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ACCIDENT HAZARD INDEX:
A Multi-attribute Method for Process Industry Hazard Rating

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Traditionally, the severity of accidents in the chemical process industries has been gauged on the basis of the human lives lost[1–5]. However, factors such as loss of assets, contamination of the surroundings, and the resultant trauma also contribute to a very large extent towards the adverse impacts of such accidents.

We have developed Accident Hazard Index (AHI) as a new system for a comprehensive yet rapid assessment of the damage caused by accidents in the chemical process industries. The index can also be used to assess the impacts of accidents likely in a yet-to-be-commissioned industry on the basis of site characteristics and the industry's process and operational details; the index thus enables one to choose between possible sites for setting up a new industry.

Keywords: hazard indices; hazard identification; hazard ranking; hazard assessment; industrial hazards.

INTRODUCTION

Since the days of industrial revolution accidents have been occurring in the chemical process industries. But the frequency as well as severity of these accidents have significantly increased during the last few decades as the pace of industrialization, as well as the density of population near industrial complexes, have increased rapidly with time. Table 1 presents examples of some of the larger accidents of the last 25 years. It may be seen that the adverse impacts of the accidents depend not only on the type of industry but also on its surroundings.

Most accidents in the chemical process industries are caused either by material failure (such as cracks in storage vessels), operational errors (such as raising the pressure/temperature/flow-rate beyond critical limits), or external perturbation (such as damage caused by a projectile). Some accidents have catastrophic consequences. For example, the Bhopal gas tragedy of 1984 killed or maimed over 20,000 people and the LPG terminal accident at Mexico City in the same year claimed 600 lives. There have been numerous other accidents in which the death toll would have been as high as in Bhopal and Mexico, if the areas where the accidents took place were not less densely populated.

Apart from causing damage to property and claiming human lives, many accidents also cause long-term contamination of the surroundings. For example, in the well-known Seveso disaster[6], which occurred near Milan, Italy, in 1976, about 2 kg of TCDD (tetrachloro dibenzo dioxin) was released. TCDD is one of the most toxic and persistent chemicals known[6] and decontamination of the affected area posed a very serious problem in spite of the low quantities involved. Some authors believe that the area could never be decontaminated and the adverse effects of TCDD on humans are witnessed to this day.

Yet, traditionally, the severity of an accident is measured by the number of fatalities it causes. On 12 March 1995 a tanker carrying benzene crashed into a passenger bus and a tractor on a highway, about 50 km from the city of Chennai (Madras). The triple accident caused the tanker to explode. The resulting missiles, shock waves and fire-ball killed 150 people[7]. Had the same event occurred after the tanker had entered the populous Chennai city, the number of fatalities would have run into thousands, and the accident would have assumed the dimensions of a notorious disaster.

Indeed, the number of fatalities is a very important parameter in assessing the damage potential of an accident. But there are many other parameters which have more or less the same importance and contribute in equal measures to the damage potential of an accident. These include long-term contamination of the environment, damage to property and other support systems which bring socio-economic depression in the areas surrounding the accident sites, trauma caused to injured—especially debilitated–persons, and to the relatives of the deceased.

To characterize the hazard associated with any process industry, it is essential that all the probable accident scenarios are identified, their magnitudes quantified, their impacts assessed, and the knowledge used to work out net losses of lives, assets, and damage to ecosystems. But such an elaborate study of the likely causes, likely accidents, and likely consequences would require substantial input of expert personnel, time and money. If one has to screen a large number of industries and industrial sites within a short span of time and limited budget, it is necessary to have an appropriate ranking technique which is quick to execute yet has adequate accuracy and precision. In the literature we find reports on the identification and ranking of hazards in process industries; the noteworthy among these include the Dow Index[8,9], Mond Index[10] and Toxicity Index[11]. We, too,

Table 1. Comparison of index values for accidents[1,4,5,13].

Accident	Event (s)	Deaths	Financial loss, million $	Christen's disaster index (DI)[11]	Significance as per DI	Accident hazard index (AHI) $g(x)$	$h(y)$	AHI	Significance as per AHI
Flixborough (1974)	Explosion + fire	28	450	0.50	Severe accident	6.5	3.7	7.5	Severe accident
Beek (1975)	Explosion + fire	14	10	0.33	Incident	3.5	2.7	4.4	Accident
Seveso (1976)	Toxic release	–	350	0.70	Catastrophe	6.5	5.5	8.5	Catastrophe
Dhurabar (1983)	Explosion + fire	47	25	0.34	Incident	5.8	3.1	6.5	Severe accident
Cubatao (1984)	Fire	100	50	0.43	Severe accident	4.3	3.5	5.5	Severe accident
Bhopal (1984)	Toxic release	2500	350	1.0	Catastrophe	10.0	5.4	10.0	Catastrophe
Basel (1986)	Fire + toxic release	–	245	0.51	Catastrophe	5.5	3.8	6.7	Severe accident
Arzamas (1988)	Explosion + fire	23	55	0.57	Catastrophe	5.5	4.1	6.8	Severe accident
Ufa (1989)	Explosion + toxic release	7	570	0.75	Catastrophe	7.5	4.6	8.8	Catastrophe
Bangkok (1990)	Fire + toxic release	17	55	0.41	Severe accident	3.5	3.3	4.8	Accident
Bombay (1990)	Fire	10	145	0.46	Severe accident	4.4	3.1	5.4	Severe accident
Panipat (1993)	Explosion + toxic release	3	85	0.39	Incident	3.7	3.5	5.1	Severe accident
Dronka (1994)	Toxic release	4	25	0.33	Incident	3.4	2.7	4.3	Accident
Madras (1995)	Explosion + fire	150	45	0.57	Catastrophe	6.1	2.1	6.4	Severe accident
Bombay (1996)	Fire	2	150	0.27	Incident	3.5	1.8	3.9	Accident

$g(x)$ represent value of damage potential as well as direct impact.
$h(y)$ represent value of indirect impact.

have developed a index—HIRA (Hazard Identification and RAnking) for this purpose. But all these indices take into account only the premises of the industries and do not consider the surrounding population, environment, and assets at all. But, as elaborated earlier, these factors can have a very strong influence on the damage caused by accidents. These factors determine the *real* magnitude of an accident's adverse impacts. Furthermore they must be taken into consideration when deciding on the location of new industries from among the various potential sites.

Keller *et al.*[12], Wyler and Bohnenblust[1] and Christen *et al.*[13] have proposed schemes to rank past accidents keeping some site characteristics in view but these schemes can only be used to rank accidents that have already occurred and not in *forecasting the damage likely to occur* at different sites from the same type of accident. Among these the scheme proposed by Christen *et al.*[13] is the most modern and takes into account many parameters. It uses a scale of 0 to 1 to characterize the severity of an accident. However, it does not incorporate site-specific attributes such as proximity to sensitive ecosystems, and nature of support facilities, medical care, fire-fighting, transportation, etc.

To overcome the aforesaid limitations, the authors have proposed a scheme to rank probable accidents or those which have already occurred. This index can be used as a tool to rank an industry in terms of hazard to the plant as well as the surroundings. The technique incorporates the effect of various parameters such as chemicals in use, site characteristics, direct/indirect damage to surrounding population and the environment. A brief description of the importance of the various parameters and the methods used to calculate the index is presented below.

ACCIDENT HAZARD INDEX

The accident hazard index (AHI) represents the consequences of an accident on a standard scale (1–10). The procedure is shown in Figure 1. The process begins with the anticipation of the most credible accident scenario. The accident scenario is developed to estimate potential damage, and the impact of other factors on the severity of the accident is evaluated. These factors influence the severity of an accident in two ways:

- direct impact;
- indirect impact.

Direct impacts are due to those parameters which are directly related to the accident's consequences and have

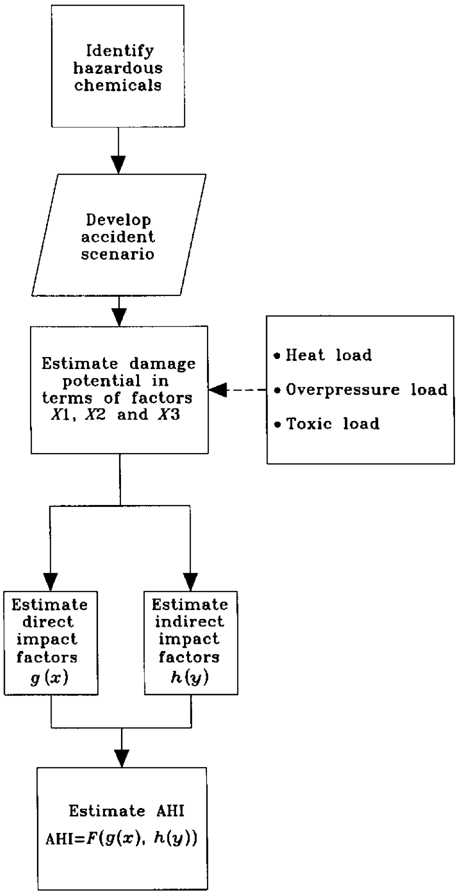

Figure 1. Systematic procedure of AHI computation.

instant (with a maximum delay of few hours) effects. The three most important direct impact parameters considered here are:

- population;
- asset;
- ecosystem.

The indirect impacts are due to those parameters which are indirectly related to the accident's consequences. The three main indirect impacts considered in the present study are the:

- soil environment;
- water environment;
- air environment.

These impacts (direct and indirect) make a major contribution to characterizing an accident's severity. The stages of the AHI algorithm and the method to quantify direct and indirect impacts are discussed in detail in subsequent sections.

ACCIDENT SCENARIOS

An accident scenario is a description of an expected situation. It basically depicts different likely events that may occur in an industry leading to an accident. The expectation of a scenario does not mean it *will* occur, but it means it has a *reasonable probability of occurrence.* Accident scenarios are generated based on the properties of chemicals handled by the industry, physical conditions under which reactions occur or reactants/products are stored, geometry and material strengths of the vessels and conduits involved, valves and safety arrangements, etc. External factors such as site characteristics (topography, presence of trees, ponds, rivers in the vicinity, proximity to other industries or residential areas, etc.) and meterological conditions are also considered.

The construction of an accident scenario achieves the following objectives:

(1) It is the basis of a risk study; it tells us what may happen so that we can devise ways and means of preventing or minimizing the possibility of an accident.
(2) An accident scenario forms a focal point of an heuristic process. It uses the wisdom of hindsight (experiences of past accidents) and state-of-the-art knowledge in forecasting accident situations. The forecast generates new knowledge. An accident scenario is thus a reference point as well as a link between the past, present and future.

At this stage of AHI calculation an accident scenario is generated for the industry under study. It is a very important input for the subsequent stages. The more realistic the accident scenario, the more accurate is the forecasting of the type of accident, its consequences and associated risks.

From the studies reported in literature[14,15,16] one gathers that generally the authors have considered only one or a few more obvious accident scenarios, omitting several other credible accidents from consideration. We have discussed this aspect in detail elsewhere[3,5], showing how the entire complexion of the risk assessment and disaster prevention/ management strategies can change if the scenarios of all credible accidents are taken into consideration. For example, the scenario for an accident in an ethylene storage vessel (storage under high pressure in the liquefied state) is generally visualized as a confined vapour cloud explosion (CVCE) followed by a fire-ball. A high pressure build-up in the storage vessel, either due to external heat absorption or to a runaway reaction caused by the presence of impurities, leads the vessel to fail with a CVCE and, as the released chemical is highly flammable, a fire-ball is generated. But a toxic release may also occur, leading to overpressure load along with toxic load due to the violence of the sudden release. Unless all such credible accidents are considered and their impacts carefully evaluated, one can miss out on the various possibilities and the damage control exercises are accordingly incomplete and inadequate.

Visualization of such accident scenarios can be achieved by analysing the chemical characteristics and operating conditions in detail with the help of thermodynamic, heat transfer and fluid dynamics models. The logistics associated with generation of scenarios are presented in Figure 2.

ESTIMATION OF DAMAGE POTENTIAL

This stage estimates the damage potential of the developed accident scenario. The assessment of damage potential involves a wide variety of mathematical models. In the present study the three main damaging effects considered are heat load, blast wave (overpressure) and toxic load. To make the assessment easier, simplified equations have been developed to calculate three different

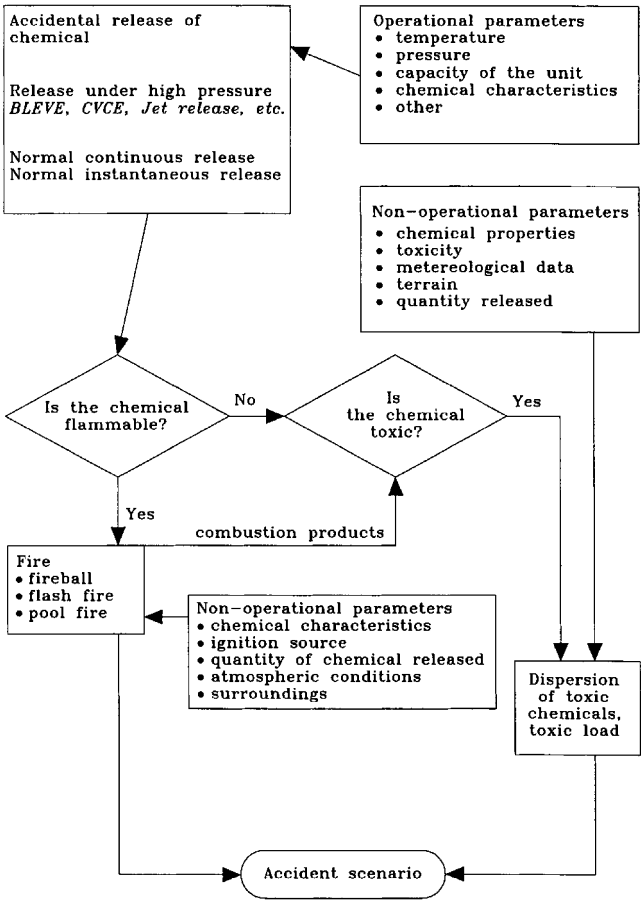

Figure 2. Logistics associated with the generation of scenarios.

factors (one for each damaging effect). These equations are derived from detailed analysis of each effect and are based on the formulations of References 4, 17, 18, 19, 20, 21 and 22. A brief explanation of each damaging event is given below.

Heat Load

The damage potential due to heat load can be estimated using:

$$R = K1\,(Hcm)^{1/2} \tag{1}$$

$$X1 = f1\,(R) \tag{2}$$

where $K1$ is a constant with a value of 51, Hc is heat of combustion ($\mathrm{kJ\,kg^{-1}}$) and m is the quantity of chemical involved in the event (kg). All parameters are measured in SI units.

The factor R is used to predict severity factor $X1$ using Figure 3. Figure 3 has been produced by a detailed study of heat load potential and its impact on the surroundings. A scale of 0–10 has been used to characterize this factor. The characterization was done with reference to the literature[4,13,20,21].

Overpressure Load

The effect of overpressure can be quantified as:

$$R = K2(Hcm); \text{ where } K2 = 7.0 \times 10^{-06} \tag{3}$$

$$X2 = f2\,(R) \tag{4}$$

The severity factor $X2$ is a measure of the severity of damage potential due to overpressure on a scale of 0–10. $X2$ can be estimated using Figure 4. This severity factor was designed using equations reported in References 18, 22, 23 and 24.

Toxic Load

The consequences due to toxic effect can be quantified as:

$$R = (q/\mathrm{LC}_{50})^{1/3} \tag{5}$$

$$X3 = f3\,(R) \tag{6}$$

where q represents quantity released (kg) in one hour (release rate × one hour) for continuous release and total quantity release (kg) for instantaneous release, and LC_{50} (based on an exposure time of 4 hours[11,17]) represents lethal concentration (50% chance of lethality) ($\mathrm{kg\,m^{-3}}$). This severity factor $X3$ can be estimated using Figure 5. The figure assumes dispersion under slightly unstable conditions over flat terrain and instantaneous exposure (short-term exposure limit) through inhalation[17].

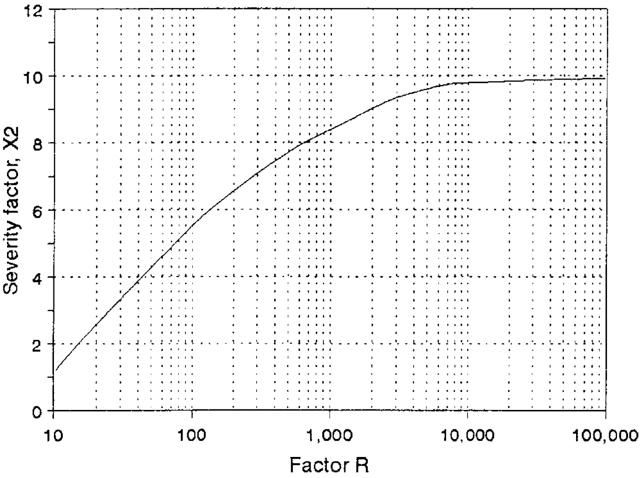

Figure 4. Profile of severity factor $X2$ due to toxic load.

DIRECT IMPACT FACTORS

The severity factors $X1$, $X2$ and $X3$ estimated at the previous stage represent the severity of each damaging effect due to the inherent characteristics of the industry or process. As discussed earlier, the direct impact parameters are also major contributors to the severity. In this section, the effect of these parameters is discussed in detail and the weightage (penalty) will be estimated for each parameter.

Population

As mentioned earlier, population density is one of the important factors which contribute to the severity of an

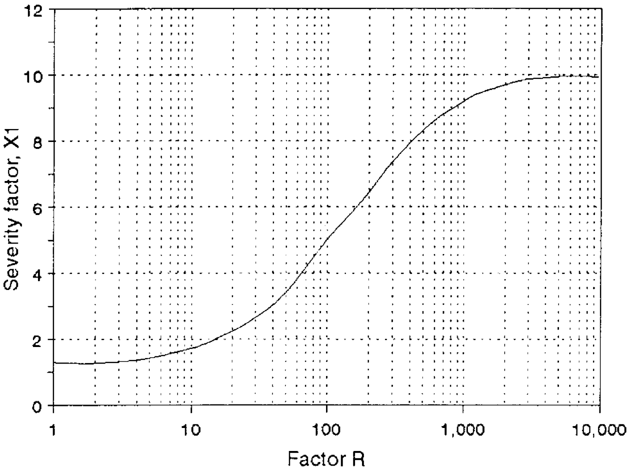

Figure 3. Profile of severity factor $X1$ due to heat load.

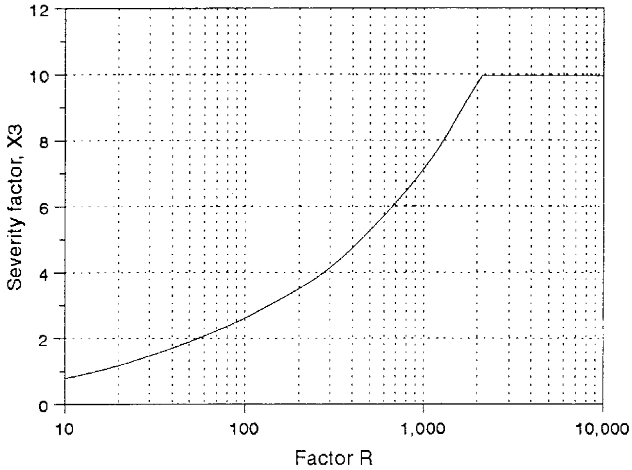

Figure 5. Profile of severity factor $X3$ due to overpressure.

accident. For example, an accident occurring in Connaught Place (a congested market place), New Delhi (population density 6139 person/km^2) will have much more disastrous consequences compared to exactly the same accident occurring in Jaselmair (a desert area), Rajasthan (population density 9 person/km^2). The impact of population on the severity of an accident is assessed by the penalty $Pn1$ which is a function of population density of the area. The penalty has a maximum value of 1, corresponding to the population density of Connaught Place, and a minimum value of 0, corresponding to Jaselmair. The penalty of any intermediate population density can be estimated using Figure 6. Figure 6 has been drawn with reference to Keller *et al.*[12], Wyler and Bohnenblust[1], TNO[19] (1992) and with the recommendations of experts[25,26].

$$Pn1 = g1 \quad \text{(Population density)} \qquad (7)$$

Asset

Loss of assets is another very important factor contributing to the severity of an accident's impact. This type of impact is assessed through the penalty $Pn2$. It is a function of the asset density of the area. The maximum value of $Pn2$ is 1 for a market place (Connaught Place) and a value of 0 is given for a remote area. Intermediate values of the penalty can be drawn using Figure 7.

$$Pn2 = g2 \quad \text{(Asset density)} \qquad (8)$$

Ecosystem

Impacts of accidents on the surrounding ecosystems have rarely been considered because such impacts are much less visible than loss of lives and assets. But damage to ecosystems can have serious long-term consequences. For example, the release of TCDD (tetrachloro dibenzo dioxin) at Seveso, Italy (Abbasi *et al.*[6]) and pesticides at Basel, Switzerland (Christen *et al.*[13]) caused long-term contamination of the environment with long-lasting adverse impacts.

The impact on the ecosystem is assessed in terms of the area affected by the accident. Further, high penalties are assigned if some sensitive or important ecosystem happens to come within the periphery of an accident. Figure 8 is tentatively suggested based on a Delphi study to draw a penalty for this parameter. This figure may be refined in due course with the help of a more comprehensive Delphi study involving large numbers of experts across the world.

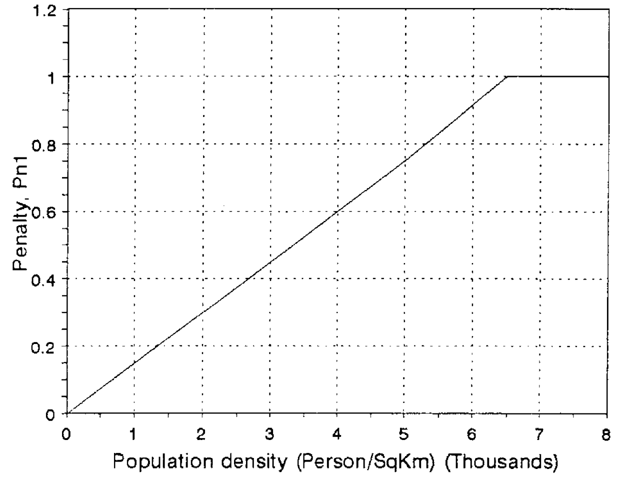

Figure 6. Curve for penalty estimation to assess damage to the population.

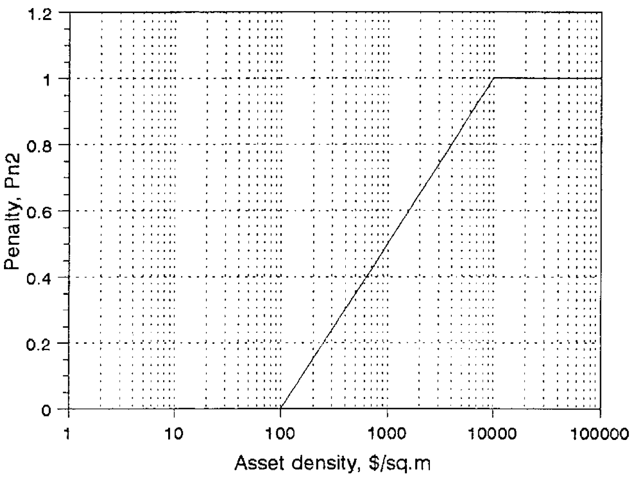

Figure 7. Curve for penalty estimation to assess loss of asset.

$$Pn3 = g3 \quad \text{(Area of ecosystem)} \qquad (9)$$

The penalties estimated above are used to upgrade the severity parameters $X1$, $X2$ and $X3$.

INDIRECT IMPACT FACTORS

The indirect impact is a measure of the impact on accident severity of the parameters which are dependent on the accident but have secondary effects. For example, a release of hazardous liquid may contaminate water, part of the liquid may evaporate and hence contaminate the air and some liquid may be absorbed by the soil and so contaminate the land. Thus, release of a hazardous chemicals affects the air, water and soil environment which later affects living organisms including humans.

The curves to assess the weightage of such impacts are presented in Figures 9–11. In order to develop these index components for the indirect impacts, we have once again taken recourse to a Delphi study as there is no other means to

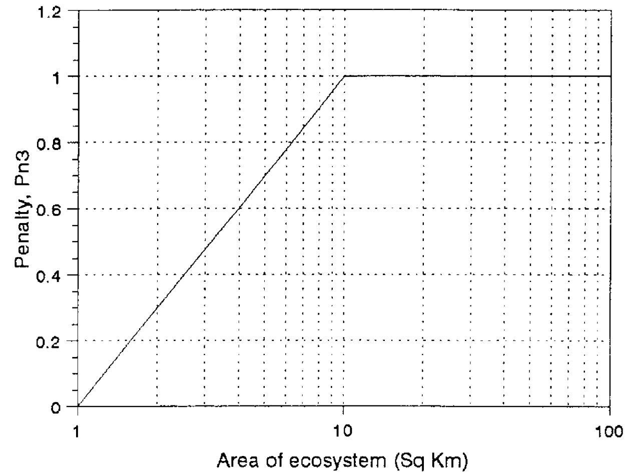

Figure 8. Curve for penalty estimation for ecosystem damage.

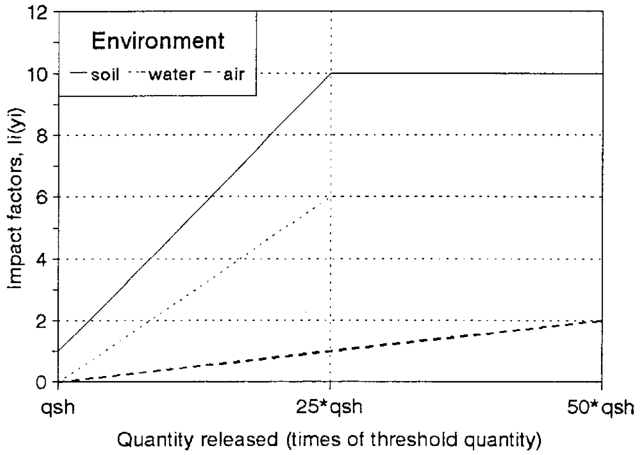

Figure 9. Indirect impact factors due to solids deposited; *qsh* represents threshold quantity in kg.

provide an 'importance' weightage for such impacts (Arya and Abbasi[25,26]). In due course the components can be refined by a more comprehensive Delphi study.

INDEX COMPUTATION

As discussed earlier, AHI is a function of damage potential, direct impact and indirect impact, and hence can be expressed as:

$$AHI = F(g(x), h(y))$$
$$= \text{minimum of } (10, (g(x)^2 + h(y)^2)^{1/2}) \qquad (10)$$

where $g(x)$ is a function defining damage potential and direct impact while $h(y)$ is a function specifying indirect impact.

The function $g(x)$ can further be expanded as:

$$g(x) = \text{minimum of } [10, \{\{(g1(x1))^p + (g2(x2))^p + (g3(x3))^p\} \times (1+z)\}^{1/p}] \qquad (11)$$

where 1,2,3 specify the damaging effects due to heat load, peak overpressure and toxic release respectively, and p is a fuzzy expression parameter. Studies[1,13,27] suggest a p value of 3.

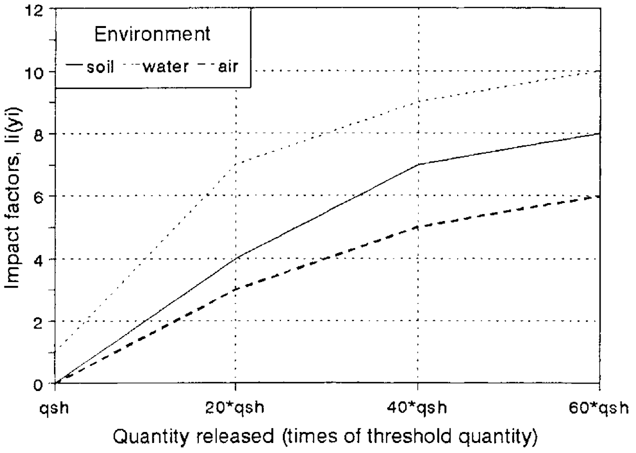

Figure 10. Indirect impact factors due to liquid releases; *qsh* represents threshold quantity in kg.

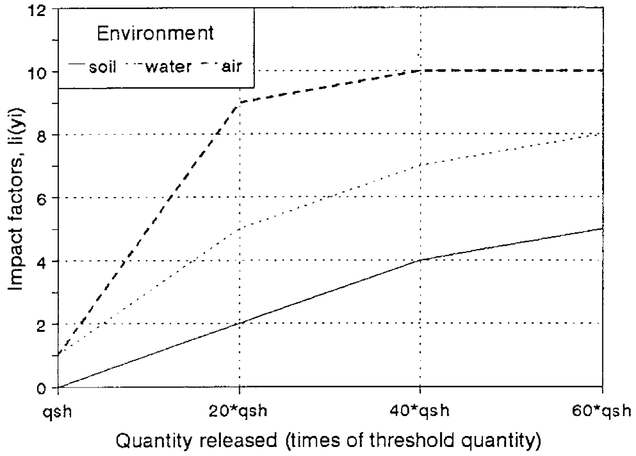

Figure 11. Indirect impact factors due to gaseous releases; *qsh* represents threshold quantity in kg.

The function $gi(xi)$ can be given as:

$$gi(xi) = \sum_{i=1-3} [Xi\{\prod_{j=1-3} (1 + Pnj)\}]$$
$$= \sum_{i=1-3} [Xi(1 + Pn1)(1 + Pn2)(1 + Pn3)] \qquad (12)$$

where Xi represents the damage potential of a particular effect and Pnj represents the penalty of the direct impact of each parameter. The factor z represents the hazard characteristics of the chemical. The National Fire Protection Agency (NFPA) rating has been used to calculate z. The rating is scaled down to a scale of 0 to 1 instead of 0 to 4 without affecting its significance.

Similarly, the function for indirect impact $h(y)$ can be expanded as:

$$h(y) = \text{minimum of } [10, \{(l1(y1))^p + (l2(y2))^p + (l3(y3))^p\}^{1/p}] \qquad (13)$$

where $li(yi)i = 1, 2, 3$ represents the indirect impact of an accident on the different environments and 1,2,3 represent the impact on the soil, water and air environments respectively. The function $li(yi)i = 1, 2, 3$ can be further explained as:

$$li(yi = 1 - 3) = f\ (\text{hazardous properties, quantity of release and condition of release}) \qquad (14)$$

Curves to estimate $li(yi)$ values are presented in Figures 9–11.

As mentioned earlier, AHI is categorized on a scale of 0 to 10, where severity of damage is at a maximum at a value 10 and at a minimum at 0. The classification of accident type and hazard potential according to AHI values is as follows:

0–1—Normal operation	(minor hazard)
1–3—Incident	(low hazard)
3–5—Accident	(high hazard)
5–8—Severe accident	(severe hazard)
8–10—Catastrophe	(extremely severe hazard)

Table 2. Input data to estimate accident hazard index for the methyl isocyanate release at Bhopal, 1984.

Parameters	Values
Total quantity of MIC released	5 ton (10 times threshold quantity)
Population density within plant	350 persons/km^2
Population density of surrounding area	1540 persons/km^2
Asset density within plant boundary	250 \$/m^2
Asset density of surrounding area	45 \$/m^2
Area of ecosystem damaged	2.25 km^2
Hazard potential of MIC (on scale of 0–1)	0.75

The classifications—accident type and hazard potential—are interrelated. A minor hazard potential always exists in any process operation (normal operating conditions), whereas an accident may have a wide range of hazard potentials from low to extremely severe. This is qualitative classification based on the values of the AHI index which represent the severity of hazard. An industry or plant with an AHI value greater than 3 requires a detailed evaluation of its safety system, whereas a value higher than 8 requires immediate action to identify vulnerable locations and develop strategies to manage them.

CASE STUDY

The AHI value has been calculated for a number of past accidents. The list of accidents and their corresponding index values are presented in Table 1. The input data and intermediate calculation results for the Bhopal accident are presented in Tables 2 and 3 respectively. The results presented in Table 1 are compared with the ratings proposed by Christen *et al.*[13]; it is observed that the AHI's wide range allows better characterization than the narrow band of characterization of the disaster index ranking[13], which has lesser tolerance for any uncertainty in parameter estimation.

SUMMARY AND CONCLUSIONS

The indices reported thus far for ranking the severity of accidents in the chemical process industries either do not take into account the surroundings (population density, assets and sensitive ecosystems) or do not possess features to enable forecasting of impacts of likely accidents on the surroundings.

In this paper we have emphasized the necessity for consideration of the surroundings of an industry as crucial inputs in determining the severity of accidents in the industry. An elaborate Accident Hazard Index (AHI) has been developed which incorporates direct and indirect impacts of accidents in the chemical process industries on the population, assets and ecosystems present within striking distance of the accidents which have occurred, or are likely to occur, in an industry. The special ability of AHI to not only rank past accidents in terms of severity but also to forecast the impacts of *likely* accidents makes it valuable as a management tool in choosing between potential sites when setting up a new industry.

Table 3. Intermediate calculation stage of the accident hazard index for the Bhopal disaster.

Parameters	Values
Bhopal disaster, 1984	
Accident scenario : Toxic gas (MIC) release	
Factor, R	1651
Severity factor, $X2$	8.3
Direct impact	
Population density penalty, $Pn1$	0.15
Asset density penalty, $Pn2$	0.10
Ecosystem penalty, $Pn3$	0.34
Hazard factor	0.75
The total direct impact factor , $g(x)$	10.0
Indirect impact	
Air environment	5.2
Water environment	2.5
Soil environment	1.6
The total indirect factor, $h(y)$	5.43
Accident hazard index	**10.0**

NOMENCLATURE

$f1$	function relating heat load to severity of factor $X1$
$f2$	function relating overpressure load to severity factor $X2$
$f3$	function relating toxic load to severity factor $X3$
$g1$	function relating population impact to penalty $Pn1$
$g2$	function relating asset impact to penalty $Pn2$
$g3$	function relating ecosystem impact to penalty $Pn3$
Hc	heat of combustion, kJ kg^{-1}
LC_{50}	lethal concentration, kg m^{-3}
m	mass of chemical, kg
q	chemical released, kg
$Pn1$	penalty due to population
$Pn2$	penalty due to asset
$Pn3$	penalty due to ecosystem
$g(x)$	function representing direct impacts
$h(y)$	function representing indirect impacts
$X1$	severity factor due to heat load
$X2$	severity factor due to overpressure load
z	hazard characteristic of chemical

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