Journal of Hazardous Materials, 19 (1988) 237-269
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

MANAGING HAZARDOUS FACILITIES: LESSONS FROM THE BHOPAL ACCIDENT

B. BOWONDER and T. MIYAKE
UN-ESCAP/APCTT, 49 Palace Road, Bangalore-52 (India)*
(Received September 8, 1987; accepted in revised form July 10, 1988)

Summary

A brief description of the Bhopal Plant and how the accident occurred has been presented. Using a framework developed for assessment of technology, the error which caused the accident are identified in terms of Technoware (facilities) errors, Humanware (skills) errors, Inforware (factual) errors, Orgaware (regulatory) errors and Climoware (climate) errors. Lessons for managing hazardous facilities in terms of these five factors are derived based on the shortcomings identified. The most important factor that needs improvement for reducing accidents is the institutional risk analysis systems, hazard management procedures and commitment for safe operation of facilities.

Introduction

Managing hazardous facilities [1,2] have assumed considerable importance after the recent major accidents, namely the Seveso accident [3], the Flixborough accident [2], the Bhopal accident [4–25], the Mexico gas explosion [14] and the Chernobyl accident [22]. It is necessary to use a general framework for analyzing the structure of technological accidents, if corrective steps for improving safety have to be identified. In this paper, first, a brief description for the Union Carbide pesticide manufacturing facility at Bhopal and the factors which caused the accident [4] are presented. Then, a generalized framework for analyzing accidents are presented. Using this framework the Bhopal accident is analyzed to derive lessons for safe handling of hazardous facilities.

A brief description of the plant at Bhopal

The Bhopal accident was caused by the accidental release of methylisocyanate (MIC) by a pesticide manufacturing unit in the night of 2/3 December

*United Nations-Asian and Pacific Centre for Tranfer of Technology (APCTT) of Economic and Social Commission for Asia and the Pacific (ESCAP).
The views and interpretations in this article are the authors' and should not be attributed to the United Nations Organization with which the authors are affiliated.

0304-3894/88/$03.50

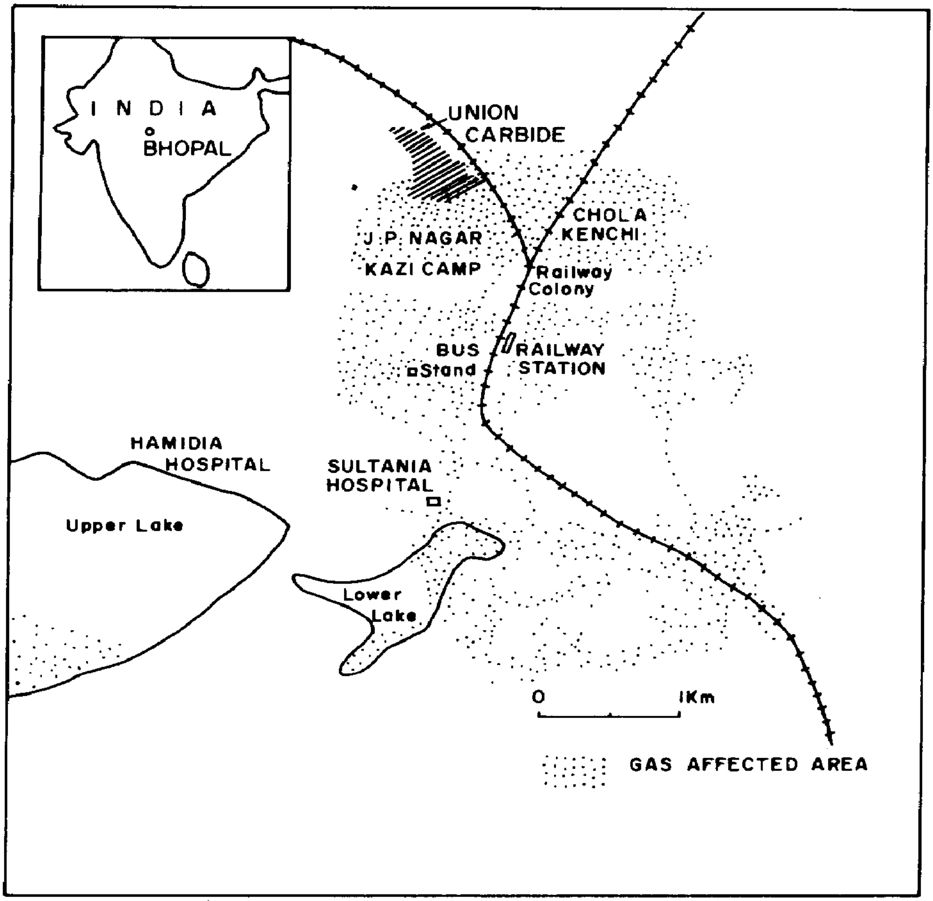

Fig. 1. Extent of MIC dispersal.

1984 [6]. Bhopal is the capital of a relatively less developed state [17], Madhya Pradesh, with limited number of industries. This state provided a number of incentives for attracting industries. The Bhopal plant of Union Carbide India Ltd. (UCIL) was making carbaryl pesticides using imported raw materials. In 1977, UCIL applied for a license to manufacture MIC-based pesticides. The license was granted in 1979 [10]. The production of MIC-based pesticides started in 1980. Initially technical experts from the US were manning the plant. After 1981, all the managerial positions were occupied by Indian personnel. This has actually been the case with all major multinational corporations in India. Because of competition from synthetic pyrethroids, the demand for MIC-based pesticides did not pick up. The unit was running at a lower capacity and did not make profit. UCIL was licensed to produce 5,000 tonnes of carbaryl pesticides. MIC is a raw material for manufacturing carbaryl pesticides. The production of the carbaryl pesticides achieved during 1981, 1982 and 1983 were

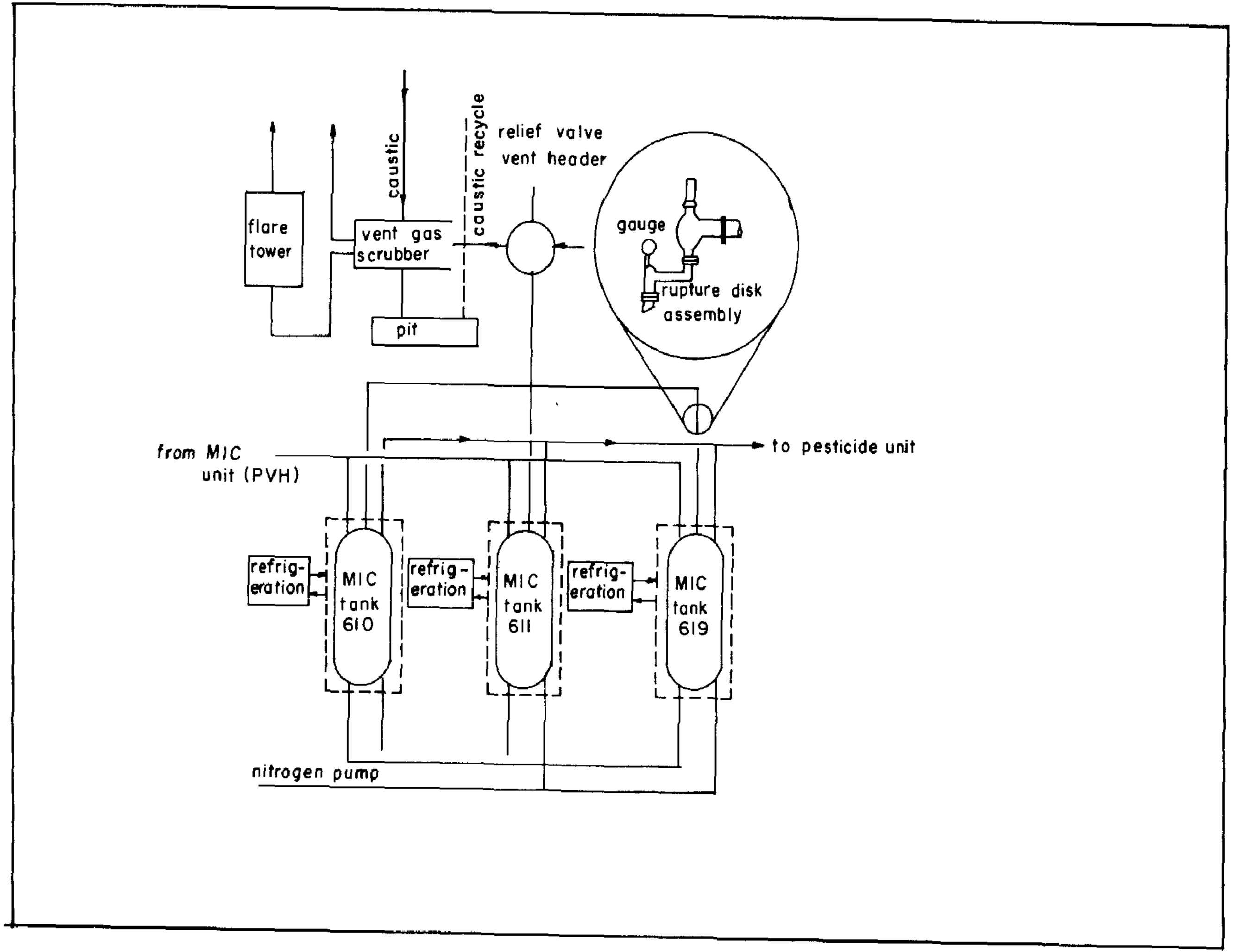

Fig. 2. MIC storage system (source: Chem. Eng. News, March 25, 1985).

2.074 tonnes, 2,308 tonnes and 1,657 tonnes. The sales of carbaryl pesticides in 1983 was only 1,500 tonnes compared to a sales of 2,211 tonnes in 1982. Low demand, low capacity utilization, and competition from synthetic pyrethroids had its impact on UCIL. Safety was neglected since the unit did not make profit. Some of the technically experienced engineers left the UCIL plant. This had severe implications on safety.

MIC is a highly reactive and toxic substance [8,26]. It reacts violently with water, alkali, acids, alcohols, etc. It is biologically very active and reacts with a number of body enzymes, as per the Materials Data Sheet of Union Carbide Corp Ltd. (UCC), [28]. MIC has to be stored close to 0°C and in no case the temperature of storage should exceed 15°C. In pure form MIC polymerizes easily. While storing phosgene is added to MIC to inhibit polymerization. There are three MIC storage tanks at the Bhopal plant (Fig. 2) which have to be kept refrigerated. A number of sequential safety features are incorporated in the MIC plant [6]. There is a vent gas scrubber to neutralize any escaping MIC through the use of an alkali spray. Besides the vent gas scrubber, there is a flare tower which can burn any unneutralized MIC. The last safety system is a toxic gas alarm to alert the public in the vicinity of the plant. Bhopal is a city which expanded rapidly during 1971–1981 when the population grew at an approximate rate of 75% during this period [4]. There is a large number of squatter settlements close to the UCIL unit. The Bhopal unit of UCIL was established in 1969, very close to the Bhopal railway station and bus station for the convenience of location [17] (Fig. 1). The squatter settlements in the vicinity of UCIL were densely populated and belonged to the low income category i.e. mostly workers who earned their wages on a daily basis [9].

According to the safety manual of the MIC plant [28], the vent gas scrubber should be kept in active mode i.e., the pump of the vent gas scrubber has to spray alkali as long as the MIC unit operates. In October 1984, a decision was taken to keep the vent gas scrubber in passive mode i.e. operate it only when needed [11,13]. Similarly, it was decided to shut down the refrigeration plant. Both these actions in themselves would not have caused any problem. There are two process venting lines, RVVH (Relief Valve Vent Header) and PVH (Process Vent Header), in the MIC plant (Fig. 3). RVVH is a line for toxic gases from the pressure relief valve to the vent gas scrubber in case there is a pressure build up in any one of the tanks and gases are released [13]. The second vent line is PVH leading from tanks to the vent gas scrubber (VGS). This line is connected to the nitrogen pressurization system. The routine release of process gases goes through PVH to the VGS. Following the process chart given by UCC, RVVH and PVH are not interconnected. A decision was taken to carry out a plant modification connecting RVVH and PVH [12,13] sometime in May 1984 (Jumper line in Figs 3 and 4). UCC is a corporation with a highly centralized style of decision-making and UCIL had given approval for this plant modification [17]. The UCC investigation report of the

Bhopal accident does not mention anything about the plant modification interconnecting RVVH and PVH [6].

Sequence of events leading to the accident

The Bhopal unit was closed for annual maintenance. On 26 November 1984, the operators tried to transfer MIC from tank 610 to the processing facility. But the tank failed to get pressurized [13]. This in itself was sufficient reason to point out the possibility of a leak. On December 2, another attempt was made to transfer MIC from the tank. The MIC plant supervisor, who was posted to UCIL was from a non-MIC based unit [6], considered that the reason for the non-pressurization of the MIC tank was a blockage of the MIC lines. On December 3 1984, order was given by the plant supervisor for washing the lines. Washing started at 21.15 h and was carried out without inserting the slip blind for isolation [6,17]. The operator began washing the four MIC lines. All these four lines were connected to the RVVH [12,13,17]. Water was not freely flowing indicating its accumulation. The operator reported this to the supervisor [16]. Washing was stopped for a short while. Again at 22.00 h, the MIC plant supervisor ordered washing of the lines to continue. At about 21.20 h the pressure in tank 610 was about 2 psi ($\sim$0.14 bar). At about 21.45 h, the shift changed. At about the same time the water which had accumulated in the line slowly entered through the jumper line and came into the MIC tank through a leaky valve [14,16]. The route of water entry is shown in Figs. 3 and 4.The operator logged the pressure in the tank as 10 psi ($\sim$0.7 bar). Water entered the MIC tank along with ferric ions, since ordinary steel pipes were used for MIC transport. Ferric ions act as catalysts in the polymerization of MIC and this polymerization caused a sharp rise in the temperature and pressure (about 55 psig ($\sim$4.9 bar) — top of the scale) of MIC [6]. Entry of ferric ions has been confirmed even in the investigation report of the Bhopal accident by the Union Carbide Corporation Headquarters Team [6]. Between 22.30 h and 22.45 h, the operator detected the first leak of MIC. The Plant Supervisor was informed about the high pressure of the MIC tank as well as MIC leak. At 23.50 hours the MIC plant operator saw a yellow drip from RVVH. At about midnight the plant supervisor ordered stopping of washing operations. Between midnight and 00.15 h operators did not do anything. This was probably a teabreak for the operators, as they were all away from the control room. At about 00.20 h, the safety valve set at 40 psi (2.7 bar) ruptured and MIC escaped through the vent line. At the same time an attempt was made to start the pump of the vent gas scrubber [13]. At about 00.25 h, the plant superintendent was informed about the leak and he arrived on the spot. The temperature of the concrete cover of the MIC tank was about 300°C [6]. At 00.40 h an MIC operator reported leakage of MIC through the vent line at 33 m height. At 01.00 h the toxic gas leak alarm sounded, but it was switched off immediately. By

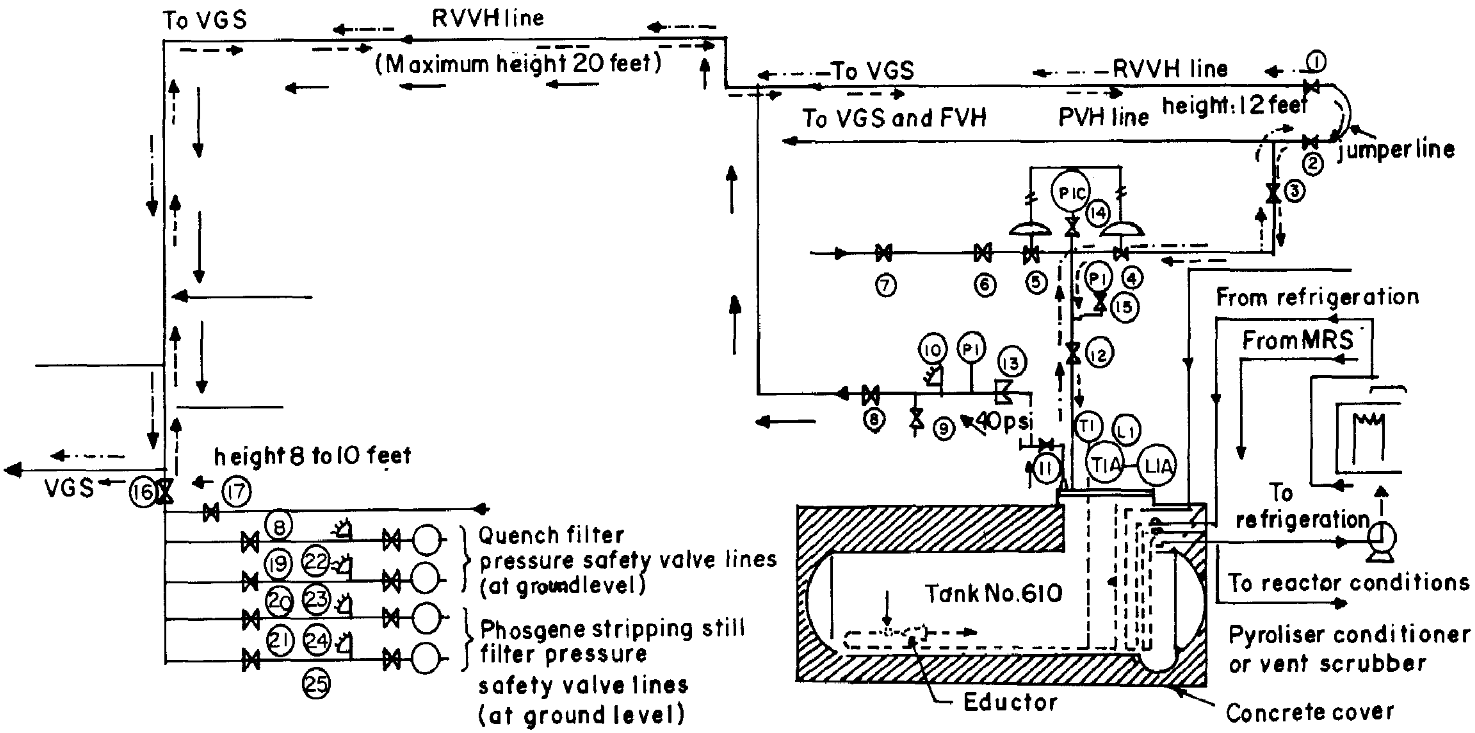

Fig. 3. Details of MIC plant.

Key: 1. Intereconnection RVVH isolation valve. 2. Interconnection PVH isolation valve. 3. PVH isolation valve. 4. Blow down DMV. 5. Make up DMV. 6. Check valve for nitrogen line. 7. Nitrogen header isolation valve. 8. RVV isolation valve. 9. RVV bleeder valve. 10. Relief valve for MIC tank. 11. First RVVH isolation for MIC tank. 12. First PVH isolation valve MIC tank. 13. Rupture disk. 14. PIC isolation valve. 15. PI isolation valve. 16. RVVH isolation valve. 17. Valve from which water for flushing was let in 18,19,20,21. Downstream isolation valves for filters 22,23,24,25. Bleeder valves.

RVVH — relief valve vent header, PVH — process valve vent header, VGS — vent gas scrubber, PVH — flare vent header, MRS — MIC reactor side. - - - Route of water ingress, – – – Route of gas leakage before 00.30 h, – Route of gas leakage after 00.30 h.

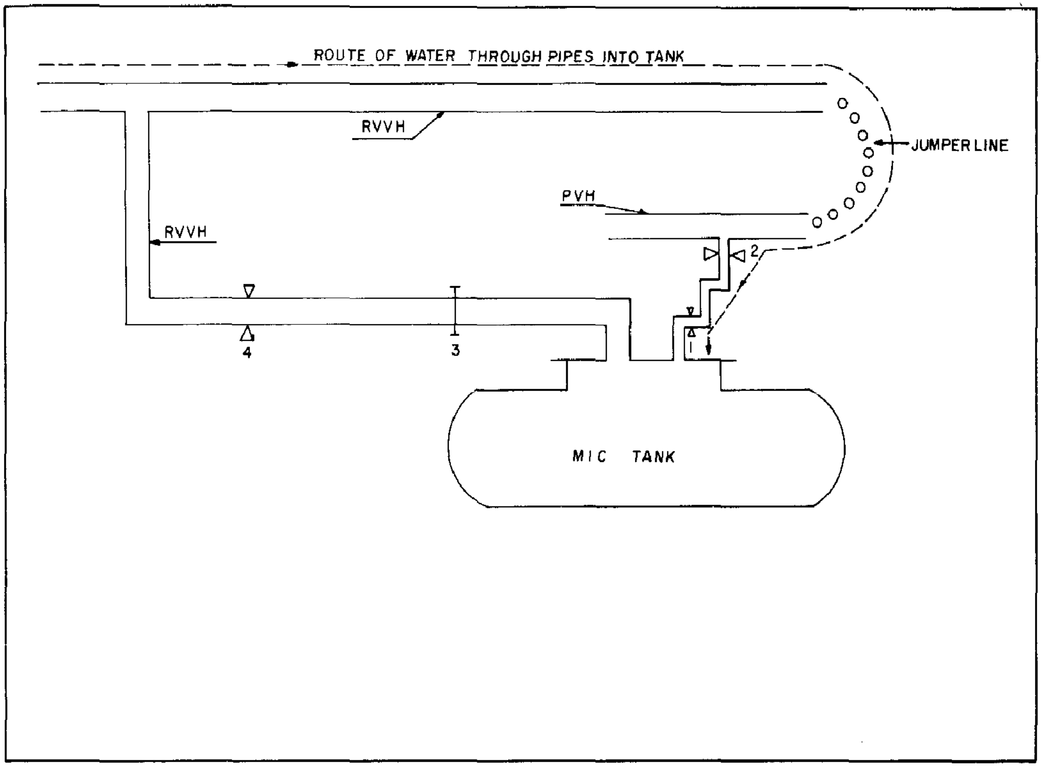

Fig. 4. How the water entered (Source: Fera, 1985).
1. Nitrogen out valve. 2. PVH isolation valve, 3. Rupture disc, 4. Safety valve.
RVVH — Relief Valve Vent Header, PVH — Process Vent Header.

that time a police official on patrol reported to the police control room that something had gone wrong at UCIL. At 01.15 h the city police control room informed the city police chief about the gas leak. When the police contacted UCIL, the staff reported that nothing abnormal had happened at the plant. At 01.45 h the Additional District Magistrate of Bhopal informed the Works Manager of UCIL at his residence about the leak [15]. Between 02.00 and 02.30 h, the safety valve was reseated, but in the meantime 40 to 45 tonnes of MIC had escaped. At 02.30 h the public siren was restarted at full blast. Water had accumulated at 6 metres height in the RVVH line [12,13] because of neglecting the usage of a slip blind. Washing without a slip blind was the trigger of the event of water entry. The route of water entry [12,13,17] and the two paths of gas leak are shown in Fig. 3, (sources for Fig. 3 are Refs. 13 and 17). The jumper line gave a direct route through the leaky nitrogen valve to the MIC storage tank [13,16,17]. If the washing had not been carried out or if the jumper line was not provided, the whole sequence of events leading to entry of water to the MIC tank would not have occurred [14,16].

The major causes of the accident can be summarized as:

i) Flushing the pipelines with water (though it is a routine maintenance step) led to the admission of water into tank 610 because of:
- partly leaky isolation valves;
- omission to insert a slip blind;
- a remote operated valve being open (it should have been shut — this was not known at the control room); and
- a plant modification connecting relief valve and process vent header.

ii) Large quantities of MIC were stored in the tanks, contrary to instructions and the empty tank was not used for evacuation.

iii) The safe systems for mitigating the release of MIC were not operational or adquate to handle such a large release.

Before analyzing the accident and its causes, a brief description of the subsequent events at Bhopal are given.

People living in squatter settlements close to UCIL started feeling suffocated and started running away [15] at about 23.45 h. Since most of the people were poor workers and had no transport facilities, they started moving in all directions. To the south of the UCIL plant there was a firm called Straw Board Products India Ltd. [9]. The General Manager of that firm transported almost all the workers in buses at 23.40 h saving most of them [9]. There was panic in the city. On the morning of 4 December, about 12,000 people were brought to the Hamidia Hospital [15]. But it only had facilities to handle 750 persons. Again, when temperature dropped during the night of 4 December MIC recondensed from the atmosphere and more people were exposed to MIC. On the morning of 5 December 1984 about 55,000 came to the Hamidia Hospital [15]. The death and intensive reaction was due to sensitization in people who were exposed the previous night. There was severe confusion about the nature of the gas that leaked as UCIL did not give any details. There was a severe controversy regarding the line of treatment as well as the amount and type of gas that leaked [18,20]. The Head of the Department of Forensic Medicine at Hamidia Hospital said that the people who died showed symptoms of cyanide poisoning. The Director of Health Services, Government of Madhya Pradesh disagreed with this observation [18]. On 5 December a telex came from UCC Headquarters indicating that if cyanide poisoning symptoms persisted, people should be given injections of sodium thiosulphate and amyl nitrate [19]. This telex was not disclosed. The private doctors handling people exposed to the gas, treated them for specific symptoms which the subjects exhibited in the absence of information on the line of treatment [4,18]. On 7 December a well known German toxicologist visited Bhopal with 50,000 injectible vials of sodium thiosulphate [17]. Though he demonstrated the efficacy of sodium thiosulphate, he was asked to leave Bhopal. The consequences of Bhopal gas leak incident are summarized in detail elsewhere [4,29]. The number of people died has been another controversial issue — government sources report a number close to 1,250 [30] whereas media reported a number of around 2,500 and detailed door-to-door surveys indicated the number of deaths to be between 5,000 to 8,000 [31].

Framework for analyzing hazardous technology accidents

The Bhopal accident is an example of poor safety management practice in a facility handling hazardous materials. Below a framework is given which can be used for assessing technology aspects. For analyzing the major errors which caused this severe accident, a framework developed for the assessment of technology by APCTT [32] is used. Before analyzing the errors that caused the accident, a brief description of the framework is given.

It is possible to classify any technology into five basic components (Fig. 5), namely:

- Object-embodied technology (Technoware).
- Person-embodied technology (Humanware).
- Document-embodied technology (Inforware).
- Institution-embodied technology (Orgaware).
- Technology climate factors influencing the absorption, utilization and regulation of the technology as well as safety systems in a given local setting (Climoware).

In a hazardous materials facility, Technoware consists of storage tanks, refrigeration devices, scrubbers, safety equipment, instruments and monitoring equipment, process control equipment, flare towers, etc.

Humanware refers to experience, skills and other person-related aspects.

Inforware includes all kinds of documentation pertaining to process speci-

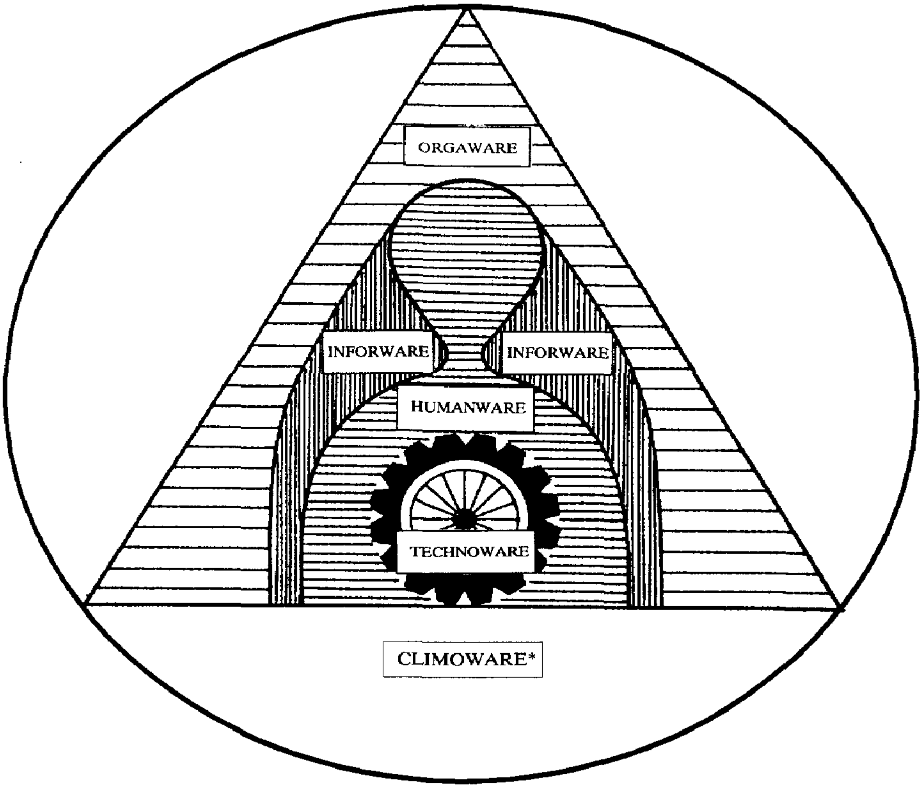

Fig. 5. Dynamically interacting components of technology.
*Regulations, risk assessment procedures, safety consciousness, media awareness, public pressure, government commitment, etc.

fications, safety specifications, material handling specifications and safety and emergency procedures.

Orgaware is the linkage required for the effective integration of Technoware, Humanware and Inforware and it consists of aspects such as management practices, clarity of objectives, linkages, management commitment towards safety, etc.

The last aspect is the national climate (Climoware) in which Technoware, Humanware, Inforware and Orgaware work. The climate factors are the regulatory aspects as well as technology absorption aspects which provide the climate for the siting of facilities, growth of industries, and dissemination of information for safe management of hazardous facilities. Technology for handling hazardous materials in a developed country and a developing country may be the same, but the interactions of technological climate factors with Technoware, Humanware, Inforware and Orgaware will be entirely different in the two systems.

Technoware errors

Technoware errors (Table 1) are the ones such as design defects, wrong material selection, malfunctioning of equipment, poor levels of instrumentation, lack of monitoring equipment, plant modifications, manufacturing defects, wear and tear, metal fatigue, contamination, etc. The specific Technoware errors which caused the spillage of methylisocyanate are briefly given in Table 2. Some of the important Technoware errors are discussed below so that lessons can be derived for avoiding their recurrence in hazardous facilities.

- The capacity of the vent gas scrubber was insufficient, as there was more than 70 tonnes of MIC in the storage tanks, but the scrubber had a capacity to neutralize only 5 to 8 tonnes. There was no alkali for neutralization in the vent gas scrubber. According to the investigation report of the Union Carbide Corporation, the flow meter did not indicate that alkali had been pumped into the scrubber [6].
- The refrigeration unit of the MIC tank was not in operation, though safety manual states that contents of the MIC tanks are circulated through heat exchangers cooled by a 30 ton refrigeration system to maintain the MIC at a temperature of about 0°C [6].
- In the MIC tanks there were no automatic sensors to warn about possible temperature increases. The temperature indicator of the MIC tank was not functioning [17,33].
- The MIC unit did not have sufficient gas masks, and the operator refused to check the gas leak because of non-availability of gas masks. The whole UCIL plant had only two gas masks [13,15].
- The flare tower for burning the released MIC (either from tanks of vent gas scrubber) was not functional [16].
- Vent gas scrubber was not in active mode when MIC leaked, even though the safety manual stated that whenever the MIC plant is operating, VGS should circulate alkali to neutralize any possible methylisocyanate escaping [6,16].
- The route of entry of water was due to the plant modification connecting RVVH and PVH [12,12,16,17]. Union Carbide Corporation's investigation report [6] does not say anything about this plant modification, although all the other investigation reports [12–14,16,17] have stated this as a major error.
- Another major error was the use of ordinary steel pipes [6], even though the safety manual specifies the use of stainless steel 403 for piping. Iron acts as a catalyst for polymerizing MIC. Union Carbide reported that the residue in the MIC tank contained considerable quantities of iron [6].
- The vent gas scrubber had only a manual mechanism for switching [13].
- There was no on-line monitor for the MIC tanks [17]. Entry of extraneous matter could be identified in the absence of an on-line monitor.
- The plant started in 1979 and subsequent to this there was no major main-

TABLE 1

Structure of accidents

Technoware errors	
1.	Design defects
2.	Wrong material selection
3.	Malfunctioning of equipment
4.	Disconnection of facilities
5.	Poor instrumentation
6.	Plant modification
7.	Insufficient safety margin
8.	Difference in balance of plants
9.	Manufacturing defects
10.	Fatigue and metal failure
11.	Corrosion
12.	Contamination
13.	Low level of safety provisions
14.	absence of hotlines for quickly informing the civil authorities
Humanware errors	
1.	Tension and operator stress
2.	Poor training and skills
3.	No training for handling emergencies
4.	Inability to perceive the risk
5.	Neglecting safety instructions
6.	Error in judgement
7.	Non communication of uncommon events
8.	Faulty operations
9.	Faulty safety procedures
10.	Absence of experienced personnel at site
11.	Delay in taking decisions because of lack of experience
12.	Carelessness
13.	Deviating from specified operating procedures
Inforware errors	
1.	No manual for operators on handling emergencies
2.	Absence of documentation on toxicity and sharing of information
3.	Delay in getting toxicological information
4.	Non-disclosure of line of treatment
5.	Non-communication of precautions for handling toxics
6.	Proprietary nature of hazardous inputs and processes involving secrecy
7.	Absence of emergency warning procedures
8.	Different quality assurance standard and material specifications and involvement of different contracting parties causing incompatibility of systems
Orgaware errors	
1.	Absence of rehearsing for handling emergencies
2.	Poor emergency planning (on-site)
3.	Neglecting early warning signals

TABLE 1 (continued)

4.	Poor industrial siting criteria
5.	Neglecting safety even after a number of accidents
6.	No hazard assessment procedures
7.	Unplanned manpower allocation and transferring
8.	Non-review of safety procedures
9.	Non-institutionalization of systems safety
10.	Treating hazardous and non-hazardous facilities alike
11.	Overemphasis on profits
12.	Poor corporate information exchange
13.	Large scale storage of toxics
14.	Large manpower turnover
15.	Poor disclosure of critical information
16.	Poor commitment for safety at the top levels
17.	Non-specification of emergency procedures
18.	Absence of a system for analyzing and assessing accidents objectively
Climoware errors	
1.	Weak factory safety inspection
2.	Factory/safety inspectorate ill-equipped to handle complex facilities
3.	Absence of hazard management systems in government
4.	Poor emergency planning (off-site)
5.	Poor coordination of emergencies (off-site)
6.	Poor industrial siting procedures and policy
7.	Absence of strong hazardous substances information centre
8.	Poor communication facilities
9.	Illiteracy, poverty and underdevelopment
10.	Absence of emergency transportation and evacuation systems
11.	Insufficient levels of medical facilities for handling large scale disasters
12.	No permanent structure or institutional arrangement for handling emergencies
13.	Absence of emergency communication systems
14.	Permitting human settlements close to hazardous facilities or poor zoning policy

tenance programme for checking the status of pipelines and valves or for replacing the faulty ones, even though the Materials Handling Manual [34] stipulated that regular cleaning and changing of pipes and valves have to be carried out.

- The water curtain for neutralizing MIC (high pressure water sprayers) could reach a height of only 10 metres whereas MIC leaked at about 33 metres height [13,16].
- There was no indicator in the control room monitoring the position of valves in the MIC tank and RVVH [17].

These Technoware errors were compounded by the human errors. Some of the Technoware errors could have been compensated by appropriate Humanware interventions. But this did not happen at Bhopal.

Humanware errors

Humanware errors are more critical since they interface Technoware and Inforware and can cause the system to fail independently. Examples of Humanware errors (Table 1) are stress of the operator, absence of expertise and skills, inability to perceive the risk, inexperience in handling emergency situations, error in judgement, negligence of safety instructions, non-communication of uncommon events to supervisors by operators, use of faulty procedures, delay in taking decisions, deviating from the specified operating procedures, etc. (Table 1). In the case of the Bhopal accident the major Humanware errors are summarized in Table 2 and presented below.

- The MIC plant operator had no prior experience with working in a hazardous facility [17].
- The number of operating and maintenance staff were reduced to almost half the normal strength, mainly to reduce expenses [9], as shown in Table 3.
- The pressure of MIC tank increased from 2 to 10 psig but the serving shift operator did not communicate this change to the supervisor or the next shift operator [16].
- MIC tank 610 could not be pressurized on 26 November and 2 December, although nitrogen was reported to be flowing into the tank [6]. No investigation was carried out on this. This was the route for entry of water subsequently.
- Issuing orders for washing the MIC pipelines by the inexperienced supervisor when the MIC tank could not be pressurized was an error in judgement [16].
- Washing the MIC pipelines without inserting the slip blind by the operator was the most critical error [12,13,16,17,23].
- Not confirming the leak when the civil authorities telephoned the factory staff to enquire about the leak, delayed the evacuation process [15,23]. This caused confusion among the police and civil authorities.
- Though there was a toxic gas alarm to warn the people in the vicinity, it was not operated until 01.00 h (till the leak became severe) [13].
- Though the siren was activated at 01.00 h, it was switched off and reactivated only after 02.00 h after the escape of the whole contents of the MIC tank.
- Failure to recognize (i) the source of the MIC leak when it started, (ii) the sharp pressure rise in the tank, and (iii) the seriousness of the leak had been the major Humanware errors.
- Failure to use the empty MIC tank 619 when tank 610 showed sharp rise in pressure had been another major error [16]. The operators became panicky and the empty tank was not used. The high levels of stress which an operator is likely to experience in an emergency makes it difficult to make correct decisions [34].

TABLE 2

Causes of Bhopal accident: An analysis

	Technoware errors	Operator failure/design failure	Poor hazard management/safety management practices	Poor regulatory practices
1.	Capacity of vent gas scrubber insufficient		*	
2.	Refrigeration plant not functioning		*	
3.	No automatic sensors for MIC storage tanks		*	
4.	Pressure indicator not working		*	
5.	Sufficient gas masks not avialable		*	
6.	Flare tower was disconnected		*	
7.	Vent gas scrubber not kept in active mode		*	
8.	Plant modification connecting RVVH and PVH		*	
9.	Use of steel pipelines instead of stainless steel		*	
10.	There was only a manual mechanism for scrubber operation		*	
11.	No online monitor for monitoring contamination		*	
12.	Corroded valves not changed	*		
13.	Water curtain could rech only 10 m	*		
14.	No indicator for monitoring position of valves in the control room	*		
15.	Absence of hot lines		*	
	Humanware errors			
1.	MIC plant operator had no prior experience		*	
2.	Reduction in operating staff		*	
3.	Failure of shift operator to communicate about pressure increase	*	*	
4.	Repressurizing the tank without checking reasons for non-repressurization	*	*	
5.	Issuing orders for washing MIC pipelines	*	*	
6.	Not following safety precautions while washing	*	*	
7.	Not confirming leak when police officials called	*	*	
8.	Not operating the toxic alarm siren (switched off)		*	

TABLE 2 (continued)

	Technoware errors	Operator failure/design failure	Poor hazard management/safety management practices	Poor regulatory practices
9.	Failure to recognize the seriousness of the leak	*		
10.	Failure to use the empty tank		*	
11.	Failure to inform works' manager	*	*	
	Inforware errors			
1.	Panic reaction since no emergency plan		*	
2.	No risk analysis before plant modification		*	
3.	Information on possiblity of runaway reaction not communicated		*	
4.	Doctors did not know the line of treatment		*	
5.	Information on precautions against MIC exposure not disclosed		*	
6.	Significance of toxic gas alarm not known to public		*	
7.	Information on toxicity of MIC not disseminated properly		*	
8.	Considering phosgene as more toxic		*	
	Orgaware errors			
1.	Absence of emergency rehearsals to check systems and procedures		*	
2.	Poor emergency planning on site		*	
3.	Poor emphasis on systems' safety		*	
4.	Not relocating the facility when applied for licence		*	
5.	Absence of hazard assessment procedures		*	
6.	No improvements in safety even after six accidents		*	
7.	Not developing expertise for handling toxics		*	
8.	Treating hazardous and non-hazardous facilities alike		*	
9.	Safety audit results not communicated to UCIL		*	
10.	Non-review of safety procedures even after newspaper reports		*	
11.	Storing large quantities of MIC		*	

TABLE 2 (continued)

	Technoware errors	Operator failure/design failure	Poor hazard management/safety management practices	Poor regulatory practices
12.	Large manpower turnover		*	
13.	Non-disclosure of critical information		*	
14.	Poor commitment to safety		*	
15.	Absence of an emergency procedures manual		*	
16.	Absence of system for analyzing accidents		*	
17.	Heavy reliance on inexperienced opertors		*	
18.	Neglecting the warning of Factory Inspector		*	
19.	Carrying out plant modifications without hazard analysis		*	
20.	Inability of the operating managers to make operators comply		*	
	Climoware errors			
1.	Weak factory inspection procedures			*
2.	Factory inspectors not trained for complex tasks			*
3.	No hazard management system			*
4.	No emergency plan for the city of Bhopal			*
5.	Not disseminating information on wind movement			*
6.	Absence of a zoning policy or industrial location policy			*
7.	Not resolving medical controversy in time		*	*
8.	Absence of toxicological information on MIC		*	*
9.	Public not educated about the true risk		*	*

- The failure of the operators to inform the Works Manager as soon as the leak started [16].

Most of the Humanware errors arise due to lack of training, development of skills and absence of procedures and lack of experience in handling such situations. In hazardous facilities, all possible emergency actions should have been anticipated and interventions prescribed so that no actions, however elementary, have to be improvised by decision of the operator [34].

TABLE 3

Operating personnel in MIC Unit (Taken from [9])

Position	Planned number per shift	Actual number at the time of accident
Superintendent	One exclusively for MIC plant	One for the whole factory
Supervisors	3	1
Maintenance supervisors	2	None in night shift
Operators	12	6

Inforware errors

Lack of a proper emergency manual, absence of documentation on toxicity, non-disclosure of line of treatment, non-communication of precautions for handling toxics, absence of emergency warning procedures etc. are Inforware errors (Table 1). Most of the information available on MIC was proprietary in nature and very little information was available in open literature [35,36]. Experimental difficulties and relatively small industrial use of MIC have limited examination of its impact on health; its long term effects are almost entirely unknown [37]. All these compounded the problem of safe handling of MIC. The workers also did not know about the acute toxicity of MIC. The major Inforware errors at the Bhopal accident are given below and summarized in Table 2.

- There was a panic reaction since there was no emergency plan at the plant. The absence of an emergency plan was the major reason for the panic and ad hoc nature of response of the operators.
- The most critical Inforware error was not carrying out risk analysis or hazard assessment before the plant modification of connecting RVVH and PVH and before stopping the refrigeration facility for cooling the MIC tanks.
- At Union Carbide plant in West Virginia, U.S.A., a safety audit was carried out in July 1984 [28]. It was indicated that there can be a possibility of a runaway reaction in the MIC storage tank due to contamination. Action was initiated to prevent this [28]. At that time the UCIL plant was under maintenance shut down, but no action was initiated at UCIL.
- Doctors at Bhopal did not know the line of treatment to be used for treating MIC exposed subjects [29]. UCIL had a MIC leak earlier in 1983 and 24 persons were hospitalized, but it did not disclose the nature of treatment [10,16]. In the absence of a clear line of treatment, doctors provided only symptomatic treatment [18].
- Information on precautions of how to reduce the toxic effects of MIC exposure was not communicated to the public or public health authorities.

- The significance of the toxic alarm siren was not known to many people living in the vicinity of the Bhopal plant [15].
- Though Union Carbide Headquarters despatched a telex [18] on 5 December indicating that the line of treatment to be adopted for pulmonary complications arising from MIC exposure, this information was not communicated to public of doctors or government authorities fearing a panic response from public [38,39].
- UCIL as well as UCC considered phosgene as more toxic compared to methylisocyanate [40], though available toxicological information [4] does not support the contention that phosgene is more toxic. This aspect made emergency response very ad hoc in nature.

In other words, absence of toxicological information of methylisocyanate and non-disclosure of information by the corporation made the situation very complex.

Orgaware errors

The errors at the corporate level or Orgaware errors (Table 1) will have maximum impact since it will have repercussions on Technoware, Humanware and Inforware. It has been shown by Batstone [41] that most of the major industrial accidents have occurred because of poor organizational commitment for safe operation of hazardous facilities. In the absence of commitment for safety management: (i) sufficient Technoware will not be installed; (ii) proper skills will not be maintained; and (iii) proper procedures and manuals will not be prepared and implemented. The major Orgaware errors at Bhopal are given in Table 2. The errors are discussed briefly below and summarized in Table 2.

- The emergency planning was very weak at the Bhopal plant. Absence of a rehearsal of emergency on the real plant with the active involvement of all levels of management resulted in the poor identification of failure of many of the safety systems.
- Poor emergency planning on site made emergency coordination and communication difficult [17]. Since no action plan was prepared there was a panic reaction even among operators.
- In any major hazardous facility there will be a number of near misses or early warning signals [42,43]. There were two internal safety audits carried out at UCIL in 1979 and 1981 [13,17]. Both these audits indicated that safety procedures were poor, but no corrective action was initiated. Both these audits covered individual equipments and did not examine safety management systems in operation [5].
- When UCIL applied for a license for manufacturing MIC based pesticides in 1977, it did not consider relocating the facility even though the facility was close to human settlements. Though the Administrator of the Bhopal city suggested shifting of the pesticide facility away from human settle-

ments of Bhopal, the State Government rejected this suggestion [17]. This has been due to the absence of comprehensive industrial siting criteria.

- There were six accidents in the Bhopal plant of UCIL between 1978 and 1983 [3,16,17,36]. Three of these six accidents were toxic spills. Systematic analysis of these accidents were not carried out [10,11]. Hazardous and nonhazardous facilities cannot be treated alike and minor accidents have to be considered as early warning signals for poor safety management practices.
- Another major Orgaware error was the absence of a hazard assessment procedure at the firm.
- In the case of the UCIL plant, a well trained superintendent with long term experience in the MIC plant was transferred to a non-MIC based plant. The MIC plant superintendent was new to the plant and he could not conceptually grasp the complexities of the system when emergency arose [17]. Same policies for training cannot be used for hazardous and nonhazardous facilities [5], since operators must have capability to perceive risk properly and deal with complex situations.
- No review of safety procedures even after the appearance of newspaper reports indicated that safety systems at UCIL are poor. This is a consequence of non-institutionalization of systems' safety procedures.
- Treating hazardous and non hazardous facilities on similar lines by top management is another Orgaware error [11]. Hazardous facilities have to be treated as systems with two competing objectives i.e., economic profit making and operating safely. Overemphasizing one over the other, affects the system adversely.
- There was a major safety audit review at the UCC plant in USA during July–August 1984. This audit had identified that there was a possibility of a runaway reaction in the MIC tank while storing MIC [28], but no corporate action was initiated to take corrective measures at UCIL.
- Another major Orgaware error is the large scale storage of MIC at the Bhopal plant [13,14,16,17]. Though the daily usage of MIC was only 5 tonnes, the total storage amounted of 70 tonnes. Amounting to 12 days requirement of MIC when it was being produced internally has been a decision with low safety concern. The former Managing Director of UCIL had suggested a lower quantum of storage in smaller containers, but the UCC Headquarters had rejected this and suggested large scale storage in large containers [17]. In Japan there is one firm using MIC but it does not store any MIC [44].
- UCIL was not making profit and many senior persons were leaving to join other companies [9]. This had affected the Corporation's ability to maintain the safety procedures.
- Another error was the poor disclosure of critical information. UCIL had

obtained critical toxicological information on effects of MIC in 1983 [28]. This was revealed in a US Congressional Hearing [28] after the accident.

- There are enough circumstantial evidences [17] to indicate that safety was not a major issue for the senior managers at UCIL or UCC. In centralized systems, safety concerns cannot get institutionalized without top management commitment [41,45].
- Absence of an emergency checklist or procedures complicated the response and no early warning systems were activated on time.
- Absence of a system for assessing and analyzing accidents objectively has been another error.
- Heavy reliance on inexperienced operators [16,17] was another cause just as was the decision to reduce operating staff at UCIL. Both these factors brought down the ability for handling the emergency.
- Carrying out plant modification [4,5] without hazard and operability studies is an error at the corporate level.
- In 1981, a factory inspector had indicated to UCIL that washing MIC lines with slipblinds can have severe consequences [46]. The corporate safety set-up did not initiate any action on this.
- The inability of the operating managers to see that specific safety procedures are strictly adhered to. After the accident, the plant operators had indicated that safety was neither a concern of the management nor the operators [38]. At both levels there was negligence.

There have been a large number of Orgaware errors which compounded the Technoware and Humanware errors at Bhopal.

Climoware errors

Any hazardous facility is operated in the setting of a country namely, Climoware (Table 1) which controls, regulates and maintains te Technoware, Humanware, Inforware and Orgaware. For a hazardous facility, Climoware will have large interactions with these four components. In the national setting of a developing country modes of interactions with these four components will be even more complex. The major errors with reference to Bhopal are given in Table 2. These are examined below.

Safety regulations, expertise and experience of safety inspectorate staff, facilities available for inspection, hazard management systems in government, emergency planning systems, emergency coordination procedures, toxicological information support, communication systems support, organizational structures for emergency management etc. are the examples of Climoware factors that affect management of hazardous facilities.

The Climoware errors of Bhopal are given below.

- Weak factory inspection procedures in India interacted with the other factors [46]. In the Factory Act prevalent in India in 1984 hazardous and non-hazardous facilities were treated alike. In Madhya Pradesh, one Factory Inpector has to inspect 280 facilities, though the norm [46] specified by ILO is one Factory Inspector for every 150 facilities. This made it very difficult for the Factory Inspector to have a thorough examination of the facilities.

- Factory Inspectors in India are mostly mechanical engineers or electrical engineers and they are not well versed with complex chemical plants [5]. This makes the factory inspection procedures very cursory and superficial.
- The government had no institutionalized system for risk assessment (absence of organization and procedures) in India. A number of reports appeared in 1982 and in 1984 stating that Union Carbide had poor safety management practices [13,17]. The issue was raised in the State Legislative Assembly of Madhya Pradesh. The Minister replied that all necessary steps would be taken to improve safety. But in practice nothing happened.
- Bhopal had no emergency plan or emergency coordinator [16,17]. Because of this, there was severe confusion and lack of coordination. Immediately after the accident people were confronted with questions such as: (i) whether the water supply was safe (the source was a lake close to UCIL); (ii) whether any treatment was needed before consuming the MIC exposed water; and (iii) whether vegetables and meat exposed to MIC could be consumed.
- Meteorological information such as wind speed and direction, temperature, humidity, mixing height and cloud cover were not disseminated and used for estimating the MIC cloud movement and dispersion characteristics. Use of dispersion models with proper meteorological information might have provided the four kinds of information [47] needed for emergency planning, namely, (i) the direction in which the toxic cloud is moving; (ii) whether concentrations of the chemical downwind from the plant site will exceed critical toxicity; (iii) how soon the cloud will arrive at population areas and (iv) when the cloud will disperse. Use of computer models with continuously fed meteorological data along with the identity of chemicals involved, construction and use of a real-time model for studying the movement of the toxic cloud would have been possible, and this could have reduced the delays in emergency planning by civil authorities [48].
- Absence of a zoning policy or industrial location policy resulted in overlapping of industrial and residential zones [49]. Bhopal expanded rapidly and the squatter settlements close to UCIL grew fast. These squatter settlements were legalized by the Government in 1984, close to the firm [5].
- There was a severe medical controversy on the line of treatment to be adopted for the MIC exposed subjects. There was a long delay in suggesting a line of treatment due to the severe controversy [35]. This controversy created a panic reaction among the affected public [19,20,35]. Absence of a coordinating system for recommending the line of treatment has also

been partly responsible for the high mortality. Proper medical emergency coordination was absent at Bhopal [13,17].

A major Climoware error has been the absence of a centralized data base for toxicological information. The problem was compounded by the proprietary nature of information on MIC [50]. Some of the problems related to the absence of information are highlighted below:

i) One of the most commonly used sources, Handbook on Toxicology (1982 ed), did not contain any information on toxicity of MIC [51].

ii) The second most commonly used source, Handbook on Hazardous Materials in its 1979 edition did not include any information on MIC [52]. Only in the 1981 edition there was a mention of MIC [53], where it was reported as a minor skin irritant.

iii) Handbook of Reactive Chemical Hazards (1982) did not contain any toxicological information [54] on MIC.

iv) In addition to the lack of information on the dose response, time dependence and outcome of the sublethal effects, a further problem has been the uncertainty about the metabolic or chemical breakdown products of MIC [35,36].

v) There was only one study on toxicity of MIC and that too in a German Journal [55]. Only after the Bhopal accident, a number of papers appeared on toxicity of MIC [28,29,56–60].

vi) The 1984 Edition of the Handbook of American Conference on Governmental Industrial Hygienists (ACGIH) [28] mentioned that MIC is a skin irritant and can cause permanent eye damage. It also reported that inhalation of methylisocyanate vapour was dangerous even at great dilutions giving reference to the German paper that appeared earlier.

vii) Combination of reactivity, toxicity and volatility makes MIC a tough chemical to handle [61] but experimental difficulties and relatively small industrial use of MIC have limited examination of its impact on health, although its long term effects are almost entirely unknown yet [36,37].

viii) National Institute of Health, Bethesda (U.S.A.) informed the US Embassy at New Delhi on 6 December 1984, that MIC is known to be highly reactive and acutely toxic to mammals causing corrosive damage to the eyes, skin and membranes. But they were unable to locate any information on the potential long term human health effects of MIC [28]. However, isocyanate can cause pulmonary sensitization to exposed individuals, and later subsequent exposure to extremely low levels of exposure may trigger asthmatic episodes [28]. This probably was the reason for severe problems following the second exposure.

ix) Methylisocyanate is not included in products in the eleven exposure categories of the toxic Data Base of Stanford Research Institute [28].

x) Information Profiles on Potential Occupational Hazards prepared in 1977 for NIOSH (U.S.A.), reported that the TLV for MIC is 0.02 ppm based on an ACGIH report of 1971 [28].

xi) Union Carbide's Industrial Hygiene Monitoring Program reported (in

1983) a rating of 4 for MIC stating that it has the following characteristics: (a) known carcinogen; (b) causes irreversible central nervous system disturbances; (c) have OSHA standards of permissible exposure limits of less than 5 ppm; (d) result in cumulative long term organ toxicity that is irreversible; and (e) is predominantly fast acting and can produce major injury [28].

Poverty, illiteracy, underdevelopment and absence of communication facilities resulted in the absence of information [62]. The persons living in the vicinity of UCIL did not perceive that MIC was a toxic substance. They considered it as a chemical used for medicines for trees and agricultural crops. The Bhopal accident has been described as an example of blind technology transfer in which a complex and hazardous technology was transferred to an area which could not handle it safely because of lack of experience in handling hazardous products, absence of trained personnel, poor safety consciousness and poor work culture [62].

Lessons for Managing Hazardous Facilities

Based on the analysis of the Bhopal accident given in the earlier section, the imperatives needed for managing hazardous facilities can be identified in detail as follows (Fig. 6).

1) Technoware

- Setting up of condition monitoring equipments/emergency handling equipments;
- Installing reliable control systems using microprocessors/distributed data processing systems, etc;
- Installing safety interlocks for preventing operation of systems if certain vital subsystems are inoperative;
- Automation of facilities to reduce the need to have human operators;
- Hazardous facilities with zero venting or completely closed loops; and
- Non-destructive testing systems for regular inspection.

2) Humanware

- Skill development for systems safety procedures;
- Imparting hazard analysis skills;
- Developing emergency handling capability;
- Strengthening EIA capability;
- Improving capability for inspecting hazardous facilities; and
- Training people in hazard and operability studies.

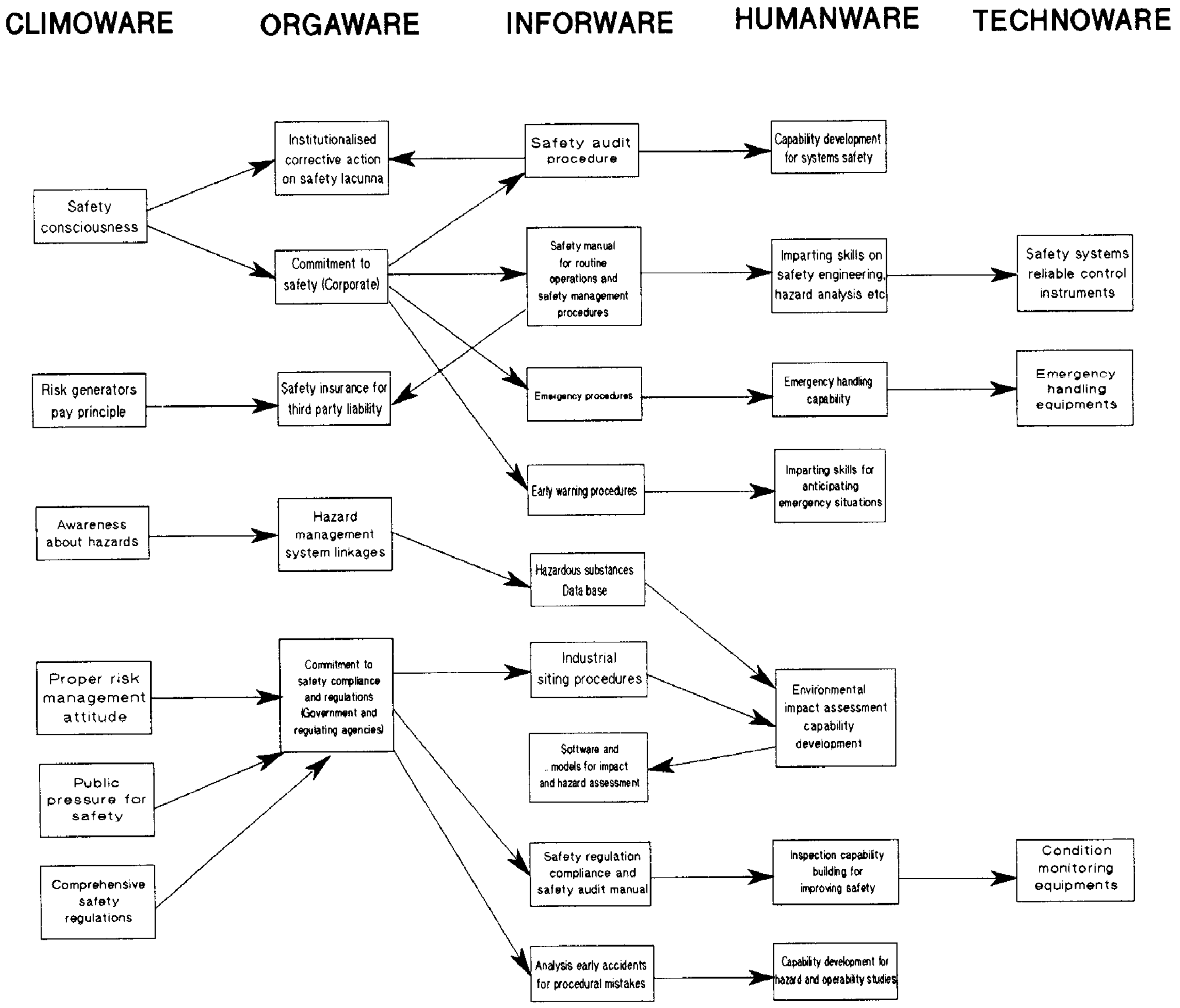

Fig. 6. Imperatives for safety in hazardous facilities.

3) Inforware

- Safety audit to be made statutory involving external persons and a manual to be prepared;
- Preparing hazard assessment manuals;
- Institutionalizing emergency procedures;
- Early warning procedures to be made specific;
- Special industrial zoning procedures for hazardous facilities;
- Software and models for hazard assessment;
- Safety regulations manual; and
- Analysis or investigation procedures for accidents so that smaller accidents are analyzed for procedural mistakes.

Conclusions

Some of the specific conclusions that can be arrived at based on the analysis of factors at work during the Bhopal accident are discussed below:

1) Organizational level or corporate failures are the most critical factors [41,63] that need attention if accidents are to be avoided. Table 4 identified the operators/managers who have the responsibility of reducing various errors in hazardous facilities. The most important prerequisite for accident prevention is the top management commitment towards safety. Regulatory agencies and insurance agencies [63] can provide a basic framework for safety and support systems needed, but the basic institutionalization of safety procedures should be at the corporate level. At the corporate level, in hazardous facilities, maximum emphasis has to be placed for properly equipping the facilities, installing early warning systems, training operators, informing public and agencies [65] about the hazards involved, assessing and reviewing hazards, institutionalizing safety practices, preparing emergency plan and complying with all safety standards. Table 4 shows that corporate level action will have the maximum impact on reducing the safety errors, in hazardous facilities (strengthening Orgaware).

2) Safety levels that are to be adopted in any hazardous facility have to be determined in terms of the population at risk. When hazardous facilities are built in developing countries, the levels of safety to be achieved must be higher and not lower than that planned for developed countries since operators in developing countries may not be skilled, population densities around industrial centres are likely to be high, communication infrastructure may not be well developed, emergency management procedures are likely to be slow (because of communication problems), and hazard management practices may not be properly institutionalized (Strengthening Orgaware).

3) Conventional safety management structures used for non-hazardous facilities are likely to be ineffective for hazardous facilities since safety is a lower level objective in non-hazardous facilities. Production or financial targets can-

not be the prime objective in hazardous facilities since a subservient safety system cannot gear up the corporate commitment towards higher levels of safety (strengthening Orgaware).

4) Another major step to ensure institutionalizing of hazard management is the implementation of the principle that hazard generators have to bear the hazard control costs through internalization of damage costs in the form of a proper insurance system [64]. As of now there is no agreed international arrangement [66] for hazard accident insurance. Hazardous facilities may have to pay insurance charges commensurate with the risk they pose. Regulatory agencies can press for this reform since this procedure will reduce the administrative cost of regulators and will ensure that safety is not neglected (strengthening Climoware).

5) The siting procedures for hazardous facilities have to be made comprehensive. Hazard assessment has to be a part of the project appraisal system. The siting procedures for hazardous facilities prone to low probability-high consequence [67] accidents have to be open and not secretive. Starting from the project formulation stage itself the project proposers have to be open in approach with respect to the nature of hazards, precautions etc. (strengthening Climoware).

6) A complete formalization of all operations is a necessary step in hazardous facilities so that operators do not take any ad hoc decisions [34]. Otway and Misenta [34] have shown that at the time of an emergency, operators will be under severe stress and there should be minimum intervention by the operators in a hazardous facility. The operation should be aware of the steps to be taken if anything unusual is noticed and also provision should be made for complete logging and monitoring of all parameters even if some of them may be considered to be unnecessary by the operator (strengthening Inforware). Action imperatives have to be made explicit so that the operator cannot intervene wrongly. The Bhopal accident could have been completely averted, if the reasons for non-pressurization of the MIC tanks that occurred on 26 and 30 November 1984 were thoroughly investigated before attempting the washing of MIC processing lines (upgrading Inforware).

7) Emergency planning and emergency rehearsals have to be made statutory for all hazardous facilities and cities with hazardous facilities (strengthening safety climate factors). Early warning procedures, evacuation procedures, medical relief procedures and emergency communication procedures should be explicitly stated with the necessary action imperatives (strengthening Inforware).

8) An independent Hazardous Substances Information Centre linked to major toxic substances data base has to be established. The United Nations Environment Programme has a network called International Registry of Potentially Toxic Chemicals [68]. Such data bases have to be updated with

TABLE 4

Responsibility for preventing hazardous accidents

Error type	Operators designers	Corporate managers	Controlling agencies
Technoware errors			
Design defects	*	*	
Wrong material selection	*	*	
Malfunctioning of equipment	*	*	
Disconnection of facilities		*	
Poor instrumentation		*	
Plant modifications		*	
Insufficient safety margin	*	*	
Contamination	*	*	
Low levels of safety provisions		*	
Absence of hot lines		*	
Humanware errors			
Poor training		*	
Inability to perceive risk		*	
Neglecting safety instructions	*	*	
Error in judgement	*	*	
Faulty operations	*	*	
Faulty safety procedures		*	
Absence of experienced personnel		*	
Delay in taking decisions	*	*	
Deviating from specified operating procedures	*	*	
Inforware errors			
No manual emergency operations		*	
Absence of documentation on safety		*	
Delay in getting toxicological information		*	
Non-disclosure of line of treatment		*	
Non-communication of precautions		*	
Absence of use of emergency warning procedures		*	
Orgaware errors			
Poor emergency planning (on-site)		*	
Neglecting early warning signals		*	
Poor industrial siting criteria		*	*
Neglecting safety even after accidents		*	
Absence of hazard assessment		*	
Non institutionalization of system safety		*	

TABLE 4 (continued)

Error type	Operators designers	Corporate managers	Controlling agencies
Treating hazardous and non-hazardous facilities alike		*	*
Over emphasis on profits		*	
Poor corporate information exchange		*	
Large scale storage of toxics		*	*
Large manpower turnover		*	
Poor disclosure of critical information		*	
Poor commitment for safety		*	
Non specification emergency procedures		*	
Absence of systems for assessing previous accidents		*	
Climoware errors			
Weak factory inspection procedures		*	
Safety inspectorate ill-equipped		*	
Absence of hazard management systems in Government			*
Poor emergency planning off-site			*
Poor coordination of emergency off-site			*
Absence of a strong toxicological data base		*	*
Poor emergency communication		*	*
Absence of emergency evacuation		*	*
Insufficient emergency medical care		*	*
No permanent structure for emergency management			*
Permitting human settlements close to hazardous facilities			*

more toxicology information and identification of proper national focal points (strengthening Inforware).

9) The hazard causal structure of accident prone facilities will be such that there is a number of near misses before a high consequence event happens [42,43]. The management system should be such, that near misses have to be investigated fully [42,43]. Apart from this, monitoring systems in hazardous facilities may have to have a higher level of redundancy through: (i) duplication of monitoring and control instrumentation; and (ii) reduction of operator intervention through automated early warning systems (using complex Tech-

noware). Hazardous facilities should completely eliminate non-formalized operator interventions and reduce the need for the operators' role in actuating early warning signals [69] (upgrading Technoware).

10) Hazard assessments have to be carried out by internal persons with the help of external 'Hazop' experts. The leading part in the formulation of a detailed 'Hazop' or 'Hazan' study [70] on a completed installation has to be done by internal staff and should be used for safety management of day to day operations. Relief and blow down reviews and hazard and operability studies normally take place late in design [71]. If we are to build simpler, cheaper and safer plants, then we need to allow time in the early stages of design for a critical review and evaluation of alternatives before the detailed engineering starts [71]. Corporations should strengthen the hazard or risk assessment capability within them and prepare proper hazard assessment and emergency management manuals. Management has to stimulate activities for improving perceptual skills (improving Humanware skills) by creating an environment that makes it possible for anyone concerned to work on diminishing the risk of occurrence of low probability events, by encouraging open mindedness (improving Humanware).

11) Inspection capability of safety inspectors have to be upgraded through power training and skill development programmes. A new cadre of safety inspectors capable of dealing with hazardous and complex systems have to be developed. They should be trained in hazard assessment and systems safety (improving Humanware).

12) Statutory regulations like "Right to Know" [72] should be enacted so that Corporations dealing with hazard substances have a responsibility to provide all the necessary toxicological information (strengthening Climoware).

13) There is always a strong tendency to underestimate risks in complex facilities. In the case of the Bhopal plant also, inspite of the fact that there was a large number of clear warning signals, the risks were not perceived or discounted but underestimated. Some of the common reasons leading to underestimation of risks are [73]:

- Failure to consider the ways in which human errors can affect technological systems;
- Overconfidence of experts to deal with hazardous situations;
- Failure to appreciate how technological systems function as a whole;
- Slowness in detection chronic, cumulative effects;
- Failure to anticipate human response to safety measures; and
- Failure to anticipate common mode failures.

Underestimation of risks is a natural consequence of the working of a human information processing system [74]. Through systematic skill development, some of these failures are to be corrected (improving Humanware).

In summary, risk is inherent to operating all hazardous facilities. Efforts must be made to anticipate and prevent large scale releases of toxics or spills of toxics through proper institutionalized procedures and education of experts with multidisciplinary skills (within Corporations) for carrying out hazard assessments.

Acknowledgements

The authors would like to express their thanks to the two referees and Dr. M.N. Sharif (Director, APCTT) who have given valuable suggestions on the manuscript.

References

1 P. Lagadec, Major Technological Risk, Pergamon Press, New York, NY, 1982.
2 C.E. Perrow, Normal Accidents, Basic Books, New York, NY, 1984.
3 G.U. Fortunati, The Seveso accident, Chemosphere, 14 (1985) 792.
4 B. Bowonder, J.X. Kasperson and R.E. Kaperson, Avoiding future Bhopals, Environment, 27 (7) (1985) 6.
5 B. Bowonder, Bhopal incident, Environmentalist, 5 (1985) 89.
6 Union Carbide Corporation, Methyl Isocyanate Incident: Investigation Team Report, UCC, Danbury, 1985.
7 The Study Group on Bhopal Accident, Bhopal — Death City, Technology and Human Being Company, (Published in Japanese), Tokyo, 1985.
8 J. Ui and R.K. Keshwani, The Lesson of Bhopal, The World, April, pp. 224–235, 1986 (in Japanese).
9 A. de Grazia, A cloud over Bhopal, Popular Prakashan, Bombay, 1985.
10 Ekalavya, Bhopal, Ekalavya, E1/208 Arera Colony, Bhopal, 1985.
11 T.N. Gladwin, The Bhopal tragedy, NYU Business, 5 (1985) 17.
12 I. Fera, Not Sabotage, Illustrated Weekly of India, 106 (17) (1985) 32.
13 B. Bhushan and A. Subramanian, Bhopal: What really happened, Business India, 182 (1985) 102.
14 T.A. Kletz, What Went Wrong, Gulf Publ., Houston, TX, 1985.
15 S. Khandekar and S. Dubey, Bhopal: City of death, India Today, 9 (1985) 4.
16 Technica, An Analysis of Bhopal Accident: Contributory Causes, Technica, London, 1985.
17 W. Morehouse and M.A. Subramaniam, The Bhopal Tragedy, Council on International and Public Affairs, New York, NY, 1986.
18 APPEN, The Bhopal Tragedy: One Year After, Sahabat Alam Malaysia, Pengang, 1986.
19 R. Ramaseshan, Bhopal Tragedy: Profit Against Safety, Economic and Political Weekly, 19 (1984) 214.
20 R. Ramaseshan, Bhopal Gas Tragedy, Economic and Political Weekly, 20 (1985) 56.
21 P. Shrivastava, Managing Industrial Crisis, Vision Books, Delhi, 1987.
22 T. Miyake and B. Bowonder, Bhopal Tragedy: Analysis of Problems on the Safety Control, J. Jpn. Soc. Saf. Eng., 26 (6) (1987) 346.
23 B. Bowonder, An Analysis of the Bhopal Accident, Project Appraisal, 2 (1987) 157.
24 B. Bowonder, The Bhopal Accident, Technol. Forecasting and Social Change, 32 (1987) 169.
25 B. Bowonder and H.A. Linstone, Notes on the Bhopal Accident: Risk Analysis and Multiple Perspectives, Technol. Forecasting and Social Change, 32 (1987) 183.
26 C.D. Kumar and S.K. Mukherjee, Methyl Isocyanate: Profile of a Killer Gas, Sci. Today, 19 (1) (1985) 10.

27 R. Wilson, A visit to Chernobyl, Science, 236 (1987) 1636.
28 House Committee on Energy and Commerce, Subcommittee on Health and Environment, Hazardous Air Pollutants, Dec. 14, 1984, 98th Congress Hearing, 2nd Session, 1984, Serial 192, Washington, DC, 1984.
29 S.K. Das, The worse aftermath, Economic and Political Weekly, 22 (1985) 2192.
30 The Central Pollution Control Board, Report on Bhopal Disaster, Central Pollution Board, Nehru Place, New Delhi, 1985.
31 Delhi Science Forum, Bhopal gas tragedy, Soc. Sci., 13 (140) (1985) 36.
32 The Technology Atlas Team, Technological capabilities assessment in developing countries, Technol. Forecasting and Social Change, 32 (1987) 5.
33 D. Weir, Bhopal syndrome, International Organization of Consumers Unions, Penang, 1986.
34 H.J. Otway and R. Misenta, Some human performance characteristics of nuclear operations, Futures, 18 (1980) 340.
35 A.G. Salmon, M.K. Muir and N. Andersson, Acute toxicity of methyl isocyanate, British J. Ind., 42 (1985) 795.
36 D.R. Varma, Anatomy of the Methyl Isocyanate Leak in Bhopal, in: J. Saxena (Ed.), Hazard Assessment of Chemicals, Hemisphere Publishing Corp., Washington, DC, 1987, Vol. 5, pp. 233-289.
37 R. Dagani, Data on MIC's toxicity are scant, leave much to be learned, Chem. Eng. News, 63 (6) (1985) 37.
38 T.A. Kletz, Hazop and Hazan, The Institution of Chemical Engineers, Rugby, 1986.
39 S.R. Kamat, Early observations on pulmonary changes and clinical morbidity due to the isocyanate gas leak at Bhopal, J. Postgraduate Med., 31 (2) (1985) 63.
40 P. Bidwai, A. Deadly Delay in Bhopal, Times of India, 7 December 1984.
41 R.J. Batstone, Preventing Major Hazard Accidents, Paper Presented at IAEA/UNEP/WHO Workshop, World Bank, Washington, DC, 1986.
42 F.P. Lees, The hazard warning structure of major hazards, Trans. Inst. Chem. Eng., 60 (1985) 211.
43 F.P. Lees, Hazard warning structure, Reliability Eng., 10 (1985) 65.
44 The Study Group on Bhopal Accident, What is the Problem in Japan, Technology and Human Being, September 1985, pp. 187-198, (in Japanese).
45 International Labour Organization, Safety and Health Practices of Multinational Organizations, ILO, Geneva, 1984.
46 P.G. Mathai, Industrial safety: Belated awakening, India Today 10 (2) (1985) 112.
47 G. Graff, Beyond Bhopal: Toward a fail safe chemical industry, High Technol., 5 (4) (1985) 55.
48 M.P. Singh and S. Ghosh, Bhopal gas tragedy: Model simulation of the dispersion scenario, J. Hazardous Materials, submitted.
49 B. Bowonder, S.S.R. Prasad and R. Reddy, Project siting and environmental impact assessment in developing copuntries, Project Appraisal, 2 (1987) 11.
50 A.R. Michaelis, The lesson of Bhopal, Interdisciplinary Sci. Rev., 10 (1985) 193.
51 G.D. Clayton and F.E. Clayton, Patty's Industrial Hygiene and Toxicology: Vol. 2C: Toxicology, Wiley, New York, NY, 1982.
52 M. Sittig, Hazardous and Toxic Effects of Industrial Chemicals, Noyes Data Corp., Park Ridge, 1979, pp. 266-267.
53 M. Sittig, Hazardous and Toxic Effects of Industrial Chemicals, Noyes Data Corp., Park Ridge, 1981.
54 L. Bretherick, Handbook of Reactive Chemical Hazards, Butterworths, London, 1982, pp. 298.
55 K. Kimmerle and A. Eben, Zur Toxicität von Methylisocyanat und dessen Quantitativer Bestimmung in der Luft, Archiv Toxicol., 20 (1964) 235 (in German).

56 W.F. ten Berge, The toxicity of methylisocyanate for rats, J. Hazardous Materials, 12 (1985) 309.
57 D.R. Varma, Reproductive toxicity of methyl isocyanate in mice, J. Toxicol. Environ. Health, 21 (1987) (to appear).
58 D.R. Varma, Epidemiological and experimental studies on the effects on methyl isocyanate on the course of pregnancy, Environ. Health Perspec., 1987 (to appear).
59 B. Nemery, D. Dinsdale, S. Sparrow and D. Ray, Effect of methyl isocyanate on the respiratory tract of rats, Br. J. Ind. Med., 42 (1985) 779.
60 J.S. Ferguson, M.F. Stock and Y. Alarie, Respiratory effects of methyl isocyanate, Toxicol. Appl. Pharmacol., 82 (1986) 329.
61 W. Worthy, Methyl isocyanate: The chemistry of a hazard, Chem. Eng. News, 63 (6) (1985) 27.
62 G.R. Lanza, Blind technology transfer: The Bhopal example, Environ. Sci. Technol., 19 (7) (1985) 581.
63 R.J. Batstone, Major Accident Prevention, Int. Symp. on Prevènting Major Chemical Accidents, Am. Inst. Chem. Eng., Washington, DC, 1987.
64 P. Kleindorfer and H. Kunreuther, Insuring and Managing Hazardous Risks, IIASA (Int. Int. Appl. Syst. Anal.), Laxenburg, 1986.
65 W.D. Conn and N.R. Feimer, Communicating with the public on environmental risk, The Environ. Professional, 7 (1985) 39.
66 D.H. Ott, Bhopal and the law, Third World Q., 7 (1985) 648.
67 H. Kunreuther and J. Linnerooth, Low probability accidents, Risk Anal., 4 (1984) 143.
68 United Nations Environment Programme, Annual Report: 1986, UNEP, Nairobi, 1987.
69 T.A. Kletz, An Engineer's View of Human Error, The Institute of Chemical Engineers, Rugby, 1987.
70 J. Petts, J. Withers and F. Lees, Expert evidence at inquiries into major hazards, Project Appraisal, 1 (1986) 3.
71 T.A. Kletz, Inferently safer plants, Plant Oper. Prog., 4 (1985) 164.
72 J.S. Himmelestein and H. Frumkin, The right to know about toxic exposures, New Eng. J. Med., 312 (1985) 687.
73 B. Fischhoff, P. Slovic and S. Lichtenstein, Lay Foibles an Expert Fables in Judgements About Risks, in: T. Oriordan and T.K. Turner (Eds.), Progress in Resource Management and Environmental Planning, Vol. 3, 1981 p. 161.
74 B. Bowonder, Environment risk assessment issues in the third world, Technol. Forecasting Social Change, 19 (1981) 99.