participants must be vigilant that they do not fall into the trap of assuming that a hazardous situation cannot develop simply because it has not previously occurred.

Once the hazard identification technique has been selected, the next stage of this step is to implement the technique, identify the hazardous events that can occur, and document the results.

3.4 UNCERTAINTIES IN HAZARD IDENTIFICATION

The objective of the hazard identification phase of a risk assessment is to identify a finite list of hazardous scenarios that will be modelled for frequency and consequences. For each hazard scenario, there is an initiating event that results in the release of material from the containment envelope. The initiating event could be a containment breach that directly results in the release or it could be a process upset that, due to subsequent process/operator events, develops into a containment breach. In addition, there are post-release factors (e.g., atmospheric stability) that shape the hazardous event.

A large number of hazard scenarios can be postulated. Analyzing even a large number is generally not feasible. In a risk assessment, a limited number of scenarios are identified. Each scenario will be representative of a range of events. This simplifying approach introduces uncertainty. Decreasing the number of scenarios selected reduces the cost of the study, but increases the uncertainty in the results. Conversely, use of more scenarios, each of which covers a smaller range of events, increases the cost of the risk assessment but improves the accuracy.

In order to ensure that these uncertainties do not lead to insufficient risk control decisions that would result in unacceptably high risk exposures, conservative assumptions are made. For example, a hazardous scenario representative of a range may be defined by the highest release rate within that range of release rates, whereas the frequency of that hazardous scenario includes the frequencies of all releases within the range. Additionally, it is conservative to postulate that all material is released from containment even though this is not always the case.

A major source of uncertainty that could be considered as part of hazard identification, is the selection of characteristics of a containment breach (size of hole, location, shape, orientation). More discussion on these uncertainties is provided in the section on consequence modelling (source term).

4. CONSEQUENCE ANALYSIS

4.1 INTRODUCTION

Once the hazardous events are identified, the next step in the risk analysis is to analyze their consequences, i.e., estimate the magnitude of damage to the receptors of interest should those hazardous events occur.

Consequence estimation can be accomplished by:

- Comparison to past incidents,
- Expert judgement, or
- Using mathematical models (consequence modelling), which can be at various levels of detail and sophistication.

Consequence Modelling is an analytical approach used to determine the possible physical effects resulting from the release of a hazardous substance. The inputs to this analysis include the physical, chemical and toxicological characteristics of the hazardous substance and the characteristics of the system in which it is contained (e.g., pressurized vessel, pipe, reactor, bulk carrier container).

The decision on the level of sophistication of the consequence analysis depends on the desired objective and accuracy of the results. If the results and the insight gained from the modelling will be used for emergency response planning, siting of critical plant units within an industrial facility, or in complex land use decisions, then detailed modelling should be preferred. If a quick assessment is all that is required, for example, for deciding whether to put an additional risk control measure such as an isolation valve, then use of sophisticated models may not be necessary (especially if the cost of the risk control measure is not large compared to the cost of the analysis). The rule of thumb is to *undertake detailed modelling if the cost of the risk control measure under consideration by the decision maker, or the potential consequence cost of not implementing the risk control measure, is much larger than the cost of the modelling.*

The credibility of any given modelling result depends upon the credibility of the release scenario (hazardous event) chosen, the supporting assumptions made in the analysis and the technical merits of the model itself. Numerous studies have attempted to develop comprehensive consequence models for the hazards of interest; however, due to the wide range of variables that may affect the behaviour of hazardous releases, there is no single model that will satisfy all situations. There is a wide range of available models that may be based on simple or complex equations, state-of-the-art research and actual field test results. *When the intent of the modelling exercise is to use the results to support decisions, it is important that the decision makers or at least their advisors understand the key considerations which have gone into the development of these models.* This knowledge will help with the model selection and establish confidence in the final results. Considerable judgement is required to assess which models are appropriate and relevant to a particular situation. *A good understanding of the underlying physics of the scenario is essential to the success of model selection.*

Since modelling results are highly sensitive to supporting assumptions, consistency is best achieved by having the **same** person(s) carry out the modelling calculations. The assumptions are generally left to the discretion of the modeller; they must be consistent with the laws of physics and should reflect experience for the system or location under study. They should also recognize the broader experience gained from the history of previous events.

This section of the guide describes the important underlying physical mechanisms for some of the more common types of hazardous material releases, and gives guidance on the type of models that should be used to provide an acceptable level of accuracy in estimates of event consequences (and hence individual risk, which is the desired end point for comparison against the MIACC Risk Acceptability guidelines).

The focus is on estimation of concentrations of toxic or flammable gases in the atmosphere, thermal radiation (heat intensity) levels from fires, and explosion overpressures. Each of these effects is capable of causing serious injuries or fatalities. Results are normally expressed at selected receptor locations and, for time-varying hazards, as a function of time.

Consequence modelling generally involves three distinct steps:

1. Estimation of the source term (**source term modelling**), i.e., how much material in what form (gas/liquid/two-phase) is being released from containment as a function of time, and development of the release scenarios or possible hazard outcomes (toxic cloud, fire, explosion, etc.) following the release (a powerful tool to develop and keep track of possible outcomes following a release is an event tree; event trees are commonly used in quantifying the frequency of these various outcomes and therefore will be described in the section on Frequency Analysis),
2. Estimation of the hazard level (**hazard modelling**) as a function of time and at selected receptor locations, i.e., estimation of:
   - Ambient concentrations for a toxic or flammable gas release (for modelling the effects of a toxic cloud or flash fire),
   - Thermal radiation flux for fires (for a jet fire, pool fire, or fireball),
   - Overpressure for explosions (for a confined explosion, boiling liquid expanding vapour explosion [BLEVE], or vapour cloud explosion [VCE]),
3. Estimation of damage level on the selected receptor, based on the hazard level at the receptor location (**vulnerability modelling**).

In scenario development, usually only minimum allowance is made for active hazard mitigating factors such as emergency shutdown or isolation devices, alarms or emergency response plans, especially in initial stages of analysis to reduce the complexity of the analysis, thereby saving costs. This is the approach suggested in the 1996 US EPA Risk Management Program Legislation and will tend to build a degree of conservatism in the results (i.e., overestimation of risk). When communicated appropriately, this approach may give additional comfort to the stakeholders in making any decisions if even these overestimates are within acceptable limits. If, however, the risks estimated using this assumption turn out to be unrealistically high, further detailed analysis which would take into account active mitigation systems and their failure frequencies is then recommended.

4.2 PHYSICAL MECHANISMS AND PARAMETERS IMPORTANT FOR DETERMINING SOURCE TERMS AND OUTCOMES OF HAZARDOUS MATERIAL RELEASES

The total mass of the release and its rate of release are probably the most important parameters that influences the hazard zone associated with a release.

A release rate will normally vary with time and as a function of hole size and location, containment conditions, system inventory, and external conditions. If a mixture is involved, the composition of the release may also vary with time.

It is important to establish the initial release rate (over the first 10 seconds or so) for releases of high-pressure gases or liquefied gases from pipelines and vessels, because very often it is these initial release rates which control the maximum extent of the hazard zone. One of the major difficulties is in dealing with two phase flow since there is a high degree of variability in how various models predict these release rates.

In the case of an instantaneous release, the source strength is specified in terms of the total mass released. For a "continuous" release, the source strength is a function of outflow expressed in terms of mass per unit of time. In order to determine the strength of the source, the physical state of a contained substance must be defined and described. The physical properties of the substance, together with containment pressure and ambient temperature, determine the physical state.

In the case of a continuous release, it is necessary to determine whether it is a gas, a liquefied gas or a liquid that is being released. The release rate from a breach in the containment wall will generally be proportional to the square root of the pressure difference between the containment and outside pressures and the area of the opening. If there is no liquefied gas in the system, and if no new material is being supplied from within the system, the containment pressure will start decreasing as soon as the breach takes place. As a result, the strength of the source will decrease as a function of time.

If the release point is located above the liquid level in the vessel, vapour outflow will occur. In the case of a pressure-liquefied gas, the liquid in the vessel will start boiling as a result of the drop in pressure, as the liquid-vapour system tries to reach equilibrium at saturated vapour pressure. The necessary heat of evaporation will be drawn from the liquid in the vessel, the liquid thus cooling down to its boiling point at the (dropping) vessel pressure. The source strength of the releasing vapour, being a function of the vessel pressure (unless it is choked flow at the hole, in which case it is a function of temperature), is controlled by a balance between the amount of material escaping the vessel and heat transfer from the surroundings. For relatively large release rates (large hole sizes), the temperature of the liquid will quickly reach its boiling point at near-atmospheric pressure; after this occurs, the source strength will be controlled primarily by heat transfer from the surroundings and will remain relatively constant until all liquid is depleted. Also for large hole sizes, the boiling inside the vessel will be rapid, possibly resulting in frothing of the material; this may lead to release of some liquid along with the vapour, even when the hole is located above liquid level.

If the release point is located below the liquid level, liquid outflow will occur. In the case of a pressure-liquefied gas, the escaping liquid will rapidly flash. As the pressure of the escaping material drops to atmospheric as it is going through the hole, some of the material will become vapour, absorbing heat from the liquid and cooling it to its boiling point at atmospheric pressure (or even below its boiling point as the droplets further evaporate), resulting in a cold two-phase jet. Depending on the liquid content of the two-phase jet, some of the liquid may fall to the ground and form a liquid pool. However, under most situations, the rapidly expanding vapour, as it is formed, will break up any adjacent liquid particles into very small droplets (flash atomization), commonly referred to as aerosol. Thus, assumption of no rain-out is recommended in modelling such conditions.

The aerosol (droplets which do not fall to the ground), together with the vapour, will form a cloud which is colder and denser than the air around it. This heavy cloud will spread laterally under the influence of gravity, and takes much longer to disperse than a buoyant gas cloud. The cold liquid from the liquid pool and from the droplets within the cloud will continue to evaporate and will continue contributing to the cloud. “Quasi-adiabatic” evaporation of the aerosols will tend to reduce the cloud temperature to below the normal boiling point. Any humidity in the air that gets entrained into the cloud may condense, forming small water or ice droplets, and then re-evaporate further downwind. This humidity may also react with the hazardous material, thus influencing the behaviour of the cloud through, for example, heat of reaction effects.

If the cloud is flammable and it ignites, it could result in a flash fire or vapour cloud explosion, depending on the degree of confinement, the degree of turbulence and mixing, and the total flammable mass within the cloud.

When a refrigeration-liquefied gas is quickly released, it will boil off and will generally form a cold heavy gas cloud. A liquid pool may also form. The boil-off is primarily controlled by heat transfer from the surfaces that the liquid contacts. The gas cloud will contain less aerosol than the case of a release from pressure-liquefied state.

A flammable gas cloud, if ignited at a distance from its release location, may burn back to its source and result in a jet fire and/or a pool fire, depending on the conditions at the source.

The source modelling for the above situations should consider the thermodynamics and dynamics of what happens inside the vessel and to the released material once it is outside containment, the heat transfer between the vessel and its surroundings, and the heat transfer between the released material and its surroundings, along with the appropriate chemical/ physical reactions and mass balances.

A fire-induced BLEVE is a physical explosion which can occur when flame impingement locally overheats the vapour space of a storage vessel containing a liquefied material under pressure. As a result of the increased temperature, the vessel pressure will increase due to the higher vapour pressure. For vessels that lack adequate pressure relief, rupture can occur due to local overheating because the metal may be sufficiently weakened so that it is unable to withstand even the normal vessel design pressures. When contents are non-combustible (e.g., water), a mechanical explosion (liquid expanding rapidly into vapour) will occur. When flammable, as with hydrocarbons, a fireball will also follow.

Missiles and projectiles may also cause injuries or fatalities at considerable distances from source depending upon the energy of an explosion and the mechanical integrity of the system in which it occurs. Missiles are more likely to occur as a result of a BLEVE. The risk of direct impact at any specified location is primarily a function of the frequency distribution of ranges of missiles.

It is important to recognize that some fire hazards also produce toxic combustion products, which may require modelling. This will involve estimation of the source strength followed by dispersion modelling, plume rise being an important factor. Estimation of the source strength for such incidents present particular challenges due to uncontrolled conditions of such fires.

For releases into water bodies, the modelling of spread and trajectory of liquids should take into account not only evaporation, but also dissolving and sinking of the hazardous materials.

For liquid releases, the modelling of evaporation should take into account evaporative cooling, since this will affect the evaporation rate.

Table 4.2.1 summarizes the outcomes of events resulting from the release of hazardous substances and the types of models required for their consequence analysis.

Table 4.2.1 Required Models for Different Hazards

HAZARD CATEGORY	POTENTIAL OUTCOME	MODEL REQUIRED
Flammable liquids, including those liquefied by refrigeration	Pool fire	Liquid discharge, liquid spread, pool fire
	Flash fire	Liquid discharge, liquid spread, evaporation/boil-off, (passive or heavy) gas dispersion
Flammable gases, liquefied by compression	Boiling Liquid Expanding Vapour Explosion (BLEVE)	BLEVE
	Fireball	Fireball
	Jet fire	Two-phase discharge, jet fire
	Vapour cloud explosion (VCE)	Two-phase discharge, heavy gas dispersion and/or VCE
	Flash fire	Two phase discharge, rain-out, evaporation/boil-off, heavy gas dispersion
	Pool fire	Two phase discharge, rain-out, liquid spread, pool fire
Flammable gases, gas under pressure	Fireball	Gas discharge, fireball
	Flash fire	Gas discharge, (passive or heavy) gas dispersion
	Jet fire	Gas discharge, jet fire
Toxic liquids, including those liquefied by refrigeration	Toxic vapour cloud from liquid pool	Liquid discharge, liquid spread, evaporation/boil-off, (passive or heavy) gas dispersion
Toxic gases liquefied by compression	Toxic gas cloud	Two phase discharge, rain-out, liquid spread, evaporation/boil-off, heavy gas dispersion
Toxic gases, gas under pressure	Toxic gas cloud	Gas discharge, (passive or heavy) gas dispersion
Toxic combustion products	Toxic gas cloud	Model for the combustion process, gas dispersion

4.3 GAS DISPERSION

This group of models describes the atmospheric dispersion of clouds of gases and gas/aerosol mixtures. The objective of these models is to estimate the variation of concentration in air of the released material as a function of time and distance from release location.

Dispersion calculations should take into consideration the time varying rates of gas release (source strength), as well as atmospheric turbulence conditions.

Atmospheric turbulence is primarily a function of:

1. Solar heating/radiative cooling (determined by cloud cover, surface cover, latitude from the equator, time of day, and time of year),
2. Wind speed,
3. Surface roughness,
4. Terrain,
5. Height from ground.

In general, less information is required about site source details to calculate consequences of a given release scenario at larger distances from the release location.

For toxic materials, hazard level end-points are generally on the order of a fraction of a percent of material by volume in air. Thus, the assessment of toxic hazards involves modelling large dilutions in the atmosphere, typically on the order of 1000:1 or larger. Such high dilutions require cloud travel over relatively large distances from the source, and it is atmospheric dispersion (and total emitted gas) which primarily controls the extent of the hazard zone; source characteristics such as height, geometry and release velocity are generally not significant.

For flammable materials, hazard level end-points are generally on the order of several percent. The assessment of flammable hazards typically involves modelling dilutions on the order of 10:1 or 100:1. For the same amount of material released, the hazard zones are therefore much smaller than for toxic clouds and source characteristics will play a more important role along with atmospheric dispersion. A knowledge of momentum jet and buoyant versus dense gas plume mixing is important to these dispersion calculations. Key variables include site source details such as:

1. Source diameter;
2. Initial jet density, velocity, and orientation;
3. Proximity and shape of impeding obstacles and confining structures;
4. Initial chemical reactions, droplets, aerosols, and initial fallout.

In modelling the behaviour of gas clouds, it is very important to select between passive/ buoyant and dense gas dispersion as appropriate for the situation.

The passive gas dispersion models are usually based on the Gaussian plume model. In Gaussian models, atmospheric dispersion is taken into account through empirical dispersion coefficients which vary by atmospheric turbulence class (stability class) and distance from source. Dilution by the wind is taken into account through division by wind speed. No consideration, however, is given to the difference of the density between the ambient air and the gas, other than to calculate an initial plume rise if the release is hot (buoyant plumes rise according to relatively well established approximations and then behave as a plume characterized by Gaussian concentration profiles). Because of this, these models must only be used for gas mixtures with a density approximately the same as air.

The Gaussian model is based on analytical solutions of the general transport equation for a point source. Steady continuous and instantaneous releases ("plumes" and "puffs") can be modelled. For time-varying continuous releases, time-integrated puff models should be used. For area sources, such as a liquid pool, two approaches are possible. In the first approach, an imaginary point source is assumed upwind of the actual source, so that the width of the cloud matches the source dimensions at the site of the actual source. The second approach is based on an area integration of the point source equations over the source area.

Heavy gas dispersion models are used if the gas is expected to exhibit heavy gas behaviour upon release. Not all gases with a density greater than that of the surrounding air will exhibit heavy gas behaviour. In order to establish whether a release will exhibit heavy gas behaviour, empirical formulations taking into account the density difference, release rate, source diameter, and wind speed are available.

Heavy gas clouds tend to slump, flow down sloping ground, and spread in a radial direction because of gravity, even on flat ground. In contrast to a passive gas, the gas released may spread against the direction of the wind. Downwind from the source area, a dense gas will lead to a wide low lying cloud, which is more difficult to disperse than a passive gas cloud. Eventually, the dispersion of the cloud becomes passive due to dilution. The cloud may also lift off and rise depending on the material and atmospheric conditions.

Most releases are influenced by buildings or structures either at the source or during the dispersion of the plume. Most available models are unable to handle these complexities well; they are suitable only for dispersion over flat homogeneous terrain.

Since most model formulations contain a division by wind speed to account for dilution by the wind, they become increasingly conservative and unreliable for calm situations with wind speeds less than 1 - 1.5 m/s.

Recommended Atmospheric Conditions for Use in Risk Analysis

The main input parameters used in dispersion models for estimating the downwind extent of hazard zones are atmospheric stability, wind speed, and wind direction. For any location in Canada, joint frequency distribution for these variables can be obtained from Environment Canada, Atmospheric Environment Service, in terms of:

- The six Pasquill-Gifford stability classes (A-F);
- A selected number of wind speed classes, including calms (typically five);
- 36 or 16 wind direction classes.

Full treatment of the range of these inputs requires a large number of modelling runs and this is often unnecessary for arriving at risk estimates with reasonable accuracy. Thus, the following approach is recommended for a simplified analysis:

- Use only two meteorological conditions for modelling purposes:
  - Stability D and wind speed 5 m/s (D5), with an associated probability of 0.7;
  - Stability F and wind speed 1.5 m/s (F1.5), with an associated probability of 0.3.

  These two conditions are consistent with the requirement of the 1996 US EPA Legislation on the Risk Management Program (not the associated probabilities – the RMP does not include probabilistic concepts).
- Use a uniform wind rose (equal probability in all directions), unless certain wind directions are significantly different, such as in a deep valley situation. In this case, use of the local wind rose appropriate for each grouping of stability classes is recommended.

4.4 TOXIC EFFECTS

Toxic substances can have immediate and severe physiological effects on people and may ultimately cause death. Toxic effects are derived from a wide range of concentration and exposure time combinations. A relatively short term, high level exposure to a highly hazardous substance such as methyl isocyanate is very different from a long term exposure to low concentrations of benzene. In consequence modelling exercises for accidents, the usual focus is on highly toxic substances which can kill or cause serious injury over a relatively short time frame of minutes or hours. Such substances are normally referred to as acutely toxic. Experience has shown that the types of acute toxicity most likely to result in human fatalities in an industrial emergency are highly irritating or corrosive substances like chlorine, ammonia or hydrogen fluoride, or fast acting nervous system toxins like hydrogen sulphide.

The relationship between concentration and effects on humans is highly non-linear, i.e., a doubling of concentration will generally result in more than a doubling of the damage. This non-linearity requires the estimation of peak and time-mean concentrations through modelling of concentration fluctuations for improved accuracy in predicted toxic effects.

For rapid releases of toxic materials into the atmosphere, such as a sour gas pipeline burst or rupture of a chlorine vessel, the passage time of the toxic cloud over a receptor point may be relatively short. This affords an opportunity for sheltering within buildings until the cloud passes over the receptor. During the passage of the cloud, the infiltration rate into a building will be a function of the type of building, whether the windows are open or closed and whether the air exchange fans are operational. The build-up of concentration within the building will be slower than outside. Once the cloud passes, however, the concentration within the building will remain higher than outside for a period of time. Modelling of these situations will provide critical input to emergency response planning near areas where large releases of hazardous materials are possible.

4.5 THERMAL RADIATION EFFECTS

Thermal radiation effects arise from flash fires, pool fires, jet fires, or fireballs. These involve the combustion of flammable mixtures.

Intensity of thermal radiation (measured in terms of thermal radiation flux or energy per unit area and time) at a receptor outside a fire depends on its distance from the fire, the flame height, flame emissive power, and atmospheric transmissivity.

Flash Fires

For flash fires, the controlling factor for the amount of damage that a receptor will suffer is whether the receptor is physically within the burning cloud or not. This is because most flash fires do not burn very hot and the thermal radiation generated outside of the burning cloud will generally not cause significant damage due to the short duration. Thus, modelling of flash fire consequences consists of primarily an exercise in dispersion modelling, the hazard zone being essentially the extent of the flammable zone of the cloud.

Other Types of Fires

For the other types of fires, available models are broadly classified as either point source models (simple or with multiple sources), or view factor models based on either an equivalent radiator or a solid flame approach. They differ in their required input parameters according to the type of fire and to the level of detail and complexity inherent in the inputs and submodels needed to describe the physical event.

Point source models are generally less complex than the view factor models. They are appropriate when the receptor is sufficiently separated from the fire that the specific shape and size of the fire is no longer important. In contrast, view factor models allow the geometry of the flame, as well as the receptor configuration, to be taken into account in the estimation of thermal flux. These are therefore more applicable to cases where the receptor is close to the fire and/or when the geometric details of the fire are important (e.g., wind effects, receptor orientation).

4.6 EXPLOSION EFFECTS

Explosion overpressure effects that are of interest here result either from the rapid combustion of a fuel/air mixture (confined explosion or VCE), or a sudden release of pressure energy (BLEVE).

BLEVE

For BLEVEs, the available models are based on the similarity of the blast waves in the far-field to those generated by high-explosive detonation. The compressed gas' stored energy is first calculated based on pressure at the time of burst. The energy of explosion is obtained as the difference between the initial and final states, assuming isentropic expansion. This energy contributes primarily to the production of a blast wave and of missiles. The fraction of pressure energy that contributes to the blast wave can be taken to be about 40%. Overpressure and impulse are then read from charts which relate detonation-blast parameters to charges of high explosive with the same energy. In the near field, this similarity to high explosives is not valid, and correction factors based on numerical simulations should be used.

Missile damage from BLEVEs is more difficult to model and of relatively little importance in risk assessments. A statistical account of the extent of missile damage from actual BLEVEs involving primarily LPG is described in Lees (1996).

Confined Explosions

Confined explosions occur when a flammable mixture in a confined space is ignited. A typical example is the case of a flammable liquids tank. When these tanks are emptied, residual liquid may evaporate and form a flammable mixture in the tank. If ignited, a confined explosion would be produced. The modelling of confined explosion effects is analogous to the modelling of BLEVEs. Here the explosion energy released is obtained from the enthalpy of combustion.

VCE

For a fuel/air mixture outside containment, conditions favouring a VCE as opposed to a flash fire include:

1. The mass of the cloud (e.g., 5 tonnes appears to be a lower limit for propane vapour cloud explosions outside containment)
2. Flame speed
3. Degree of confinement
4. Degree of turbulence in the cloud.

A rapid violent release, if not ignited immediately, may result in sufficient mixing through self-generated turbulence for explosive conditions to occur. The portion of the vapour cloud within the explosive range at the time of ignition will contribute directly to the explosion. The resulting overpressure at a given point is a function of :

1. The distance from source
2. Fuel properties
3. Mass of the cloud
4. Degree of confinement (affected by the presence of obstacles).

Two different types of models are generally used in practice for estimating VCE overpressures at a distance from a source.

1. The TNT equivalency method relates the explosive potential of a release to the total quantity of fuel in the vapour cloud, whether or not it is within flammable limits. The explosive power of the vapour cloud is expressed as an energy equivalent amount of TNT located at the centre of the cloud. The value of the proportionality factor is determined from damage patterns observed in a large number of similar vapour cloud explosion incidents. Calculated blast overpressures tend to be high near the cloud centre (regardless of physical surroundings) and a gradual decay is observed as distance from the cloud centre increases. This translates into a localized high damage zone with low to moderate damage in outlying areas.

   It is important to apply conservative values to the proportionality constants used for the TNT method. An explosion efficiency of 0.06 to 0.10 should be used even in areas which are not tightly confined. Scaling factors should be averaged among several literature sources and used to calculate overpressure profiles. These data are often material specific and, if not averaged, could introduce additional errors.

2. The multi-energy method reflects current consensus that one of the controlling factors of severe explosions is turbulence. One source of such turbulence is the high velocity flow of fuel being ejected from a pressurized system. Explosive combustion rates may develop in such a turbulent fuel air mixture. Another source of turbulence is combustion within a partially confined / physically obstructed environment. The expansion of combustion gases against a confining structure can cause exponential increases in the combustion rate and an overall increase in overpressure. The explosive power of a vapour cloud is determined primarily by the energy of fuel present in the confined areas of a vapour cloud.

It should be noted that, in cases where VCEs may be possible, the footprint of the flash fire zone (the zone within the lower flammability limit [LFL] of the material) should also be estimated and used in the overall risk estimation with its corresponding frequency.

4.7 RECOMMENDED SOURCE TERM AND HAZARD MODELS

It is difficult to specify the use of any model for a particular application without assessing all the features of each model and establishing the end purpose for which the modelling will be used. Table 4.7.1 provides a list of public domain model references which are suitable for modelling hazardous releases.

Table 4.7.1 Recommended Source Term and Hazard Models

Discharge models, liquid	Bernoulli equation
Discharge models, two phase	Fauske and Epstein (1988)
Discharge models, gas	Sonic discharge equations (for choked flow)
Heavy gas dispersion models	Britter and McQuaid (1988) SLAB, (Ermak, 1990) HGSYSTEM (Post, 1994)
Passive gas dispersion models	Gaussian plume, puff or integrated-puff equations
Concentration fluctuations in atmosphere	Wilson (1986)
Building infiltration models	Basic mass balance with air exchange
Liquid pool spread models	Cavanaugh, et al. (1994)
Liquid pool evaporation models	Cavanaugh, et al. (1994)
Rainout models	SUPERCHEMS (1998)
Jet fire models	CCPS (1994), Lees (1996), Baker et al. (1983)
Pool fire models	Crocker and Napier (1986)
BLEVE models	CCPS (1994)
VCE models	TNT (see Baker, et al., 1983) Multi-Energy (Van den Berg, 1985)
Toxic combustion products models	TNO (1997, Yellow Book)

Other excellent references on consequence modelling techniques are CCPS (1989a), CCPS (1994), CCPS (1995a, c), Lees (1996) and TNO (1992 Green Book, 1997 Yellow Book).

The following are some of the available computer models which attempt to combine a number of the above (and other) models in an attempt to provide complete modelling packages for users.

<u>Public Domain Models</u>

ALOHA	NOAA
HGSYSTEM	Shell Research (Post, 1994)

<u>Proprietary Models</u>

CHARM	Radian Corp.
PHAST	DNV Technica Ltd.
SUPERCHEMS	iMosaic
TRACE/SAFER	SAFER

4.8 VULNERABILITY MODELLING

Once the hazard level (i.e., concentration, thermal radiation flux, or overpressure) is estimated at a receptor point following a hazardous event, the next and final step in consequence modelling is estimation of the level of damage on the receptor. For all hazards except flash fires, there are two commonly used methods for this:

- Fixed-limit methods, and
- The PROBIT method.

The fixed-limit method consists of comparing the estimated average (or maximum) hazard level to which a receptor is exposed, against fixed limits which are available from the literature. For example, for toxic clouds, estimated concentration levels can be compared to IDLH (immediately dangerous to life and health) levels to establish whether fatality or serious injury might occur at a receptor point. Appendix A2 contains the commonly used fixed-limit values for some toxic materials and for fires and explosions.

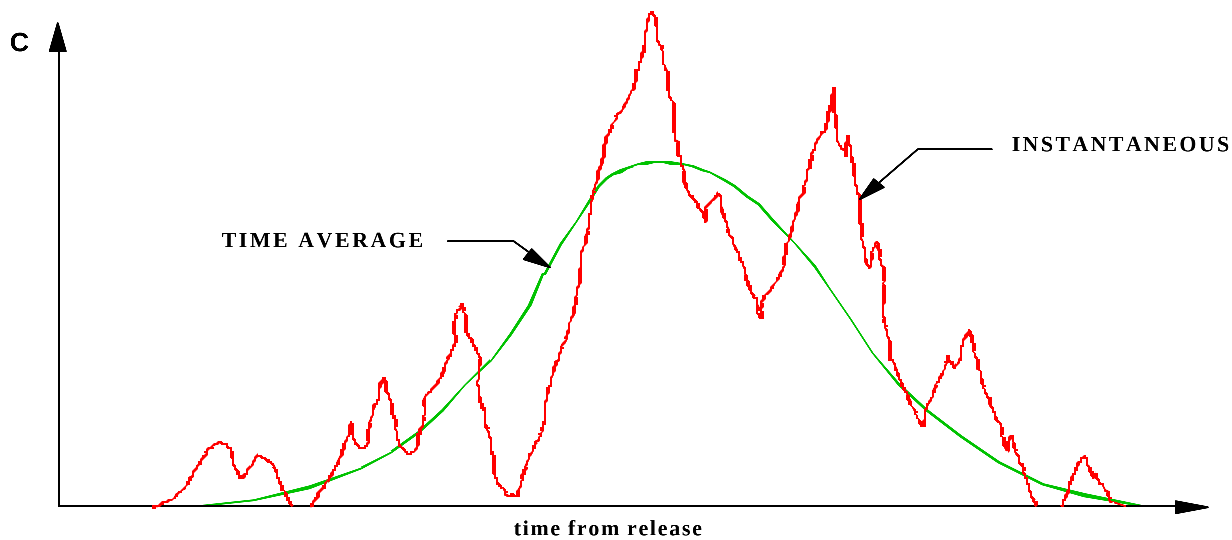
The advantage of the fixed-limit method is its simplicity. *Its disadvantage is that it can be very misleading for time-varying hazards, which is generally the case under major accident conditions*.

For example, a short duration toxic release may be over in a matter of minutes, with exposure duration of receptors not much longer than that. The time variation of concentration at a given receptor point may look like that shown in Figure 4.1. Typical dispersion models will output what is shown as the "time average" in this figure.

If one compares the maximum in this curve to a fixed-limit value, such as the IDLH (which is a 30 minute exposure limit for exposed persons to be able to leave the area unaided, but could nevertheless lead to severe injuries), this could *lead to severe overestimates of fatality risk*, since the actual exposure to these levels could be only a few minutes as opposed to 30 minutes.

Any use of the ERPG (Emergency Response Planning Guide) values will be even more conservative and will not be appropriate for estimating fatalities. This information is provided in Appendix A2 only for reference purposes and completeness.

Figure 4.1 Typical Time Variation of Concentration at a Down-wind Receptor Following a Short-Duration Release



A more appropriate and the recommended method is to use the PROBIT method, which can readily handle time-varying situations, including concentration fluctuations (Alp, et al., 1990).

To apply this method, a "hazard load" L is estimated at each receptor point,

$L = \int C^n \, dt$ for toxic clouds (C is the time varying concentration at the receptor point, estimated by the dispersion model);

$L = \int I^n \, dt$ for thermal radiation hazards (I is the time varying thermal radiation flux resulting from the fire);

$L = P_o$ for explosion hazards (P_o is the overpressure resulting from the explosion).

Here, the integration essentially represents the total amount of contaminant or thermal energy received by the receptor (weighted by the power n), and n is an empirical PROBIT parameter appropriate for the chemical and type of hazard. The integration is performed over the time of exposure during the hazardous event. (Effect of evacuation or sheltering in a building can thus be incorporated into the results if desired).

We then estimate the PROBIT (probability unit) Y:

$Y = k_1 + k_2 \, \mathit{1n} \, L,$

where k_1 and k_2 are additional empirical PROBIT parameters.

The values of the PROBIT parameters for some common toxic chemicals are given in Appendix A3. Information for some other toxic chemicals and description of an approximate method for estimating these parameters from LC50 data can be found in TNO (1992, Green Book). PROBIT constants for fire and explosion effects are also given in Appendix A3.

Y can then be related to the level and type of hazardous effect in terms of "% probability of death, injury, or damage occurring" ($P_{e,h}$) using Table A3.3.

Flash Fires

For flash fires, the maximum extent of the hazard zone is generally based on the lower flammable limit (LFL) of the material. Sometimes, LFL/2 is also used to take into account the possibility of having high-concentration pockets of gas which might result from concentration fluctuations in the atmosphere. However, this is not the whole story. Ignition of a gas cloud can occur as the leading edge of the cloud reaches an ignition source and the cloud will burn towards the source. Hence, the flash fire will only affect the area between the ignition point and the release location. By estimating the probability of ignition as the cloud reaches each ignition source, one can estimate the probability of affecting any receptor as a function of distance from the release point.

A common assumption for probability of fatality for people caught in a flash fire is 10% for those having protective (fire-retardant) clothing (such as NOMEX suits), and 90% for those without such protection. Both are somewhat on the conservative side and include major injury, which will lead to overestimates of risk of fatality.

4.9 UNCERTAINTIES IN CONSEQUENCE MODELLING

Uncertainties in consequence estimation arise due to uncertainties in modelling the sources term, the migration of a hazard away form the hazard source (hazard modelling), the effects of a level of hazard on receptors (vulnerability modelling), and due to assumptions made with respect to the degree of protection afforded to receptors. As discussed below, these uncertainties are for the most part treated conservatively.

In the estimation of consequences, a major source of uncertainty is the modelling of the source term. The source term describes the rate of release of material from containment and into the carrying medium (e.g., atmosphere). In effect, the source term determines the amount of the material released.

There are a number of uncertainties related to source term. These include:

- Hole characteristics – size, location, shape
- Orientation of the release – vertical, horizontal
- Degree of pooling of flashing two-phase discharges
- Degree and size of confinement – release outdoors/indoors, into a diked area
- Amount of material involved

With the above, conservative assumptions can usually be made to avoid underestimation of consequences. For example, one can assume that a tank/system is full when the accident happens and that all of the inventory is released. Also, pooling of liquid from a two-phase release can be neglected. These conservative assumptions, however, need to be made with care. Take the case of a release of a toxic gas released indoors. The release indoors will likely result in a substantial hold-up of material within the indoor volume. Generally, this material will subsequently be vented relatively slowly to the outdoors. If an indoor release is assumed to occur as if it were outdoors, the consequences may be substantially overestimated.

In consequence modelling, it is also important that appropriate hazard migration models be used. An error often made is that use of a Gaussian dispersion model for gas clouds that are initially heavier than air. This would lead to the underestimation of hazard distances. State-of-the-art models have undergone various degrees of validation. However, due to the vast number of atmospheric, terrain, and material factors which complicate the prediction of hazard levels, these models are not capable of predicting experimental observations with accuracy over a large range of conditions. In fact, models that predict experimental observations within a factor of two are considered reasonably good.

Also, due care must be taken in specifying model input parameters. Factors such as atmospheric transmissivity in fire models, or ambient temperature in modelling cold heavier-than-air gas clouds affect model results. They are typically specified conservatively to avoid a large number of model runs.

Modelling health effects from various hazard levels is a difficult task. Risk assessments are typically based on the risk of death or serious injury. Obviously there is no experimental data available on the dose-response relationship of material concentration and exposure duration, thermal radiation intensity or blast overpressures on humans. What little there is has been inferred from actual accidents. Models that predict the impact of exposure to hazardous materials are heavily influenced by animal experiments. Typically, they have large safety factors built in. It is believed that models based primarily on experimental animal exposures are conservative when applied to humans, especially when, on a body weight difference, the animals are much smaller than humans. In fact, many will argue that they are too conservative. These estimates are difficult to make and unfortunately little can be done to improve the degree of uncertainty.

Finally, in modelling the impact of a hazard level on a human, it is typically assumed that the exposed individual is outdoors and stationary (does not retreat nor take shelter). In reality, in Canada, individuals are indoors most of the time. This affords considerable protection from exposure to all types of hazards. Taking credit for sheltering in a risk assessment may improve the accuracy of the results by reducing the conservatism, but increases the cost of the assessment because additional consequence modelling runs are required.

4.10 CONSEQUENCE MODELLING SUMMARY

Depending on the type of hazard, and at each receptor of interest,

- Estimate the hazard level, using mathematical models (selection of the appropriate model is critical for accuracy of risk assessment):
  - Concentration, for gas clouds;
  - Thermal radiation flux, for fires;
  - Overpressure or impulse, for explosions.
- Calculate load, PROBIT, and probability of "effect" ("fatality" in the present context) at each receptor point (also called event individual consequence);

- Alternatively, compare the hazard level to an appropriate fixed-limit, and thus estimate the probability of effect;
- For flash fires, estimate ignition probability as a function of ignition sources in the down-wind direction, and thus estimate the probability of effect;
- The number of receptors affected can then be calculated by integrating the product of individual consequence and population density over the exposed area, if an estimate of event societal consequences is within the scope of the analysis (Alp and Zelensky, 1996. Local municipal planning, land use and population maps should be considered as data sources when identifying receptors. In addition, local off-site surveys and reviews may be considered to assess the density of permanent inhabitation and the frequency of inhabitation by transient community members.

5. FREQUENCY ANALYSIS

5.1 INTRODUCTION

The risk presented by a facility is dependent on the frequency at which an undesired event can be expected to occur and the adverse consequences which could result from the event. The undesired events which were identified using the techniques outlined in the Hazard Identification section must be analyzed to determine their expected frequency.

A number of different techniques are available to estimate the frequency of a given type of major hazardous event occurring at a specific facility, on a transportation corridor, or along a pipeline. These vary in complexity and type of information they yield. Their selection depends on the desired outcome, amount of time, and effort available. The techniques we will consider are:

- Historical data analysis,
- Fault tree analysis,
- Event tree analysis,
- Human reliability analysis,
- External events analysis.

All of these techniques rely on past experience to a certain extent. Fault and event trees are the most common frequency modelling techniques for complex situations that require tracking of chains of events. Human reliability analysis and external events analysis can be considered essentially as components of fault and event tree analysis, the information generated from their application to be fed into the fault and event trees.

An important factor to be considered in deciding the amount of effort to spend in improving the accuracy of event frequencies is whether the numbers will be used in an absolute sense or for a comparative exercise. For complex land use decisions regarding pipelines, dangerous goods transportation corridors or industrial plants, accuracy of the frequencies is important because the end result will be compared to the established risk acceptability guidelines for land use. This may not be the case for the addition of controls or mitigation for the specific purpose of reducing overall risk. In such a study, it may be more important to be consistent in approach rather than seek high levels of accuracy in the frequency estimates.

Also, accuracy implies rigor both in the determination of failure rates and in ferreting out possible failure paths.

Less rigorous (and therefore less accurate) analyses are acceptable if based on conservative assumptions, and possibly upper bound failure rates. Frequency estimates will then err on the safe side. These estimates can be “fine-tuned” by improving accuracy if necessary.

Here it will be worthwhile to make a distinction between frequency and probability. Probability is expressed as a fraction between 0 and 1 (0 to 100%), and is dimensionless. It represents the chance of a given outcome from a large number of trials under similar circumstances. Frequency, on the other hand, represents the number of events in a given time duration and is expressed in units such as events per year.

5.2 HISTORICAL DATA ANALYSIS

Use of historical data in the estimation of hazardous event frequencies is a suitable approach if the operating experience of the equipment is sufficient to produce a statistically meaningful database.

Historical data can be used in two different ways:

- To estimate directly the frequency of the hazardous event of interest ("top event") identified in the Hazard Identification step of the risk analysis;
- To estimate frequency of events or causes that contribute to the occurrence of the top event.

The latter is generally used in conjunction with fault trees.

There are common types of equipment that are used in the various industries (e.g., pumps, valves, pipelines). Industry average failure frequency rates are available for these pieces of equipment. However, not all facilities experience failures at the same rate. These rates can vary considerably depending on site or company conditions such as:

- Management practices;
- Operating practices;
- Appropriateness of design, plant layout, and construction materials;
- Level of testing, inspection and maintenance;
- Equipment age;
- Severity of operating conditions; and
- Nature of the materials handled.

Therefore, it is best to use site- or company-specific release data if it is available. However, any given site or company will not generally experience a significant number of major events to form a statistically significant database. In this case, it will be necessary to use general industry data for overall failure rates as a first approximation.

When using general industry data, it is common practice to adjust the data up or down by up to an order of magnitude based on engineering judgement, depending on the specific site or company conditions.

A common problem in generating frequency information for hazardous events is lack of "*divisor*" information. In a risk analysis, the units of frequency needed for estimating annual risk is "events/year". For example, for a hydrocarbon storage tank fire in a facility containing three independent tanks, we would need base frequency information in terms of "tank fires/tank-operating-year", and multiply this quantity by three to obtain the frequency of the event we are looking for in terms of "tank fires/year in that three-tank facility". Historical data from government or industry sources may be available in terms of "tank fires/calendar year in Canada or in the world" but not in terms of "tank fires/tank-operating-year". In order to estimate the base frequency information "tank fires/tank-operating-year" from "tank fires/calendar year in Canada or in the world", one would need to *divide* it by the "number of operating tanks in that calendar year in Canada or in the world" (hence the term "*divisor*"), but this parameter is generally not easily obtainable. The same situation generally exists for all industries including rail transportation, pipeline transportation, chemical industries and others. Some industries and government agencies have commissioned special studies to resolve this issue and provide base frequency information that can be directly used in risk analyses. Examples of such data are presented in this guide in Section 5.7.

In any case, use of fault and event trees is strongly recommended instead of such approaches in all quantitative risk assessments.

5.3 FAULT TREE ANALYSIS

When failure rate data is not available for the undesired event or the top event, or its accuracy is not judged to be sufficient, it is possible to estimate the event frequency using analytical methods, specifically Fault Tree Analysis. Fault Tree Analysis uses a "backward logic" which begins with an undesired event (e.g., a release of a hazardous material from containment), analyzes the system to determine the basic cause(s) of the undesired event, and enables the user to quantify the likelihood of the top event. This is done through a "top down" tree whose branches identify the main causes and influencing factors contributing to the top event. The tree-like or branching investigation of each scenario gives rise to the name 'fault trees'. Since the method is deductive, it focuses attention on the particular event in question, thereby eliminating time spent following trains of thought which do not lead to hazardous situations.

Fault Tree Analysis (FTA) is a tool employed in the analysis of complex systems. It has been applied, for example, in safety evaluations of nuclear power plants, space missions, air, rail, highway, marine and pipeline transport, liquefied natural gas, chemical manufacturing, and other hazardous material facilities. With this method, all material, personnel, and environmental factors of a complex system can be systematically presented. A well-developed fault tree identifies the combination of failures which would not normally be discovered, and provides for both qualitative and quantitative evaluation.

5.3.1 Construction of Fault Trees

Fault Tree Analysis is used to estimate the likelihood of an accident scenario. This technique starts with a particular undesired top event, such as a flammable material release and fire or explosion from a particular system. It then breaks down the causes of an accident into all the identifiable contributing sequences, and each sequence is separated into all necessary components or events. The presentation of all this information is facilitated by the use of a logic diagram, or 'fault tree'. The fault trees are generally developed only as far as necessary down to a level where failure or event frequencies are known with a reasonable degree of accuracy from past experience or historical data. The elemental parts of a fault tree at the bottom level are known as "basic events".

Figure 5.1 illustrates the symbols used in developing fault trees.

To quantify a fault tree, failure rates are assigned to the basic events at the bottom levels of the tree. The occurrence rates for human error and equipment failure used in the fault trees are based either on information reported in the literature, specific facility or company history, or on analyst estimates which combine information supplied by the company (operating procedures, personnel organization and experience, and design information) with information from other sources in the literature. If available, it is best to use site-specific failure data when quantifying the tree. This data is often available from preventive maintenance records or from a review of incident reports.

The sequence of events forms pathways, along which are found ‘AND’ or ‘OR’ gates. These gates connect the basic initiating event and contributing events to the higher-order events. When the occurrence of all of a set of lower-order events is necessary for the next higher order event to occur, they are joined by an ‘AND’ gate. By multiplying together the probabilities of each event in the set, the probability of the next higher event is obtained. When the occurrence of any one of the set of lower order events is sufficient for the next higher order event to take place, the events in the set are joined by an ‘OR’ gate, and their probabilities are added. Probabilities of the top events are expressed as a yearly rate, e.g., 10^{-4} chance of occurrence per year (once in every 10,000 operating years on average).

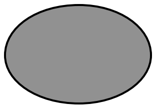
Since the probability of each top event (accident scenario) is to be expressed as a yearly rate, no more than one event leading into an ‘AND’ gate can be a frequency. Otherwise, the overall rates will be in terms of something similar to ‘occurrence rate per year squared’ - a meaningless concept. Thus, at most one event leading into an ‘AND’ gate can be expressed as a frequency; the remaining events are expressed as conditional probabilities, or failures per demand.

At ‘OR’ gates it is essential that all the events entering the gate be quantified in the same units, i.e., as either frequencies or probabilities, since they are to be added. The next higher-order event will be in the same units as the events preceding it. One of the most common mistakes is to multiply two or more frequencies together, yielding meaningless results.

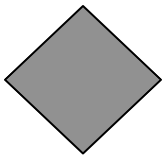
Figure 5.2 gives an example of a simple fault tree. The resulting fault tree provides a visual understanding of the basic causes of the undesired event and a structure which can be quantified to arrive at the expected frequency of the undesired event.

The literature contains several examples of fault trees which have been developed for specific situations. For example, the Health and Safety Executive of the UK has developed a Fault Tree for the BLEVE of a butane storage bullet (Blything and Reeves, 1998). They consider the ways in which a leak may occur and progress to a BLEVE, and assign failure data to arrive at a top event frequency in the range of 10^{-8} to 10^{-6}/vessel-year. Other examples can be found in CCPS (1989a).

Figure 5-1 Fault Tree Logic Symbols

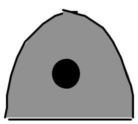


Basic Event: Circles or ovals represent basic events. These are basic initiating faults requiring no further development. They include initiating events having yearly rates of occurrence, and response (demand) events having failure rates of occurrence per demand, i.e., conditional on the prior initiating and contributing events having taken place.



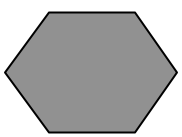
Undeveloped Event: Diamonds represent events that are not developed further either because the event makes an insignificant contribution to the top event or because information relevant to further development is unavailable.

Rectangles represent states which are the product of several initiating and/or contributing events through an “AND” or “OR” gate and may therefore have rates of occurrence either yearly or per demand.



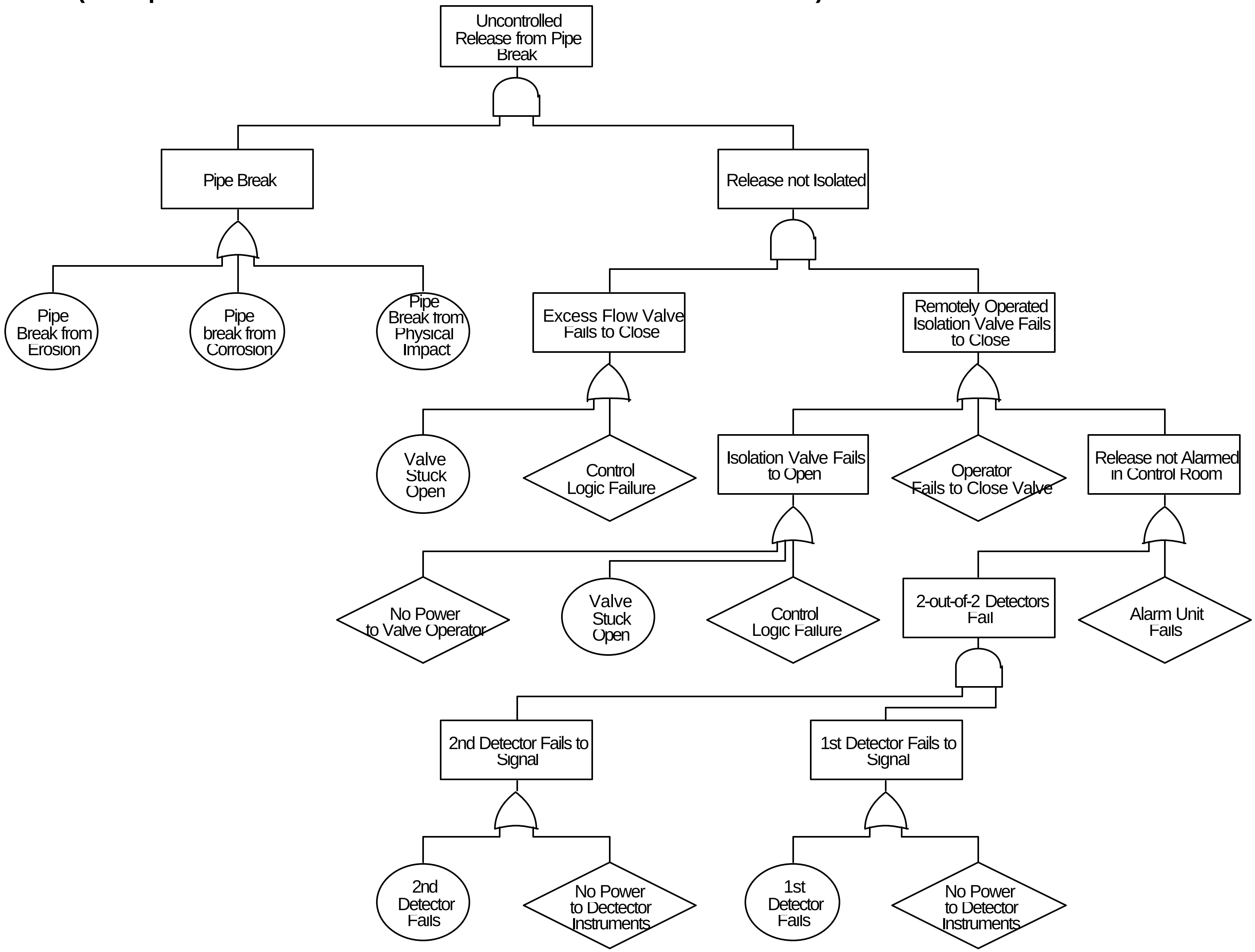
“AND” gate – the rates of occurrence on the incoming branches are multiplied.

“OR” gate – the rates of occurrence on the incoming branches are added.



Hexagons represent numbers of components and serve as multipliers.

Figure 5-2 Example of Fault Tree for Release from a Pipe Break
(Example assumes excess flow valve and isolation valve in series)



5.4 EVENT TREE ANALYSIS

Event tree analysis is a "forward looking" method that takes an initiating event, identifies post-initiating-event influencing factors, and combines the information into a logic tree in which the occurrence of each influencing factor is either "true" or "false."

Two types of event trees are commonly used in risk assessments. These are referred to as pre- and post-incident event trees.

Pre-incident event trees are generally used to develop and track the responses of a control system after failure of that control system, this failure being the initiating event. A typical example is shown in Figure 5-3. Each possible outcome following the initiating event is tracked with a series of positive or negative branches, examining what would happen if the next line of defense functions as designed or fails to function, each with its associated probability of failure. In this way, probabilities of undesirable outcomes such as hazardous material releases, can be estimated.

Post-incident event trees are used to track possible outcomes following hazardous material release on other "top events" examined by a fault tree, and to estimate the frequencies of these outcomes. A typical example is shown in Figure 5-4, which shows the possible outcomes of a propane release from pressure-liquefied storage.

Use of event trees during the hazard identification step in a risk analysis for scenario development is attractive in that it helps organize the thinking process and helps the analyst see how all the parts fit together. The conditional probabilities used in quantifying the branches of the event trees are commonly based on engineering judgement, historical data, and fault trees, also taking into account the types of ignition sources in the surrounding area for flammable releases.

5.5 HUMAN RELIABILITY ANALYSIS

This component of frequency analysis refers to quantitative examination of human responses to given routine and emergency situations which require human intervention. The information is generally in the form of conditional probability of "failure to respond in the appropriate manner to a given signal" or "failure to perform a certain task correctly." Failure rates will be higher for high-stress situations, and also depend on environmental conditions, timing of events, experience, availability of written procedures and training levels. In risk analyses, this information is used in fault and event trees.

Human reliability analysis is an important component of risk analysis. Reviews of past accidents show that human error accounts for the vast majority of these events. The technique most widely used for estimating human error probabilities is called THERP (Swain and Guttman, 1983). The method uses event trees drawn in a different format (see Figure 5.5 for an example) to arrive at a human error probability. In these event trees failure paths branch right and success paths branch left.

Figure 5-3 **Example of a Pre-Incident Event Tree (for failure of a Chlorine storage vessel pressure control system)**

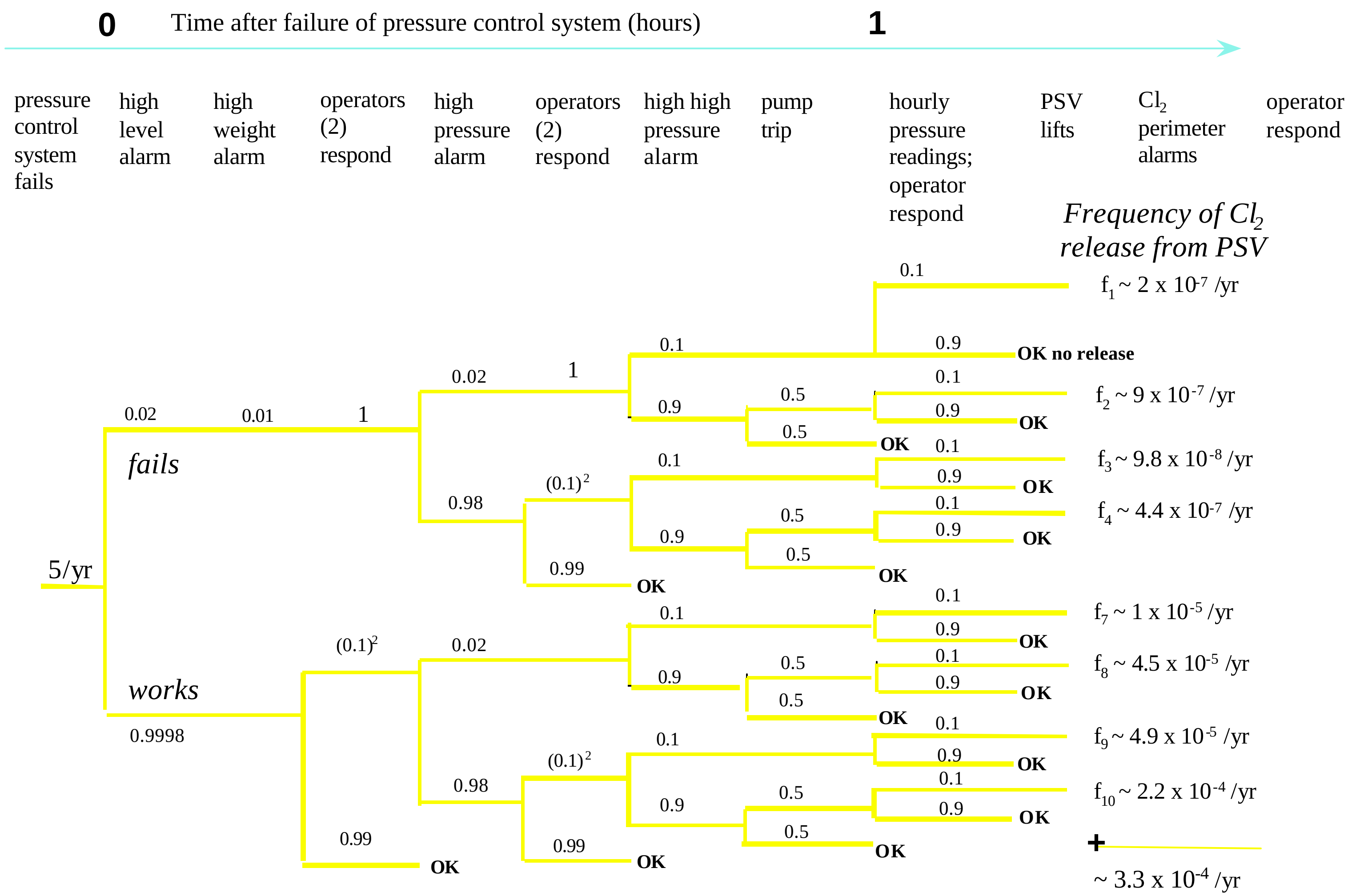
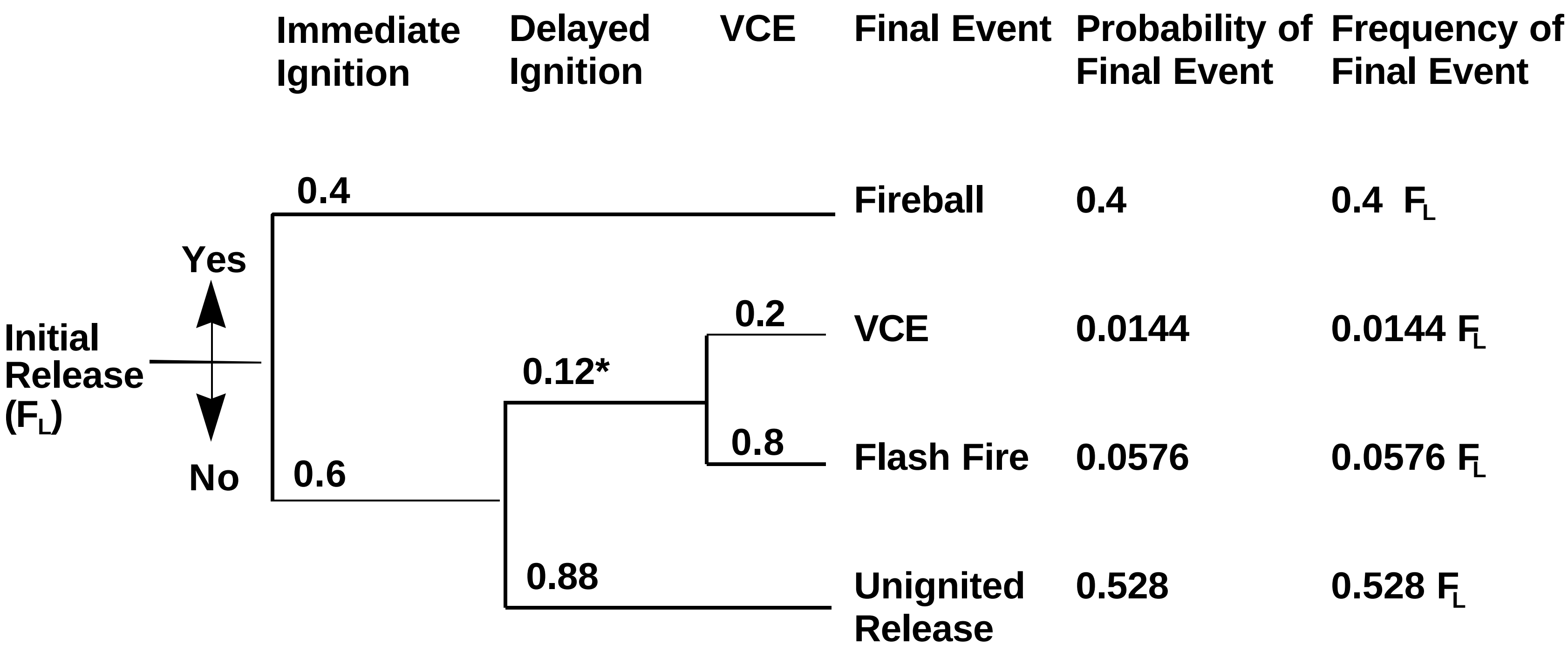
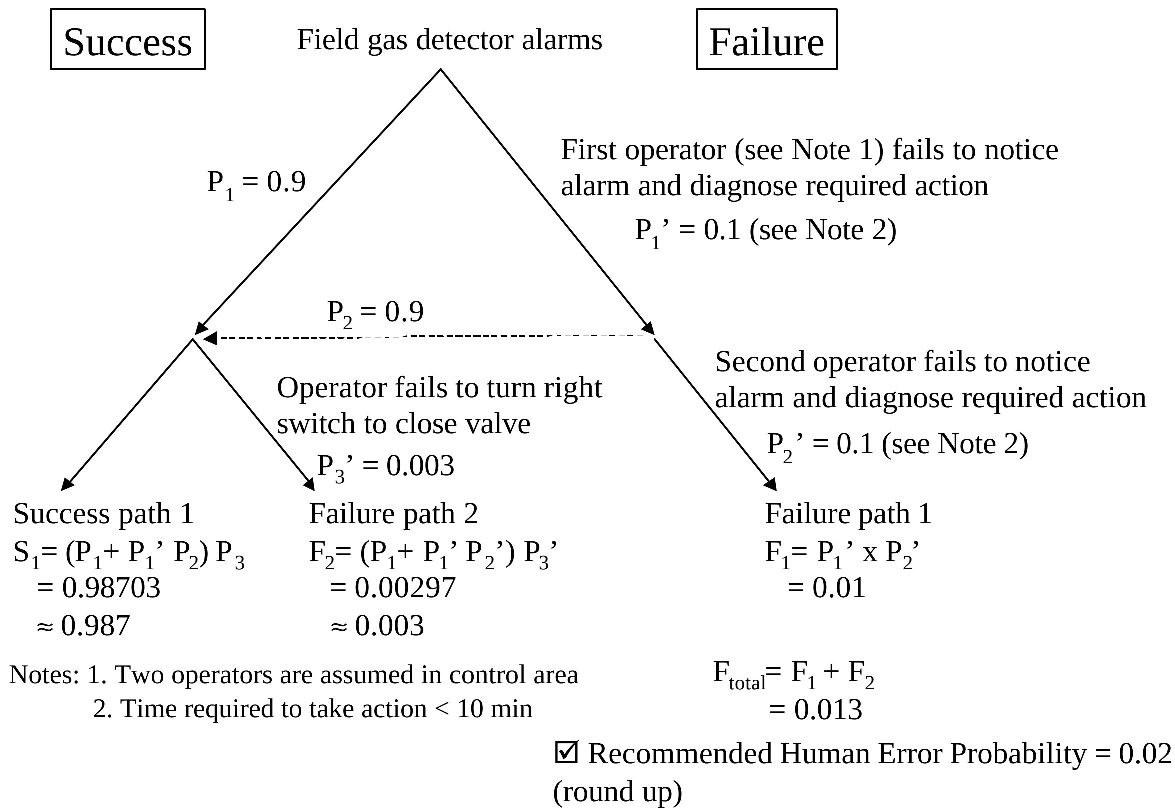


Figure 5-4 Example of a Post-Incident Event Tree



* Example for Suburban Population Density

Figure 5-5 Example of a Human Reliability Event Tree (for failing to close a remotely operated isolation valve given a field gas detector alarm)



5.6 EXTERNAL EVENTS ANALYSIS

This component of frequency analysis considers the impact of external events (such as earthquakes, tornadoes, floods, aircraft crashes, terrorism, and vandalism) as initiating events to undesirable event scenarios. Quantitative frequency information is then used in fault and event trees.

5.7 QUANTIFICATION BASED ON EXPERIENCE

The availability of concrete failure data is rare for most operations, although there are standard data bases available. The best data to use for plant fault trees are those which refer directly to the site in question. Equipment failures can often be determined from maintenance records; component failures can often be determined from warehouse records which show the use of a given product, e.g., solenoid valves, over a period of time.

If such information is not readily available, it is still possible to quantify a given cause by asking other staff members how often they would expect a failure to occur using a Delphi technique. Such an estimate is often accurate enough, especially for an initial evaluation.

One possible procedure for obtaining this data would be as follows:

1. Select a group of experts (usually three or more)
2. Solicit, in isolation, their independent estimates on the value of a particular parameter and reasons for their choice.
3. Provide initial results to all experts and allow revisions to the initial estimates. In some cases, the experts are brought together and allowed to discuss the basis for their estimates in order to try to reach a consensus.
4. Use the average of the final estimates as the best estimate of the parameter. Use the standard deviation of the estimates as a measure of the uncertainty.

If it is determined that the estimated event plays a critical part in the undesired event frequency, then time can be spent to obtain more detailed data from records, from supplier data, or by testing the components.

5.8 AVAILABLE DATA ON EVENT FREQUENCIES

A number of sources are available where historical data on undesirable event frequencies can be found. These data sources can be grouped into three:

1. Component failure rate and human error data

   These sources provide generic data on failure rates of components such as valves, flanges, pipes on a per unit time or per demand basis as appropriate. Commonly used references include CCPS (1989b), Lees (1980, 1996), Rijnmond (1982), EPRI (1981), CONCAWE (1982), GRI (1981), IEEE500 (1983), OREDA (2002), TNO Red Book (1997), WASH-1400 (1975), CR-1278 (1980).

2. Industry top event frequency data

   These data sources provide information on industry-average frequencies of "top-events" that could be used directly in risk analyses. They are published:

   - As part of industry guidelines or recommended practices (e.g., API 752, 1995),
   - By government agencies, e.g., Alberta EUB annual, sour gas incident data reports, Transportation Safety Board annual reports containing air, marine, rail accident statistics, HSE annual reports containing offshore accident and release statistics, others such as:
     - The National Transportation Safety Board (US),
     - The Federal Railroad Administration (FRA, US),
     - The Federal Transit Administration (FTA, US),
     - The Federal Highway Administration (FHWA, US),
     - The Research and Special Programs Administration (RASP, US),
     - The Office of Pipeline Safety (US, part of the RSAP),
     - The Bureau of Transportation Statistics (US),
     - The Office of Hazardous Materials Safety (US),
     - The Transportation Research Record (National Research Council, Transportation Research Board, US),

  - The International Transportation Safety Association (ITSA),
  - The Railroad Commission of Texas.

- By consulting companies under contract to government agencies (e.g., Worldwide Offshore Accident Databank—WOAD, 1999), or
- As occasional research papers or reports (e.g., papers on rail and truck accident rates, reports on pipeline accident rates from groups such as the Institute for Risk Research, University of Waterloo).

Selected industry-average information from various sources can be directly used in risk analyses. Due to the large variability in actual experience from facility to facility and from company to company, extreme caution should be exercised in use of such industry-average data. Use of facility-specific data in combination with fault and event trees is recommended wherever possible.

3. Government of Canada accident data

Various government agencies in Canada collect and report information on accidents. These provide country-wide incident information on a yearly basis, but are not directly useful in risk analyses as they do not include appropriate "divisor" data (See Section 5.2). These include:

- National Analysis of Trends in Emergencies System (NATES) Database

  The NATES database was established in 1973 by Environment Canada to record information from voluntary reporting of pollution incidents involving hazardous substances.

  The database contains spill information entered under a number of data fields, including location, material spilled, quantity, cause, source, and sector.

  NATES captures the most significant of the spill events reported each year. For the sake of clarity, the name 'NATES' is used to encompass all of the data sources for various analyses of trends undertaken by Environment Canada. However, NATES is only one of the data sets used; data are also obtained through the Department's co-operative agreements with the provincial and territorial reporting agencies and other government departments.

- National Pollutant Release Inventory (NPRI)

  In addition to NATES, Environment Canada also maintains a national database called the National Pollutant Release Inventory (NPRI). It is designed to collect and make available to the public, on a yearly basis, comprehensive national data on releases to air, water and land, transfers in waste, and ongoing emissions of specified substances. Under the authority of the *Canadian Environmental Protection Act*, owners or operators of facilities that manufacture, process or otherwise use one or more of the 176 specified substances under prescribed conditions are required to report to the NPRI. The NPRI reports for the years 1994 and 1995 can be found on the Environment Canada web site (http://www.ec.gc.ca/pdb/npri/).

  One of the main differences between NATES and NPRI is that reporting to NATES is voluntary, while reporting to the NPRI is mandatory. Also, NPRI covers all emissions including spills, whereas NATES covers only spills. In addition, the thresholds and reporting criteria exempt many fixed facilities from reporting to NPRI, whereas all spills may be reported to NATES.

- Dangerous Goods Accident Information System (DGAIS)

  Transport Canada maintains the Dangerous Goods Accident Information System (DGAIS). All transportation incidents resulting in spills must be reported to the Transport Dangerous Goods Directorate by the person responsible for the dangerous goods consignment at the time of the incident. Since July 1985, dangerous goods incident information has been submitted under the reporting requirements of Section IX of the Transportation of Dangerous Goods Regulations.

- National Environmental Emergencies System (NEES)

  Recognizing the incompatibilities among the various Environment Canada regional spill databases, the Environmental Emergencies Program began developing the National Environmental Emergencies System (NEES) in the fall of 1993.

  The NEES incorporates historical data tables from the regional systems, as well as the NATES database and data from various contributing agencies.

5.9 UNCERTAINTIES IN FREQUENCY ESTIMATION

The greatest influence on uncertainty in risk results can be attributed for uncertainties in frequency estimates.

They arise from:

- Uncertainties in modelling,
- Errors in modelling,
- Omissions in modelling of safety features, and
- Uncertainties in failure data.

Each of these can cause the estimated frequency to deviate from the “true mean” frequency.

Uncertainties in modelling occur due to a variety of reasons. The analyst may not have sufficient design, layout, or operating information to enable the development of accurate logic tree models. For example, the total length of pipeline in a plant may not be known with confidence. Another type of uncertainty may arise from taking short cuts in the modelling in order to simplify the effort required. Usually conservative assumptions can be made for the above factors.

Errors in modelling may arise if due care is not taken in developing fault/event tree models or in the identification of appropriate failure data. An example would be the case where an area has two toxic gas detectors, either of which can close an emergency isolation valve. In the fault tree, both detectors would have to fail for leak detection failure to occur and the events would be “ANDed” together. The fault tree should be described down to the power supply level. This would ensure that the Boolean solution to the fault tree would capture the case where power is supplied to the detection equipment from the same power bus. Another example is the case of sour gas pipeline failure rates. Because of the corrosive nature of sour gas, these failure rates are significantly higher than for sweet gas pipelines. Using a sweet gas pipe failure rate for sour gas service will underpredict the frequency of releases.

Omission in taking credit of safety features can cause a hazardous event frequency to be overestimated significantly (by up to two orders of magnitude or more). The magnitude of this uncertainty alone may be greater than the cumulative uncertainties in all other assessments. If the results are acceptable, then there is no need for a second iteration and the analyst would have confidence that frequency and risk have not been underestimated.

In the above factors, the analyst has control over the uncertainties. However, when it comes to failure data based on historical observations, the analyst has little control over the uncertainties. This data tends to be generic (i.e., “average”) and limited. The unique conditions at a specific plant (e.g., component service, age, or environmental conditions) may not be captured in the data. In addition, not all components or component failure modes may have data available. Inevitably, approximations are made; these should be made conservatively. Failure rates that are available will also have significant uncertainties—divisors (i.e., component years of service) may not be well known or the number of component failures in the database may be under-reported. This is particularly important if using generic hazardous event frequencies (i.e., BLEVEs per tank-year) in that they are unlikely to capture the design, layout, operational and mitigation features of a particular plant. Here, the uncertainty in the frequency estimates may be so significant to render the risk results meaningless.

In summary:

- As described above, there are a number of different factors that may result in uncertainties in frequency estimates.
- In most situations, uncertainties in frequency estimates have the greatest contribution to uncertainties in risk estimates.
- Analysts experienced in frequency estimation can minimize these uncertainties and ensure, where possible, that they err on the safe side (i.e., overestimating frequency without going overboard).
- In choosing the method for delivering frequency estimates, the use of fault/event logic trees is superior to deriving hazardous event frequency from generic historical data; however, it is also more costly.

6. RISK ESTIMATION AND EVALUATION - MATRIX METHODS

Once the consequences and frequencies of representative hazardous events are estimated, a very useful step for evaluating the significance of these specific events is to rank them using a matrix method.

Note that the results of matrix evaluation *may* provide sufficient justification and guidance for action plans and decision making on an event basis, especially for facility safety management decisions (i.e., actions that can be undertaken by the operator of the hazardous facility). However, for situations that have public safety and land use implications, full quantitative estimation of the total facility risk, and comparison against public risk acceptability guidelines, become necessary for decision making.

In the matrix method, each hazardous event identified as part of the hazard identification step is first categorized using broad categories of frequency and consequence. Commonly used definitions of these categories are presented in Tables 6.1 and 6.2. In these tables, Category 1 indicates a "low" frequency or consequence; Category 4 indicates a "high" frequency or consequence.

By progressively changing the definitions for different categories, an operating company can gradually make the criteria for risk acceptability more stringent. The matrix approach can therefore be used by an operator as a tool for continuous improvement of its safety culture and performance.

Three different frequency categorization schemes are provided in Table 6.1. The first scheme is considerably less stringent than the second, which in turn is considerably less stringent than the third. The first scheme is useful for companies who might be in their early stages of development in terms of their safety culture and performance. One can then gradually start using the second and third schemes for continuous improvement. Another way of looking at these different frequency categorization schemes is from the perspective of application focus. If the application of the method is focusing on maintenance and reliability, the first scheme would be appropriate. If the focus is on very rare but potentially very high consequence events for public safety, the second or third scheme would be more appropriate.

Consequences may be treated in many different categories, such as: consequences to the public, the employees, the environment, consequences in terms of production loss, capital loss, and finally in terms of loss of market share due to loss of goodwill on the part of the markets. The category that is the focus of this guideline is 'public' and hence only an example ranking scheme for this consequence category is given in Table 6.2. Further information can be found in Alp (1996).

Each hazardous event, once categorized, can then be represented on a risk matrix such as the one shown in Figure 6.1, and prioritized with respect to the urgency of risk control measures that should be implemented to reduce the risk from that particular type of event. A commonly used set of definitions for each risk category on this matrix is given in Table 6.3.

Table 6.1 Example Frequency Categories and Categorization Schemes

CCPS (1992, adapted)

CATEGORY	DESCRIPTION
1	< 0.02/year (Not expected to occur during the facility lifetime)

2	0.02 - 0.05/year (Expected to occur no more than once during the facility lifetime)
3	0.05 - 1/year (Expected to occur several times during the facility lifetime)
4	> 1/year (Expected to occur more than once in a year)

from (Alp, 1996)

CATEGORY	DESCRIPTION
1	< 0.001/year (Less frequent than 1 in 1,000 years)
2	0.001 - 0.01/year (Between 1 in 1,000 and 1 in 100 years)
3	0.01 - 0.1/year (Between 1 in 100 and 1 in 10 years)
4	> 0.1/year (More frequent than 1 in 10 years)

CCPA (1992, adapted)

CATEGORY	DESCRIPTION
1	< 10^{-6}/year (Less frequent than 1 in 1,000,000 years) (Remote)
2	10^{-6} - 10^{-4}/year (Between 1 in 1,000,000 and 1 in 10,000 years) (Unlikely)
3	10^{-4} - 0.01/year (Between 1 in 10,000 and 1 in 100 years) (Moderately Likely)
4	> 0.01/year (More frequent than 1 in 100 years) (Likely)

Table 6.2 Example Consequence Categories

CATEGORY	PUBLIC CONSEQUENCES
1	No injury or health effects
2	Minor injury or health effects
3	Injury or moderate health effects
4	Death or severe health effects

A summary table showing all the hazardous events and their assigned frequency/ consequence categories is useful for presentation purposes and decision making. In such a table, it is recommended that the different consequence categories be kept separate, and not combined to a single overall risk ranking by assigning weights to each consequence category. Combining of the different risks into a single risk ranking may be warranted in some applications as long as the detail is not lost to the decision-maker.

For the purposes of the present guidelines, which focuses on public safety, the events with significant off-site consequences should then be analyzed using the quantitative techniques presented in the other sections of this document.

Other matrix schemes are also widely used. Some examples are the schemes provided in CAN/CSA-Q634-91, and in CCPA (1992).

Figure 6.1 Example Risk Matrix (adapted from CCPS, 1992)

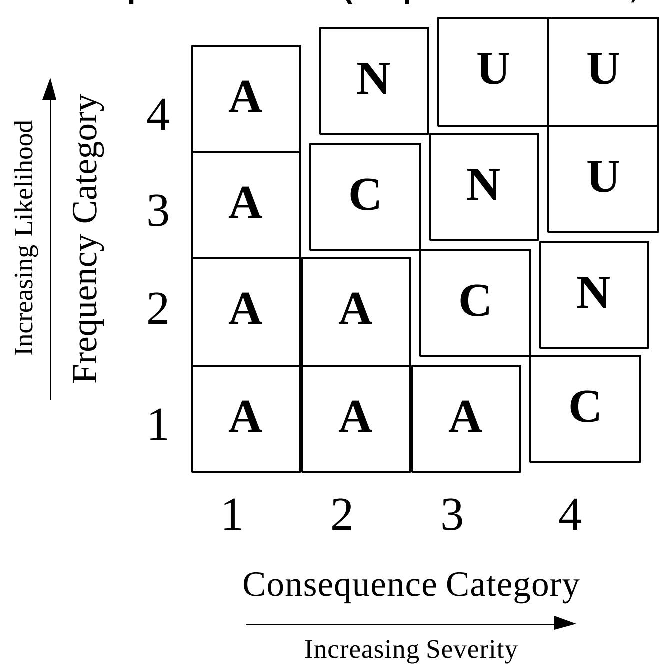


Table 6.3 Example Risk Ranking Categories (adapted from CCPS, 1992)

Code	Category	Description
U	Unacceptable	Should be mitigated with engineering and/or administrative controls to a risk ranking of C or less within a specified period such as six months.
N	Not desirable	Should be mitigated with engineering and/or administrative controls to risk ranking of C or less within a specified time period such as 12 months.
C	Conditionally acceptable with controls	Should be verified that procedures or controls are in place.
A	Acceptable as is	No mitigation required.

7. RISK ESTIMATION AND EVALUATION - QUANTITATIVE METHODS

Following estimation of frequencies and consequences of representative hazardous events, if there is a need for estimation of total individual risk for the facility from a land use perspective, such as in the case of exploring acceptability of the facility (or a residential development *near* the facility), then the next step is to fully quantify the risk. We use the commonly accepted measure of risk for this purpose:

Event Individual Risk at a receptor point	=	*Event Frequency*	*x*	*Event Individual Consequence at that receptor point*

The total facility risk is then the sum of all the event risks at a receptor point. Repeating the process at different receptor points will generate a risk curve where generally risk decreases with increasing separation distance from the risk source (see Figure 7-1). The units of this risk measure can be expressed as "the annual chance that a person living near the hazardous facility might die due to potential accidents in that facility." (The MIACC risk acceptability guidelines are for a specific receptor location and not for a receptor who may spend some of his or her time away from that receptor location. Hence, the risk calculation should also assume continuous exposure of the receptor).

In the calculation of the total facility risk, it is important that all significant representative accident scenarios are identified. Due to the large number of potential scenarios in complex installations, events with similar consequences are normally grouped together to reduce the amount of effort required to quantify their consequences. *Then a representative scenario is selected for each event category and is assigned the* ***total*** *frequency of* ***all*** *events falling into that category of events.*

The implications of this effort-saving step must be understood and evaluated very carefully by all stakeholders:

In public risk assessments, the representative scenario selected for each event category is generally the worst credible case in that category of events. This is done to ensure that the risk estimates are conservative (i.e., risks are over-estimated) so that public safety is not compromised. If the number of event categories used in the assessment is too small, this standard practice of risk analysis may lead to unrealistically high risk estimates, thus losing their usefulness in decision-making. A balance, therefore, must be sought between the amount of effort spent (which is proportional to the number of event categories used) and the degree of over-prediction tolerable in the risk estimates.

For events with little or no dependence on meteorology and wind direction (such as explosions) in facilities that can be considered as point sources (such as chemical plants and storage facilities), the mathematical expression for the total individual risk is relatively straightforward:

$$I(P;P') = \sum F_h \, P_{e,h}(P;P').$$

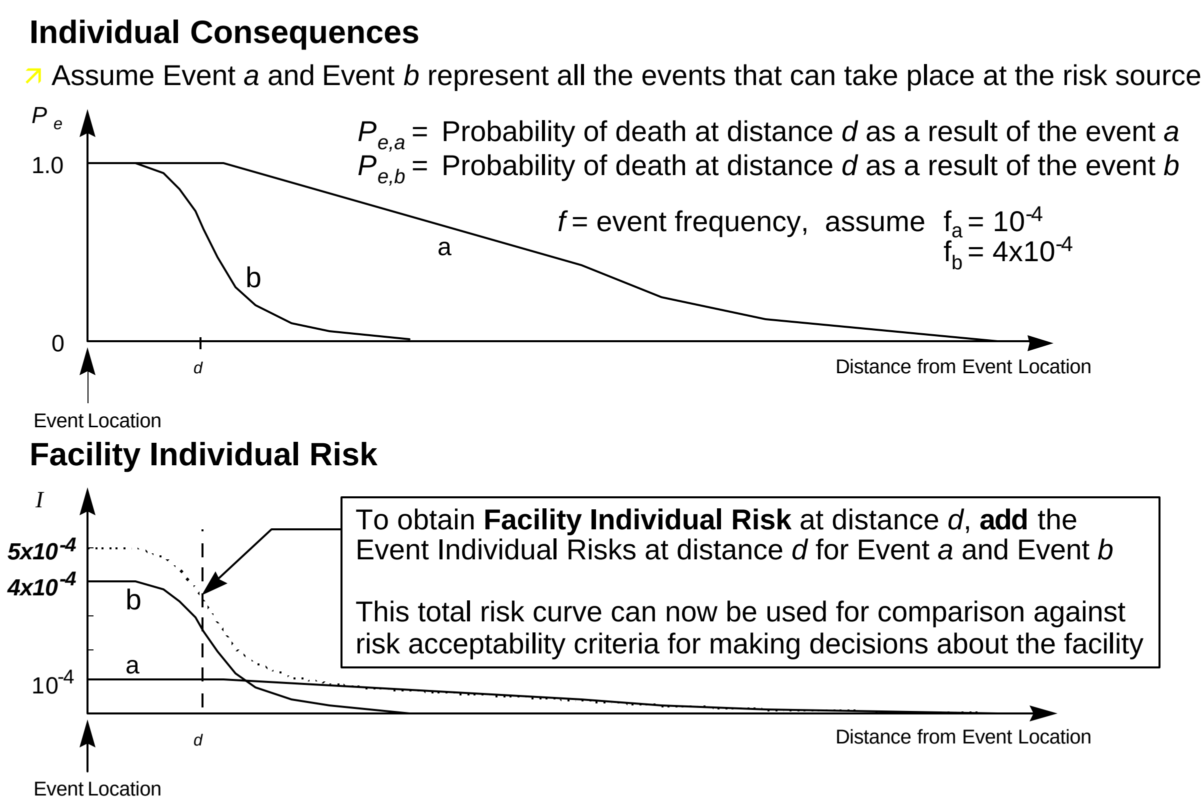
Here $P_{e,h}(P;P')$ denotes the probability of hazardous ***e***ffect (e.g., fatality) at receptor location P due to the risk source at P′ and hazardous event ***h***, F_h denotes the annual frequency of the hazardous event ***h***, the multiplication of the two gives the event individual risk at receptor point P, and the sum is over all the event categories. This process is described in graphical form in Figure 7-1 where risk from two events, each with its own risk distribution, is added together at each distance from the event location to arrive at the total risk at that distance.

For meteorology- and wind direction-dependent events (such as gas clouds), the treatment is more complex, requiring consideration of joint frequency of occurrence of different weather conditions with wind direction.

For hazardous installations of a linear nature, such as pipelines and rail, truck, and marine tanker transportation corridors, the estimation of individual risk also involves an integration along the corridor. For multiple sources, the sum of the individual risk from all sources at a given receptor location must be considered before comparison to the risk acceptability criteria.

Complete formulations for these situations are given in a recently published paper in the international literature (Alp and Zelensky, 1996) and are summarized in Appendix A4. Other simplified formulations are given in TNO (1999, Purple Book), CCPS (1989a) and CCPS (1995b).

Figure 7-1 Estimation of Total Facility Risk (for events with little or no dependence on meteorology and wind direction – explosions, pool fires, simple jet fires)



Once the total facility risk profile is calculated, then this curve can be compared to the MIACC risk acceptability guidelines (Figure 1-1), and distances from the risk source to 10^{-4}, 10^{-5}, and 10^{-6} risk levels can be established.

8. DOCUMENTATION OF RISK ASSESSMENTS

Adequate documentation of the risk analysis methodology and results is essential for success of any risk assessment. This is important for communicating the methodology of the results to both the stakeholders and the decision-makers.

The documentation for describing the risk assessment should include as a minimum the following:

- Objectives of the analysis.
- Description of the physical system, the surrounding land-use including adjacent hazardous facilities, and stakeholders.
- Description of the methodology for hazard identification and resulting hazardous events selected for detailed quantitative analysis; justification for selection of these events.
- Description of the methodology for consequence analysis, including all significant modelling assumptions and models used with justification, with references to technical publications as appropriate.
- Description of the methodology for frequency analysis, including all significant assumptions and data sources; justification for selection of the methodology and data sources used.
- Description of the risk estimation methodology, including all significant simplifying assumptions.
- A discussion on the sources of error, sensitivity of the results on the assumptions used, and level of uncertainty in the quantitative results.
- Comparison of the quantitative results to the MIACC risk acceptability criteria, if appropriate, with reference to any existing land use and adjacent hazardous facilities in the area.

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APPENDIX A1 – COMMON RISKS

In evaluating levels of individual risk, and putting the risk acceptability criteria into perspective, it is useful to keep in mind the risk levels encountered in other activities. Some common risks are presented in Table A1.1 for this purpose.

Table A1.1 Common Risks in Canada[(a)]

Cause	Individual Risk[(b)] (Chances in a million of death per year)
Motor Vehicle Accident	109
Falls	82
Poisoning[(c)]	25
Dwelling Fires	7.9
Water Transport Accidents	3.6
Air & Space Transport Accidents	3.2
Excessive Cold	3
Electrical Current	1.1
Railway Accidents	1.1
Drowning in Bathtub	0.8
Earth Movements	0.4
Lightning	0.2
Cataclysmic Storm	0.03

(a) Data are Canada-wide and were derived from information in "Causes of Death" Statistics Canada Publication #84-208 (1995).

(b) These are average individual risk values, based on a population of ~29,600,000. Data are rounded.

(c) Poisoning includes accidental poisoning due to poisonous and other substances, surgical complications and misadventures to patients.

The data in this table indicate that some of the risks that we are familiar with range from 109 chances in a million (~$1.1x10^{-4}$) per year (chance of death due to a motor vehicle accident) to 0.03 chances in a million ($3x10^{-8}$) per year (cataclysmic storm). While not directly comparable, these values are presented to put into perspective the risk acceptability guidelines presented in Figure 1.1, where it is indicated that, above 100 chances in a million (10^{-4}) no land use other than the risk source would be allowed, and no restrictions to land use would apply below an individual risk level of 1 in a million (10^{-6}) per year. It should be noted that, the risks shown in Table A1.1 are different in character from the risks due to a hazardous facility. (For example, dying in a motor vehicle accident is usually considered to be a voluntary risk, i.e., one chooses to get into the vehicle. Dying as a result of lightning may or may not be considered voluntary since one can try to avoid being in places susceptible to a lightning strike (such as being in the middle of a field during an electrical storm with a metal rod in one's hand). The distinguishing feature of these risks from risks due to a hazardous facility is that these are not considered "dread" hazards. Dread hazards usually have the following characteristics: potential for multiple fatalities, man-made, imposed on members of the public by others). Therefore, the numbers given in the table should not be used to justify a hazardous facility but rather only to put the risk numbers in perspective.

APPENDIX A2 – HAZARD LIMITS FOR SELECTED MATERIALS

Table A2.1 Table of Inhalation Exposure Limits for Selected Hazardous Materials

MIACC LIST 1 Substances	IDLH (ppm)	ERPG (ppm) 1	2	3	LC50 ppm at 30 min
ACETALDEHYDE	CA (2,000)	10	200	1000	
ACETYLENE	N.D.				
AMMONIA, ANHYDROUS	300				11538.62
AMMONIA SOLUTIONS with more than 35% and less than 50% ammonia	300				
AMMONIA SOLUTIONS with more than 50% ammonia	300				
ARSINE	CA (3)				
BENZENE	CA (500)	50	150	1000	9206.85
BROMINE & BROMINE SOLUTIONS	3	0.2	1	5	376
BUTANE & BUTANE MIXTURES	N.D.				
CHLORINE	10	1	3	20	250.19
CYCLOHEXANE	1,300 (LEL)				80
ETHYLBENZENE	800 (LEL)				32000
ETHYLENE	Not listed				
ETHYLENE DICHLORIDE	CA (50)				14000
ETHYLENE OXIDE	CA (800)	N/A	50	500	12400
FLUORINE	25	0.5	5	20	
GASOLINE	CA (N.D.)				
HYDROGEN CHLORIDE/ACID	50	3	20	150	1851.59
HYDROGEN FLUORIDE/ACID	30	2	20	50	6530.59
HYDROGEN SULPHIDE	100	0.1	30	100	440.75

MIACC LIST 1 Substances	IDLH (ppm)	ERPG (ppm) 1	2	3	LC50 ppm at 30 min
LIQUEFIED PETROLEUM GASES	2,000 [LEL]				
MERCURY	10 (mg/m3) (as Hg)				210
METHANE	Not listed				128000
NAPHTHA, PETROLEUM NAPTHA or NAPTHA SOLVENT	1,000 [LEL]				19200
NITRIC ACID, FUMING or RED FUMING	25				84
PROPANE, and PROPANE MIXTURES	21,000 [LEL]				
PROPYLENE OXIDE	CA (400)	50	250	750	36130.14
SODIUM CHLORATE	Not listed				9600
SULPHUR DIOXIDE	100	0.3	3	15	627.45
SULPHURIC ACID, FUMING	15 (mg/m3)	2 (mg/m3)	10	30 (mg/m3)	275
TETRAETHYL LEAD	40 (mg/m3) (as PB)				1064
TOLUENE	500	50	300	1000	26964.22
VINYL CHLORIDE	CA (N.D.)				128000
XYLENE	900				50800

Notes:

IDLH: Immediately Dangerous to Life and Health. Data taken from NIOSH (National Institute of Occupational Safety and Health) Pocket Guide to Chemical Hazards, Washington, U.S. Government Printing Office, 1994. According to this Guide, the definition of IDLH exposure condition is a condition “that poses a threat of exposure to airborne contaminants when that exposure is likely to cause death or immediate or delayed permanent adverse health effects or prevent escape from such an environment”. IDLH values are based on the effects that might occur as a consequence of a 30-minute exposure.

ERPG: Emergency Response Planning Guidelines taken from the AIHA (American Industrial Hygiene Association) Emergency Response Planning Guidelines and Workplace Environmental Exposure Level Guides Handbook, Fairfax VA, American Industrial Hygiene Association, 1998.

ERPG-1: The maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 hour without experiencing other than mild transient adverse health effects or perceiving a clearly defined objectionable odour.

ERPG-2: The maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 hour without experiencing or developing irreversible or other serious health effects or symptoms that could impair their abilities to take protective action.

ERPG-3: The maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 hour without experiencing or developing life-threatening health effects.

CA: Refers to substance NIOSH considers to be potential human carcinogen. Any IDLH values accompanying a 'CA' notation were determined before NIOSH began considering carcinogenic effects.

LEL: Indicates that the IDLH was based on 10% of the lower explosive limit for safety considerations even though recent toxicological data indicated that irreversible health effects or impairment of escape existed only at higher concentrations.

N.D.: IDLH has not yet been determined.

LC50: Lethal concentration at 30 minutes exposure.

Table A2.2 Effects of Thermal Radiation (CCPS, 1989a)

Radiation intensity (kW/m^2)	*Observed effect*
37.5	Sufficient to cause damage to process equipment
12.5	Minimum energy required for piloted ignition of wood, melting of plastic tubing
9.5	Pain threshold reached after 8 s; second degree burns after 20 s
4	Sufficient to cause pain to personnel if unable to reach cover within 20 s; however, blistering of the skin (second degree burns) is likely; 0% lethality
1.6	Will cause no discomfort for long exposure

Table A2.3 Exposure Time Necessary to Reach the Pain Threshold (API 521)

Radiation intensity ($Btu/hr/ft^2$)	*kW/m^2*	*Time to pain threshold (s)*
500	1.74	60
740	2.33	40
920	2.90	30
1500	4.73	16
2200	6.94	9
3000	9.46	6
3700	11.67	4
6300	19.87	2

Table A2.4 Table of Explosion Effects (Lees, 1986)

Pressure (psig)	***Damage***
0.02	Annoying noise (137 dB), if of low frequency (10-15 Hz)
0.03	Occasional breaking of large glass windows already under strain
0.04	Loud noise (143 dB), sonic boom glass failure
0.1	Breakage of small windows under strain
0.15	Typical pressure for glass breakage
0.3	"Safe distance" (probability 0.95 no serious damage beyond this value); projectile limit; some damage to house ceilings; 10% window glass broken
0.4	Limited minor structural damage
0.5-1.0	Large and small windows usually shattered; occasional damage to window frames
0.7	Minor damage to house structures
1.0	Partial demolition of houses, made uninhabitable
1-2	Corrugated asbestos shattered; corrugated steel or aluminium panels, fastenings fail, followed by buckling; wood panels (standard housing) fastenings fail, panels blowing
1.3	Steel frame of clad building slightly distorted
2	Partial collapse of walls and roofs of houses
2-3	Concrete or cinder block walls, not reinforced, shattered
2.3	Lower limit of serious structural damage
2.5	50% destruction of brickwork of houses
3	Heavy machines (3000 lb) in industrial buildings suffered little damage; steel frame building distorted and pulled away from foundations
3-4	Frameless, self-framing steel panel building demolished; rupture of oil storage tanks
4	Cladding of light industrial buildings ruptured
5	Wooden utility poles snapped; tall hydraulic press (40,000 lb) in building slightly damaged
5-7	Nearly complete destruction of houses
7	Loaded train wagons overturned
7-8	Brick panels, 8-12 in. thick, not reinforced, fail by shearing or flexure
9	Loaded train boxcars completely demolished
10	Probable total destruction of buildings; heavy machine tools (7000 lb) moved and badly damaged, very heavy machine tools (12,000 lb) survived
300	Limit of crater lip.

APPENDIX A3 – PROBIT CONSTANTS FOR SELECTED MATERIALS AND HAZARDS

Table A3.1 Probit Constants for Lethal Toxicity (CCPS, 1989a)

Substance	*k_1 (ppm)*	*k_2 (ppm)*	*N (min)*
Acrolein	-9.931	2.049	1
Acrylonitrile	-29.42	3.008	1.43
Ammonia	-35.9	1.85	2
Benzene	-109.78	5.3	2
Bromine	-9.04	0.92	2
Carbon Monoxide	-37.98	3.7	1
Carbon tetrachloride	-6.29	0.408	2.50
Chlorine	-8.29	0.92	2
Formaldehyde	-12.24	1.3	2
Hydrogen chloride	-16.85	2.00	1.00
Hydrogen cyanide	-29.42	3.008	1.43
Hydrogen fluoride	-35.87	3.354	1.00
Hydrogen sulfide	-31.42	3.008	1.43
Methyl bromide	-56.81	5.27	1.00
Methyl isocyanate	-5.642	1.637	2
Nitrogen dioxide	-13.79	1.4	1
Phosgene	-19.27	3.686	1
Propylene oxide	-7.415	0.509	2.00
Sulfur dioxide	-15.67	2.10	1.00
Toluene	-6.794	0.408	2.50

Table A3.2 Probit Constants for Fire and Explosion Damage (Lees, 1980)

Type of Injury or Damage	*Hazard Load L*	k_1	k_2
FIRE			
Burn deaths	$\frac{1}{10^4}\int I^{4/3}\,dt$	-14.9	2.56
EXPLOSIONS			
Death (lung haemorrhage)	P_o	-77.1	6.91
Eardrum rupture	P_o	-15.6	1.93
Deaths from impact	J	-46.1	4.82
Injuries from impact	J	-39.1	4.45
Injuries from fragments	J	-27.1	4.26
Structural damage	P_o	-23.8	2.92
Glass breakage	P_o	-18.1	2.79

t = exposure time (s)

I = radiation intensity (W/m^2)

P_o = peak overexposure (N/m^2)

J = impulse ($N\ s/m^2$)

Table A3.3 Transformation of PROBITS to Percentages (CCPS, 1989a)

%	0	2	4	6	8
0	-	2.95	3.25	3.45	3.59
10	3.72	3.82	3.92	4.01	4.08
20	4.16	4.23	4.29	4.36	4.42
30	4.48	4.53	4.59	4.64	4.69
40	4.75	4.80	4.85	4.90	4.95
50	5.00	5.05	5.10	5.15	5.20
60	5.25	5.31	5.36	5.41	5.47
70	5.52	5.58	5.64	5.71	5.77
80	5.84	5.92	5.99	6.08	6.18
90	6.28	6.41	6.55	6.75	7.05
99	7.33	7.41	7.46	7.65	7.88

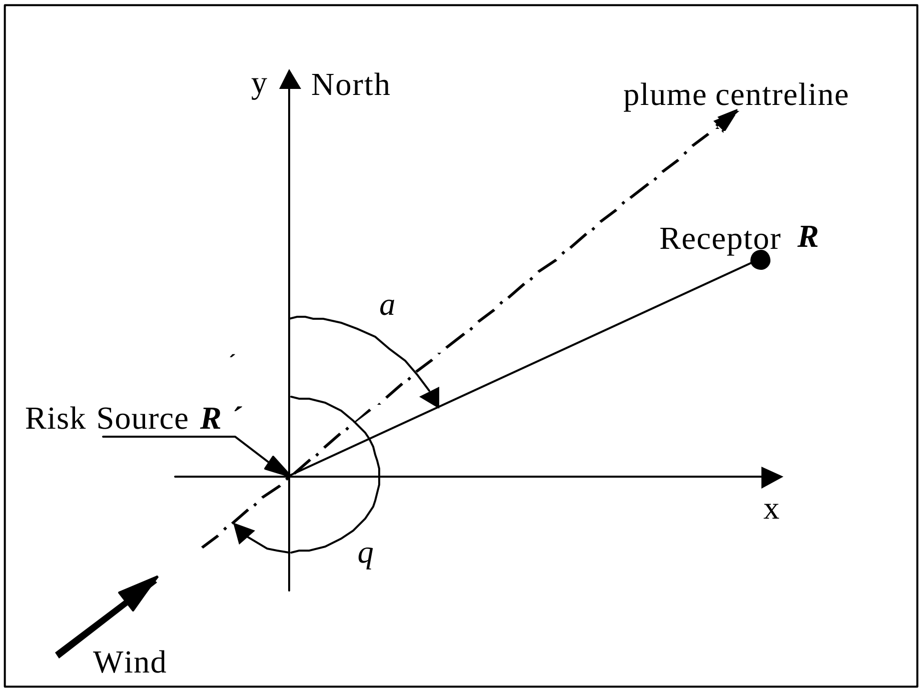
For example, if PROBIT $Y(x) = 5.00$ at location x, then the corresponding probability of effect level (e.g., fatality) at that location is *50* %. If PROBIT $Y(x) = 5.99$, then $P_e(x) = 84$ %

APPENDIX A4 – RISK ESTIMATION

Summary of Detailed Formulations

Figure A4.1 shows the coordinate system and the situation of interest. For full details, the readers are referred to Alp and Zelensky (1996).

Figure A4.2 Coordinate System



For a hazard which is not dependent on meteorology and wind direction (such as an explosion), the individual risk can be estimated by:

$$I_{e,h}(R;R') = F_h \; P_{e,h}(R;R') \qquad \text{(A4.1)}$$

Where R is the receptor location,

R' is the risk source

$I_{e,h}(R;R')$ is the individual risk at R due to the risk source at R'

$P_{e,h}(R;R')$ is the probability of effect e (e.g., death) at R due to event h taking place at R'

F_h is the frequency of event h

For a hazard which depends on meteorology and wind direction (such as a toxic cloud), the individual risk can be estimated by:

$$I_{e,h,m}(R;R') = \int_{o}^{2P} F_h \; P_{e,h,m}(R;R') \; \boldsymbol{j}_{i,m}(q)\, dq \qquad \text{(A4.2)}$$

Where $P_{e,h,m}(R,R')$ is the probability of effect e (e.g., death) at R due to event h taking place at R'

$I_{e,h,m}(R;R')$ is individual risk at R due to risk source at R'

F_h is the frequency of event h

$j_{i,m}(q)\ dq$ is the proportion of time the wind spends between q and $q + dq$ within wind sector i during meteorological condition m (m defined by atmospheric stability and wind speed combination)

The total risk for that event h over all meteorological conditions is then:

$$I_{e,h}(R;R') = \mathring{a}_{m=1}^{M} I_{e,h,m}(R;R') \qquad \text{(A4.3)}$$

For a linear risk source (such as a pipeline, or rail corridor) of length L', the individual risk at R can be calculated by integrating the individual risk due to an infinitesimal risk source of length ds' at location R' (see Figure A4.2)

$$I_{e,h,m}(R;L') = \int_{l_o}^{l_o+L'} F'_h(R') \left[\int_o^{2P} P_{e,h,m}(R;R')\ j_{i,m}(q)\ dq \right] ds' \qquad \text{(A4.4)}$$

Where $F'_h(R')$ is the per-unit-length event frequency.

Equation A4.3 again applies for obtaining the total risk for the event h over all meteorological conditions.

These formulations can be readily extended to estimation of societal consequences and societal risk as shown in Alp and Zelensky (1996).

Figure A4.2 Formulation for Linear Risk Sources