

INTEGRATED RISK ASSESSMENT OF A PLANT HANDLING HAZARDOUS CHEMICALS

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In this paper, safety, health and environmental risks of a typical installation handling anhydrous hydrogen chloride were assessed in an integrated approach. A four-step procedure was used as risk assessment framework for this integrated risk assessment. The safety risk was presented as individual risk while Hazard Quotients were calculated for health and environmental risks. Some advantages of such an integrated approach were identified through the exercise. Difficulties were also encountered and discussed for causes and possible solutions.

Keywords: integrated risk assessment, safety, health, envrironment

INTRODUCTION

The integrated management of Safety, Health and Environment (SHE) has gained increasing priority within the chemical and process industry. The opportunities of integration arise from the common areas shared by SHE management systems. One such common management element is Risk Assessment. Chemical and process companies initiated risk-based process safety management decades ago. Environmental risk assessments* are often seen in major governmental development projects and redevelopment project of hazardous waste site. The health risk** of carcinogen in the environment is assessed in terms of incremental cancer occurrence caused by the carcinogen.

In the distinct realms of Safety, Health and Environment, risk assessment is currently employed in different degrees. Both qualitative and quantitative risk assessments are routinely employed in process safety management. Various risk assessment techniques are well developed for process safety applications, such as HAZAN, Fault Tree Analysis, Event Tree Analysis, dispersion modelling, etc. For environmental risk, the majority of risk assessments are carried out qualitatively as evident in most Environmental Impact Assessments. The rarity of detailed quantitative environmental risk assessments could be attributed to public apathy, the complexity of such assessments and a lack of suitable methods and data resources[1]. The risk of cancer caused by exposure to a health hazard is assessed quantitatively. On the other hand, the health risk of non-cancer effects are often assessed semi-quantitatively as hazard quotients based on the assumption of threshold limits.

These different forms of risk assessment possess similarities as well as incompatibilities. The similarities are inherent. The structure of the all risk assessments can be summarized in a four-step procedure: a source assessment, an exposure assessment, an effects assessment, and a summarizing risk characterization[2]. The first step, source assessment, is to identify and evaluate a potential hazard and or the route leading to an accident. In the exposure assessment, the receptors affected by an accident or exposed to a risk agent are chosen and the level of exposure determined. Effects assessment links the exposure levels to the extent of

* In modern environmental impact analysis, *environment* is often broadened to encompass the total surroundings of the proposed development in both physical and societal dimensions. In this paper, *environment* is restricted to the meaning of ecological surrounding; and *environmental risk* is interchangeable with *ecological risk*.

** In certain contexts, health risk caused by occupational and environmental exposure is termed environmental risk. Here, the *health risk* includes any risk posed to human health caused by prolonged exposure to the toxicant in any background media.

adverse effects. In risk characterization, the results of the above steps are summarized and compiled into an overall measure of the risk level.

The incompatibilities are often the results of differences in choices of receptors & end-points, exposure modes, exposure assessment techniques, underlying assumptions for effect assessment and risk characterization methods, etc. In both safety and health risk assessment, the receptors are, by default, human. The end-points, however, are often the level of exposure to cause acute health effect (such as 2^{nd} degree burns and mortality) in safety risk assessment and the exposure level to cause chronic health effect (such as cancer) in health risk assessment. In environmental risk assessment, due to the vast number of species in a natural community, selection of receptors is often difficult and debatable[1]. The values of the management or stakeholders are of great influence here. The end-point selection of environmental risk assessment is also different from that of safety and health risk. Risk assessment of humans intends to protect the individual, while the environmental risk assessment typically seek to protect populations or communities of important species in the eco-system of interest[3]. Therefore, the end-points of environmental risk are often relevant to population dynamics, such as reproductive effects, development anomalies or behavioural changes affecting ability to survive. Acute exposure through inhalation, radiation and direct contact (overpressure, dermal exposure) are the main exposure modes in safety risk assessment. Chronic exposure through inhalation, radiation, dermal contact and ingestion are of equivalent importance in health and environmental risk assessment. Safety risk assessment uses consequence modelling almost exclusively for exposure assessment, while health and environmental risk assessment often use fate or transport models as well as field sampling and bioassay to assess the level of exposure. There is the assumption of a threshold exposure level, below which no adverse effect will occur, for safety and environmental hazards and non-cancer health hazards, but not for cancer-causing hazards. Safety risk can be characterized qualitatively or quantitatively and in terms of individual risk or societal risk. Environmental risk, however, is often characterized qualitatively or semi-quantitatively using Hazard Quotient (HQ). Health risk, on another hand, is often characterized quantitatively for cancer effect and semi-quantitatively for non-cancer effect.

The similarities indicate the opportunities for integrated risk assessment. At the same time, the incompatibilities pose obstacles to full integration. In addition, the incompatibilities render the comparison of the results of risk assessments in different forms difficult and prioritisation of risks among all SHE aspects impractical. In this paper, an attempt is made to assess the major SHE risks in a single risk assessment for the case of a typical semiconductor facility handling anhydrous hydrogen chloride. Efforts were directed to taking full advantage of the similarities and minimizing the incompatibilities.

Many governments have favoured risk-based controls over prescribed or performance-based controls. Some authorities, such as EPA, use risk assessment as base for regulatory decision-making. Following the trend, the Ministry of the Environment in Singapore has developed a unique set of land planning criteria for hazardous installations. The set of criteria are a hybrid of consequence-based and risk-based factors. It was used as a guideline in the risk characterization.

In the following sections, an integrated risk assessment is described according to the four-step procedure. Firstly, a typical anhydrous hydrogen chloride handling facility based in Singapore is described briefly, followed by hazard identification and scenario development. Secondly, transport modelling and exposure assessment are presented for the scenarios developed. Next, the acute and chronic health effects as well as ecotoxicology data of anhydrous hydrogen chloride are detailed. The final step is the characterization of SHE risks.

In the discussion, factors important to the comparability of the risk assessment results are discussed. The advantages and difficulties of such an integrated approach are also presented.

FACILITY DESCRIPTION AND HAZARD IDENTIFICATION

FACILITY DESCRIPTION AND CHARACTERIZATION

The semiconductor industry has been the fastest growing economic sector in Singapore over the past decades. The industry handles many hazardous chemicals, including but not restricted to anhydrous hydrogen chloride (HCl), trichlorosilane, nitric acid, hydrogen fluoride, phosgene and hydrogen, etc. These chemicals are highly flammable or toxic or both, and are present in various quantities. A survey of seven EPA RMP-regulated semiconductor facilities indicated that among the hazardous chemicals present, anhydrous hydrogen chloride and trichlorosilane are in the greatest quantities. In the silicon wafer preparation process, anhydrous hydrogen chloride is mainly used as a wafer-cleaning agent and trichlorosilane is used for deposition of silicon layer onto the wafer. Anhydrous hydrogen chloride was chosen for this study in the light of its clearly described process and well-defined release scenarios in the RMP reports, and the availability of well-documented toxicology studies.

Five of the seven facilities have tube trailers as on-site anhydrous hydrogen chloride storage. For these five facilities, the worst scenarios and the alternative scenarios of HCl release were all defined for releases from an HCl tube trailer. A typical HCl tube trailer is a combination of seven cylinders each containing 1360.8 kg liquefied anhydrous HCl under its own vapour pressure of 42 barg at 21 °C. Each cylinder has a length of 12.2 m and outside diameter of 55.88 cm. At one end of each cylinder, a safety device (usually rupture disk) is installed to prevent overpressure in case of exposure to elevated temperature. All operating valves and fittings are located at the other end of the cylinders and connected to the in-house process through transfer hose.

In this paper, a typical composite semiconductor facility handling anhydrous hydrogen chloride located in one of the industrial parks on Singapore main-island is considered. The nearest residential area is located 1.5 km away from the chosen site. Parks and industrial and commercial buildings surround the proposed site. Three meteorological conditions to be used in the transport modelling were derived from meteorology data provided by the Singapore Meteorological Service. An eight-point wind rose was used in the analysis. The data were tabulated below in Table 1.

Table 1 Meteorological Data

Meteorological Condition	**Occurring Probability (%)**
Stability Class F, 1m/s wind speed	10.6
Stability Class B, 2m/s wind speed	64.4
Stability Class C, 3m/s wind speed	25
Wind Direction	**Probability (%)**
East	19.49
North East	19.59
North	13.78
North West	12.85
West	13.67
South West	5.82
South	5.82
South East	9.00

SCENARIO DEVELOPMENT

With the focus on possible accidental releases within the installation fence line, two scenarios are defined considering both the likelihood and consequence. One is the failure of rupture disk at normal pressure. This scenario was reported as the worst credible release scenario by three of six RMP installations handling HCl tube trailer. The rupture disk was fitted with a 0.8 cm (5/16") orifice as reported in one of the RMP report. The release duration was assumed to be 30 min, which was the estimated time required to bring the release under control.

The other accidental release scenario was the leakage of HCl through the connecting hose. A hole of 2mm diameter was assumed and the condition was assumed to be under control after 20 minutes of release.

The release scenario for health and environmental risks was the emission of HCl from an elevated stack. The emission rates of five semiconductor installations were averaged to give 731 kg per year. The emission was assumed to be 24 hours per day and 365 days per year. The emission concentration of 200 mg/Nm^3 was set according to the National Standards of Concentration of Air Impurities of Singapore[4]. Without sufficient data, the stack parameters were arbitrary, with stack height of 10 m, stack diameter of 0.3 m and flue gas temperature of 303 K. Fugitive emission was also recorded in EPA Envirofacts Reports. The fugitive emission rate is much lower than point emission (about an order of magnitude). The difficulty of modelling fugitive emission prevented detailed assessment. In this paper, the facility was assumed to be well-ventilated and the workplace exposure level was controlled below PEL(Ceiling) of 5 ppm stipulated by Singapore Law[5].

EXPOSURE ASSESSMENT

RECEPTOR SELECTION

Safety Risk

The receptor in the case of safety risk is usually plant personnel and members of the general public in the vicinity of the hazardous installation. In some cases, the plant equipment and facilities are also considered as receptors. Since in this case, the toxicity of anhydrous HCl is the major hazard, corrosion damage to equipment is expected to be minor and therefore ignored.

Health Risk

According to exposure limit documentations, incidents of gastritis, chronic bronchitis, dermatitis, and photosensitization have been reported in individuals exposed to HCl occupationally[6,7]. However, by the concept of a threshold exposure level, the workers would be protected by strict adherence to the PEL(Ceiling) limit and therefore would not suffer any adverse health effect. Therefore, only chronic health risk arising from elevated stack release and affecting the general public is considered.

Environmental Risk

Singapore is a city-state with the main island 90% urbanized[8]. The 2879 hectares natural reserves (4% of the total land area) are mostly located at central and northern part of the island. There is very little natural eco-system around the industrial area. The prevalent form of wildlife in urban area is bird. The Common Myna (Acridotheres tristis) is a resident bird which frequents urban areas mainly feeding on seeds, insects or scavenging on waste food and rubbish. It nests in tree holes and roof eaves and roosts in large numbers often in trees close to housing estates[9]. Although the common myna is not a threatened species in the local ecological system, it is chosen because its huge population and habit of visiting urban areas making it the most likely species to be affected by increased level of HCl in the atmosphere and an indicator of the deterioration of the environment quality.

EXPOSURE MODE

The primary exposure mode of anhydrous HCl is by inhalation. Once released, the liquefied anhydrous HCl would vaporize immediately and possibly form acid fumes. Skin contact with the acid fumes is a probable outcome to the on-site workers. With the assumption of adequate safety training and provision of personal protective equipment, the risk of dermal exposure can be minimized.

TRANSPORT MODELLING

There are various air dispersion modelling packages, which are able to handle dense gas dispersion as well as stack emission. One of such software package, TRACE™[18] was used for this exercise. The common exposure mode in all three kinds of risk allowed a considerable saving in transport modelling effort. The effect of rainfall was not considered in the transport modelling. However, it is predicted that rainfall will downwash the vapour cloud and reduce the impact of accidental release.

Accidental Releases

The accidental releases were modelled as dense gas dispersion. Peak concentrations and toxic dose were calculated for receptors located downwind over regular distance intervals for all three weather conditions.

Stack Emission

Continuous stack release was the model used for stack emission scenario. The receptors defined for the modelling were located downwind at regular distance intervals. At each downwind distance, the concentrations at 10m, 5m and 1m elevations were averaged to give an average atmospheric concentration.

EFFECT ASSESSMENT

EFFECTS OF ACUTE EXPOSURE

Inhalation of HCl vapour or fumes may cause irritation and a burning sensation in the throat, coughing and choking. High levels may cause inflammation and occasionally ulceration of the nose, throat or larynx, bronchitis, pneumonia, palpitations and headache. Higher concentrations may cause necrosis of the tracheal and bronchial epithelium, nasoseptal perforation, atelectasis, emphysema, damage to pulmonary blood vessels and lesions of the liver and other organs. Death may be due to laryngeal spasm, bronchopneumonia or pulmonary edema[6,7,10].

The assessment endpoint was set at a lethal dose, which would cause 3% fatality, as stipulated by the hazardous installation control rules. Probit equation is the most common expression of acute/lethal dose-response relationship in safety risk assessment. The CPD (Green Book) value of parameters in probit equations for lethality of hydrogen chloride are k_1=-6.7 (mg/m^3), k_2=1(mg/m^3), n=1(min)[11].

A second assessment endpoint, the IDLH level of the toxic gas, is also required by the hazardous installation control rules. In this case, the second endpoint is taken to be 50 ppm, the IDLH value of hydrogen chloride.

The possible chronic health effect resulting from acute exposure was not considered in this study. It was partly because the chronic health effect was not significant comparing to the acute effect[12] and partly because insufficient data was available to characterize the chronic health effects.

EFFECTS OF CHRONIC EXPOSURE

Repeated or prolonged exposure may cause erosion and discoloration of exposed teeth, chronic bronchitis, gastritis, dermatitis, and photosensitization[6,7,10]. Without suitable mathematical expression for the non-cancer chronic health effect of hydrogen chloride, a threshold exposure level was used as endpoint for this assessment. There are two possible values for the threshold exposure level. One is EPA Inhalation Reference Concentration, the other is Environmental Exposure Level.

The EPA has published an Inhalation Reference Concentration (R_fC) of 0.02 mg/m^3 for hydrogen chloride, based on a LOAEL (human equivalent concentration) of 6.1 mg/m^3, an uncertainty factor (UF) of 300 (3 for interspecies differences, 10 for intraspecies extrapolations, 10 for derivation of NOAEL from LOAEL), and a modifying factor (MF) of one[13]. The following equation was used for calculation of R_fC:

$$R_fC = NOAEL / (UF \bullet MF) \tag{1}$$

According to the EPA, the R_fC is an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily exposure to the human population (including sensitive subgroups) that is likely to be without appreciable risk of deleterious effects during a lifetime. R_fCs are based on an assumption of lifetime exposure and may not be appropriately applied to less-than-lifetime exposure situations.

Another value, Environmental Exposure Level (EEL), could be derived from TLV or PEL value using the following equation[14]:

$$EEL = \frac{TLV \times D_{af} \times M_{af}}{S_f} \times 10^3 \tag{2}$$

where EEL is expressed in μg/m^3
- TLV = ACGIH-TLV or OSHA-PEL as 8-hr TWA, mg/m^3
- D_{af} = duration of exposure adjustment factor
  = working lifetime (80,000hr)/ biological lifetime for women (77.8yr)
  = 0.12
- M_{af} = magnitude of exposure adjustment factor
  = inhalation rate of adult/ inhalation rate of a 10-year-old child
  = 0.72
- S_f = safety factor, 10 to 1000

Since for hydrogen chloride, only TLV (Ceiling) value of 7 mg/m^3 (5 ppm) is available, a nominal value of 6 mg/m^3 was assummed as the TLV (TWA) value. With a safety factor of 10, the calculation gave an EEL value of 50 μg/m^3 or 0.05 mg/m^3 for HCl.

The assessment endpoint was set at the R_fC level since it was the lower (more conservative) one of the two candidates. It was assumed that if the atmospheric concentration was at or below the R_fC, no adverse effect was expected to occur.

ECOTOXICITY

The scarcity of ecotoxicity data is one of the major difficulties in environmental risk assessment. In this case, no ecotoxicity data were available for common myna with respect to environmental exposure to hydrogen chloride. Some derivation was necessary to obtain a suitable endpoint.

As mentioned before, the end-points of environmental risk are often relevant to population dynamics, such as reproductive effects, development anomalies or behavioural changes affecting ability to survive. The only reproductive and development studies of HCl were that of Pavlova's[13] on female rats. The chronic health data on rats were used to derive an endpoint for health effect. Although this is not the best approach for environment risk assessment, it was used as an estimate in order to complete a meaningful environmental risk assessment. The derivation was based on the same chronic rat inhalation study used for human R_fC and conducted in the similar manner. The rat LOAEL value was corrected to common myna equivalent value for gas respiratory effect in the extrathoracic and tracheobronchial regions as shown in the following equation[13]:

$$\text{LOAEL (common myna)} = \text{LOAEL (rat)} \times \left(\frac{IR_{rat}}{S_{rat}} / \frac{IR_{myna}}{S_{myna}}\right) \tag{3}$$

where LOAEL(rat) = 2.5 mg/m^3
IR is the inhalation rate of the respective species (m^3/day), and
S is the surface area of extrathoracic and tracheobronchial region of the respective species (m^2).

In the derivation for human R_fC, inhalation rate for the test rat was 0.5 m^3/day[13]. The inhalation rate of common myna was calculated by the allometric equation suggested by EPA[15]:

$$IR = 0.00202\ Wt^{0.77} \tag{4}$$

where IR = inhalation rate (m^3/day)
Wt = body weight (g)

The body weight of common myna was taken as 110g[16]. The calculated inhalation rate was therefore 0.075 m^3/day. A factor of 2 to 3 was suggested by the EPA to account the higher metabolic rate of free-living birds. Therefore the inhalation rate of was corrected to 0.15 m^3/day.

There was no data available regarding the surface area of extrathoracic and tracheobronchial region of common myna. The ratio of S_{rat}/S_{myna} was assumed to be one.

The calculated value for LOAEL (common myna) was 8.33 mg/m^3. Applying the UF of 100, which included a factor of 10 for interspecies extrapolation, 10 for extrapolating from LOAEL to NOAEL, and the MF of 10 considering the inter-taxon extrapolation from mammal to avian, the reference concentration was 8.33x10^{-3} mg/m^3.

RISK CHARACTERIZATION

SAFETY RISK

The hybrid land-use planning control approach of Ministry of Environment of Singapore has been implemented since 1998. It combines the consequence-based and risk-based factors. Two types of zones are established around a hazardous installation: Hazard Zone and Risk

Zones. Hazard zone is determined based on the consequences of the worst credible accident scenario. No residential developments are permitted within the hazard zone. A set of risk zones is determined based on the individual risk calculated around the hazardous installation. Following criteria and guidelines for land use of risk zones are imposed (Table 2).

Table 2 Hazard & Risk Zones and Land Use Guidelines

Hazard/Risk Zone	**Development Allowed**
Hazard Zone · IDLH levels of toxic gas releases · 4 kW/m^2 of heat radiation from fires · 1 psi (6.9 kPa) blast overpressure from explosions	No residential developments
Risk Zone(Individual Risk, frequency/yr) · $5x10^{-5}$* – $5x10^{-6}$ · $5x10^{-6}$ – $1x10^{-6}$ · Less than $1x10^{-6}$	 Only industries Industries and commercial buildings Industries, commercial buildings and parks

* Note: No risk greater than $5x10^{-5}$ shall be allowed beyond installation fence line.

The frequencies for the two accidental release scenarios were estimated as $6x10^{-5}$ /yr for the rupture disk failure and $1x10^{-3}$ /yr for the connecting hose leakage based on historical data[11] and engineering judgment. Combining the information of accident frequency, dispersion modelling results and meteorological data, the individual risk was calculated. The results are summarized in Table 3.

Table 3 Hazard Zone and Individual Risk Zones

Zone	**Max. distance from release point (m)**
Hazard zone (IDLH)	5269
Risk Zones	
$\geq 5x10^{-5}$ /yr	273
$\geq 5x10^{-6}$ /yr	723
$\geq 1x10^{-6}$ /yr	814

Comparing the safety risk results with the land use guidelines, the risk was not acceptable. The nearest residential area was only 1.5 km away from the proposed site whilst the hazard zone in this case extended to 5.3 km. Also the individual risk of $5x10^{-5}$ /yr extended beyond the installation fence line, from which the nearest point to the tube trailer was 100m. The installation would not be permitted at the proposed site under the current rules of hazardous installation control.

To reduce the consequence of the release, several measures could be implemented. The tube trailer could be kept in an enclosed storage area with ventilation routed to a scrubber. Water spray/ water curtain could be installed around the tube trailer area. Other measures could be used to reduce the frequency of the accidental release. Administrative controls could be implemented to ensure more frequent inspections of connecting hose and rupture disk. The connecting hose could be replaced every half year to reduce the probability of developing leakage.

HEALTH RISK

Hazard Quotient (HQ) was used to characterize health risk in this analysis. Inhalation Health Hazard Quotient was defined by the following equation:

$$HQ = \frac{C_{air}}{R_f C} \tag{5}$$

where C_{air} = concentration of health hazard agent in atmosphere, mg/m^3
R_fC = inhalation reference concentration, mg/m^3

Values of hazard quotient were calculated based on the results of stack emission modelling. The results were summarized in Table 4.

Table 4 Health Hazard Quotient at Various Downwind Distances

Downwind Distance	**Hazard Quotient**
30m	9.59
50m	3.46
70m	1.76
90m	1.88
100m	1.81
120m	3.61×10^{-1}
150m	1.30×10^{-8}
200m	1.30×10^{-8}

The high health risk was present within the installation boundary and the nearby industrial area. The general public would be exposed to insignificant health risk.

ENVIRONMENTAL RISK

Environmental Hazard Quotient was used as the risk measurement of environmental risk. The hazard quotient was calculated based on the predicted air concentrations of stack emission. The environmental hazard quotient is summarized in Table 5.

Table 5 Environmental Hazard Quotient at Various Downwind Distances

Downwind Distance	**Hazard Quotient**
30m	23
50m	8.30
70m	4.22
90m	4.52
100m	4.35
120m	8.67×10^{-1}
150m	3.11×10^{-8}
200m	3.11×10^{-8}

As in the case of the health risk, the environmental risk was also controlled and no great risk extended far beyond the fence line of the installation.

DISCUSSION

COMPARABILITY

It is often in the interest of management to compare the relative importance of different issues in order to set priorities and locate resources. Although ranking involves non-risk factors such as management goals, stakeholders' interest, perception of the general public and regulatory forces, etc, it is important to first understand how comparable the risks are. Some important factors that must be bared in mind when comparing risks of different contexts are: intentions of the risk assessment, risk representation and uncertainties associated with the risk estimates.

Intentions of the Risk Assessments
The intention of a risk assessment is very important as it directs the general approach of the assessment, and the selection of assessment endpoint and risk criteria. All three risk assessments were carried out to assess the impact of the installation to its surroundings. The primary concern was given to the health and well being of the general public. However, the objective was different in three risk assessments. Both health and environmental risk assessments employed the no effect level as the benchmark for exposure level. In other words, the risk assessment was intended to ensure that the general public and the ecosystem would not be adversely affected by the discharge of HCl. On the other hand, the safety risk assessment was carried out to maintain the balance between efficient land use and adequate protection of the general public against the hazardous installation. That is, the emphasis was a tolerable level of risk. Although, technically, a hazard quotient of 1 does not rule out the possibility of exposed receptor developing adverse effects, the difference in the intention must not be overlooked.

Risk Representation
Two types of risk measurement were used for the risk characterization in this case: individual risk and hazard quotient. Both risk measurements had a fixed consequence component, which were closely tied to the intention of the risk assessments: 3% fatality in the case of individual risk and no adverse effect in the case of hazard quotient. The likelihood component was represented quantitatively by the frequency in individual risk; while in health and environmental risk assessments, the probability of being affected by the HCl discharge was semi-quantitatively related to the magnitude of HQ.

Uncertainty
Risk assessments are subjected to various sources of uncertainty. Finkel has classified all uncertainties into four categories: decision rule uncertainty, model uncertainty, parameter uncertainty, and variability[17].

Decision rule uncertainty is present when management decisions must be made to balance different concerns in a single risk study. These decisions are often more of an exercise of management values and goals than scientific judgement. For safety risk, decision rule uncertainties are introduced when the risk assessor decides to select 3% fatality as the assessment endpoint, to choose individual risk as the measurement of risk, to accept the definitions of hazard and risk zones, and to exclude risk from transportation of the hydrogen chloride tube trailer, for instance. For health risk, the decisions of using R_fC as assessment endpoint, and exclusion of fugitive emission brought in uncertainties. During the environmental risk assessment, selection of exposure receptor & assessment endpoint, placing focus on stack emission only, and neglecting the existing HCl level in air were also sources of decision rule uncertainty.

Model uncertainty is a familiar source of uncertainty to risk assessors. The uncertainty is inherent since models are simplified realities. However, the uncertainty could be reduced by the proper selection of models and the advancement of the model. The transport modelling for all three risks were performed using the same commercial software package. The models involved were dense gas dispersion and continuous stack source dispersion. The uncertainty associated with the transport models was low judging from the extensive studies on the involved dispersion models and the fact that the software was widely accepted. High uncertainty was present in most dose-response models. The probit model used in safety risk assessment was known to be problematic at extreme ends of the dose-response curve. No dose-response model uncertainty was introduced in the health and environmental risk assessment, since no dose-response model was used.

Parameter uncertainty is caused by the inability to measure the needed parameters precisely or accurately. Meteorological data, dispersion coefficients and dose-response data are common sources of parameter uncertainty to the three risks. The first two sources were of same magnitude to all three risks. Dose-response data for acute health effect was in general more reliable than chronic health effect.

Variability uncertainty refers to the uncertainty caused by ignoring the variation in physical, chemical and biological processes. Statistical analysis could be employed to represent the variability with good certainty; however, failure to recognize the inherent variability in natural process or inadequate statistical analysis introduces uncertainty. In this case, the variability in weather condition was explicitly included in terms of probability. The variation in lethal dose of HCl took the form of probit equation. Uncertainty factor was used to account the variation in human NOAEL. Large variation in the response of different species to the exposure of HCl was expected. However, the variation could not be included in the assessment of environmental risk due to insufficient data; therefore variability uncertainty was high for the calculated environmental risk.

Overall, the uncertainty of safety and health risk results were of the same magnitude, and the uncertainty level of environmental risk was substantially higher. It must be known to the management that high uncertainty in the risk assessment often results in overly conservative risk estimates.

SOME LESSONS

The difficulties of assessing three types of risk in a single project were mainly in exposure and effect assessment phases, although in this particular case, the difficulty in exposure assessment phase was greatly reduced owing to a single exposure mode. The differences can be daunting. Transport of chemicals in different media requires different models, each having its own limitations. Modelling fate of chemicals in ecosystem is drastically different from that of transport modelling and requires expertise in ecology and biology. In addition, safety risk assessment often involves explosion and fire modelling, which is not encountered in health and environmental risk assessment.

Effect assessment in safety risk is relatively straight forward as dose-response data of heat radiation, explosion overpressure and toxicity of major chemical hazards have been published in many easy-to-use forms (e.g. probit equations). On the other hand, dose-response data for health and environmental risk assessments are scarce and expert judgment often required for parameter derivation and verification.

The benefits of conducting a combined risk assessment for safety, health and environment lie in the integration of closely related concerns. Effort was saved where the same information was needed to assess two or more risks. Examples of one-for-all procedures were facility & site characterization and exposure mode analysis. It is foreseeable that when two or even all three of the SHE risks were to be assessed for regulatory compliance purpose, an integrated risk assessment approach would increase the efficiency of such process.

Accident frequency estimation, an important step in safety risk assessment does not appear to have a proper place in the general four-step structure for risk assessment. It is mainly because the measurements of health risk (except cancer effect) and environmental risk do not include a quantitative expression for likelihood. A possible solution would be placing the frequency estimation in the first step --- hazard identification, since some techniques used in frequency estimation are also effective methods for hazard identification. It could be included as part of the scenario characterization.

CONCLUSION

Safety, health and environmental risk assessment with an integrated approach accords well with the principle of an integrated SHE management system. Such an approach has the advantages of resource saving and higher efficiency over individual risk assessments. Non-trivial difficulties in performing a truly integrated SHE risk assessment still persist. Challenges remain in several areas: the need for complete and ready-to-use databases; the need for a refined common risk assessment framework suitable for the chemical and process industry; and the need for a better risk presentation format for health and environmental risks.

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LIST OF ABBREVIATION

HQ	Hazard Quotient
EPA	U.S. Environmental Protection Agency
RMP	Risk Management Plan
PEL	Permissible Exposure Level
TLV	Threshold Limit Value
CPD	Committee for the Prevention of Disasters
IDLH	Immediate Danger to Life and Health
R_fC	Reference Concentration
LOAEL	Lowest-Observed-Adverse-Effect Level
NOAEL	No-Observed-Effect Level
UF	Uncertainty Factor
MF	Modifying Factor
EEL	Environmental Exposure Level