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Probabilistic Risk Assessment and Risk Management for Chemical Hazards at Nuclear Plants

by

MARCELLO OLIVERIO
Senior Design Engineer
Probabilistic Risk Assessment Department
Ontario Power Generation

INTRODUCTION

Nuclear facilities contain a variety of hazardous chemicals (e.g. hydrazine, propane) that can pose a hazard to human health and to ecosystems. Probabilistic Risk Assessment (PRA) (referred to as QRA - i.e. Quantitative Risk Assessment in the chemical industry) has emerged as the state-of-the-art process for addressing safety issues regarding these materials. Ontario Power Generation, Nuclear (OPG,N) has successfully used PRA to resolve a number of issues involving chemical hazards at its nuclear facilities. These have primarily involved worker health & safety concerns.

The objective of the paper is to describe the PRA process as it applies to chemical hazards that have the potential to impact workers, the public and ecosystems in the vicinity of nuclear plants. Where appropriate, comparison to methods used in Nuclear PRA is made. How QRA fits into broader Risk Management (decision-making) is also described. Several examples are provided.

RISK ASSESSMENT AND RISK MANAGEMENT BACKGROUND

Before we can describe risk assessment and risk management, the definition of three key terms is required; these being ***hazard***, ***risk*** and ***safety***:

HAZARD: Any situation that has the potential for causing damage to life, property and/or the environment.

RISK: Risk arises from the possibility of harm that may result from a hazard. Mathematically, it is expressed as:

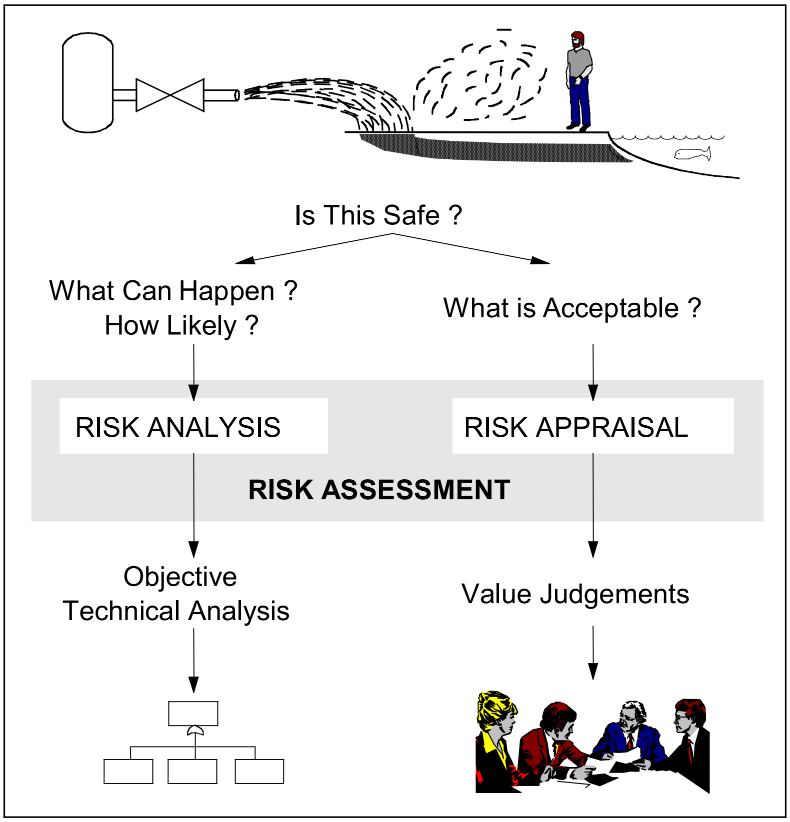
Risk = Frequency x Consequence

SAFETY: Safety is a judgement of the acceptability of risk. An activity is deemed "safe", if the associated risks are judged to be acceptable.

Before we can manage risks we must first understand them. This involves conducting a ***risk analysis***, a quantitative evaluation of the consequences of chemical accidents and their likelihood (expected frequency) to risk receptors.

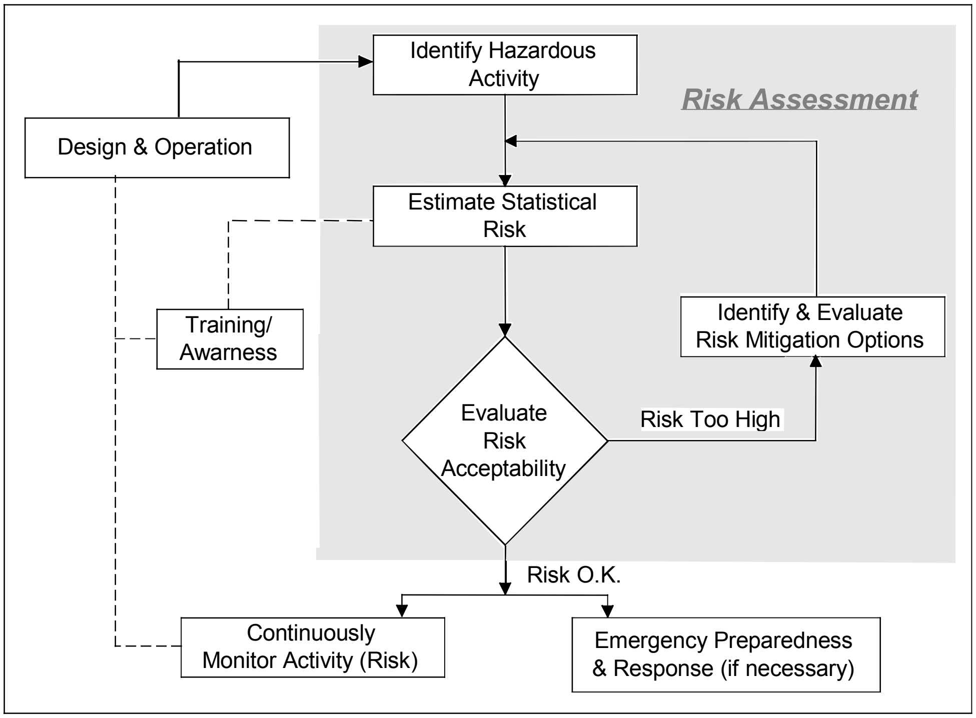
Once this is evaluated, judgements need to be made about risk acceptability. This process is referred to as ***risk appraisal***. Its outcome is the identification of appropriate risk criteria, applicable for decision-making. These are typically established in standards, guidelines or regulations. They vary according to the risk receptors, which could be employees, the public, the environment or the financial impact to the owner. In contrast to risk analysis, a relatively objective and technical (engineering) activity, the risk appraisal involves subjective value judgements - a sociological endeavor (see Figure 1). In a ***risk assessment***, the results of the risk analysis are compared against the risk criteria in order to draw conclusions about risk acceptability.

FIGURE 1
Risk Assessment Process



Managing risk implies decision-making (Figure 2). If the estimated risk to the risk receptor of interest is acceptable, there is no need to reduce risk. If the risk is not acceptable, then risk reduction options should be considered. This component of risk management is called ***risk control***. In the context of reducing risk it is important to point out that no activity is totally free from risk. Risk can never be totally eliminated, but it can usually be reduced to “negligible” or “tolerable” levels. Tolerability does not mean acceptability, but refers to acceptance of higher risk levels to secure certain benefits - e.g. employment, provided all reasonably practicable control measures and "best safe practices" for conduct of work (e.g. pre-job briefings) have been implemented.

FIGURE 2
Risk Management Process



Managing risk also requires:

- periodic monitoring of hazardous activities at a facility, especially when design modifications or operating changes are proposed, and
- establishing an Emergency Response Plan that includes a trained HAZMAT (hazardous material spill response) team.

TYPES OF CHEMICAL HAZARDS PRESENT AT NUCLEAR SITES

In addition to radiological hazards, nuclear facilities can pose a variety of chemical hazards. These can affect both human health and the environment. Relative to chemical plants the inventories of these chemicals are small. As a result, potential human health impacts are predominantly onsite.

Chemical hazards can be grouped according to their potential impact as follows:

- Acute chemical hazards
  - Fires (e.g. fuel oil, hydrogen)
    - flame impingement; exposure to thermal radiation
  - Explosions (e.g. propane)
    - blast overpressure; missiles
  - Acute toxins (e.g. hydrazine, ammonia)
    - e.g. pulmonary oedema, central nervous system failure
  - Asphyxiants (e.g. nitrogen in reactor vaults)
- Chronic chemical hazards (e.g. hydrazine, PCBs)
  - Cancers

    - Non-cancer effects
- Ecological (e.g. hydrazine, oil)

In order to manage safety effectively for a multi-chemical facility a comprehensive risk management framework is required. This should include consideration of all of the above hazards in a consistent manner. Risk analysts who undertake these assessments require broad technical knowledge in such areas as:

- human reliability analysis
- fault tree / event tree analysis
- process system design and operation
- dispersion modelling
- environmental fate modelling
- toxicology - dose-response modelling

CHEMICAL RISK ASSESSMENT FRAMEWORK

The Chemical Risk Assessment Framework includes the following steps:

1. Identification of hazardous activities that can produce potentially hazardous spills
2. Risk screening to prioritize hazardous activities for detailed evaluation
3. Quantitative risk assessment (if necessary)
4. Evaluation of risk mitigation options (if necessary)

A hazardous activity is any

- activity (e.g. unloading and transporting hydrazine drums within a station),
- process (engineered) system (e.g. fuel oil storage and delivery system), or
- facility (e.g. flammable stores)

that can produce a ***spill*** that can have adverse effects on risk receptors. A risk receptor can be:

- a worker
- a member of the public
- an ecosystem
- the company (economic risk)

A systematic review of chemical hazards can be facilitated using commercially available software that includes such widely used techniques as HAZOP (hazard and operability studies), FMEA (failure modes and effects analysis) and "What-if" analysis. The output of this process is a list of hazards at a facility.

The next step is to conduct some sort of risk analysis for these. There may be many dozens of hazards that are identified. It is both impractical and unnecessary to conduct a detailed risk analysis for each hazard. A useful "next step" is to perform a ***risk-screening*** exercise where each hazard is assigned a frequency (Table 1) and consequence (Table 2) rating based on the "expert judgement" of the risk analyst(s). Table 3 can then be used to prioritise the hazards for further detailed assessment.

TABLE 1

Frequency Categories

Category	Description	Expected Frequency
1	Remote event - Less than 1% chance of occurring during lifetime of a facility.	$< 10^{-4}$ /yr.
2	"Unlikely" to occur during lifetime of a facility.	$10^{-4} \rightarrow 10^{-2}$ /yr.
3	50% Chance of occurring one or more times during lifetime of a facility but less than once every 10 years.	$10^{-2} \rightarrow 10^{-1}$ /yr.
4	Expected to occur more frequently than once every 10 years.	$> 10^{-1}$ /yr.

TABLE 2

Consequence Severity Categories

Severity Category	Description
0	No impact
1	Mild health effect (e.g. bad odour, irritates eyes, headache)
2	Minor injury or health effects (reversible minor effect - e.g., dermatitis)
3	Injury or moderate illness (e.g., minor burns, reversible organ damage)
4	Death or serious injury/illness (e.g., major burns, permanent severe organ damage)

TABLE 3

Risk Screening - Hazard Priority Matrix

Consequence Rating				
4	**C**	**B**	**B**	**A**
3	**D**	**C**	**C**	**B**
2	**E**	**D**	**D**	**C**
1	**E**	**E**	**E**	**D**
0	**E**	**E**	**E**	**E**
	1	2	3	4
	Frequency Rating			

A = highest priority hazard - detailed PRA required

B = high priority hazard - detailed PRA required

C = moderate priority hazard - detailed PRA required

D = low priority hazard - qualitative or limited PRA required

E = no priority - qualitative evaluation only

Once the need for a detailed PRA has been identified, the following steps are required. These are listed in the chronological order with which they would be performed, and refer to human health risk. [A similar approach can be used for ecological risk, but has not been yet developed.] The only exception is that Step 4 may precede Step 3 if, in some cases, it is easier to estimate the frequency. The reason to normally do Step 3 first is that some hazards may be found to be insignificant. Note that this process mimics the identification and evaluation process in ISO 14001. The only difference is that here the evaluation of important hazards is quantitative as opposed to qualitative.

Step 1: Identification of Release Scenario Categories
Step 2: Identification of Hazard Exposure Scenarios
Step 3: Estimation of Consequences for each Hazard Scenario
Step 4: Estimation of Frequency for each Hazard Scenario that has significant Consequences
Step 5: Estimation of Risk for Hazardous Activity
Step 6: Appraise the Risk

Figure 3 shows these steps in a flowchart. In addition, it shows the range of tools that can be applied. A brief description of each step is provided below.

A release scenario is defined by (i) a release rate in kg/s, and (ii) a release duration in s. The combination of release rate and release duration describes a release profile. For any process system there will be a family of release profiles depending on the size and location of a hole. Each release profile will have an associated frequency of occurrence. In order to make a risk analysis manageable, all release profiles are grouped into a series of categories. The most conservative release scenario within each category is selected for consequence modelling. The frequencies of all release scenarios within a category are summed to obtain the frequency of occurrence of the release scenario category. The number of release scenarios categories selected for a risk analysis should balance:

- the level of uncertainty in the results, and
- the cost/effort spent on the study.

Release scenario categories are analogous to LOCA initiating events in nuclear risk assessments. Event trees can be developed for each of these to consider post-release factors that influence a release. The endpoints of the event tree paths lead either to a ***hazard exposure scenario*** or a benign event where there is no impact to the risk receptor of interest. Figure 4 provides an example of an event tree for a fuel oil tank spill.

Hazard exposure scenarios are analogous to Ex-plant Release Categories in OPG nuclear risk assessments. Each can be described by an exposure level to a receptor (governed by such factors as the source term, dispersion of toxin, thermal radiation flux, exposure time, environmental pathway, etc.) and a frequency equation (determined from the event tree logic).

Estimation of consequences requires establishing the exposure level, as indicated above, and estimating the dose-response relationship. The widely-used response measure of interest related to human health is death. **Therefore, the objective of the consequence assessment is to estimate the probability of death for a postulated hazard exposure scenario.** Conservatism in dose-response modelling effectively extends the scope to include serious, irreversible injury.

FIGURE 3
Risk Assessment Process

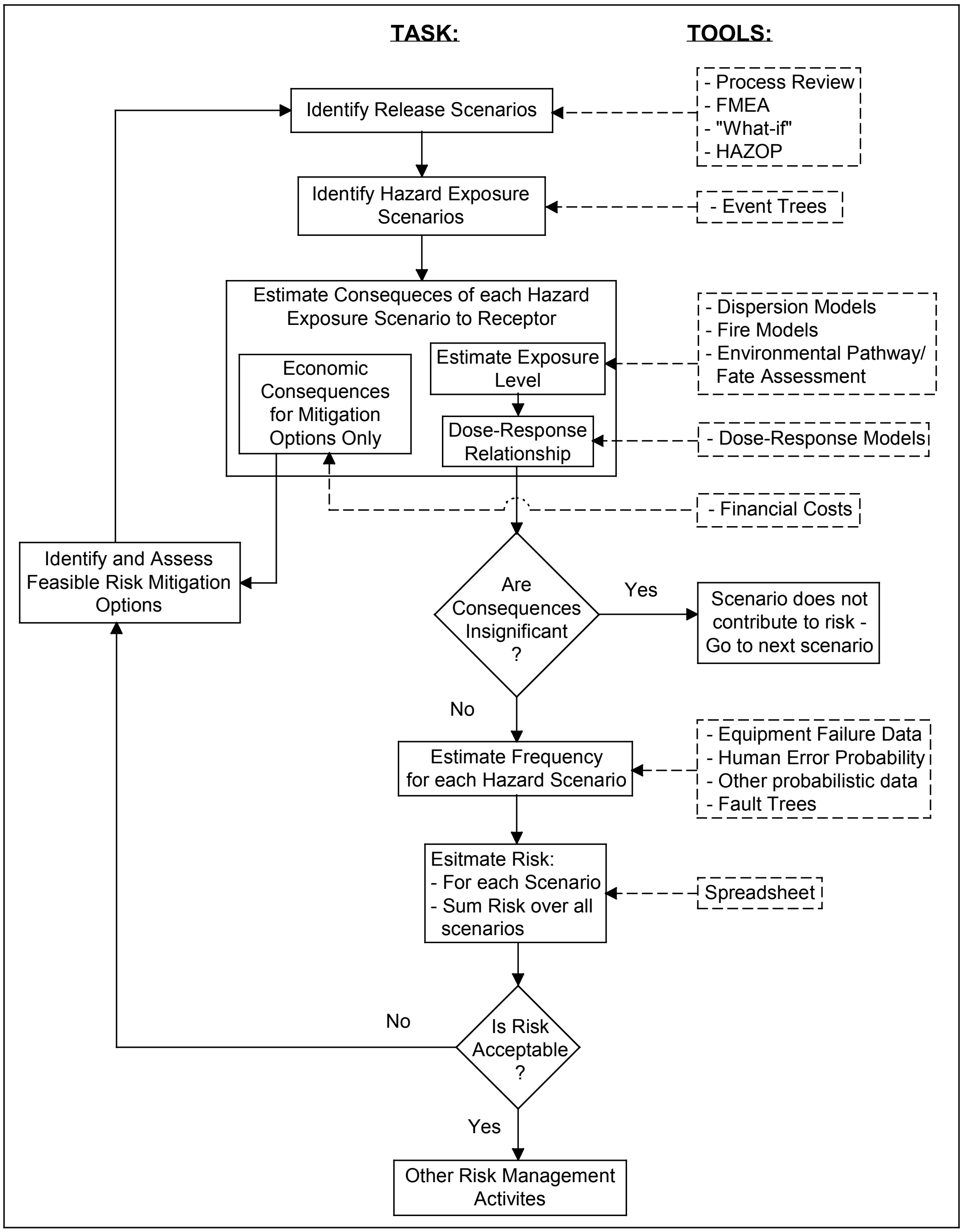
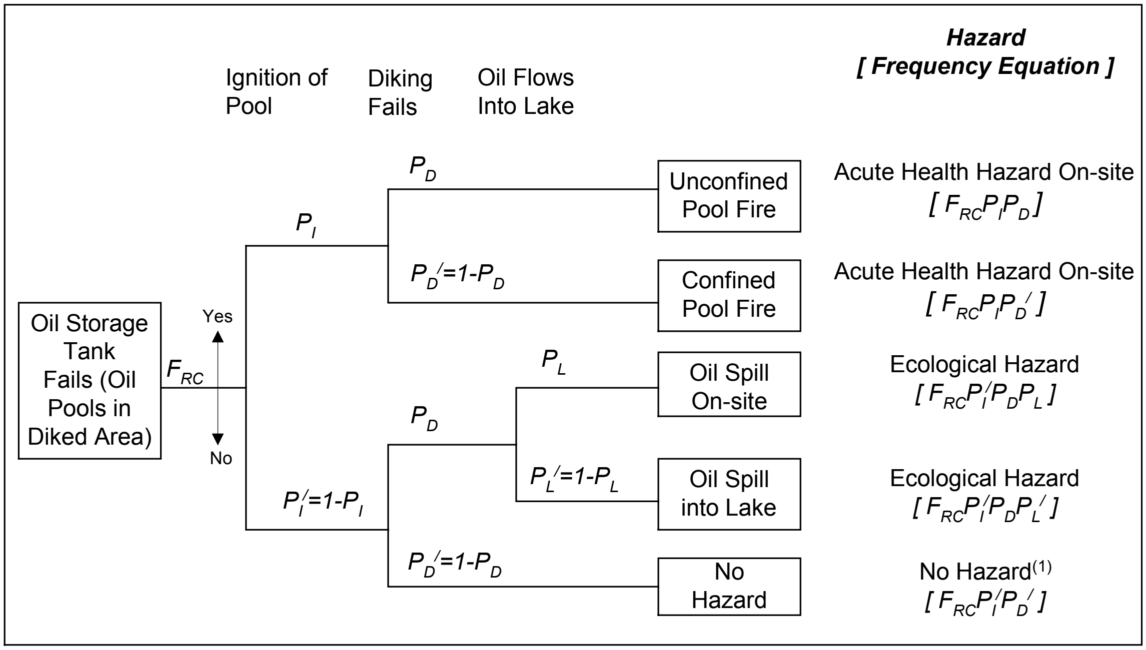


FIGURE 4

Sample Event Tree



(1) assumes spill cleaned up using safe work practices

For hazardous scenarios whose consequences are significant, an estimate of the expected (or statistical) frequency of occurrence is required in order to estimate the hazard scenario risk. Equations for estimating frequency should be developed along with the event tree for each release scenario. These will be of the form:

$$F_{HS,k} = F_{RC,i} \cdot \prod_{j=1}^{n} P_j$$

where,

$F_{HS,k}$ = Frequency of occurrence of hazardous exposure scenario ***k*** (events/yr)

$F_{RC,i}$ = Cumulative frequency of occurrence of release events ***m*** (each having a frequency of $\boldsymbol{F_{RE,m}}$) binned to release category ***i*** (events/yr)

$$= \sum_{m=1}^{L} F_{RE,m}$$

- ***L*** is the number of release events in the category
- developed from (i) system design and operation plus appropriate equipment failure rates and human error rates (and possibly using fault trees), or (ii) historical data.

P_j = Probability of occurrence of some post-release influencing factor ***j***

n = Number of post release influencing factors considered in the event tree path

If no post release factors are considered then the frequency of the hazard exposure scenario is equal to the frequency of the release event category.

The simplest part of a risk analysis is estimating the individual risk given the frequencies and consequences of all hazard exposure scenarios. This can be done in a spreadsheet using the following equation.

$$R_T = \sum_{k=1}^{q} R_k = \sum_{k=1}^{q} F_{HS,k}\, C_{HS,k} = \sum_{k=1}^{q} F_{HS,k}\, P_{Death\,k}$$

where,

R_T = Total risk from a hazardous activity (chance of death/yr.) to a risk receptor

R_k = Total risk for hazardous exposure scenario ***k***

q = Number of hazardous exposure scenarios associated with hazardous activity

$C_{HS,k}$ = Consequence to risk receptor from hazardous exposure scenario ***k*** = $P_{Death\,k}$ (Probability of death to risk receptor from hazardous exposure scenario ***k***)

Risk Appraisal involves comparing the estimated statistical risk to risk criteria. The proposed risk criteria expressed as safety goals for both the public and employees are contained in Table 4. They are used for decision-making purposes as follows:

- A statistical risk below the Goal is considered to be negligible and there is no basis for requiring additional controls.
- A statistical risk above the Limit is considered to be significant requiring either reviewing the analysis for conservatisms and/or consideration of additional controls.
- A statistical risk above the Goal but below the Limit is considered to be "tolerable" (reasonably practicable controls should be implemented).

The risk criteria are essentially derived from comparisons to common every day risks (public) and occupational risks in various industries (workers). Although they are soundly based, they are nevertheless subjective. However, without this comparison the usefulness of the risk analysis for decision-making purposes is lost.

There is no need for risk criteria only when comparing risks in a relative manner - e.g. comparing two or more options. The use of hypochlorite versus chlorine for water treatment is an example of a comparison of two competing processes that have significantly different hazards and risks.

TABLE 4
Draft OPG,N Public Safety Goals

Safety Goal (per hazardous activity)	**Average Risk** (per year)		**Comments**
	Goal	Limit	
Public: Individual Early Fatality	10^{-6}	10^{-5}	Applicable to chemicals that have acute effects. Widely used risk criteria.
Individual Delayed Fatality	10^{-5}	10^{-4}	Applicable to chemicals that are classified as carcinogens (chronic effects).
Employees: Individual Fatality	10^{-5}	10^{-4}	Applicable to both acute and chronic hazards

EVALUATING RISK CONTROL OPTIONS

A risk assessment may conclude that the risk from a hazardous activity requires reduction. There are usually several options for doing this, either by reducing the consequences or the frequency of accidents. A risk -based approach is the optimal method of evaluating candidate risk control options.

Each option will have an associated cost comprising of both capital and operating costs. Each will also have an associated risk benefit. The best option is usually the one that reduces risk to an acceptable level at the lowest cost. As shown in Figure 2, risk must be recalculated for each option.

EXAMPLES / CASE STUDIES

OPG,N has undertaken a number of assessments in order to understand chemical risks at its nuclear sites. Table 5 contains a brief description for a collection of these. These demonstrate how PRA has provided additional information to decision-makers enabling better decisions regarding the safety of potentially hazardous activities.

SUMMARY

Chemical hazards exist in nuclear facilities in large numbers. Because of small inventories their impacts tend to be primarily onsite both from a human health and ecological perspective. OPG,N has undertaken a number of PRAs related to safety issues concerning these hazards. These have been useful in that:

- Where the risk is acceptable (below the Limit)
  - assurance of adequate safety has been provided, and

    - unwarranted expenditure of funds due to the perceived need for additional controls or plant down time have been averted

- Where the risk is above the Limit
    - the need for additional controls is identified
    - in some cases the candidate controls have been evaluated.

OPG,N is currently embarking on a process to systematically assess potential chemical hazards at its facilities using the process identified in this paper. It is hoped that in the end a comprehensive "Chemical Hazards PRA" document will be developed for each site that will mimic nuclear PRAs in organization, and usefulness.

TABLE 5
Chemical Hazard PRAs Conducted at OPG,N Facilities

Issue	Safety Concern	Risk Receptor	Risk Assessment Results	Conclusions / Comments
Use of a 2000 litre liquid nitrogen dewar in a Bruce B reactor vault (615 ft elevation).	Health effect to workers in the vault during an outage.	Employee	▪ Negligible risk to workers not involved in moving dewar. ▪ Tolerable risk to workers moving dewar in vault.	▪ Proposed plan to form ice plug by introducing 2000 liter dewar in vault acceptable from risk standpoint.
Carbon dioxide fire extinguishing systems	Risk to workers in protected rooms from spurious system activation	Employee	▪ Existing risk exceeded Limit ▪ Consideration of three mitigation options (block valves, pre-discharge alarm, and electrical surge protection) reduced risk to below the Target	▪ Three mitigation options were identified from a design review. ▪ The mechanical block valves provided virtually all the risk benefit ▪ The study recommended: 1. installation of the block valves. 2. installation of surge protection and pre-discharge alarm only if cost-effective
35% hydrazine solution drum spill	Health effects both onsite and offsite	Employee + Public	▪ Negligible acute risk to workers; negligible cancer risk to critical individual residing at site boundary.	▪ Current handling of hydrazine drums acceptable from a risk standpoint.
Hydrogen Sulphide/Sulphur Dioxide hazards from operations at Bruce Heavy Water Plant	Acute health effects to public.	Public	▪ Public risk at site boundary above limit for individual assumed to permanently reside outdoors at plant boundary.	▪ By crediting emergency response actions, it was concluded that risk was tolerable (individuals would go indoors and be sheltered).
Chiller refurbishment at PNGS A	Potential R123 hazard to main control room	Employee (MCR Operators)	▪ Risk to employees negligible.	▪ Proposed design of refurbishment acceptable. No need for proposed additional controls in MCR.
Hydrogen leak from DNGS U4 generator piping.	Fire hazard.	Employee + Generator (OPG,N)	▪ Negligible consequences, therefore "zero" risk.	▪ Hydrogen release rate would only produce about a 10 cm long, low intensity flame. ▪ Temporary fix devised and implemented (with appropriate controls), averting a 5-day outage.
Comprehensive review of vault chemical hazards (Bruce B)	Health effects to workers during an outage.	Employee	▪ 11 hazards identified ▪ 8 estimated to produce insignificant consequences ("zero" risk) ▪ 3 estimated to produce significant consequences; total risk = 6 x 10^{-5} /yr.	▪ Risk tolerable ▪ Two mitigation measures were suggested : 3. emergency shut-off valves + instrumentation 4. minimize vault entries at ZPH conditions ▪ that would reduce total risk to ~1x 10^{-5} /yr., and meet the target risk.
Bruce B Hydrogen Storage Facility	Non-compliance with NFPA 50A - Facility underneath overhead power lines	Employee + Generator (OPG,N)	▪ Employee risk estimate ~ 6 x 10-4 /yr.	▪ Risk exceeds limit ▪ Mitigation measure recommended. This consists of protective, but perforated barrier over the hydrogen storage system. This satisfied the Fire Marshall's Office.