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Part 5 of 9

Methodologies for Technological Risk Assessment

Chapter E Contents

Introduction

Methodologies for Performing a Technological Risk Assessment

Methodologies for Information Gathering and Hazard Identification

Consequence Estimation

Probability and Frequency Estimation

Conclusion

References

Introduction

Up to the beginning of the industrial age, the simple compliance with rules based on experience was sufficient to ensure the design and construction of relatively safe facilities. However, things changed with the industrial revolution and the implementation of more complex systems, especially in terms of machinery and materials that often required the use of large amounts of energy.

Technological accidents began to occur by the middle of the XIXth century. These accidents generally became more frequent and more serious throughout the XXth century, but it was not until the 60s that it became evident that initiatives had to be taken to prevent such accidents.

There are three main types of technological accidents[1]:

- Accidents related to the manufacture, transportation, distribution, use and disposal of materials (chemical products, infectious substances, radioactive material, etc.);
- Accidents related to equipment and tools (cars, planes, etc.);
- Accidents related to energy-based processes (incineration, cogeneration, etc.).

Technological accidents can include therefore a wide variety of events, ranging from the unintentional release of a single toxic chemical such as chlorine[2] to an incident involving a large nuclear complex[3].

In the 60s and 70s, it was in fact the risk related to nuclear complexes that caused communities throughout the industrialized nations to become more aware of technological risks[4], especially of an extreme nature.

Following this awareness, the nuclear accident that occurred at Three Mile Island in the United States in 1979 and the Chernobyl nuclear disaster that occurred in the Ukraine in 1986 clearly demonstrated that such risks really existed and that they had not been properly assessed. Indeed, the investigations conducted afterwards revealed major shortcomings in the operations of the agencies in charge[5].

These nuclear accidents were followed in the 70s and 80s by several chemical accidents, such as in Seveso in Italy (release of dioxins), in 1976, the Pemex accident in Mexico (gas explosion)[6,7,8], and especially in Bhopal in India (release of methyl isocyanate into the atmosphere), in 1984[9,10,11].

The Bhopal accident lead the federal government to investigate the possibility of such an accident occurring in Canada. This initiative was instrumental in the creation of the Canadian Major Industrial Accidents Coordinating Committee (MIACC)[12]. The purpose of this organization is to reduce the risk of accidents involving hazardous substances through a cooperative approach. MIACC includes members from governments, municipalities, industry, emergency response organizations, labour organizations, public interest groups and universities[13].

Technological accidents often have little or no impact on human life, public health[14] , property and the environment[15], but the events described above have shown that such accidents can result in real disasters[16,17]. In addition to the impacts mentioned earlier, they can also result in a crisis[18] among the various players involved or called upon to manage the event[19]. In such cases, the impacts can extend to issues related to mental health in the communities affected[20], maintaining jobs, the corporate image[21], and even to the survival[22] of businesses or to government policy and operations[23].

In Canada as elsewhere in industrialized nations, greater consideration has been given since the early 90s to the risks related to major technological accidents, with respect to both existing facilities and new projects where a major industrial accident can occur. In Quebec, the Department of the Environment and Wildlife (DEW) has issued guidelines on the implementation of environmental impact studies. These initially covered emergency measures planning but now also require in some cases that a technological risk assessment be undertaken[24].

In 1998, there were five (5) DEW directives identifying the type of projects for which a major technological risk assessment is required:

- construction projects for an industrial project;
- pipeline projects;
- waste incinerator projects;
- projects involving dikes, dams, power plants or river diversion projects;
- port or wharf projects.

In the area of risk assessment, the concepts of frequency of occurrence, probability and impact are fundamental because they are used to assess the risk itself. The Canadian Standards Association (CSA) defines risk as a measure of the probability and severity of an adverse effect to health, property or the environment[25].

At least two types of impacts can ordinarily be identified through technological risk assessment: effects on human health and safety and effects on the environment. In the case of the first type, the assessment must include the risk of death, injury or exposure to a hazardous substance within a given group. When an impact assessment is required before an industrial process can be implemented, the goal is to identify any causal relationship likely to affect workers, neighbouring communities and emergency response personnel. In the case of the environment, risk may be more difficult to assess both qualitatively and quantitatively because the range of ecological interactions within an ecosystem is not always well understood.

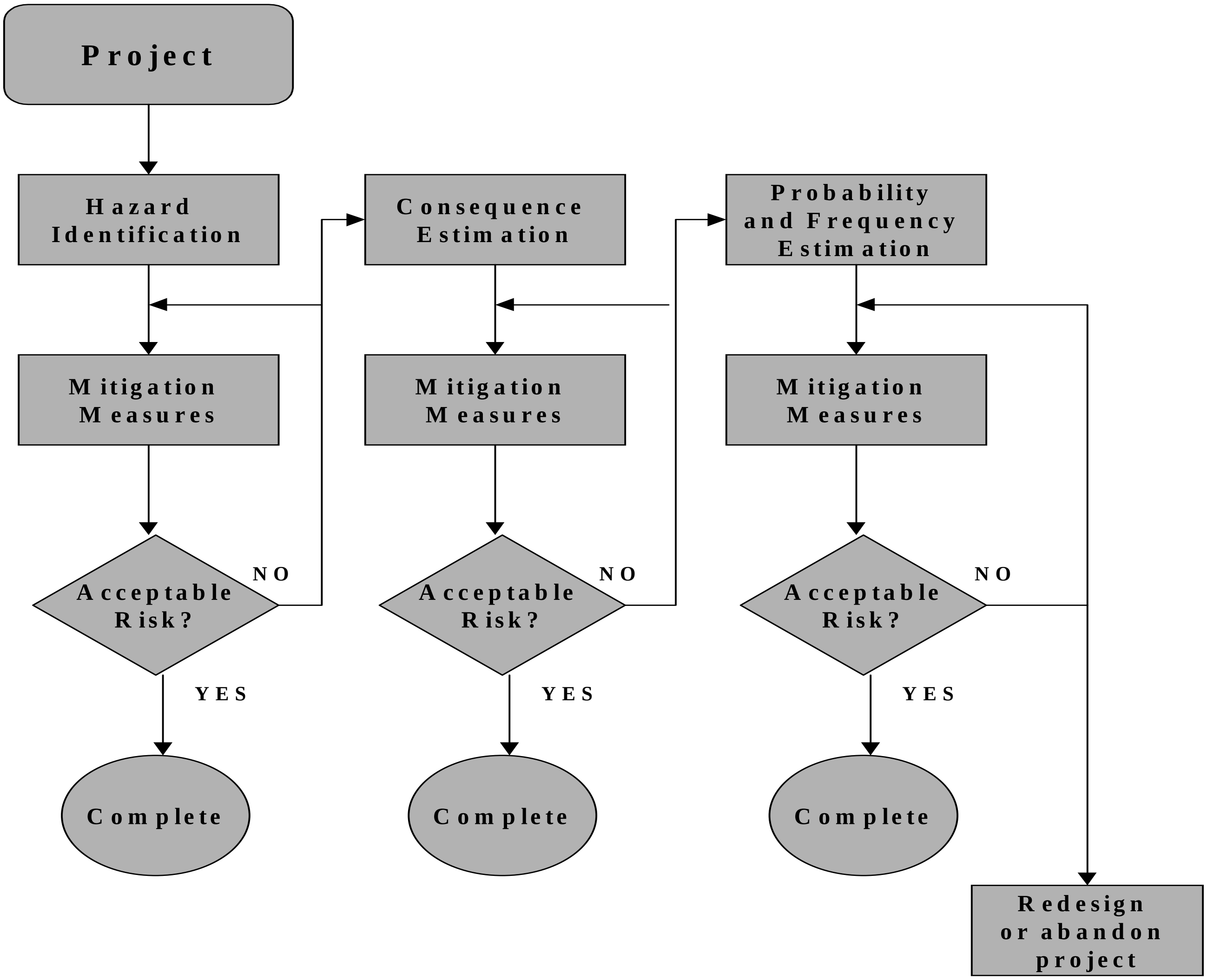
In the case of events affecting human life and public health[26], risk is viewed as the product obtained by multiplying the frequency of occurrence of the event (probability of the event occurring over time) by the probability of negative effects being produced and by the seriousness of the effects[27]. This notion of risk in relation to public health is therefore based on a different approach than the usual formula which includes only frequency of occurrence and the estimated impacts. Indeed, it is essential in the area of public health to consider the probability of occurrence of negative effects, because not all technological accidents result in negative effects on health or human life. Furthermore, the seriousness of the negative effects has to be considered, where appropriate, to ensure a complete risk assessment.

It should be noted that a technological accident can also be identified based on other parameters. According to Dynes, events can be identified according to five parameters: predictability, suddenness, warning time, length of emergency and extent of impact[28]. Burton, Kase and White suggest seven parameters: frequency, magnitude, development speed, duration, surface area, spacing over area and spacing in time[29].

Risk = Frequency of Occurrence of the Event **X** Probability of Occurrence of Negative Effects **X** Seriousness of Effects

Hazard identification, as its name implies, involves drawing up a list of the hazards associated with a project[30]. The OECD defines hazard as "an inherent property of a substance, agent, source of energy or situation having the potential of causing undesirable consequences"[31]. For example, one of the hazards of a mercury vial in a laboratory relates to the toxicity of the mercury vapors to which a person can be exposed if the vial is spilled. In the same way, one of the hazards of a nuclear complex

Figure 1 - Example of a Technological Risk Assessment Methodology



is the fact that there are large quantities of radioactive substances stored on site. If they are released from a reactor, these substances can produce undesirable effects. Therefore, the term hazard does not include the notion of frequency of occurrence which is used to determine risk.

The aim of hazard identification is to itemize all the components or systems in a technological process and to determine where they might break down. Simple methods can be used to undertake this identification, such as reviewing the relevant literature, but it can also be performed by using a more complex process such as a safety audit.

The use of some of these methodologies can be quite difficult when an environmental assessment is performed prior to the implementation of a technological process. As such, a safety audit implies that there will be a visit to the industrial complex or, at the very least, that a careful review of the company's detailed operating plans will be conducted; it will therefore be easier to perform a safety audit after implementation of the industrial process. The main methodologies are described in the following section of this chapter.

Methodologies for Performing a Technological Risk Assessment

A technological risk assessment as performed by engineering consultant firms[32] in North America usually includes the following seven (7) steps: information gathering, hazard identification[33], consequence assessment, probability and frequency estimation[34], risk quantification, risk assessment, risk management and mitigation measures. Very often, only the first three steps are carried out in a typical environmental assessment as performed by or for an industrial promoter.

When performing an environmental assessment, it can be quite sufficient in certain cases to undertake only data gathering, hazard identification and consequence assessment. The methodologies that can be used for these steps are qualitative or quantitative, but they are accurate enough to identify the causes of a failure, its main consequences, the seriousness of the event and also the preventive measures that should be implemented. Once a pattern is identified, it will be possible to make recommendations to ensure safety and to protect human health and the environment, according to the environmental assessment process.

For the probability and frequency estimation stage, the accepted methodologies imply detailed and extensive knowledge of the technological system being assessed. These methodologies are ordinarily based on a good understanding of the process flow used in the technology. An example of a systems analysis methodology allowing to determine frequencies will be provided in the third part of this section.

Methodologies for Information Gathering and Hazard Identification

Previous experience acquired when implementing various technologies is of course a basic source of information (it is in fact the simplest identification method available). However, when the technology used is new or is not well known, it is suggested to use one or several of the methodologies specifically designed to identify hazards.

These methodologies share several common characteristics[36]:

- they use an inductive approach where the effects on the system being assessed are identified based on a given cause;
- they operate from a fragmentation of the system into subsystems, functions,

components, etc., from which any hazardous element, deviation or failure can be identified in order to determine its consequences;

- they are performed by using data sheets (preestablished tables), where the various columns are filled out by an analyst working alone or by a team (see Figures 2 to 5);
- they help ensure that for each potential hazard identified, the appropriate detection mechanisms are in place;
- they only deal with simple events, i.e., they do not capture (or do so with difficulty) combinations of multiple events likely to lead to a potential risk.

Seven (7) methodologies for identifying hazards are described here, beginning with the most simple. Some of these methodologies have similarities. They differ however in several areas because some have been developed to assess specific hazards (e. g., HAZOP for the chemical industry).

The methodologies described are the following: review of the literature, plant visits, brainstorming - what if, preliminary risk analysis (PRA), Hazard and Operability Studies (HAZOP)[37], Failure Modes, Effects and Criticality Analysis (FMECA), and safety audit.

Review of the Literature: The review of relevant literature can be described as a basic method for identifying hazards. Indeed, any person involved in an environmental assessment process can use it, and it is in fact regularly applied in all cases. This method is especially attractive for several reasons: it can be applied to all products and processes and to all technologies, it can be performed by a single person and it is available to less experienced analysts. Because of these features, a review of the literature can be a very appealing method and also an excellent way to start.

Often articles describing technical incidents or accidents are available. For example, the

Seveso accident of 1976 resulted in the publication of dozens of articles which analyzed both the possible causes of this incident and its effects on health. Furthermore, if there is a little information on how the technology works, it is possible at least to determine which main products it uses. This is done by referring to the documents or data sheets describing these products and their effects in case of fire, explosion or unintentional release.

Some products, such as chlorine, maintain the same basic toxicological properties whatever the emission source. Table 1 provides nine (9) examples of sources of information on chemical products.

Table 1 - Canadian and American Sources of Information on Chemical Products

Organization	Logo	Name of Source of Information	Type of Source of Information
Environment Canada **www.etcentre.org**	**EC - DOE**	**Enviroguide**	**Documents published around 1984-1985, approx. 100 pages (currently being updated)**
Transport Canada **www.tc.gc.ca/canutec**	**TC - DOT**	**North American Emergency Response Guidebook, 1996**	**Paper format** **also available on Internet (Downloading)**
Canadian Centre for Occupational Health and Safety **www.ccohs.ca**	**CCOHS**	**CHEMINFO** **www.ccohs.ca/ products/databases/cheminfo.html**	**Available on CD-ROMs, MSDS, and CHEM Source and on CCINFO web.**
Commision de la Santé et de la Sécurité du travail (Quebec) **www.csst.qc.ca/**	**CSST**	**INFOTOX**	**Accessible by modem and eventually available on Internet**

Organization	Logo	Name of Source of Information	Type of Source of Information
US.EPA (Environmental Protection Agency) www.epa.gov/swercepp/tools.html	**EPA**	**CAMEO, ALOHA, etc.**	**Various tools Visit the site**
American Industrial Hygiene Association www.aiha.org/pubs/expopub.html	**AIHA**	**Emergency Response Planning Guidelines (ERPGs)**	**Paper format**
National Institute for Occupational Safety and Health www.cdc.gov/niosh	**NIOSH**	**RTECS www.mdx.com/po-rtecs.htm**	**Data sheets**
		NIOSH Pocket Guide www.cdc.gov/niosh/npg.html	**Paper format CD-ROM Disks**
National Fire Association www.nfpa.org	**NFPA**	**NFPA-49 Hazardous Chemical Data www.nfpa.org/resources/hazchem_resources.html**	**Document**
		NFPA-325 Fire Hazard, Properties of Flammable Liquids, Gases and Volatile Solids	**Document**
U.S. Coast Guard www.uscg.mil		**CHRIS www.mdx.com/pro-chris.html**	**Data bank Internet**
ATSDR		**Hazdat http://atsdr1.atsdr.cdc.gov:8080/hazdat.html**	**Internet**

At the international level, there are specialized data banks on industrial accidents. Table 2 provides the address for eight (8) such banks. One of the most useful is a computerized data bank called ARIA (Analysis, Research and Information on Accidents) maintained by the French Department of the Environment. This data bank provides information on accident cases throughout the world. It uses some 2,200 key parameters[38] grouped under four (4) main headings[39].

1. The site
- Location
- Legal and administrative status
- Type of economic activity
- Physical description of the facility
- Human factors in the processes used

2. The event
- Weather conditions
- Typology
- Operating conditions
- Equipment involved
- Failure analysis and determination
- Main products involved
- Personnel involved
- Response and rescue

3. The consequences
- Human implications
- Damage to property
- Loss of use

- Adverse effects on the environment
- Other damages to public property
- Adverse effects on animal life
- Adverse effects on vegetation
- Changes in biological indicators
- Economic implications

4. Aftermath

- Administrative follow-up
- Legal proceedings
- Cleanup and decontamination

TABLE 2 Specialized Data Banks on Industrial Accidents.

(To be inserted)

Review of the literature must not be limited to accessing bibliographical or factual data banks. It must include also consultations with experts working in public or semi-public organizations at the international, federal, provincial, regional or local levels. These experts are usually in a position to provide reports that are otherwise difficult to locate ("grey area literature"), and they can also provide essential personal expertise. Furthermore, in some cases, useful additional information can also be obtained from environmental protection groups. They often have access to data gathered in other countries and acquired through international exchange programs between these groups. In addition, data search through the Internet is becoming increasingly invaluable.

In conclusion, a review of the literature is a method that any person interested in hazard identification can use. Indeed, this technique is available to anyone and not just to experienced analysts. It is important to note also that most impact studies only use this method to identify hazards.

Plant Visits: A plant visit is a method that can be used in many instances, but it immediately becomes more difficult than reviewing the literature because it requires the presence elsewhere in the world of a plant or of a technological process similar to the one being assessed. For such a plant visit to be useful, the team must include experts or people experienced in the area being investigated. Otherwise, the personnel making the visit may be allowed to see only what the plant officers may decide. Furthermore, they will not be able to ask exact questions on the various operations involved in a process.

Brainstorming – What if: This method can be useful to complement a review of the literature or a plant visit because definite issues can be raised such as the presence of certain potential hazards. This method can be applied in any type of process and can be conducted by less experienced analysts. It begins with the general question "What happens if ... ?" and, based on the answers, the possible consequences of a disruption can be determined, recommendations can be made, and an accountable individual can be identified for each situation. The information must be provided in written format, as shown in Figure 2, and it can be compiled as an annex to an environmental assessment report. It is used to describe the type of hazards and also to develop the recommendations included in the assessment report. It should be pointed out that this method requires the input of a multi-disciplinary team and that the experience of this team greatly influences the results. In fact, this is a rather informal method, and because of this, the focus can easily shift to a particular area or hazard at the expense of another that the team's experience does not allow it to address.

Figure 2 - Technological Risk Assessment Based on the Brainstorming-What if Methodology - Example: Incinerator

"What happens if ...?"	Consequences	Recommendations	Officer in Charge	Date Action Taken
1. Pressure increases in incinerator	**Overpressure**	**-Fit incinerator with emergency chimney** **-Check regularly condition of emergency chimney and of its control system**	**Plan Engineer**	

"What happens if ...?"	Consequences	Recommendations	Officer in Charge	Date Action Taken
2. Emergency chimney does not work properly	**- Smoke can leak through gaps in oven** **- Carbon monoxide (CO) levels can increase** **- Employees can be exposed to CO**	**- Install barometer in oven and link it to a primary fan** **- Install smoke and carbon monoxide detectors linked to an evacuation alarm**	**Maintenance Superintendent**	

Preliminary Risk Analysis (PRA) Using Checklists: This type of analysis is performed using a table such as the one shown in Figure 3. Its aim is to identify the various hazardous components of the process or system being assessed and to determine the potential for each of these to degenerate into a more or less serious accident. The analyst performing the PRA relies on checklists showing the hazardous components and situations. These lists are customized according to the area or the technology being assessed. It should be noted that the purpose of the columns with the headings "Seriousness" and "Consequences" (Figure 3) is to set priorities, whereas the columns with the headings "Preventive Measures" and "Implementation of Measures" are used to determine what steps must be taken to identify, control or eliminate the hazard.

Figure 3 - Technological Risk Assessment Based on the PRA Methodology - (Preliminary Risk Analysis)

Subsystem or Function	
Phase	
Hazardous Component	
Event Leading to Hazardous Situation	
Hazardous Situation	

Subsystem or Function	
Event Leading to Potential Accident	
Potential Accident	
Consequences	
Seriousness	
Preventive Measures	
Implementation of Measures	

This method is not designed to provide extensive details. Its purpose rather is to quickly identify the more important problems most likely to occur. It can be used when a project is first submitted, but it is also designed to be updated during development of the project and also during the operational phase of the system being assessed. PRA can therefore be a method that goes beyond the environmental assessment prior to the implementation phase of a project. It can be used to monitor risk after implementation of the system and during its use or operation.

The HAZOP Method: The method called "Hazard and Operability Studies[40] is designed mostly to help identify hazards in the chemical industry. This is a method that has gained wide acceptance in this area because it allows to determine the influence of deviations identified in processes as compared to what these processes should normally do. This method is applied using tables with columns, an example of which is given at Figure 4. In some respects, this is a more formal approach than the "Brainstorming-what if?" method.

Figure 4 - Technological Risk Assessment Based on the HAZOP Methodology (Hazard and Operability Studies) - Example: Incinerator - Subsystem: Air Supply

GW (Group Word)	Hazardous Deviation	Possible Causes	Consequences	Mitigation Measures	Remarks	By:
None	**No flow**	**Power outage** **Primary and secondary fans not operating** **Valve blocked close** **Plugged air filter**	**Incinerator stoppage** **Oven explosion** **Damages to filtration systems**	**Automatic stoppage in case of power outage** **Install backup compressor with startup if first compressor stops** **Weekly maintenance of air filter**		

To help stimulate the investigative process, group words are used to represent the extent of deviations compared to nominal values. These include such words as greater, lesser, nil, etc. These key words are used to qualify various types of parameters such as pressure, temperature, flow, etc. In each case, the analyst seeks to identify causes, consequences, detection methods and corrective actions (mitigation measures).

The HAZOP method is used mostly by companies wishing to develop an emergency plan to deal with technological accidents. It should be noted however that data gathered during a prior analysis could be used for the environmental assessment of a similar technological process being implemented elsewhere. The HAZOP method can therefore be used again in the environmental assessment of a project. It can be applied if there is a solid multi-disciplinary team of experts working under the direction of an experienced leader who can rely on the assistance of a technical secretary and who has a very detailed knowledge of the technological application’s process flow. The

HAZOP approach is interdisciplinary, flexible, and systematic. With this method, a complete and well documented report can be prepared. The HAZOP method can be computerized and tools (such as HAZOP-PC, HAZOP Plus for Windows) are available on the market.

The FMECA Method: The FMECA method ("Failure Modes, Effects and Criticality Analysis")[41] was developed in the 60s for the aeronautical industry. It later became very popular in the space sector, the chemical industry the automobile industry, and in all technology-based sectors. This method is appealing because it is easy to use and does not require extensive theoretical knowledge. It is therefore available to analysts with little experience and it can be performed by a person working alone or in a team.

The FMECA method focuses on the analysis of the components and equipment linked to a specific technology. As with other approaches that have been described within the chapter, this method uses a specific data sheet like the one reproduced in Figure 5. In general, each technological or industrial sector has its own data sheet from which are derived technical guidebooks, standards or criteria. This method is applied by considering on an individual basis each of the components of the system being assessed and by analyzing each of the areas where this component can fail.

Figure 5 - Technological Risk Assessment Based on the FMECA Methodology
(Failure Modes, Effects and Criticality Analysis) - Example: Incinerator - Component: Valve

Component	Failure	Consequences	Mitigation Measures	Additional Mitigation Measures
Valve 1 (Temperature control through propane injection)	**Valve blocked open**	**Increase in oven temperature** **Refractory breakage** **Overpressure in oven** **Danger of explosion**	**Shut valve 2** **High temperature alarm**	**Install high pressure alarm** **Inform (handbook) and train employees**
	Valve blocked close	**Decrease in oven temperature**	**Preventive maintenance**	
	External leak	**Fire risk** **Explosion risk** **Difficulty in controlling oven temperature** **Economic loss**	**Monitor pressure in propane tank** **Monitor propane levels**	**Pipe installed on the outside**
	Internal leak	**High temperature in oven** **Explosion risk when oven is shut down**		**Install handbook valve at oven mouth** **Inform (handbook) and train employees**

This method can be refined by adding two other columns, entitled “Probability” and “Seriousness”, which can be used together to determine the “criticality” of the failure being investigated. These columns are usually filled with semi-quantitative data, including terms such as “very improbable”, “improbable”, “significant”, “catastrophic”, etc.

A study carried out under the FMECA method can be very useful because, before investigating into why a system has failed, it is necessary to know how this system works. In some cases, because of his systematic approach, the analyst has a better understanding of how the system works than the owner himself or herself.

As for the use of the FMECA method in an environmental assessment, the observations made earlier concerning the HAZOP method also apply here. In fact, the FMECA method can be used by anyone with comprehensive knowledge of how a technological process works. This is not always the case for analysts assigned to an environmental assessment. In this type of assessment, it is extremely useful to be able to refer to the results of a FMECA that has already been performed.

Safety Audit: A safety audit, or “systems safety analysis”[42, 43], is a combination of two methodologies: making plant visits and developing checklists. The latter is a formal approach that can be applied to any process and that analysts with little experience can perform. A typical checklist includes several headings whereby a hazard can be identified based on specific areas of concern (Figure 6).

Figure 6 - Technological Risk Assessment Based on a Safety Audit (Checklist) **-** Example: Danger from hazardous material (chlorine) - Chlorine stock control in a pulp and paper mill

Checklist
Inventory of hazardous materials
- corrosive
- explosive
- flammable
- leachable
- radioactive

Stock levels for each type of hazardous material
- Number of storage tanks
- capacity

Safety measures developed for each storage tank
- high-level alarm
- double liner
- restraining dike
- etc.

Hazardous Material Inventory

Plant: Les papiers du Nord Inc.
Fixed risk sites **-** Companies

Hazardous Materials

Name	Location on site
CHLORINE	Depart. Vapor (Yard)
GASOLINE	Depart. Yard
GASOLINE	Depart. Yard

Number of containers for this product: 1   Total quantity at this location: 1

Total number of containers for this address: 1

N.I.P.: UN1017

Chemical Abstract Number   **Transportation Class**
Class: 2.3

Service **(CAS) 7782-50-5**

State: Liquid
Concentration as percentage by mass: 100% **Comments**   **Storage Conditions**

A safety audit can be performed by a single person, but he or she must be accompanied by someone knowledgeable in each of the areas being assessed (fire protection, storage of hazardous materials, etc.). It should be emphasized however that this type of audit focuses on a specific process and cannot be applied as easily to an overall project. Like environmental compliance audits (ISO 14 010 series), the purpose of safety audits is mostly to assess a technological system in operation. However, audit reports on existing processes can be used as support documents for an environmental assessment aimed at a project based on a similar process.

Consequence Estimation

Unlike hazard identification, which is qualitative, a consequence estimation is performed by using quantitative methods providing information on the significance of the anticipated effects[44]. These methods have been described in technical handbooks dealing with problems such as leakages, blow-by, BLEVEs, etc. and published by organizations such as the World Bank[45] and the Institution of Chemical Engineers (IChemE)[46].

When a consequence estimation is linked to an accident scenario, it is possible to determine in which areas the health and safety of neighbouring communities and the integrity of the environment (natural and human) can be affected, and also to take into consideration sensitive issues that have been previously identified. Such information is especially useful for emergency planning[47].

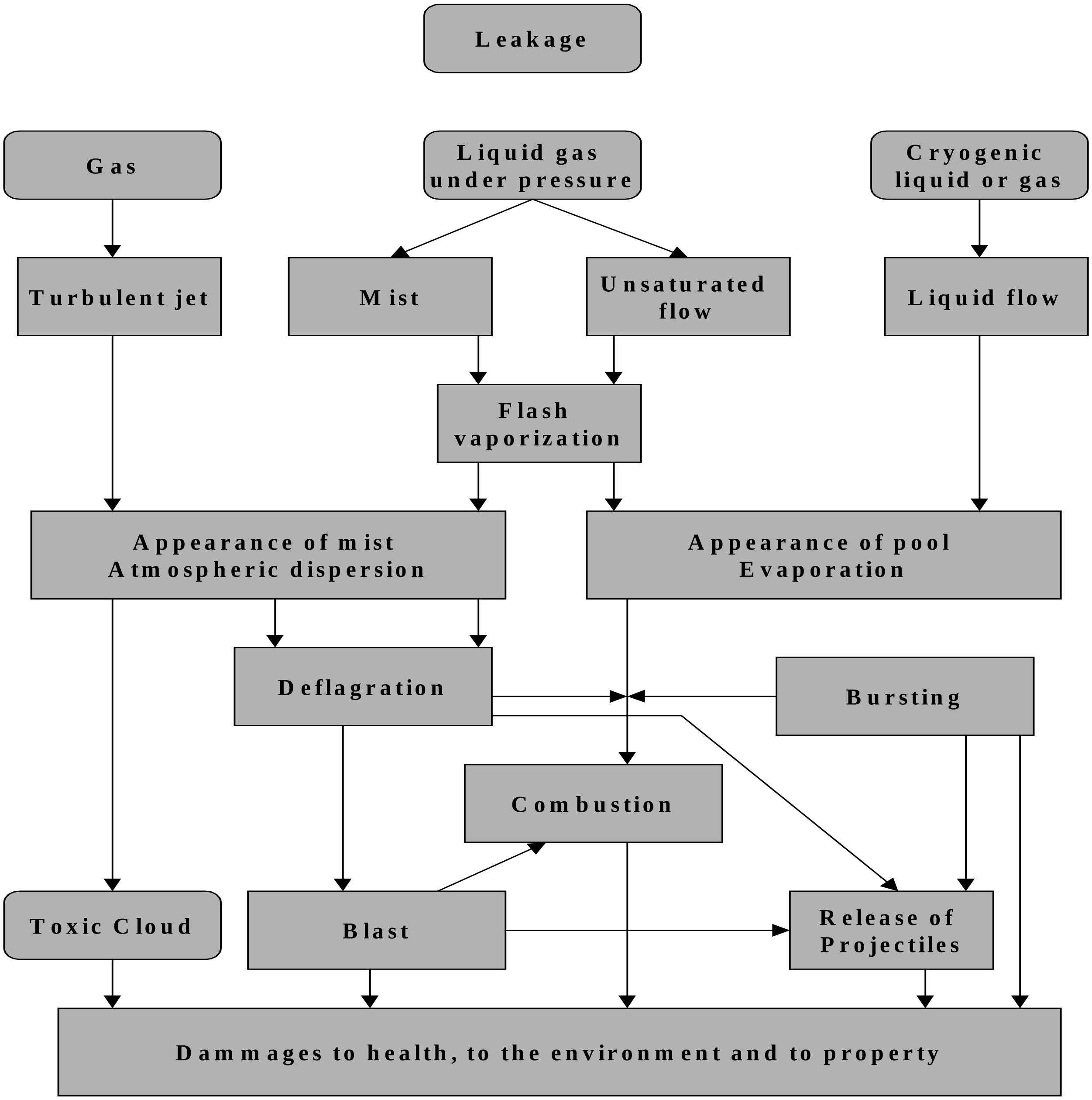
The quantitative nature of a consequence estimation is the result of two types of models used in this type of assessment. Firstly, a set of models called physical or “effect models” is required to assess the purely physical (and/or chemical) consequences of a risk and the damages to property that can result. A second set of models, called impact or “vulnerability models”, is then used to determine the exposure of humans to the effects[48].

The physical models are used to quantify the dispersion rate of a gas or a liquid that is leaking from a pipe or a storage tank, for example, mostly with the Bernouilli equation. These models are also used to predict such events as the formation of aerosols and the evaporation of volatile substances. In this way, it is possible to determine the levels of hazardous substances in a poisonous mist. Physical models are also used to determine heat flow in a fire[49].

Figure 7 shows the series of events covered in the physical models to determine exposure in the case of accidents involving flammable or toxic hazardous materiels. It identifies various phases such as breakage, dispersion and ignition, which are usually dealt with at the hazard identification stage. If total destruction has not occurred, the first thing to do is to determine how the leak occurred and how big it is. Various models are then used to determine the flow rate at the leak. This is followed by an assessment of the extent of the dispersion occurring as a cloud or a spill, which can undergo partial evaporation. Finally, if a flammable product is involved, the results of ignition must be modeled. This is done by using models for combustion, explosion or projectile emission[45].

When impact models are used to determine effects on health, these are mostly based on vulnerability models and demographic models (density and characteristics of the affected population). With these models, it is possible to determine for a given event (fire, explosion, release of a hazardous substance) the expected probabilities of immediate or delayed effects in the community[45].

Figure 7- Consequence Estimation Using a Physical Model (Adapted from Degrange, 1993)



Probability and Frequency Estimation

The methodologies used to estimate probabilities and frequency of occurrence can be based on an inductive or deductive approach. They can also be qualitative (identification) or quantitative (the estimation as such). With the inductive method, the effects are investigated beginning with the identified failures, whereas with the deductive method, the procedure is the opposite, i.e., the possible causes are investigated beginning with the effects.

In principle, the inductive approach should allow to gather all the required information (including unnecessary or irrelevant data), but it is relatively cumbersome and is therefore difficult to use when combinations of events are being investigated. As for the deductive approach, it is generally well focused and it generates only useful information. However, if the analyst overlooked an item at the beginning, he cannot make up for it elsewhere. The fault tree and the event tree are the best known and most widely used methods to determine frequency of occurrence. They are described briefly in the following paragraphs.

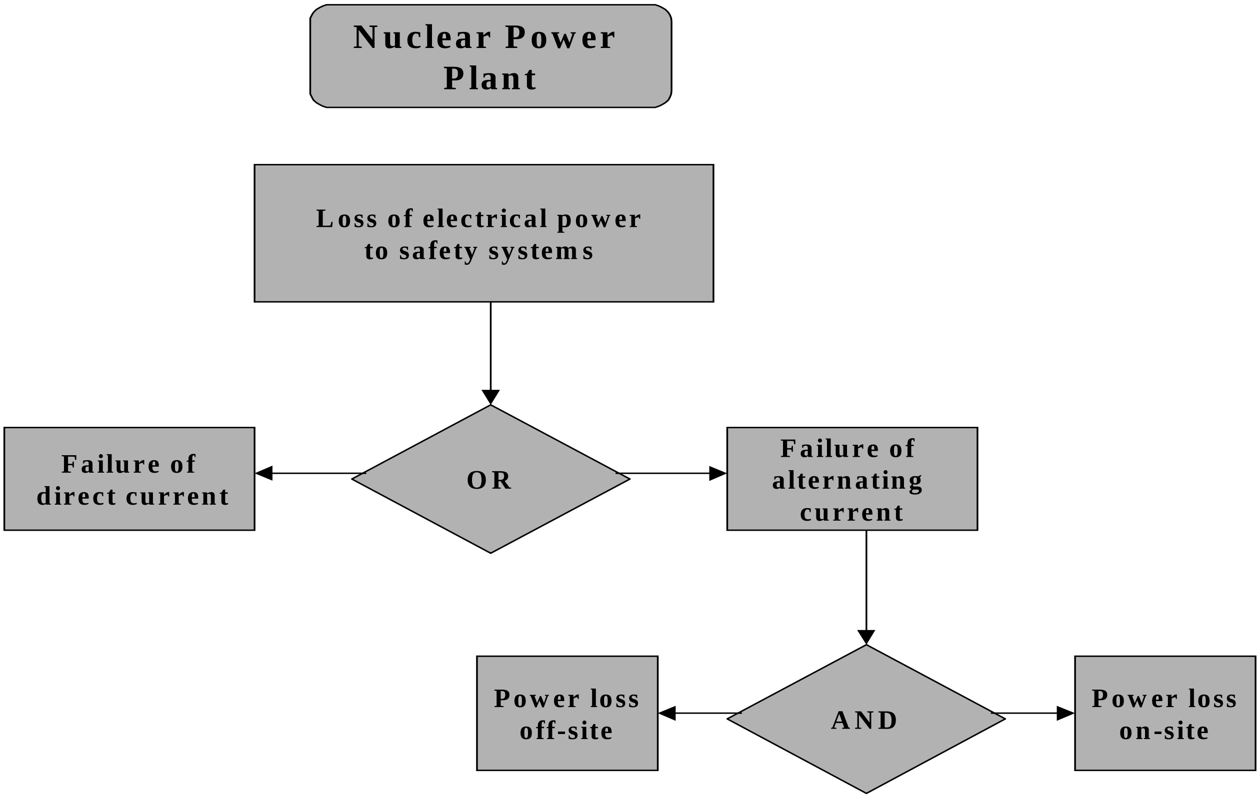
Fault Tree Analysis: Fault tree analysis[50], developed in the United States in the early 60s, is one of the most important technological risk assessment tools. This is a deductive and tree-structured method in which both qualitative and quantitative data can be used. It is used to calculate the probability of failure of a system where there is no historic data available. It is therefore used to assess technological processes where failures are rare and where new systems are being implemented. As such, it can be used for environmental pre-assessments. However, fault tree analysis requires a good knowledge of the system being assessed. To achieve this, the analyst can rely on a hazard identification method such as FMECA, which can provide him or her with the required information on how the system works.

Fault tree analysis involves two major stages: construction and assessment.

Construction is based on the division of the undesirable event (failure) into intermediate events that reveal its immediate causes. These are then divided further into other causes and this continues until any further division becomes impossible or is deemed unnecessary. The division of an event into cause-events is done through the logical operators of AND and OR, (called “doors”). In some cases, the tree can show many ramifications, as illustrated in Figure 7.

To help explain the typical reasoning governing the use of this method, Figure 8 shows a simplified fault tree illustrating a loss of electrical power to a nuclear power plant’s safety systems. These systems require an alternating current (AC) to work properly, but the control switches for these systems are activated by direct current (DC). Failure of these safety systems can therefore be caused by a loss of alternating or direct current; the logical operator that must be used is OR. In Figure 8, there is no further division of the intermediate events resulting from the loss of direct current. Division was done only in the case of the alternating current. Here, the logical operator used was AND, because the safety systems work either on power provided by an off-site producer of electricity or, if there is a power outage, they continue working through on-site diesel generators that take over. Therefore, if there is a complete loss of power, it is because these two sources of electricity have failed at the same time, and that is why the logical operator AND is used.

Figure 8 - Frequency Estimation Using Fault Tree Analysis - Example: Nuclear power plant - power loss

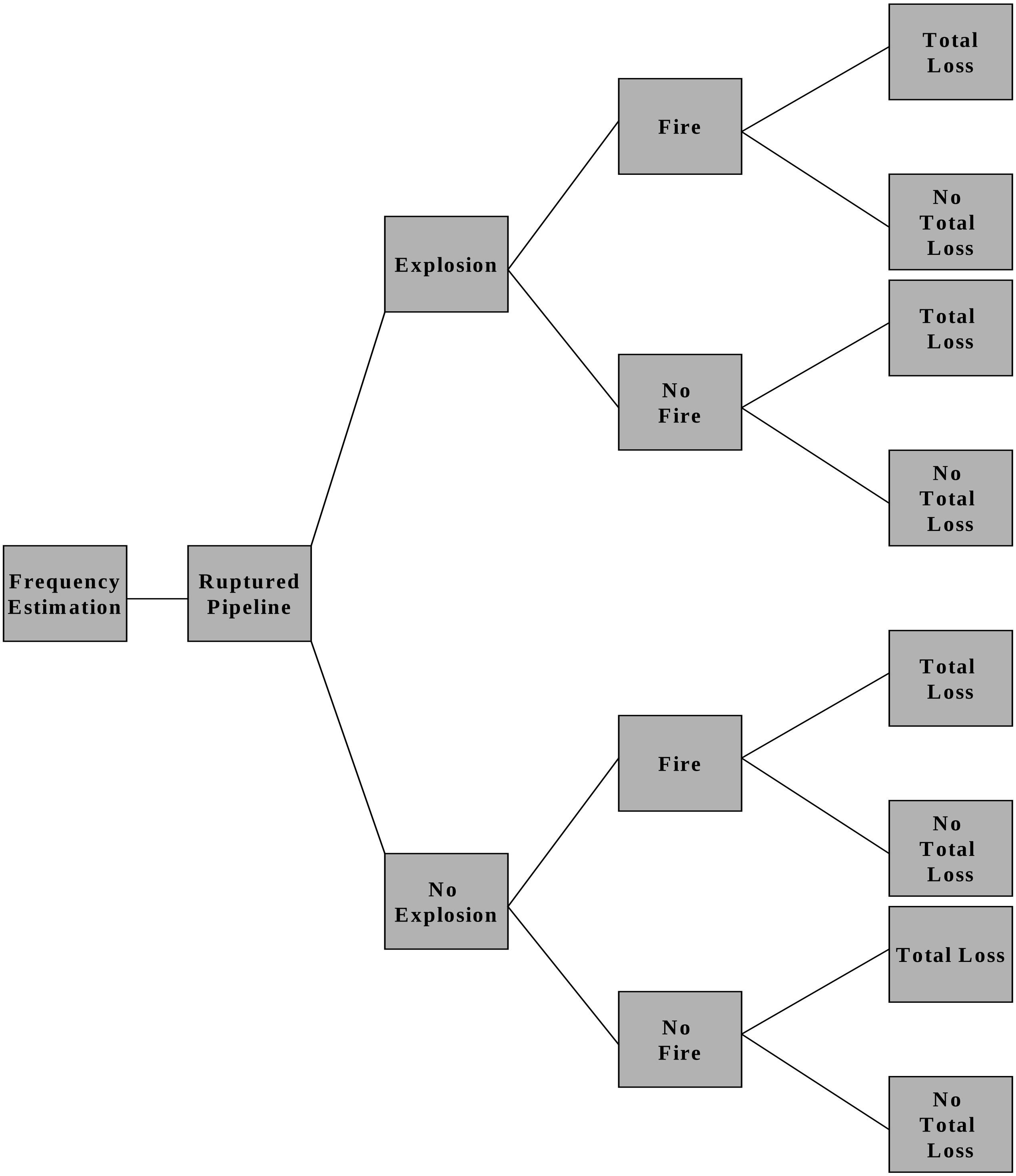


Division can continue in this way up to the point where the most basic elements, called primary failures, are reached. These can involve switches, solenoids, microprocessors, etc. Once the basic elements have been identified, the second stage, called estimation, can begin. The final estimation as to the probability of occurrence of an undesirable event must take into account the whole range of failure probabilities and/or failure rates linked to intermediate events, each of which has its own failure rate. The overall rate is used to estimate the risk associated with each potential accident.

Event Tree Analysis: Event tree analysis[51] is similar in many respects to fault tree analysis. However, the logic used is different because the process is inductive instead of deductive. In an event tree, the analysis is therefore based on identification of the effects that a failure can produce instead of on failure identification through the effects produced. The process is therefore the opposite of the fault tree. In the simplified example given in Figure 8, the failure could be a breakdown of the power generators (on-site current), and the analyst would attempt to determine its effects (upstream). It should be noted that an event tree does not include decision points requiring the logical operator's OR and AND. An event tree is made up of potential events resulting from a leading event (initiator). Probabilities are determined for each event (outcome).

Figure 9 shows what an event tree usually looks like. The example given is a failure in the form of a break in a propane pipe. Beginning with this event, which has a known frequency of occurrence, the object is to identify the effects or the sequence of events, each of which has its own probability. The probabilities associated with each event (P_1, P_2, $1\text{-}P_2$, etc.) are aggregated so as to produce an overall rate for each ramification (per year in Figure 9). In this case, beginning with the failure identified, namely a break in the pipe, the first thing to do is to determine whether there will be an explosion. If no explosion is anticipated, the upper branch is chosen (probability P_2). If an explosion is anticipated, the lower branch is chosen (probability $1\text{-}P_2$). In this case, it must then be determined if there is a risk of fire. If there is no risk, the upper branch is chosen (probability P_3). If there is a risk of fire, the lower branch is chosen ($1\text{-}P_3$). The same question as to the possibility of fire must be asked even if there is no explosion. When there is neither explosion nor fire, probability P_4 prevails. When there is no explosion but there is a fire, the probability is $1\text{-}P_4$. The same exercise is repeated with the probabilities linked to a complete loss.

Figure 9 - Frequency Estimation Using Event Tree Analysis - Example: Break in a propane pipe


Frequency Estimation
Ruptured Pipeline
Explosion
No Explosion
Fire
No Fire
Fire
No Fire
Total Loss
No Total Loss
Total Loss
No Total Loss
Total Loss
No Total Loss
Total Loss
No Total Loss

Frequency of events (Year^{-1})	Consequence of events (in thousands of $)	Economic Risk (in thousands of $/year)
2 X 10^{-2}	**5**	**100**
3 X 10^{-3}	**50**	**150**
2 X 10^{-2}	**10**	**200**
8 X 10^{-3}	**200**	**1600**
2 X 20^{-3}	**10**	**20**
3 X 10^{-3}	**200**	**600**
0	**0**	**0**
5 X 10^{-2}	**1000**	**50 000**
Total: 1.1 X 10^{-2}		**52 670**

As mentioned above, the last operation is to aggregate the probabilities (failure rates) in each of the tree's branches. Figure 9 shows similar probabilities for all of the situations, but the consequences are considerably different, considering the type of hazards (fire, explosion, complete loss). Thus, a break followed by a fire, an explosion and a complete loss has an economic impact estimated at $1 million, whereas a break where there is neither explosion, fire nor complete loss will lead to a loss (impact) of $5,000. Impacts on health, safety or the environment could of course be featured instead of economic impacts.

Fault and event trees are interesting and useful, but they have certain limitations. Indeed, it is difficult to take into account the human element and especially irrational decisions resulting from a stressful situation or, at the other extreme, from an imaginative solution that could not be included in the initial plan. Furthermore, there is a tendency to simplify the set of events when these trees are prepared; there can be hundreds of minor events or unforeseeable minor failures that the analysts do not consider. Analysts usually adopt a conservative approach (also called worst-case) which excludes imaginative human solutions. For these reasons, it not always evident that a fault or event tree will provide useful or exact information. It should be recognized that these trees are useful to identify potential failures and to take appropriate action before they occur, instead of using them as a prediction tool to determine the rates and frequencies of occurrence linked to a hazard.

Conclusion

Technological accidents such as fires, explosions or the release of hazardous chemical substances can lead in certain situations to serious impacts on the health and safety of workers and of the community in general. It is therefore crucial to take action to prevent such events from occurring in the first place or to reduce their effects.

An important tool for doing this is technological risk assessment. The notion of technological risk is based on the two concepts of hazard and probability. In the case of new projects, some hazards can be avoided at the design stage and those remaining can be dealt with by risk management through various approaches such as safety mechanisms.

The environmental assessment process is a good opportunity to identify hazards and, if necessary, to estimate the consequences and the probabilities and rates of occurrence of undesirable events, to assess the risk, and to propose mitigation measures.

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Source : Nations Unies, Département des affaires humanitaires, DHA-Geneva, (1992), Glossaire international multilingue agréé de termes relatifs à la gestion des catastrophes, p. 3.

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Terms used in French:
Hazard Identification = Analyse des dangers
Consequence Assessment = Analyse des conséquences
Frequency Assessment = Analyse des probabilités
Risk Quantification = Quantification des risques
Risk Assessment = Évaluation des risques
Risk Management – mitigation measures = Gestion des risques - mesures d’atténuation.

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